PVCPIPE association

Handbook of PVC Pipe Design and Construction

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Preface

PVC pipe's combination of strength, durability, and versatility has made it the pipe most often installed in the United States and Canada. The rise of PVC pipe to prominence is rooted in its inherent suitability for handling both the physical/mechanical and chemical/environmental conditions associated with pipe infrastructure systems. PVC pipe does not corrode and is conservatively projected to perform in excess of 100 years.

Compared to alternative types of pipe, PVC pipe requires less energy to manufacture, transport, handle, install, and operate. PVC pipe is generally easier to install and can be joined to standard appurtenances without special connections or adaptor couplings. Typically, installed PVC pipe requires little or no maintenance.

In order to better meet the growing needs of design engineers, pipe utility managers, and students, this new edition of *Handbook of PVC Pipe Design and Construction* presents the latest information on the design and installation of PVC pipe. It provides practical engineering, construction, and operations information applicable to underground PVC piping systems.

Handbook of PVC Pipe Design and Construction, 5th edition, is the collaborative result of thousands of hours of research and review. Section and subsection numbering, as well as figure and table designation, allows for easy reference and quick access to contents. As in previous editions, emphasis is placed on general principles, useful empirical rules, and practical design and installation approaches. Also presented are consensus recommendations of industry leaders, primarily from North America but also from around the globe.

All chapters are updated and new chapters have been added to the fifth edition. The material on pipe installation has been split into three chapters: general construction, pressure pipe installation, and nonpressure pipe installation. A chapter on trenchless technology has been added, providing technical guidance for this quickly growing market segment. Likewise, PVCO pipe is now discussed in its own chapter.

In the references provided the reader will find further information on related topics. Updated standards and manuals along with current contact information are listed.

English units are used in the *Handbook*, since North America has not fully converted to Système International (SI). However, SI units are included in many tables and charts. In addition, a unit conversion table is provided at the end of the book.

Handbook users are invited to contact Uni-Bell's staff of engineers for additional technical support or to obtain clarification on information contained here. Technical services are available on request through member companies or through direct request to Uni-Bell. A directory of the current membership of the Uni-Bell PVC Pipe Association is available at www.uni-bell.org.

The statements contained in *Handbook of PVC Pipe Design and Construction, 5th edition,* are those of the Uni-Bell PVC Pipe Association. They are not warranties, nor are they intended to be such. Inquiries on specific products, product attributes, and manufacturer warranties should be directed to member companies.

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November 2012

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CHAPTER 1

Polyvinyl Chloride Pipe

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1.1 Introduction

Water and wastewater infrastructures are the lifelines of modern society. In North America, over 450 million people rely on more than 60,000 water and wastewater systems. As the first line of defense against waterborne disease, these systems significantly reduce sickness and related healthcare costs in society. Each year wastewater systems keep billions of tons of pollutants out of rivers and lakes and away from coastlines, maintaining water that is safe for fishing, swimming, and everyday use.

The reliability of these critically important systems is declining at an alarming rate. Escalating deterioration of water and sewer systems threatens the provision of safe drinking water and essential sanitation services, both today and for future generations. Quite simply, the piping materials that have historically served as the backbone of the water and sewer infrastructure system are deteriorating. During the past half century, PVC pipe has taken on a constantly increasing role in replacing these older materials with a modern alternative.

1.2 PVC: A Revolutionary Pipe Material

During the twentieth century a truly remarkable advancement in pipeline materials engineering occurred. The revolution was born in polymer science and has, through many decades of technological refinement, been accelerating. The polymer that has achieved frontrunner status throughout this pipe revolution is polyvinyl chloride (PVC).

In 1999 PVC pipe was recognized by *Engineering News Record* as one of the top 20 engineering innovations of the previous 125 years, due to the material's combination of lightness, strength, ease of installation, and resistance to corrosion. In addition, PVC's chemical resistance and high stiffness account for it becoming a popular pipe material for many pressure and nonpressure applications.

According to the results of a 2010 *Trenchless Technology* survey, in the sanitary sewer market PVC is the most accepted, most specified, and most easily maintained pipe material. PVC pipe also ranked highest in life cycle performance.

The use and availability of PVC pipe has grown steadily since the 1950s. Polyvinyl chloride has become the preferred pipe material for such major markets as sanitary sewers and water transmission and distribution. PVC pipe is also widely used in the following applications:

- sewer forcemains
- reclaimed water
- storm sewer
- land and highway drainage

Fig. 1.1 48-inch PVC pipe installation.

- agricultural and turf irrigation
- trenchless installation.

In North America each year the total installed length of PVC water and sanitary sewer pipe exceeds that of any alternative piping material. Much of this handbook is devoted to the proper application of PVC pipe within these major markets.

Through technological advancements, the PVC pipe industry has been able to expand production to include larger pipe diameters (e.g., Fig. 1.1) and allow for more efficient use of materials, such as the introduction of *molecularly oriented PVC pipe*, also known as *PVCO* (detailed in Chapter 14).

More recent improvements in PVC technology have opened the door to the trenchless market; such improvements include self-restrained joints and the technology to fuse PVC pipe in the field.

1.3 Thermoplastics and Thermosets

PVC is part of the large, complex, and constantly developing group of plastics. Like metals and other pipeline materials, plastics possess a wide range of properties that lend themselves to numerous applications. Structurally, plastic materials used for pipe production can exhibit properties ranging from soft and flexible to hard and rigid.

Plastic pipe materials may be divided into two basic groups: *thermoplastics* and *thermosets*. Thermoplastics, as the name implies, soften when heated and harden when cooled. They can be formed and re-formed repeatedly, but the reprocessing steps must be controlled and limited to ensure retention of original performance properties. PVC is a thermoplastic; it is manufactured using an *extrusion process*, which is described in Chapter 4. The capacity to be reheated and re-formed also enables PVC pipe to be manufactured with post-extrusion, heat-formed bell ends for jointing. PVC fittings are generally made in an *injection molding process* or a *fabrication process* through the assembly of molded or extruded parts. Chapter 4 describes both manufacturing processes.

Thermoset plastics go through a soft plastic stage only once, then harden irreversibly and cannot again be softened without incurring permanent damage. Some of the more common thermoset plastics used for pipe are glass-fiber-reinforced thermosetting resin and cross-linked polyethylene (PEX).

1.4 History of PVC

Polyvinyl chloride was discovered in the nineteenth century when scientists observed that the organic chemical gas *vinyl chloride* (C_2H_3Cl)—itself a recently created compound—reacted in a test tube upon exposure to sunlight to form an off-white solid material. This result represented simple *polymerization* of the vinyl chloride, forming a new plastic material, *polyvinyl chloride*.

Subsequent investigation of the new polymer at first created great excitement and, somewhat later, great disappointment. The scientists were astonished by the incredible new plastic material, which seemed nearly inert to most chemicals and, in fact, virtually indestructible. However, they soon found the material so resistant to change that they were forced to concede that it could not be easily formed or processed into useful applications. Soon thereafter, PVC was seen as another of science's great discoveries that had no apparent application, and for a while the world forgot about the unique new plastic.

It was not until the 1920s that curiosity again brought polyvinyl chloride into the limelight, and scientists in Europe and North America launched an extended campaign that eventually brought PVC plastics to the modern world. Technology continued to evolve worldwide, but particularly in Germany, where PVC was used in its unplasticized, rigid form. In 1931, PVC compounds were developed by German scientists, and millions of pounds of PVC were produced, some for pipe. In large part, the PVC pipe industry was born out of a necessity created by World War II. Again, it was German scientists and engineers who turned to PVC, using it as a pipe material to quickly restore essential water and wastewater pipelines in cities damaged by Allied bombings. Several of these earliest PVC pipelines are still in service, providing testimony to PVC's outstanding durability.

Before the Second World War, and to some extent during the war, PVC processing was largely carried out on machinery developed for rubber or celluloid. Even immediately after the war, the technology remained fairly primitive and the processing machinery was not engineered specifically for PVC. In the two decades following the war, there were considerable advances in PVC technology, both in formulation and processing. During this time, the development of more effective stabilizers, lubricants, and processing aids, together with processing machinery engineered specifically for PVC, allowed for increasing success in the extrusion of quality, rigid (unplasticized) PVC pipe. The result was that PVC pipe began competing with traditional products in a number of major markets, including sewer and drainage, water distribution, electrical conduit, chemical processing, and drain, waste, and vent plumbing.

PVC pipe's success in North America parallels what occurred in Europe. After 1951, when it was introduced in North America, PVC became the largest volume plastic piping material. In 1955, the year the American Society for Testing and Materials (ASTM) organized a group to write plastic pipe standards, North American plastic pipe shipments totaled just under 40 million pounds. By 1968, sales of PVC pipe surpassed 200 million pounds annually.

Figure 1.2 charts worldwide PVC pipe industry growth from the mid-1970s to 2010, a growth rate that has been nothing short of phenomenal. Factors responsible include continuing advancements in processing technology, improved joining materials, continuing standardization programs, improved quality control testing, and a steady increase in the understanding and acceptance of PVC by designers, contractors, and municipalities.

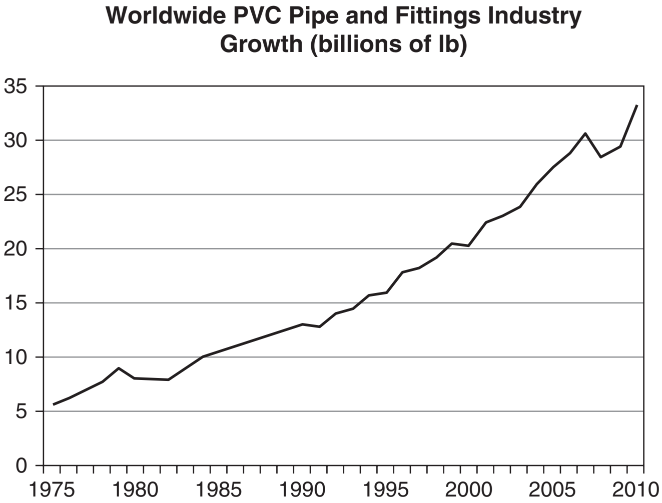

Fig. 1.2 World PVC pipe and fittings industry growth.

1.5 PVC Pipe Advantages

The range of useful properties afforded by PVC makes it one of the most versatile of all pipe materials, a fact confirmed by the variety of applications and markets served by PVC pipe. Specification or use of PVC pipe is justified by one or several of the attributes here discussed.

1.5.1 Corrosion Resistance

Corrosion is the leading cause of the water main break epidemic in North America, estimated at some 300,000 breaks annually. All told, leaking pipes lose some 2.6 trillion gallons of drinking water every year, according to the American Society of Civil Engineers (ASCE). This is 17% of all water pumped in the United States. Moreover, according to a 2002 Congressional study, this loss is a drag on the economy, costing U.S. drinking water and wastewater systems over $50.7 billion annually, translating into more than $1 trillion over the next 20 years.

PVC pipe is a non-conductor of electricity and immune to electrochemical reactions caused by acids, bases, and salts that cause corrosion in metals. Since this characteristic exists both inside and outside the pipe, PVC needs no expensive coatings or liners and can be expected to outlast pipes made from alternate materials.

1.5.2 Chemical Resistance

PVC pipes exhibit resistance to a wide range of chemicals at temperatures up to 140°F. PVC is resistant to chemicals normally found or used in homes, although some industrial applications may require an evaluation of chemical resistance. The chemical resistance ability of PVC is further evidenced by its frequent use as a protective liner for other pipe materials.

1.5.3 Light Weight

PVC pipes offer a tremendous weight advantage, which is a particularly important safety aspect. The material's ability to be handled more easily than other piping materials minimizes worker injury and facilitates lower cost transportation and installation. One person can easily carry two 20-ft lengths of 4-in. PVC pipe. According to the United States Bureau of Labor, the plastic piping industry has an outstanding safety record, experiencing far fewer injuries and illness in every phase of production on average than similar industries.

1.5.4 Flexibility

PVC pipe's resistance to fracture is an extremely important performance advantage. While PVC pipe is made from rigid (unplasticized) PVC compound, the pipe itself has the ability to yield under loading without fracturing. PVC's modulus of elasticity is a major advantage in underground applications, particularly where soil movement or vibration is anticipated. In pressure applications, PVC's modulus of elasticity also reduces the magnitude of pressure surges (i.e., water hammer).

1.5.5 Long-Term Tensile Strength

PVC pipe compounds are formulated to attain long-term tensile strength. The long-term hydrostatic design basis (HDB) for PVC is two or more times that of other common thermoplastic pipe materials.

1.5.6 Watertight Joints

A major requirement for nearly all piping applications is joint tightness. PVC pipe is available with deep insertion, push-together gasketed joints, which consistently outperform joints of alternative pipe products. PVC pipes are easy to assemble, and a pipeline can be filled, tested, and placed in service immediately after assembly.

As mentioned previously, the ASCE estimates that 2.6 trillion gallons of potable water are lost annually through leaking pipes. This loss represents a waste of $4.1 billion dollars' worth of electricity needed for pumping. PVC joints are leak-free, eliminating these additional pumping costs.

1.5.7 Abrasion/Wear Resistance

PVC pipe exhibits outstanding resistance to wear and abrasion. PVC pipe has proven itself more durable than pipes of metal, concrete, or clay for the transport of abrasive slurries.

1.5.8 Impact Strength

Under normal conditions, PVC pipe possesses relatively high resistance to impact damage compared to pipes made from clay, concrete, and most other conventional materials. Even though PVC pipe does exhibit a reduction in impact strength at very low temperatures, its impact strength remains more than adequate, usually exceeding that of alternate pipe materials.

1.5.9 Hydraulic Efficiency

PVC pipe provides smooth wall surfaces that reduce fluid friction and resistance to flow. This hydraulic smoothness inhibits slime build-up in sewers and virtually eliminates tuberculation and encrustation in water distribution mains. The end results are a more efficient pipeline design and significantly lower maintenance costs.

1.5.10 Longer Lengths

PVC pipe generally is available in standard lengths of 14 and 20 ft. These long lengths reduce the number of joints required for an application compared to most other pipe products. Fewer joints allow for faster, more efficient installation.

1.5.11 Water Quality

PVC pipe's resistance to corrosion and chemical attack ensures it will not react with drinking water. PVC pressure pipes do not adversely affect water quality and do not produce corrosion byproducts, even after decades of use. PVC is so safe that it is used for intravenous medical tubing, and it is the pipe of choice for ecologically sensitive environments like saltwater aquariums, which must use the most inert and safe pipe materials available.

In programs dating back to the mid-1960s, PVC water pipes have been tested extensively to verify their safety for drinking water. Literally millions of water quality tests have been performed on PVC pipe in the last fifty years. PVC water pipe products are listed to NSF Standard 61, Drinking Water Components–Health Effects and are approved around the world for water transmission and distribution pipes.

1.5.12 Thermal Insulation

PVC has lower thermal conductivity than traditional pipe materials. This characteristic makes PVC pipe desirable for a variety of thermal insulation applications.

1.5.13 Flame Resistance

PVC pipe is difficult to ignite: Its spontaneous ignition temperature is 850°F, well above that of most construction materials. PVC pipe is sometimes referred to as "self-extinguishing"; it will not burn in the absence of an external ignition source. Because of PVC's flame resistance, it is used to manufacture fire protection gear.

Fig. 1.3 PVC pipe for potable water service, marked to show NSF Standard 61 certification.

1.5.14 Cost Effectiveness

In light of all the above mentioned attributes of PVC pipe, it is not surprising that it is competitive with other pipes, particularly where installation and life cycle operating costs are taken into consideration.

1.5.15 Environmental Benefit

For real sustainability, a pipe material must have long-term performance qualities. Furthermore, a piping material's production must allow for efficient resource management.

PVC piping is one of the world's most sustainable products, making it ideal for long-term use in underground infrastructure. It requires less energy and fewer nonrenewable resources to manufacture than alternative pipe products and its production creates virtually no waste. Moreover, it is produced with sustainable and abundant resources: chlorine, which is derived from salt, and domestically produced natural gas, the use of which helps reduce consumption of imported oil.

PVC pipe manufacturing is extremely efficient. Manufacturing waste, or "regrind," can be returned directly to the extrusion process. An independent study has shown that PVC pipe uses one quarter of the energy needed to make concrete pipe and half that required for iron pipe. There are no smokestacks at PVC pipe facilities, and the product is completely recyclable, making its environmental footprint smaller than competing piping materials. By comparison, the cement industry is the third-largest emitter of greenhouse gases in the world. In addition, far less energy is needed to recycle PVC pipe than what is required to recycle metal pipe.

Certain ASTM and Canadian Standards Association (CSA) standards provide for recycled content in finished PVC pipe products, and markets for recycled PVC continue to grow. However, very little PVC pipe has yet to enter the recycling stream, due to its great durability.

PVC pipe's ecological attributes have been documented in numerous scientific life cycle assessments from raw material extraction to product end-of-life. But, as this overview has discussed, its greatest environmental attribute is exceptional durability and corrosion resistance—which means that its use in water piping systems improves water conservation and lowers replacement, maintenance, and repair costs.

A study by the American Water Works Association Research Foundation recently put the life expectancy of PVC pipe at more than 100 years; a European study gave PVC pipe a design life of 170 years.

1.6 PVC Pipe Technology

Through research and development, the PVC pipe industry is striving to make the best possible pipe and fittings products, continually improving its technology. With the ability to draw from PVC pipe's worldwide record, and with the opportunity to learn from the shortcomings of predecessor pipe products, the industry will maintain and continue to improve upon PVC pipe's advantages. PVC pipe is a product of modern technology, offering reliable and durable service to a variety of consumers: contractors, engineers, operators, industries, utilities, and irrigation districts. It is a tried and proven performer, with inherently superior characteristics and comprehensive engineering design.

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CHAPTER 2

Raw Materials

PVC Pipe Compounds
•
Gasket Materials

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2.1 Introduction

Gasketed joint PVC pipe derives its physical properties and performance characteristics from the properties of its raw materials. The essential components of gasketed PVC pipe are two polymeric materials: *PVC compounds* and *elastomeric seal compounds*. The following brief summary of these materials' properties provides a solid foundation for understanding and appreciation of pipe capabilities and limitations.

2.2 PVC Pipe Compounds

PVC pipe manufacturers purchase raw materials in one of two forms:

- pre-blended PVC extrusion compound
- PVC resin and other ingredients for preparation of their own compounds.

Most major manufacturers choose the second option, blending their own extrusion compounds.

2.2.1 PVC Resin

In North America, PVC resin, the building block of PVC pipe, is derived from saltwater and natural gas. Before it is processed into PVC pipe compound, PVC resin resembles granulated sugar in appearance and texture. The resin offers excellent physical, chemical, mechanical, and electrical properties for PVC pipe; however, without additional processing, it cannot be extruded successfully into finished PVC pipe.

Compounds made from PVC resins are of three types: *plastisols*, *flexibles*, and *rigids*. Each compound type is used in the manufacture of different types of PVC products: Plastisols may be used in production of footwear; flexibles, which contain plasticizers, may be used in production of hose; and rigids, which do not contain plasticizers, are used in the production of PVC pipe.

2.2.2 Properties of PVC Compounds

Rigid PVC compounds are mixtures of PVC resin and a combination of stabilizers, lubricants, pigments, and modifiers. Rigid compounds prepared for PVC pipe extrusion are carefully designed and developed to provide specific properties that are application-dependent. For example, relatively high tensile strength is required for PVC pressure pipe, while nonpressure pipe performance relies more critically on modulus of elasticity.

Therefore, formulating compounds for a specific application is an integral part of PVC pipe production.

Rigid PVC pipe compounds designed for transport of potable water must meet additional criteria based on toxicological properties and design stress properties. Design stress properties are demonstrated by long-term testing under hydrostatic pressure. Hydrostatic design stress ratings are established after long-term hydrostatic testing in accordance with ASTM International (formerly the American Society for Testing and Materials) D2837. Certification of potable water quality by an independent laboratory is provided with purchased PVC water pipe, assuring the user of its inherent health benefit.

2.2.3 Cell Class and Plastic Pipe Material Code

To define the properties of PVC compounds, ASTM has established standard specification D1784, Standard Specification for Rigid Polyvinyl Chloride (PVC) and Chlorinated Polyvinyl Chloride (CPVC) Compounds. This specification defines a five-digit cell class designation system, which describes minimum physical properties for an example compound, as shown in Table 2.1.

The five properties designated in Table 2.1 are: (1) name of base resin, (2) Izod impact strength, (3) tensile strength, (4) elastic modulus in tension, and (5) deflection temperature under heat and load. Figure 2.1 shows how this classification system can describe minimum properties for an example compound. The cell-type format provides the means for identification, close characterization, and specification of material properties, alone or in combination, for a broad range of materials. This format, however, is subject to possible misapplication, since unobtainable property combinations might be selected by a user unfamiliar with commercially available materials. The manufacturer should be consulted.

Prior to the development of the current cell classification system for PVC compounds defined in ASTM D1784, PVC pipe compounds were specified by means of a four-digit plastic pipe material code. The former plastic pipe material code defined three properties of a designated PVC compound: one digit for Izod impact, one digit for chemical resistance, and two digits describing hydrostatic design stress in units of 100 psi. Figure 2.2 shows how the former material code describes the specific properties of an example PVC pipe compound.

PVC compounds are produced in vast variety; the properties afforded by specific compounds may be easily identified and compared with standard requirements by defining the appropriate cell classifications for the compounds.

Table 2.1 Class requirements for rigid poly(vinyl chloride) (PVC) and chlorinated poly(vinyl chloride) (CPVC) compounds for ASTM D1784 (Copyright ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA. Reprinted with permission.)

Designation Order No.	Property and Unit	Cell Limits											
		0	1	2	3	4	5	6	7	8	9	10	11
1	Base resin	unspecified	poly(vinyl chloride) homopolymer	chlorinated poly(vinyl chloride)	vinyl copolymer								
2	Impact strength (Izod), min:												
	J/m of notch	unspecified	<34.7	34.7	80.1	266.9	533.8	800.7					
	ft-lb/in. of notch		<0.65	0.65	1.5	5.0	10.0	15.0					
3	Tensile strength, min:												
	MPa	unspecified	<34.5	34.5	41.4	48.3	55.2						
	psi		<5 000	5 000	6 000	7 000	8 000						
4	Modulus of elasticity in tension, min:												
	MPa	unspecified	<1930	1930	2206	2482	2758	3034					
	psi		<280 000	280 000	320 000	360 000	400 000	440 000					
5	Deflection temperature under load, min, 1.82 MPa (264 psi):												
	°C	unspecified	<55	55	60	70	80	90	100	110	120	130	140
	°F		<131	131	140	158	176	194	212	230	251	266	284
	Flammability	A	A	A	A	A	A	A	A	A			

[A] All compounds covered by this specification, when tested in accordance with Test Method ASTM D 635, shall yield the following results: average extent of burning, 25 mm; average time of burning, <10 s.

Note: The minimum property value will determine the cell number although the maximum expected value may fall within a higher cell.

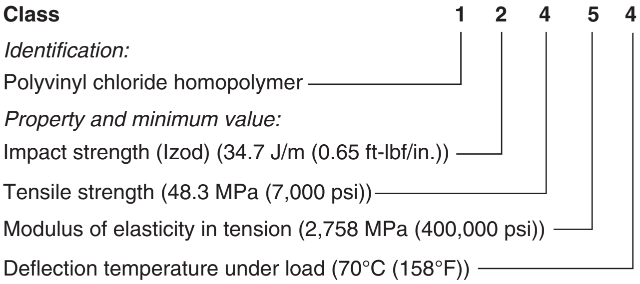

Fig. 2.1 Example compound—Class requirements for ASTM D1784. The manner in which selected materials are identified by this classification system is illustrated by a Class 12454 rigid PVC compound having the requirements shown in parentheses. (Copyright ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA. Reprinted with permission.)

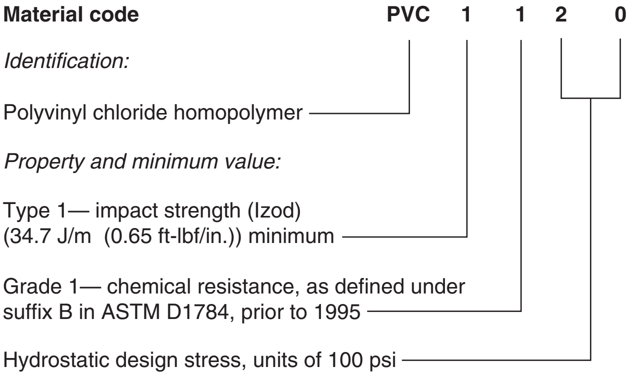

Fig. 2.2 Example compound—PVC pipe material code. The manner in which selected materials are identified by this material code is illustrated by a PVC 1120 compound having the requirements shown in parentheses. (Copyright ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA. Reprinted with permission.)

Just as PVC compounds are frequently designed for specific end-uses, so too are the cell classification systems that define the needed physical properties of those compounds. The use of these systems allows the product standards to directly address the performance characteristics of concern in the end-use product.

To summarize, pipes marked with a four-digit material code were manufactured with a compound as defined in an earlier version of ASTM D1784 (i.e., the 1965 edition of ASTM D1784). Pipes with a five-digit cell classification were made from a compound defined by the more recent editions of ASTM D1784. The current edition of ASTM D1784 provides the most commonly used cell classification system for PVC pipe. All of these standards provide for quality control in the manufacturing of compounds for pipe and fittings.

2.3 Gasket Materials

Gasket materials should comply in all respects with the physical requirements specified in ASTM F477, Standard Specification for Elastomeric Seals (Gaskets) for Joining Plastic Pipe.

ASTM F477 specifies that elastomeric gaskets be used to seal joints of plastic pipe used for gravity, low pressure, and high pressure applications. Table 2.2 defines physical requirements of elastomeric seals for plastic pipe.

Table 2.2 Physical requirements of elastomeric seals for plastic pipe (ASTM F477). (Copyright ASTM International, 100 Barr Harbor Drive, West Conshohocken, PA. Reprinted with permission.)

Tests	Low head application (below 150 kPa or 50-ft head)	High head application (150 kPa or 50-ft head and above)
Original properties:		
Tensile strength, min, MPa (psi)*	8.3 (1,200)	13.8 (2,000)
Elongation, min, %	325	400
Hardness, type A durometer	40–60	40–60
Low-temperature hardness, type A durometer, max increase, points	15	15
Compression set, max %	25	20
Ozone resistance	No cracks	No cracks
Accelerated aging (air oven test):		
Decrease in tensile strength, max % of original	15	15
Decrease in elongation, max % of original	20	20
Hardness, type A durometer, max increase, points	8	8
After water immersion:		
Change in volume max %	5	5

*For EPDM and nitrile seals, tensile strength min. MPa (psi) is 10.3 (1500).

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CHAPTER 3

Resistance to Aggressive Environments

Corrosion
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Chemical Attack
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Permeation
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Biological Attack
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Weathering
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3.1 Notation

P = partial pressure (psi)
P_o = saturated vapor pressure (psi)

3.2 Introduction

Determination of a piping system's true cost requires evaluating the system over its life. In addition to the initial costs of materials and installation, the long-term costs associated with operation, maintenance, and repair/replacement must be considered. The ability of a pipe or fitting material to resist deterioration, especially corrosion, is a critically important part of cost analysis. For both water mains and sewer lines, the long-term effects of corrosion must be considered, as premature replacement escalates infrastructure maintenance costs for the end user.

When reliability and durability are evaluated against other piping materials, PVC excels. However, successful long-term performance of PVC pipe depends upon proper system design, installation, and application. It is therefore important that engineers, contractors, and operators understand fully the response of PVC pipe to aggressive environments.

3.3 Corrosion

3.3.1 General Information

Corrosion causes numerous problems and expenses for both pressure and nonpressure piping systems throughout the world. Hundreds of millions of dollars are spent each year on maintenance, repair, and replacement of corrosion-damaged pipelines. Additional millions of dollars are spent on design, maintenance, and installation of piping systems that resist corrosion.

While monetary consequences are important, the implications of corrosion extend beyond economic considerations. The ability to control corrosion in both pressure and nonpressure systems can contribute greatly to the health and safety of the public. When the effects of corrosion compromise the pressure of a system, there is a potential for contaminated liquid backflow and inadequate flow for fire protection. Likewise, with regard to sewers, when corrosion damage results in leakage of a noxious substance, the environment and ultimately the public incur damages.

Results of tests conducted by a utility in Alberta, Canada, on 25-year-old PVC water pipes showed no significant deterioration of pipe properties. In a Water Research Foundation (WRF) study, the model projected that water utilities could expect a minimum service life of 100 years from PVC pipe.

3.3.2 External Corrosion

It has long been known that many materials buried in the earth undergo corrosion, the rate and degree of which depends upon the properties of the material and the environment in which it is installed. External corrosion is the leading cause of premature piping system failure due to degradation in material strength and/or by localized pitting of the pipeline or its appurtenances.

While corrosion is most often the cause of failure, it is not always recognized as such. Instead, incorrect reasons such as expansive soils and frost heave are cited for failure.

A number of publications are available on corrosion and the designing of pipelines to resist corrosion. These publications include a series by the National Association of Corrosion Engineers entitled Managing Corrosion with Plastics (see Uni-Bell's UNI-PUB-7, External Corrosion of Underground Water Distribution Piping Systems).

3.3.3 Internal Corrosion

Internal corrosion of water distribution systems can result in three distinct types of problems: (1) failure of the pipe itself due to leakage; (2) loss of hydraulic capacity as a result of corrosion byproduct build up; and (3) adverse change in water quality due to leaching of corrosion products into the water or the corrosion products' support of bacteria growth. Such changes can result in water quality violations and compromise water safety, with corrosion buildups and mineral precipitates harboring bacteria and inhibiting effective disinfection. These and many other findings, as well as methods for inhibiting internal corrosion in a variety of materials, can be found in the publication entitled Internal Corrosion of Water Distribution Systems, a cooperative research report published in 1985 by the AWWA Research Foundation and the Engler-Bunte Institute of Karlsruhe, Germany.

Internal corrosion due to sulfide generation in sanitary sewers has also resulted in piping failures. A description of the vast nature of this problem with recommended solutions is available in a paper entitled Case Histories of Sulfide Corrosion, by Schafer, Horner, and Witzgall, which was published in the 1990 Proceedings of the American Society of Civil Engineers (ASCE) International Conference on Pipeline Design and Installation. Furthermore, in 1991 the U.S. Environmental Protection Agency, as a result of the Water Quality Act of 1987, composed a report to Congress on the control and prevention of corrosion induced by hydrogen sulfide.

3.3.4 PVC Pipe and Fittings

PVC pipe and fittings are immune to nearly all types of corrosion experienced in underground piping systems. Soluble encrustants (such as calcium carbonate) found in some water supplies do not readily precipitate onto the smooth walls of PVC pipes. Since PVC pipe does not corrode, there is no tuberculation caused by corrosion byproducts, and no tuberculation means there is no reduction in flow areas or flow coefficients as PVC piping systems age. The long-term result of PVC pipe's resistance to tuberculation is reduced cost for operations and maintenance.

Since PVC is a nonconductor, both galvanic and electrochemical effects are nonexistent in PVC pipe and fittings. PVC suffers no damage from attack of normal or corrosive soils and is not affected by sulfuric acid in the concentrations found in sanitary sewer systems. As a result, no linings, coatings, or cathodic protection are required when PVC pipe is used, resulting in cost savings for construction and future maintenance.

Different water and sewer pipe products provide corrosion resistance in varying degrees depending on application and environment. For this reason, corrosion must be considered when piping products are selected. Because corrosive attack can be anticipated in most underground systems, PVC pipe's corrosion resistance provides considerable savings in the form of reduced operating costs and longer system life.

3.4 Chemical Attack

3.4.1 General Information

A pipe system may be subject to a number of aggressive chemical exposures, accidental or otherwise. Resistance of PVC pipe and elastomeric gaskets to attack by chemical agents has been determined through years of research and field experience, demonstrating its ability to endure a broad range of both acidic and caustic environments. In general, PVC piping systems are not adversely affected by chemicals found in typical potable water and sanitary sewer systems.

3.4.2 Factors Affecting Resistance

Chemical reactions can be very complex; there are so many factors affecting the reaction of a piping system to chemical attack that it is impossible to construct charts to cover all possibilities. Some of the factors affecting chemical resistance are:

- temperature
- chemical (or mixture of chemicals) present
- concentration of chemicals
- duration of exposure
- frequency of exposure
- PVC compound (or elastomeric compound) present
- geometry of piping system.

3.4.3 Oxidation

Disinfection is an important step in providing safe drinking water. Chemical disinfectants are added to water systems to destroy microorganisms that can cause disease in humans. The EPA Surface Water Treatment Rule requires water utilities to disinfect water obtained from surface water supplies or groundwater sources influenced by surface water. The most common chemical disinfectants are chlorine (sodium hypochlorite), chloramines, and chlorine dioxide.

There are two modes of disinfection—primary and secondary. Primary disinfection achieves the desired level of microorganism kill or inactivation; secondary disinfection maintains a disinfectant residual in the finished water that prevents regrowth of microorganisms throughout the pipe distribution system.

It has been established that some plastic pipe materials are susceptible to oxidative degradation in the presence of common water disinfectants. Even at low concentrations, these disinfectants can oxidize some pipe materials and shorten a pipe's performance life.

PVC pipe has very good resistance to oxidation by disinfectants. There is no record of oxidation-induced failure in PVC water distribution pipes. The resistance of PVC pipes to water disinfectants has been confirmed through accelerated aging studies: When assessed according to the rigorous aging tests of International Organization for Standardization (ISO) 4433 (8 ppm ClO_2 and 40ºC), PVC pipes exhibit very low sensitivity to oxidizing agents.

PVC pipe mechanical properties, including elongation at break, were not altered appreciably by aggressive ISO 4433 test conditions and have been judged suitable according to this standard. After being subjected to the aggressive conditions of ISO 4433, PVC pipes experienced no loss in thermal stability when tested by dehydrochlorination (DHC), and their thermal stability was further confirmed by thermo gravimetric analysis (TGA). Likewise, measurements of viscosity index showed no reduction in PVC's molecular weight.

At normal temperatures, no attack on PVC pipe was registered in the ISO 4433 testing, even with a relatively high concentration of ClO_2. A 2,000-hour (85-day) test with both PVC and high density polyethylene (HDPE) pipes showed no decrease in PVC elongation compared to a 70 percent decrease for HDPE. This decrease in elongation indicates significant material degradation.

Resistance to oxidative degradation makes PVC the preferred plastic piping material.

3.4.4 PVC Pipe and Fittings

Experience has shown that PVC pipe and fittings are resistant to chemicals generally found in water and sewer systems. The chemical resistance information for PVC pipe listed in Table 3.1 is based on short-term immersion of unstressed strips of PVC in the listed chemicals (usually undiluted). While these resistance data may be useful in assessing the suitability of PVC under specific or unusual operating environments, they are only a guide for estimating PVC's response to chemicals. For critical applications it is recommended that testing be performed under conditions that approximate anticipated field conditions.

Table 3.1 is not intended to provide design criteria for PVC sewer pipes that are exposed to chemicals only occasionally or to chemicals that have been diluted by wastewater.

Table 3.1 is compiled from multiple industry sources. The National Association of Corrosion Engineers publication Corrosion Data Survey, Nonmetals Section is an additional source of information on the chemical resistance of PVC pipe.

Table 3.1 Chemical resistance* of PVC pipe

Chemical	73°F (23°C)	140°F (60°C)
Acetaldehyde	N	N
Acetaldehyde, aq 40%	C	N
Acetic acid, 25%	R	R
Acetic acid, 60%	R	N
Acetic acid, 85%	R	N
Acetic acid, glacial	R	N
Acetic acid, vapor	R	R
Acetic anhydride	N	N
Acetone	N	N
Acetylene	N	N
Acetyl chloride	N	N
Acetylnitrile	N	N
Acrylonitrile	N	N
Acrylic acid	N	N
Adipic acid	R	R
Alcohol, allyl	R	C
Alcohol, amyl	N	N
Alcohol, benzyl	N	N
Alcohol, butyl (n-butanol)	R	R
Alcohol, diacetone	N	N
Alcohol, ethyl (ethanol)	R	R
Alcohol, hexyl (hexanol)	R	R
Alcohol, isopropyl (2-propanol)	R	R
Alcohol, methyl (methanol)	R	R
Alcohol, propyl (1-propanol)	R	R
Alcohol, propargyl	R	R
Allyl chloride	N	N
Aluminum fluoride	R	N
Alums (except aluminum fluoride)	R	R
Ammonia, gas	R	R
Ammonia, liquid	N	N
Ammonium dichromate	R	N
Ammonium salts (except ammonium dichromate)	R	R
Ammonium fluoride, 10%	R	R
Ammonium fluoride, 25%	R	C
Amyl acetate	N	N
Amyl chloride	N	N
Aniline	N	N
Aniline chlorohydrate	N	N
Aniline hydrochloride	N	N
Anthraquinone	R	R
Anthraquinone sulfonic acid	R	R
Antimony trichloride	R	R
Aqua regia	C	N
Arsenic acid, 80%	R	R
Aryl-sulfonic acid	R	R

*R = generally resistant; C = less resistant than R but still suitable for some conditions; N = not resistant

This table is meant to aid the designer in decisions as to transporting/conveyance of undiluted chemicals. Chemical resistance data are provided as a guide only. Information is based primarily on immersion of unstressed strips in chemicals and to a lesser degree on field experience.

Table 3.1 Chemical resistance of PVC pipe (*continued*)

Chemical	73°F (23°C)	140°F (60°C)
Barium nitrate	R	N
Barium salts (except barium nitrate)	R	R
Beer	R	R
Beet sugar liquor	R	R
Benzaldehyde, 10%	R	N
Benzene (benzol)	N	N
Benzene sulfonic acid, 10%	R	R
Benzene sulfonic acid, >10%	N	N
Benzoic acid	R	R
Black liquor – paper	R	R
Bleach, 12% active chlorine	R	R
Bleach, 5% active chlorine	R	R
Borax	R	R
Boric acid	R	R
Brine	R	R
Bromic acid	R	R
Bromine, aq	R	R
Bromine, liquid	N	N
Bromine, gas, 25%	R	R
Bromobenzene	N	N
Bromotoluene	N	N
Butadiene	R	R
Butane	R	R
Butyl acetate	N	N
Butyl stearate	R	N
Butyl phenol	R	N
Butylene, liquid	R	R
Butynediol	R	N
Butyric acid	R	N
Cadmium cyanide	R	R
Calcium bisulfide	N	N
Calcium salts (except calcium bisulfide)	R	R
Calcium hypochlorite, 30%	R	R
Calcium hydroxide	R	R
Calcium nitrate	R	R
Calcium oxide	R	R
Calcium sulfate	R	R
Camphor	R	N
Cane sugar liquors	R	R
Carbon dioxide	R	R
Carbon dioxide, aq	R	R
Carbon disulfide	N	N
Carbon monoxide	R	R
Carbitol	R	N
Carbon tetrachloride	R	N
Carbonic acid	R	R
Castor oil	R	R
Caustic potash (potassium hydroxide), 50%	R	R
Caustic soda (sodium hydroxide), < 40%	R	R
Cellosolve	R	N

Table 3.1 Chemical resistance* of PVC pipe (*continued*)

Chemical	73°F (23°C)	140°F (60°C)	Chemical	73°F (23°C)	140°F (60°C)
Cellosolve acetate	R	N	Corn oil	R	R
Chloral hydrate	R	R	Corn syrup	R	R
Chloramine, dilute	R	N	Cottonseed oil	R	R
Chloric acid, 20%	R	R	Creosote	N	N
Chlorine, gas, dry	C	N	Cresol, 90%	N	N
Chlorine, gas, wet	N	N	Cresylic acid, 50%	R	R
Chlorine, liquid	N	N	Croton aldehyde	N	N
Chlorine water	R	R	Crude oil, sour	R	R
Chloroacetic acid, 50%	R	R	Cupric salts, aq	R	R
Chloroacetyl chloride	R	N	Cyclohexane	N	N
Chlorobenzene	N	N	Cyclohexanol	N	N
Chlorobenzyl chloride	N	N	Cyclohexanone	N	N
Chloroform	N	N			
Chloropicrin	N	N	Detergents, aq	R	R
Chlorosulfonic acid	R	N	Dextrin	R	R
Chromic acid, 10%	R	R	Dextrose	R	R
Chromic acid, 30%	R	R	Dibutoxyethyl phthalate	N	N
Chromic acid, 40%	R	C	Dibutyl phthalate	N	N
Chromic acid, 50%	N	N	Dibutyl sebacate	R	N
Chromium potassium sulfate	R	N	Dichlorobenzene	N	N
			Dichloroethylene	N	N
Citric acid	R	R	Diesel fuels	R	R
Coconut oil	R	R	Diethylamine	N	N
Coffee	R	R	Diethyl ether	R	N
Coke oven gas	R	R	Diglycolic acid	R	R
Copper acetate	R	N	Dimethyl formamide	N	N
Copper salts, aq	R	R	Dimethylamine	R	R

*R = generally resistant; C = less resistant than R but still suitable for some conditions; N = not resistant

This table is meant to aid the designer in decisions as to transporting/conveyance of undiluted chemicals. Chemical resistance data are provided as a guide only. Information is based primarily on immersion of unstressed strips in chemicals and to a lesser degree on field experience.

Table 3.1 Chemical resistance of PVC pipe (*continued*)

Chemical	73°F (23°C)	140°F (60°C)
Disodium phosphate	R	R
Dioxane-1,4	N	N
Ether	N	N
Ethyl ether	N	N
Ethyl halides	N	N
Ethylene glycol	R	R
Ethylene halides	N	N
Ethylene oxide	N	N
Fatty acids	R	R
Ferric salts	R	R
Fish oil	R	R
Fluorine, dry gas	R	N
Fluorine, wet gas	R	N
Fluoroboric acid	R	R
Fluorosilicic acid, 50%	R	R
Formaldehyde	R	R
Formic acid	R	N
Freon—F11, F12, F113, F114	R	R
Freon—F21, F22	N	N
Fructose	R	R
Furfural	N	N
Gallic acid	R	R
Gas, coal, manufactured	N	N
Gas, natural, methane	R	R
Gasoline	R	R
Gelatin	R	R
Glucose	R	R
Glue, animal	R	R
Glycerine (glycerol)	R	R
Glycolic acid	R	R
Grape sugar	R	R
Green liquor, paper	R	R
Heptane	R	R
Hexane	R	N
Hexanol	R	R
Hydraulic oil	R	N
Hydrazine	N	N
Hydrobromic acid, 20%	R	R
Hydrochloric acid	R	R
Hydrocyanic acid	R	R
Hydrofluoric acid, 30%	R	N
Hydrofluoric acid, 50%	R	N
Hydrofluoric acid, 100%	N	N
Hydrofluorosilicic acid	R	R
Hydrogen	R	R
Hydrogen cyanide	R	R
Hydrogen fluoride	N	N
Hydrogen peroxide, 50%	R	R
Hydrogen peroxide, 90%	R	R
Hydrogen phosphide	R	R
Hydrogen sulfide, aq	R	R
Hydrogen sulfide, dry	R	R
Hydroquinone	R	R
Hydroxylamine sulfate	R	R

Table 3.1 Chemical resistance* of PVC pipe (*continued*)

Chemical	73°F (23°C)	140°F (60°C)
Hypochlorous acid	R	R
Iodine, aq, 10%	N	N
Jet fuels, JP-4 and JP-5	R	R
Kerosene	R	R
Ketchup	R	N
Ketones	N	N
Kraft paper liquor	R	R
Lactic acid, 25%	R	R
Lactic acid, 80%	R	N
Lard oil	R	R
Lauric acid	R	R
Lauryl acetate	R	R
Lauryl chloride	R	R
Lead salts	R	R
Lime sulfur	R	N
Linoleic acid	R	R
Linoleic oil	R	R
Linseed oil	R	R
Liqueurs	R	R
Lithium salts	R	R
Lubricating oils	R	R
Magnesium salts	R	R
Maleic acid	R	R
Malic acid	R	R
Manganese sulfate	R	R
Mercuric salts	R	R
Mercury	R	R
Methane	R	R
Methoxyethyl oleate	R	N
Methyl acetate	N	N
Methyl amine	N	N
Methyl bromide	N	N
Methyl cellosolve	N	N
Methyl chloride	N	N
Methyl chloroform	N	N
Methyl ethyl ketone	N	N
Methyl isobutyl carbinol	N	N
Methyl isobutyl ketone	N	N
Methyl isopropyl ketone	N	N
Methyl methacrylate	R	N
Methyl sulfate	R	N
Methyl sulfuric acid	R	R
Methylene bromide	N	N
Methylene chloride	N	N
Methylene iodide	N	N
Milk	R	R
Mineral oil	R	R

*R = generally resistant; C = less resistant than R but still suitable for some conditions; N = not resistant

This table is meant to aid the designer in decisions as to transporting/conveyance of undiluted chemicals. Chemical resistance data are provided as a guide only. Information is based primarily on immersion of unstressed strips in chemicals and to a lesser degree on field experience.

Table 3.1 Chemical resistance of PVC pipe (*continued*)

Chemical	73°F (23°C)	140°F (60°C)	Chemical	73°F (23°C)	140°F (60°C)
Molasses	R	R	Palmitic acid, 10%	R	R
Monochloroacetic acid	R	R	Palmitic acid, 70%	R	N
Monochlorobenzene	N	N	Paraffin	R	R
Monoethanolamine	N	N	Pentane	C	C
Motor oil	R	R	Peracetic acid, 40%	R	N
			Perchloric acid, 15%	R	N
Naphtha	R	R	Perchloric acid, 70%	R	N
Naphthalene	N	N	Perchloroethylene	C	C
Natural gas	R	R	Perphosphate	R	N
Nickel acetate	R	N	Phenol	R	N
Nickel salts	R	R	Phenylhydrazine	N	N
Nicotine	R	R	Phosphoric acid	R	R
Nicotinic acid	R	R	Phosphoric anhydride	R	N
Nitric acid, 0 to 40%	R	R	Phosphorus, red	R	N
Nitric acid, 50%	R	C	Phosphorus, yellow	R	N
Nitric acid, 70%	R	N	Phosphorus pentoxide	R	N
Nitric acid, 100%	N	N	Phosphorus trichloride	N	N
Nitrobenzene	N	N	Photographic chemicals, aq	R	R
Nitroglycerine	N	N	Phthalic acid	C	C
Nitroglycol	N	N	Picric acid	N	N
Nitrous acid, 10%	R	R	Plating solutions, metal	R	R
Nitrous oxide, gas	R	N	Potash	R	R
			Potassium amyl xanthate	R	N
Oleic acid	R	R	Potassium iodide	R	N
Oleum	N	N	Potassium salts (except potassium iodide)	R	R
Olive oil	R	R	Potassium permanganate, 10%	R	R
Oxalic acid	R	R			
Oxygen, gas	R	R			
Ozone, gas	R	R			

Table 3.1 Chemical resistance* of PVC pipe (*continued*)

Chemical	73°F (23°C)	140°F (60°C)
Potassium permanganate, 25%	R	N
Propane	R	R
Propylene dichloride	N	N
Propylene oxide	N	N
Pyridine	N	N
Pyrogallic acid	R	N
Rayon coagulating bath	R	R
Salicylic acid	R	R
Salicylaldehyde	N	N
Selenic acid, aq.	R	R
Silicic acid	R	R
Silicone oil	R	N
Silver salts	R	R
Soaps	R	R
Sodium chlorate	R	N
Sodium chlorite	N	N
Sodium hypochlorite	R	N
Sodium salts, aq (except sodium chlorate, sodium chlorite, and sodium hypochlorite)	R	R
Stannic chloride	R	R
Stannous chloride	R	R
Starch	R	R
Stearic acid	R	R
Stoddard solvent	N	N
Succinic acid	R	R
Sugars, aq	R	R
Sulfamic acid	N	N
Sulfate & sulfite liquors	R	R
Sulfur	R	R
Sulfur dioxide, dry	R	R
Sulfur dioxide, wet	R	N
Sulfur trioxide, gas, dry	R	R
Sulfur trioxide, wet	R	N
Sulfuric acid, up to 80%	R	R
Sulfuric acid, 90 to 93%	R	N
Sulfuric acid, 94 to 100%	N	N
Sulfurous acid	R	R
Tall oil	R	R
Tannic acid	R	R
Tanning liquors	R	R
Tar	N	N
Tartaric acid	R	R
Terpineol	C	C
Tetrachloroethane	C	C
Tetraethyl lead	R	N
Tetrahydrofuran	N	N

*R = generally resistant; C = less resistant than R but still suitable for some conditions; N = not resistant

This table is meant to aid the designer in decisions as to transporting/conveyance of undiluted chemicals. Chemical resistance data are provided as a guide only. Information is based primarily on immersion of unstressed strips in chemicals and to a lesser degree on field experience.

Table 3.1 Chemical resistance of PVC pipe (*continued*)

Chemical	73°F (23°C)	140°F (60°C)	Chemical	73°F (23°C)	140°F (60°C)
Tetralin	N	N	Urea	R	R
Tetrasodium	R	R	Urine	R	R
Thionyl chloride	N	N			
Thread cutting oils	R	N	Vaseline	N	N
Titanium tetrachloride	C	N	Vegetable oils	R	R
Toluene	N	N	Vinegar	R	R
Tomato juice	R	R	Vinyl acetate	N	N
Transformer oil	R	R			
Tributyl citrate	R	N	Water, deionized	R	R
Tributyl phosphate	N	N	Water, distilled	R	R
Trichloroacetic acid	R	R	Water, salt	R	R
Trichloroethylene	N	N	Whiskey	R	R
Triethanolamine	R	N	White liquor	R	R
Triethylamine	R	R	Wines	R	R
Trimethyl propane	R	N			
Trisodium phosphate	R	R	Xylene	N	N
Turpentine	R	R	Zinc salts	R	R

3.4.5 Gaskets

Because gasket and pipe materials differ, so too does their ability to resist chemical attack. Therefore, a check of the gasket's chemical resistance should be completed independent of the pipe's. Tables 3.2 and 3.3 will aid the designer in selecting an appropriate gasket material.

In applications where exposure to harmful chemicals is frequent, of long duration, or in high concentrations, further testing is recommended.

General chemical resistance information for commonly used gasket materials is presented in Table 3.2.

The factors generally considered most important in gasket material choice are:

- *Temperature of service:* Higher temperatures increase the effect of all chemicals on elastomers. The increase varies with the elastomer and the chemical. An

Table 3.2 General chemical resistance of various gasket materials

	General purpose, non-oil resistant		**General purpose, oil resistant**	
ELASTOMER/ ASTM DESIGNATION	Butadiene styrene/SBR, Butadiene/BR	Ethylene propylene/EPM, EPDM	Nitrile/NBR	Neoprene/CR
CHEMICAL GROUP	Polybutadiene, Butadiene styrene copolymer	Ethylene propylene copolymer and terpolymer	Butadiene acrylonitrile copolymer	Chloroprene polymer
GENERALLY RESISTANT TO	Most moderate chemicals wet or dry, organic acids, alcohols, ketones, aldehydes	Animal and vegetable oils, ozone, strong and oxidizing chemicals	Many hydrocarbons, fats, oils, greases, hydraulic fluids, chemicals	Moderate chemicals and acids, ozone, oils, fats, greases, many oils and solvents
GENERALLY ATTACKED BY	Ozone, strong acids, fats, oils, greases, most hydrocarbons	Mineral oils and solvents, aromatic hydrocarbons	Ozone*, ketones, esters, aldehydes, chlorinated and nitro hydrocarbons	Strong oxidizing acids, esters, ketones, chlorinated, aromatic and nitro hydrocarbons

*except PVC blends

elastomeric compound quite suitable at room temperature might fail at elevated temperatures.

- *Conditions of service:* An elastomeric compound that swells might still function well as a seal.
- *Grade of elastomer:* Many types of elastomers are available in different grades that vary greatly in chemical resistance.
- *Elastomeric compound:* Compounds designed for chemical resistance may affect mechanical properties.
- *Availability:* The pipe manufacturer should be consulted as to whether a specific elastomeric compound is available.

Table 3.2 is offered as a general guide and indication of the suitability of various elastomers used today to service the listed chemicals and fluids. Table 3.3 is a more detailed guide. The ratings are based, for the most part, on published literature of various polymer suppliers and rubber manufacturers, but in some cases they represent the considered opinion of experienced elastomer compounders.

Table 3.3 Chemical resistance* of (PVC) gasket materials

	General purpose, non-oil resistant		**General purpose, oil resistant**	
ELASTOMER/ ASTM DESIGNATION	Butadiene styrene/SBR, Butadiene/BR	Ethylene propylene/EPM, EPDM	Nitrile/ NBR	Neoprene/ CR
Acetaldehyde	N	R	N	N
Acetamide	N	R	R	C
Acetic acid, 30%	C	R	C	R
Acetic acid, glacial	N	R	N	N
Acetic anhydride	C	C	N	R
Acetone	C	R	N	C
Acetophenone	N	R	N	N
Acetyl chloride	—	—	—	N
Acetylene	C	R	C	C
Acrylonitrile	N	N	N	N
Adipic acid	—	—	R	—
Alkazene	—	N	—	N
Alum-NH_3-Cr-K	R	R	R	R
Aluminum acetate	C	R	C	C
Aluminum chloride	N	R	R	R
Aluminum fluoride	R	R	R	R
Aluminum nitrate	R	R	R	R
Aluminum phosphate	R	R	R	R
Aluminum sulfate	C	R	R	R
Ammonia anhydrous	—	R	R	R
Ammonia gas (cold)	R	R	R	R
Ammonia gas (hot)	—	C	—	C

*R = generally resistant; C = less resistant than R but still suitable for some conditions; N = not resistant

A dash indicates insufficient data to provide a rating.

This table is meant to aid the designer in decisions as to transporting/conveyance of undiluted chemicals. Chemical resistance data are provided as a guide only. Information is based primarily on immersion of unstressed strips in chemicals and to a lesser degree on field experience.

Table 3.3 Chemical resistance* of (PVC) gasket materials (*continued*)

	General purpose, non-oil resistant		**General purpose, oil resistant**	
ELASTOMER/ ASTM DESIGNATION	Butadiene styrene/SBR, Butadiene/BR	Ethylene propylene/EPM, EPDM	Nitrile/ NBR	Neoprene/ CR
Ammonium carbonate	R	R	N	R
Ammonium chloride	R	R	R	R
Ammonium hydroxide	N	R	N	R
Ammonium nitrate	R	R	R	C
Ammonium nitrite	R	R	R	R
Ammonium persulfate	N	R	N	R
Ammonium phosphate	R	R	R	R
Ammonium sulfate	C	R	R	R
Amyl acetate	N	R	N	N
Amyl alcohol	C	R	C	R
Amyl borate	N	N	R	R
Amyl chloronapthalene	N	N	—	N
Amyl napthalene	N	N	N	N
Aniline	N	C	N	N
Aniline dyes	C	C	N	C
Aniline hydrochloride	N	C	C	N
Animal fats	N	C	R	C
Ansul ether	N	N	N	N
Aqua regia	N	N	—	N
Arochlor (solid)	N	N	N	N
Arsenic acid	R	R	R	R
Arsenic trichloride	—	—	R	R

*R = generally resistant; C = less resistant than R but still suitable for some conditions; N = not resistant

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Table 3.3 Chemical resistance of (PVC) gasket materials (*continued*)

	General purpose, non-oil resistant		**General purpose, oil resistant**	
ELASTOMER/ ASTM DESIGNATION	Butadiene styrene/SBR, Butadiene/BR	Ethylene propylene/EPM, EPDM	Nitrile/ NBR	Neoprene/ CR
Askarel	N	N	C	N
Asphalt	N	—	C	N
Barium chloride	R	R	R	R
Barium hydroxide	R	R	R	R
Barium sulfate	R	R	R	R
Barium sulfide	C	R	R	R
Beer	R	R	R	R
Beet sugar liquors	R	R	R	R
Benzaldehyde	N	R	N	N
Benzene	N	N	N	N
Benzenesulfonic acid	—	—	—	R
Benzyl alcohol	—	C	N	R
Benzyl benzoate	—	C	—	—
Benzyl chloride	—	—	N	N
Blast furnace gas	N	—	N	N
Bleach solutions	N	R	—	N
Borax	C	R	C	R
Bordeaux mixture	C	R	—	R
Boric acid	R	R	R	R
Brine	—	R	R	R
Bromine, anhydrous	—	—	—	N
Bromine trifluoride	N	N	N	N
Bromine water	—	—	—	C
Bromobenzene	N	N	N	N
Bunker oil	—	—	R	—

Table 3.3 Chemical resistance* of (PVC) gasket materials (*continued*)

	General purpose, non-oil resistant		**General purpose, oil resistant**	
ELASTOMER/ ASTM DESIGNATION	Butadiene styrene/SBR, Butadiene/BR	Ethylene propylene/EPM, EPDM	Nitrile/ NBR	Neoprene/ CR
Butadiene	N	N	N	C
Butane	N	N	R	R
Butter	N	R	R	C
Butyl acetate	—	C	—	N
Butyl acetyl ricinoleate	—	R	—	C
Butyl acrylate	N	N	—	—
Butyl alcohol	R	C	R	R
Butyl amine	N	N	N	N
Butyl benzoate	—	R	—	N
Butyl carbitol	—	R	R	C
Butyl cellosolve	—	R	N	C
Butyl oleate	N	C	—	N
Butyl stearate	N	C	C	—
Butylene	N	N	C	N
Butyraldehyde	N	C	N	N
Calcium acetate	—	R	C	C
Calcium bisulfite	N	N	R	R
Calcium chloride	R	R	R	R
Calcium hydroxide	R	R	R	R
Calcium hypochlorite	N	R	N	N
Calcium nitrate	R	R	R	R
Calcium sulfide	C	R	C	R

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Table 3.3 Chemical resistance of (PVC) gasket materials (*continued*)

	General purpose, non-oil resistant		**General purpose, oil resistant**	
ELASTOMER/ ASTM DESIGNATION	Butadiene styrene/SBR, Butadiene/BR	Ethylene propylene/EPM, EPDM	Nitrile/ NBR	Neoprene/ CR
Cane sugar liquors	R	R	R	R
Carbamate	N	C	N	C
Carbitol	C	C	C	C
Carbolic acid	N	C	N	N
Carbon bisulfide	—	N	N	N
Carbon dioxide	C	C	R	C
Carbon monoxide	C	R	R	R
Carbon tetrachloride	N	N	N	N
Carbonic acid	C	R	R	R
Castor oil	R	C	R	R
Cellosolve	N	C	—	—
Cellosolve acetate	N	C	N	—
Cellulube	—	R	N	N
Chlorine (dry)	N	—	—	N
Chlorine (wet)	N	N	—	N
Chlorine dioxide	—	N	N	N
Chlorine trifluoride	N	N	N	N
Chloroacetic acid	—	C	—	—
Chloroacetone	—	R	N	C
Chlorobenzene	N	N	N	N
Chlorobromomethane	N	C	—	N
Chlorobutadiene	N	N	N	N
Chlorododecane	N	N	N	N
Chloroform	N	N	N	N
o-Chloronaphthalene	N	N	N	N
1-Chloro-1-nitroethane	N	N	N	N
Chlorosulfonic acid	N	N	N	N

Table 3.3 Chemical resistance* of (PVC) gasket materials (*continued*)

	General purpose, non-oil resistant		**General purpose, oil resistant**	
ELASTOMER/ ASTM DESIGNATION	Butadiene styrene/SBR, Butadiene/BR	Ethylene propylene/EPM, EPDM	Nitrile/ NBR	Neoprene/ CR
Chlorotoluene	N	N	N	N
Chrome plating solutions	N	N	N	N
Chromic acid	N	N	N	N
Citric acid	R	R	R	R
Cobalt chloride	R	R	R	R
Coconut oil	N	R	R	C
Cod liver oil	N	R	R	C
Coke oven gas	N	—	—	—
Copper acetate	—	R	C	C
Copper chloride	R	R	R	R
Copper cyanide	R	R	R	R
Copper sulfate	C	R	R	R
Corn oil	N	N	R	C
Cottonseed oil	N	R	R	C
Creosote	N	N	C	N
Cresol	N	N	N	N
Cresylic acid	N	N	N	N
Cumene	—	—	—	N
Cyclohexane	N	N	R	N
Cyclohexanol	N	N	C	R
Cyclohexanone	—	C	N	N
p-Cymene	—	—	—	N

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Table 3.3 Chemical resistance of (PVC) gasket materials (*continued*)

	General purpose, non-oil resistant		**General purpose, oil resistant**	
ELASTOMER/ ASTM DESIGNATION	Butadiene styrene/SBR, Butadiene/BR	Ethylene propylene/EPM, EPDM	Nitrile/ NBR	Neoprene/ CR
Decalin	N	—	—	N
Decane	N	—	C	N
Denatured alcohol	R	R	R	R
Detergent solutions	C	R	R	R
Developing fluids	C	C	R	R
Diacetone	—	R	—	—
Diacetone alcohol	N	R	N	R
Dibenzyl ether	N	C	N	C
Dibenzyl sebecate	—	C	—	N
Dibutyl amine	N	N	N	N
Dibutyl ether	N	N	N	N
Dibutyl phthalate	N	R	N	N
Dibutyl sebecate	N	C	N	N
o-Dichlorobenzene	N	N	N	N
Dichloro-isopropyl ether	N	N	N	N
Didaclohexylamine	N	—	N	—
Diesel oil	N	N	R	C
Diethylamine	C	C	N	N
Diethyl benezene	N	N	N	N
Diethyl ether	N	N	N	N
Diethyl sebecate	—	C	N	N
Diethylene glycol	R	R	R	R
Diisobutylene	—	—	C	N
Diisopropyl benzene	N	N	N	N
Diisopropyl ketone	—	R	N	N
Dimethyl aniline	N	C	—	N
Dimethyl formamide	—	—	C	N

Table 3.3 Chemical resistance* of (PVC) gasket materials (*continued*)

	General purpose, non-oil resistant		**General purpose, oil resistant**	
ELASTOMER/ ASTM DESIGNATION	Butadiene styrene/SBR, Butadiene/BR	Ethylene propylene/EPM, EPDM	Nitrile/ NBR	Neoprene/ CR
Dimethyl phthalate	N	C	N	N
Dinitrotoluene	N	N	N	N
Dioctyl phthalate	—	C	—	N
Dioctyl sebecate	N	C	N	N
Dioxane	—	C	—	—
Dioxolane	N	C	N	—
Dipentene	—	—	C	—
Diphenyl oxides	—	R	—	—
Dowtherm oil	N	N	—	N
Dry cleaning fluids	N	N	N	N
Epichlorohydrin	N	C	—	—
Ethane	N	N	R	C
Ethanolamine	C	C	C	C
Ethyl acetate	N	C	N	N
Ethyl acetoacetate	N	C	N	N
Ethyl acrylate	—	C	—	—
Ethyl alcohol	R	R	R	R
Ethyl benzene	N	N	N	N
Ethyl benzoate	—	C	—	—
Ethyl cellosolve	—	C	—	—
Ethyl cellulose	C	C	—	C
Ethyl chloride	C	R	R	C
Ethyl chlorocarbonate	N	—	—	N

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Table 3.3 Chemical resistance of (PVC) gasket materials (*continued*)

	General purpose, non-oil resistant		**General purpose, oil resistant**	
ELASTOMER/ ASTM DESIGNATION	Butadiene styrene/SBR, Butadiene/BR	Ethylene propylene/EPM, EPDM	Nitrile/ NBR	Neoprene/ CR
Ethyl chloroformate	—	—	—	N
Ethyl ether	—	N	N	N
Ethyl formate	N	C	N	C
Ethyl mercaptan	N	N	N	—
Ethyl oxalate	R	R	N	N
Ethyl pentochlorobenzene	N	N	N	N
Ethyl silicate	C	R	R	R
Ethylene	—	—	R	—
Ethylene chloride	—	N	—	—
Ethylene chlorohydrin	C	—	N	C
Ethylene diamine	C	R	R	R
Ethylene dichloride	N	N	N	N
Ethylene glycol	R	R	R	R
Ethylene oxide	—	N	N	N
Ethylene trichloride	—	N	N	N
Fatty acids	N	N	C	C
Ferric chloride	R	R	R	R
Ferric nitrate	R	R	R	R
Ferric sulfate	R	R	R	R
Fish oil	—	—	R	—
Fluorinated cyclic ethers	—	R	—	—
Fluorine (liquid)	—	N	—	—
Fluorobenzene	N	N	N	N
Fluoroboric acid	R	R	R	R
Fluorocarbon oils	—	R	—	—
Fluorolube	N	R	R	R

Table 3.3 Chemical resistance* of (PVC) gasket materials (*continued*)

	General purpose, non-oil resistant		**General purpose, oil resistant**	
ELASTOMER/ ASTM DESIGNATION	Butadiene styrene/SBR, Butadiene/BR	Ethylene propylene/EPM, EPDM	Nitrile/ NBR	Neoprene/ CR
Fluorosilicic acid	—	—	R	R
Formaldehyde	—	R	C	R
Formic acid	R	R	C	R
Freon 11	N	N	R	C
Freon 12	R	C	R	R
Freon 13	R	R	R	R
Freon 21	—	N	N	C
Freon 22	R	R	N	R
Freon 31	C	R	N	R
Freon 32	R	R	R	R
Freon 112	—	N	C	C
Freon 113	C	N	R	R
Freon 114	R	R	R	R
Freon 115	R	R	R	R
Freon 142b	R	R	R	R
Freon 152a	R	R	R	R
Freon 218	R	R	R	R
Freon C316	R	R	R	R
Freon C318	R	R	R	R
Freon 13B1	R	R	R	R
Freon 114B2	N	N	C	R
Freon 502	R	—	C	R
Freon TF	C	N	R	R

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Table 3.3 Chemical resistance of (PVC) gasket materials (*continued*)

	General purpose, non-oil resistant		**General purpose, oil resistant**	
ELASTOMER/ ASTM DESIGNATION	Butadiene styrene/SBR, Butadiene/BR	Ethylene propylene/EPM, EPDM	Nitrile/ NBR	Neoprene/ CR
Freon T-WD602	C	C	C	C
Freon TMC	N	C	C	C
Freon T-P35	R	R	R	R
Freon TA	R	R	R	R
Freon TC	C	C	R	R
Freon MF	C	—	R	N
Freon BF	N	—	C	C
Fuel oil	N	N	R	C
Fumaric acid	R	—	R	C
Furan, furfuran	N	N	N	N
Furfural	N	C	N	C
Gallic acid	C	C	C	C
Gasoline	N	N	R	C
Gelatin	R	R	R	R
Glauber's salt	N	C	—	—
Glucose	R	R	R	R
Glue	R	R	R	R
Glycerin	R	R	R	R
Glycols	R	R	R	R
Green sulfate liquor	C	R	C	C
Halowax oil	N	N	N	N
n-Hexaldehyde	N	R	N	R
Hexane	N	N	R	C
n-Hexene-1	N	N	C	C
Hexyl alcohol	R	N	R	C

Table 3.3 Chemical resistance* of (PVC) gasket materials (*continued*)

	General purpose, non-oil resistant		**General purpose, oil resistant**	
ELASTOMER/ ASTM DESIGNATION	Butadiene styrene/SBR, Butadiene/BR	Ethylene propylene/EPM, EPDM	Nitrile/ NBR	Neoprene/ CR
Hydraulic oil (petroleum)	N	N	R	C
Hydrazine	—	R	C	C
Hydrobromic acid	N	R	N	R
Hydrochloric acid (cold) 37%	C	R	C	C
Hydrochloric acid (hot) 37%	N	N	N	N
Hydrocyanic acid	C	R	C	C
Hydrofluoric acid, anhydrous	N	C	—	—
Hydrofluoric acid (conc) (cold)	N	C	N	C
Hydrofluoric acid (conc) (hot)	N	N	N	N
Hydrofluorosilicic acid	C	R	C	N
Hydrogen gas	C	R	R	R
Hydrogen peroxide, 90%	N	N	N	—
Hydrogen sulfide, wet (cold)	N	R	N	R
Hydrogen sulfide, wet (hot)	N	R	N	C
Hydroquinone	C	—	N	—
Hypochlorous acid	C	C	N	—

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Table 3.3 Chemical resistance of (PVC) gasket materials (*continued*)

	General purpose, non-oil resistant		**General purpose, oil resistant**	
ELASTOMER/ ASTM DESIGNATION	Butadiene styrene/SBR, Butadiene/BR	Ethylene propylene/EPM, EPDM	Nitrile/ NBR	Neoprene/ CR
Iodine pentafluoride	N	N	N	N
Iodoform	—	R	—	—
Isobutyl alcohol	C	R	C	R
Isooctane	N	N	R	C
Isophorone	—	R	N	—
Isopropyl acetate	—	R	N	N
Isopropyl alcohol	C	R	C	R
Isopropyl chloride	N	N	N	—
Isopropyl ether	N	N	C	C
Kerosene	N	N	R	N
Lacquer solvents	N	N	N	N
Lacquers	N	N	N	N
Lactic acid	R	R	R	R
Lard	N	N	R	N
Lavender oil	N	N	C	N
Lead acetate	—	R	C	C
Lead nitrate	R	R	R	R
Lead sulfamate	C	R	C	R
Lime bleach	R	R	R	C
Lime sulfur	N	R	N	R
Lindol	—	R	—	N
Linoleic acid	—	N	C	N
Linseed oil	N	C	R	C
Liquefied petroleum gas	N	N	R	C

Table 3.3 Chemical resistance* of (PVC) gasket materials (*continued*)

	General purpose, non-oil resistant		**General purpose, oil resistant**	
ELASTOMER/ ASTM DESIGNATION	Butadiene styrene/SBR, Butadiene/BR	Ethylene propylene/EPM, EPDM	Nitrile/ NBR	Neoprene/ CR
Lubricating oils (petroleum)	N	N	R	C
Lye	C	R	C	C
Magnesium chloride	R	R	R	R
Magnesium hydroxide	C	R	C	R
Magnesium sulfate	C	R	R	R
Maleic acid	C	N	—	—
Maleic anhydride	C	N	—	—
Malic acid	C	N	R	C
Mercuric chloride	R	R	R	R
Mercury	R	R	R	R
Mesityl oxide	N	C	N	N
Methane	N	N	R	C
Methyl acetate	N	C	N	C
Methyl acrylate	N	C	N	C
Methyl alcohol	R	R	R	R
Methyl bromide	—	—	C	N
Methyl butyl ketone	N	R	N	N
Methyl cellosolve	N	C	—	C
Methyl chloride	N	N	N	N
Methyl cyclopentane	N	N	—	N
Methyl ethyl ketone	N	R	N	N

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Table 3.3 Chemical resistance of (PVC) gasket materials (*continued*)

	General purpose, non-oil resistant		**General purpose, oil resistant**	
ELASTOMER/ ASTM DESIGNATION	Butadiene styrene/SBR, Butadiene/BR	Ethylene propylene/EPM, EPDM	Nitrile/ NBR	Neoprene/ CR
Methyl formate	N	C	N	C
Methyl isobutyl ketone	N	N	N	N
Methyl methacrylate	N	N	N	N
Methyl oleate	N	C	N	N
Methyl salicylate	—	C	—	N
Methylacrylic acid	N	C	—	C
Methylene chloride	N	N	N	N
Milk	R	R	R	R
Mineral oil	N	N	R	C
Monochlorobenzene	N	N	N	N
Monoethanolamine	C	C	N	N
Monomethyl aniline	N	—	N	N
Monomethylether	C	R	R	R
Monovinyl acetylene	C	R	R	C
Mustard gas	—	R	—	R
Naphtha	N	N	N	N
Naphthalene	N	N	N	N
Naphthenic acid	N	N	C	—
Natural gas	N	N	R	R
Neatsfoot oil	N	C	R	—
Neville acid	N	C	N	N
Nickel acetate	—	R	C	C
Nickel chloride	R	R	R	R
Nickel sulfate	C	R	R	R
Niter cake	R	R	R	R
Nitric acid (conc)	N	N	N	N

Table 3.3 Chemical resistance* of (PVC) gasket materials (*continued*)

	General purpose, non-oil resistant		**General purpose, oil resistant**	
ELASTOMER/ ASTM DESIGNATION	Butadiene styrene/SBR, Butadiene/BR	Ethylene propylene/EPM, EPDM	Nitrile/ NBR	Neoprene/ CR
Nitric acid (dilute)	N	C	N	R
Nitric acid—red fuming	N	N	N	N
Nitrobenzene	N	N	N	N
Nitrobenzine	—	N	—	N
Nitroethane	C	C	N	N
Nitrogen	R	R	R	R
Nitrogen tetroxide	N	N	N	N
Nitromethane	C	C	N	N
Octachlorotoluene	N	N	N	N
Octadecane	N	N	R	C
n-Octane	N	N	—	—
Octyl alcohol	C	R	C	R
Oleic acid	N	C	N	N
Oleum spirits	—	—	C	N
Olive oil	N	C	R	C
Oxalic acid	C	R	C	C
Oxygen (cold)	C	R	C	C
Oxygen (200–400°F)	N	N	N	N
Ozone	N	R	N	C
Paint thinner, Duco	N	N	—	—
Palmitic acid	C	C	R	C

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Table 3.3 Chemical resistance of (PVC) gasket materials (*continued*)

	General purpose, non-oil resistant		**General purpose, oil resistant**	
ELASTOMER/ ASTM DESIGNATION	Butadiene styrene/SBR, Butadiene/BR	Ethylene propylene/EPM, EPDM	Nitrile/ NBR	Neoprene/ CR
Peanut oil	N	N	R	C
Perchloric acid	—	C	—	R
Perchloroethylene	N	N	N	N
Petroleum (below 250°F)	N	N	R	C
Petroleum (above 250°F)	N	N	N	N
Phenol	—	C	—	N
Phenylbenzene	N	N	N	N
Phenylethyl ether	N	N	N	N
Phenyl hydrazine	C	N	N	N
Phorone	—	C	—	—
Phosphoric acid, 20%	N	R	C	C
Phosphoric acid, 45%	N	C	N	C
Phosphorous trichloride	N	R	N	N
Pickling solution	—	N	—	—
Picric acid	C	C	C	R
Pine oil	N	N	C	N
Pinene	N	N	C	C
Piperidine	N	N	N	N
Plating solution–chrome	N	R	—	—
Plating solution–others	—	R	R	—
Polyvinyl acetate emulsion	—	R	—	C
Potassium acetate	—	R	C	C
Potassium chloride	R	R	R	R
Potassium cupro cyanide	R	R	R	R
Potassium cyanide	R	R	R	R
Potassium dichromate	C	R	R	R

Table 3.3 Chemical resistance* of (PVC) gasket materials (*continued*)

	General purpose, non-oil resistant		**General purpose, oil resistant**	
ELASTOMER/ ASTM DESIGNATION	Butadiene styrene/SBR, Butadiene/BR	Ethylene propylene/EPM, EPDM	Nitrile/ NBR	Neoprene/ CR
Potassium hydroxide	C	R	C	R
Potassium nitrate	R	R	R	R
Potassium sulfate	C	R	R	R
Producer gas	N	N	R	C
Propane	N	N	R	R
Propyl acetate	N	C	N	N
n-Propyl acetate	N	R	N	—
Propyl alcohol	R	R	R	R
Propyl nitrate	—	C	—	—
Propylene	N	N	N	N
Propylene oxide	—	C	—	N
Pydrauls	N	C	N	N
Pyranol	N	N	R	N
Pyridine	N	C	N	N
Pyroligneous acid	—	C	—	C
Pyrrole	N	N	N	N
Radiation	C	C	C	C
Rapeseed oil	N	R	C	C
Red oil	N	N	R	C
Sal ammoniac	R	R	R	R
Salicylic acid	C	R	R	—

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Table 3.3 Chemical resistance of (PVC) gasket materials (*continued*)

	General purpose, non-oil resistant		**General purpose, oil resistant**	
ELASTOMER/ ASTM DESIGNATION	Butadiene styrene/SBR, Butadiene/BR	Ethylene propylene/EPM, EPDM	Nitrile/ NBR	Neoprene/ CR
Salt water	R	R	R	R
Silicate esters	N	N	C	R
Silicone greases	R	R	R	R
Silicone oils	R	R	R	R
Silver nitrate	R	R	C	R
Skydrol 500	N	R	N	N
Skydrol 7000	N	R	N	N
Soap solutions	C	R	R	R
Soda ash	R	R	R	R
Sodium acetate	N	R	C	C
Sodium bicarbonate	R	R	R	R
Sodium bisulfite	C	R	R	R
Sodium borate	R	R	R	R
Sodium chloride	R	R	R	R
Sodium cyanide	R	R	R	R
Sodium hydroxide	R	R	C	R
Sodium hypochlorite	N	C	C	C
Sodium metaphosphate	R	R	R	C
Sodium nitrate	C	R	C	R
Sodium perborate	C	R	C	C
Sodium peroxide	C	R	C	C
Sodium phosphate	R	R	R	R
Sodium silicate	R	R	R	R
Sodium sulfate	C	R	R	R
Sodium thiosulfate	C	R	C	R
Soybean oil	N	N	R	C
Stannic(ous) chloride	R	C	R	R

Table 3.3 Chemical resistance* of (PVC) gasket materials (*continued*)

	General purpose, non-oil resistant		**General purpose, oil resistant**	
ELASTOMER/ ASTM DESIGNATION	Butadiene styrene/SBR, Butadiene/BR	Ethylene propylene/EPM, EPDM	Nitrile/ NBR	Neoprene/ CR
Steam under 300°F	N	R	N	N
Steam over 300°F	N	C	N	N
Stearic acid	C	C	C	C
Stoddard solvent	N	N	R	N
Styrene	N	N	N	N
Sucrose solution	R	R	R	R
Sulfite liquors	C	C	C	C
Sulfur	N	R	N	R
Sulfur chloride	N	N	N	N
Sulfur dioxide	N	R	N	N
Sulfur hexafluoride	R	R	R	R
Sulfur trioxide	N	C	N	N
Sulfuric acid (dilute)	N	C	N	C
Sulfuric acid (conc)	N	C	N	N
Sulfuric acid (20% oleum)	N	N	N	N
Sulfurous acid	C	C	C	C
Tannic acid	C	R	R	R
Tar, bituminous	N	N	C	N
Tartaric acid	C	C	R	C
Terpincol	N	N	C	N
Tertiary butyl alcohol	C	C	C	C
Tertiary butyl catechol	N	C	N	C

*R = generally resistant; C = less resistant than R but still suitable for some conditions; N = not resistant

A dash indicates insufficient data to provide a rating.

This table is meant to aid the designer in decisions as to transporting/conveyance of undiluted chemicals. Chemical resistance data are provided as a guide only. Information is based primarily on immersion of unstressed strips in chemicals and to a lesser degree on field experience.

Table 3.3 Chemical resistance of (PVC) gasket materials (*continued*)

	General purpose, non-oil resistant		**General purpose, oil resistant**	
ELASTOMER/ ASTM DESIGNATION	Butadiene styrene/SBR, Butadiene/BR	Ethylene propylene/EPM, EPDM	Nitrile/ NBR	Neoprene/ CR
Tertiary butyl mercaptan	N	N	N	N
Tetrabromomethane	N	N	N	—
Tetrabutyl titanate	C	R	C	R
Tetrachloroethylene	N	N	N	—
Tetraethyl lead	N	N	C	N
Tetrahydrofuran	N	C	—	—
Tetralin	N	N	N	N
Thionyl chloride	N	N		N
Titanium tetrachloride	N	N	N	N
Toluene	N	N	N	N
Toluene diisocyanate	N	R		N
Transformer oil	N	N	R	C
Transmission fluid type A	N	N	R	C
Tributoxy ethyl phosphate	C	R	N	N
Tributyl mercaptan	N	N	N	N
Tributyl phosphate	N	R	N	N
Trichloroacetic acid	C	C	C	C
Trichloroethane	N	N	N	N
Trichloroethylene	N	N	N	N
Tricresyl phosphate	N	R	N	N
Triethanol amine	C	C	N	R
Trinitrotoluene	N	N	N	C
Triocetin	N	R	C	C
Trioctyl phosphate	N	R	N	N
Trioryl phosphate	N	R	N	N
Tung oil	N	N	R	C

Table 3.3 Chemical resistance* of (PVC) gasket materials (*continued*)

	General purpose, non-oil resistant		**General purpose, oil resistant**	
ELASTOMER/ ASTM DESIGNATION	Butadiene styrene/SBR, Butadiene/BR	Ethylene propylene/EPM, EPDM	Nitrile/ NBR	Neoprene/ CR
Turbine oil	N	N	C	C
Turpentine	N	N	R	N
Unsymmetrical dimethyl hydrazine (ODMH)	—	R	C	C
Varnish	N	N	C	N
Vegetable oils	N	R	R	C
Versilube	R	R	R	R
Vinegar	C	R	C	R
Vinyl chloride	—	C	—	N
Wagner 21B fluid	R	R	N	R
Water	R	R	R	R
Whiskey, wines	R	R	R	R
White oil	N	N	R	C
White pine oil	N	N	C	N
Wood oil	N	N	R	C
Xylene	N	N	N	N
Xylidenes	N	N	N	N
Zeolites	R	R	R	R
Zinc acetate	N	R	C	C
Zinc chloride	R	R	R	R
Zinc Sulfate	C	R	R	R

*R = generally resistant; C = less resistant than R but still suitable for some conditions; N = not resistant

A dash indicates insufficient data to provide a rating.

This table is meant to aid the designer in decisions as to transporting/conveyance of undiluted chemicals. Chemical resistance data are provided as a guide only. Information is based primarily on immersion of unstressed strips in chemicals and to a lesser degree on field experience.

3.5 Permeation

Permeation is the molecular transport of chemicals through the pipe wall or gasket. Permeation may have adverse effects on the piping system, the conveyed fluid, or both. Because PVC is widely used for the transmission and distribution of potable water, it is important to understand PVC pipe's advantages and limitations regarding permeation.

The issue of permeation started to receive considerable attention in the late 1970s; since then, the topic has been thoroughly studied, evaluated, and reported on by several independent researchers, including Berens, Park, Pfau, Veenendaal, Vonk, and Gaunt. A summary of their individual findings is as follows:

- Water quality can be affected if organic soil contaminants are able to permeate water pipe walls or gasket materials.
- Organic solvents of sufficient concentration have demonstrated their ability to permeate through elastomeric gaskets, thermoplastic pipes, and asbestos cement pipes.
- PVC pipe and ductile iron pipe are impervious to gasoline and can be safely used in soils contaminated with gasoline regardless of level of contamination. There is no level of contamination at which HDPE pipe is resistant to permeation by gasoline or chlorinated solvents.
- Limited gasoline permeation takes place through the gaskets for PVC and ductile iron, as the AWWA Research Foundation (now WRF) study found.
- PVC pipe is also resistant to water solutions of benzene, toluene, and trichloroethylene (TCE) for all but the most extreme levels of environmental contamination.
- No significant permeation occurs through PVC pipes with:
  - alcohols, aliphatic hydrocarbons, and organic acids; Table 3.4 lists aliphatic hydrocarbons where permeation is not a concern;
  - benzene or alkylated benzenes if the activity of the organic chemical is less than 0.25; and
  - anilines, chlorinated hydrocarbons, ketones, and nitrobenzenes if the activity of the organic chemical is less than 0.1.

Note: An activity level of 0.25 for toluene corresponds to approximately 125 ppm in groundwater. Activity level is approximately the ratio of chemical concentration to solubility. In the vapor phase, activity is the ratio of the partial pressure (P) of the substance to its saturated vapor pressure (P_o) at the same temperature (activity = P/P_o). For liquid or solid phases, activity is most simply determined by measuring P of the vapor in equilibrium with either the liquid or solid phase.

Table 3.4 Aliphatic hydrocarbons for which permeation through PVC pipe is not a concern

- 1,2-butadiene
- 1,3-butadiene
- butane
- butane-1
- cycloheptane
- cycloheptene
- cyclohexane
- cyclohexene
- cyclooctane
- cyclopentane
- 2,2-dimethylbutane
- 2,3-dimethylhexane
- dimethylpentane
- 2,2-dimethylpropane
- ethane
- ethylene
- ethyne
- heptane
- 2-heptene
- hexane
- 1-hexene
- isoprene
- methane
- 2-methylpentane
- 3-methylpentane
- 2-methyl-1-pentene
- 3-methyl-1-pentene
- 4-methyl-1-pentene
- methylpropane
- 2-methylpropene
- nonane
- octane
- 1-octane
- 1,3-pentadiene
- 1,4-pentadiene
- pentane
- pentene-1
- pentene-2
- propane
- propylene
- 2,2,4-trimethylpentane

The potential for PVC watermain permeation is extremely low. In those very few areas where gross organic chemical contamination does exist, no gasketed water pipeline should be installed without a site investigation taking place first.

3.6 Biological Attack

3.6.1 General Information

Biological attack is defined as degradation caused by the action of living micro- or macroorganisms. Microorganisms that attack organic materials include fungi and bacteria. Macroorganisms that can affect organic materials located underground include tree roots, insects, and rodents.

3.6.2 System Components

3.6.2.1 PVC Pipe and Fittings

During the natural cycle of growth and decay, nearly all man-made products break down. However, some plastic products are exceptions, including PVC pipe and fittings, which have proven to be immune to biological attack. Once PVC pipe has been installed in underground water and sewer systems, it is not susceptible to natural processes of deterioration.

The performance of PVC pipe in severe environments has been studied since the birth of the industry in the 1930s. These studies have found that PVC pipe does not deteriorate or break down under biological attack because PVC does not serve as a nutrient for organisms. Investigations have failed to document a single case in which buried PVC pipe products have suffered degradation or deterioration due to biological attack.

3.6.2.2 Gaskets

Elastomers used in pipe gaskets are manufactured with a variety of properties (see Chapter 2). Although natural elastomers are susceptible to biological degradation, the synthetic materials used in pipe gaskets provide high resistance to attack. For potable water systems, a material that will not support the growth of microorganisms is required.

3.6.2.3 Lubricants

Assembly of gasketed joints is facilitated by use of a lubricant recommended by the pipe manufacturer and applied in accordance with the manufacturer's instructions. Lubricants have been developed that are compatible with pipe and gasket materials and that do not support the growth of microorganisms.

3.6.3 Types of Attack

3.6.3.1 Tree Roots

Prevention of tree root intrusion is imperative in modern piping systems, and such prevention requires that: (1) pipe joints do not leak and (2) pipe does not crack. Any opening in the pipe joints may admit leakage and infiltration, providing easy access for tree roots into the pipe. Extensive experience with gasketed joint PVC pipe has found that PVC pipe is not vulnerable to root intrusion.

One research study using tree roots and gasketed pipe was performed in 1977 in Pell City, Alabama. Six PVC sewer joints (6-in. ASTM D3034, SDR 35) were assembled and then installed in a soil box. A 7-ft weeping willow tree was planted directly over the pipe joint assembly (see Fig. 3.1). A constant flow of water was provided through the pipe for the duration of the test. The results were conclusive: The test was discontinued because the tree died from lack of water.

Research conducted at the Utah State University Buried Structures Laboratory has shown that PVC pipe will not allow root intrusion even when subjected to abusive installation

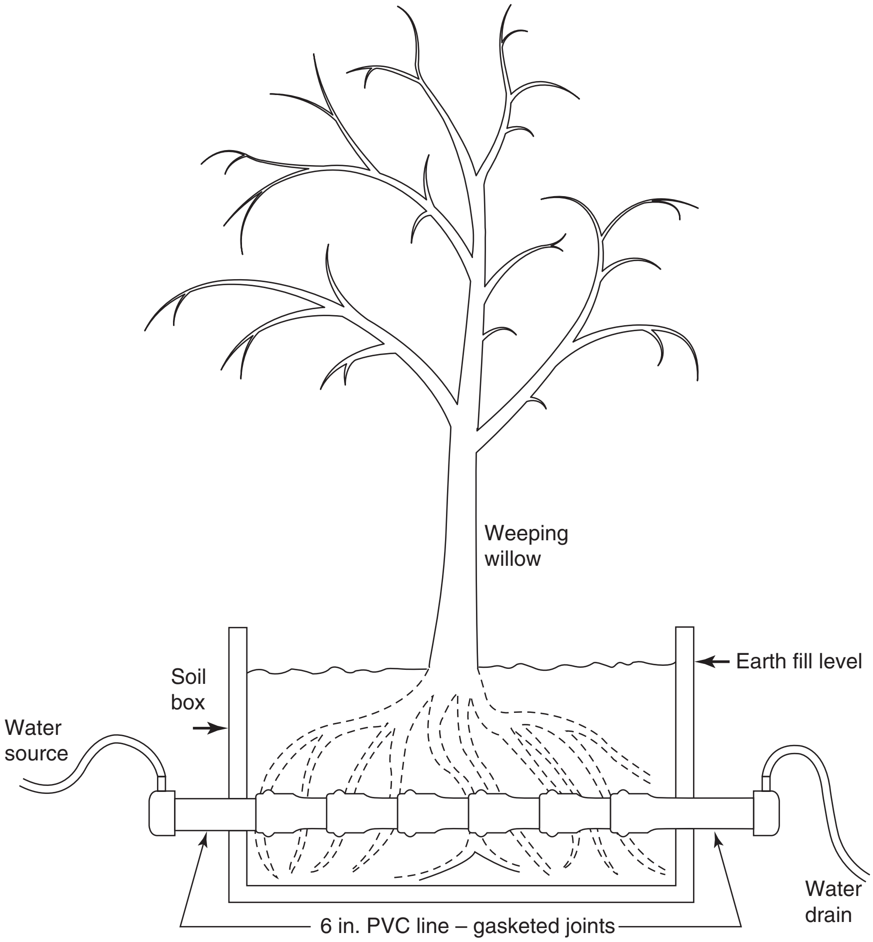

Fig. 3.1 Root resistance research.

conditions. Gasketed PVC joints remain leak-resistant, and the longitudinal flexibility allows movement without cracking, even under severe loading conditions. In this study, tests were conducted on 8-in. PVC sewer pipe (ASTM D3034, SDR 35) with integral bell-gasketed joints. Specimens were tested under loads equivalent to buried depths greater than 35 ft, and abusive conditions were created by placement of a 10-lb rock on the male spigot end adjacent to the bell joint (see Fig. 3.2). Joints were then tested with 3.5 psi air pressure, which was held for 5 min. Results summarized in Table 3.5 reveal the resistance of PVC pipe joints to leakage and associated root intrusion.

Both field experience and laboratory data clearly show that PVC sewer pipe with properly installed gasketed joints is not subject to root intrusion. The use of saws, augers, or chemicals for root removal is not necessary for PVC sewer pipe (see Uni-Bell's UNI-TR-3, Maintenance of PVC Sewer Pipe).

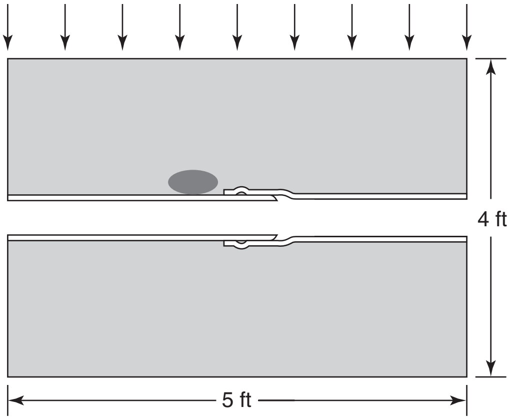

Fig. 3.2 Abusive test condition for PVC joint test in soil cell with 10-lb rock on spigot end.

Table 3.5 Results of PVC joint test

Test no.	Test description	Percent deflection when test terminated			Comments*
		Location			
		A	B	C	
1	85% soil density, no rock	33	NM	27	No leakage at 11,700 lb/ft^2 (H = 97 ft)
2	85% soil density, with rock	33	43	32	No leakage at 11,700 lb/ft^2 (H = 97 ft)
3	65% soil density, with rock	20	43	18	Joint leaked at 4,370 lb/ft^2 (H = 36 ft)
4	65% soil density, no rock	30	NM	25	No leakage at 5,840 lb/ft^2 (H = 48 ft)
		43	NM	NM	No leakage at 11,687 lb/ft^2 (H = 97 ft)

NM = no measurement.

*Leakage test conducted with 3.5 psi air pressure held for 5 min.

3.6.3.2 Insects

The insect of most concern is the termite. However, though termites have been known to attack some types of plastic, they do not attack the unplasticized PVC used in pipe. In 1955, samples of PVC were exposed to termite attack in Gulfport, Mississippi (an area regularly used for termite testing of materials). After more than four years of exposure, inspection showed no signs of termite attack on the samples. PVC pipe is not subject to attack by termites or other insects.

3.6.3.3 Rodents

NSF International (formerly the National Sanitation Foundation) conducted a series of tests designed to determine the susceptibility of PVC pipe to attack by rodents. Test sections of PVC pipe were installed in the openings of rat enclosures as barriers between rats and sources of food and water. The rats were supplied with reduced rations calculated to maintain good health but constant hunger. After one month the pipe test sections showed evidence of the rats' attempts to gnaw through to obtain food, but there was no penetration. There was also no evidence of attempted attack on the pipe where it did not interfere with access to food. PVC is not a source of nutrition, so rodents are not prone to attacking PVC pipe.

3.7 Weathering

3.7.1 UV Exposure

PVC pipe can suffer surface discoloration when exposed to ultraviolet (UV) radiation from sunlight. UV radiation affects PVC when energy from the sun causes excitation of the molecular bonds in the plastic. The resulting reaction occurs only on the exposed surface of the pipe and down to extremely shallow depths of 0.001 to 0.003 in. The effect does not continue when exposure to sunlight is terminated.

A two-year study was undertaken to quantify the effects of UV radiation on the properties of PVC pipe (see Uni-Bell's UNI-TR-5, The Effects of Ultraviolet Aging on PVC Pipe). The study found that exposure to UV radiation results in a change in the pipe's surface color and a slight reduction in impact strength. Other properties such as tensile strength (pressure rating) and modulus of elasticity (pipe stiffness) are not adversely affected.

Presence of an opaque shield between the sun and the pipe prevents UV degradation. While UV radiation will not penetrate even thin shields such as paint coatings or wrappings, burial of PVC pipe provides complete protection against UV attack.

The most common method used to protect above-ground PVC pipe from the sun is application of latex (water-based) paint. Preparation of the surface to be painted is very important: The pipe should be cleaned first to remove moisture, dirt and oil; the surface should be roughened with fine sandpaper and then wiped with a clean, dry cloth. Petroleum-based paints should not be used, since the presence of petroleum will prevent proper bonding of paint to pipe.

PVC pipe products with enhanced sunlight resistance properties—which do not need protection from UV light exposure—are also available for above-ground applications.

3.7.2 Temperature Extremes

PVC pipe durability is not adversely affected by wet/dry cycles, hot/cold cycles, or freezing temperatures. In fact, gasketed PVC pressure pipe has performed well in climates ranging from tropical to permafrost. Specific physical/mechanical property variations with temperature are addressed in Chapter 5, Section 5.3.4, and Chapter 7, Section 7.6.

Typically, pressure pipe systems are designed never to freeze while in service. However, research from Canada, where hard freezes are common, has demonstrated that buried PVC water distribution pipes are able to accommodate the stresses created by water freezing. Specifically, the National Research Council of Canada conducted a three-year evaluation on the insulating properties of different backfill materials. In addition, an investigation of rupture behavior was undertaken by the intentional freezing solid a section of PVC pipe.

The finding was that frost loadings, even with clay backfill, did not overload the pipe. The water inside the pipe was frozen solid two of the three years, yet a leak test conducted after the third winter indicated no damage to the PVC pipe. Even though water expands about 9% upon freezing, expansion was effectively restrained by the surrounding soil and the PVC pipe withstood the stresses involved.

3.8 Abrasion

Years of experience have shown that PVC pipe has exceptional resistance to abrasion; many investigations and tests in Europe and North America have been conducted to define PVC pipe's abrasion resistance. While testing methods have varied substantially, results have been consistent: The nature and resiliency of PVC pipe cause it to gradually erode over a broad area rather than develop the characteristic localized pitting and rapid failure of most other piping materials.

Tests have been conducted to investigate the resistance of PVC pipe to abrasion caused by mechanical cleaning. In tests where standard commercial cleaning and rodding equipment was used, operating in wet lines, dry lines, and lines partially filled with sand

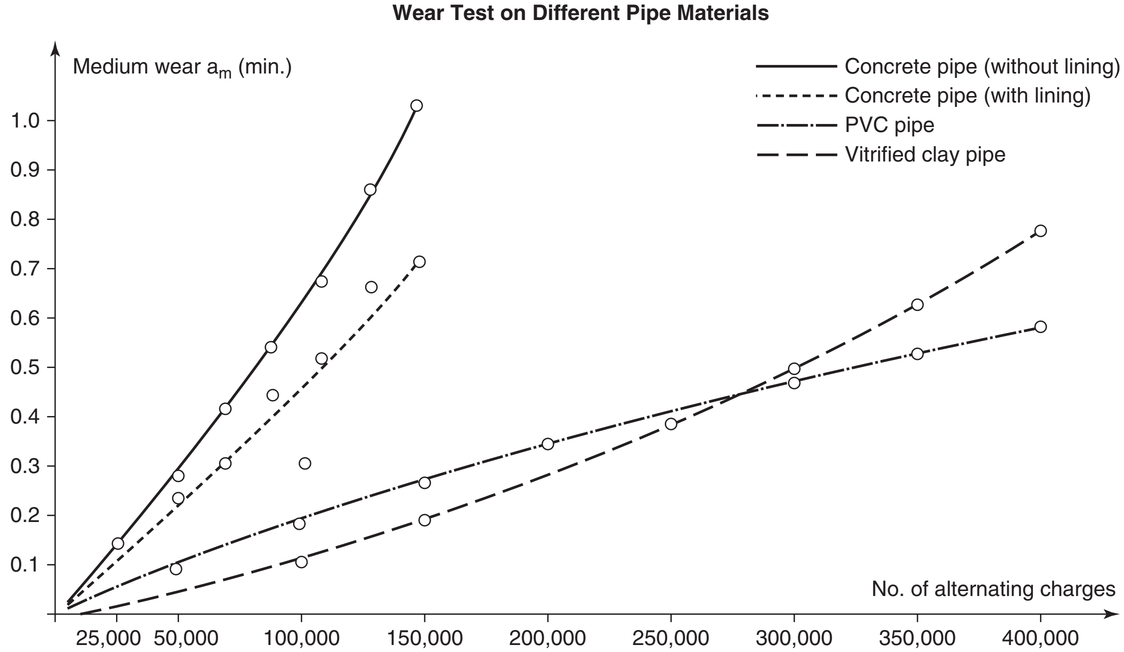

Fig. 3.3 Abrasion test results. Abrasion evaluation using river sand and gravel in unlined concrete pipe, lined concrete pipe, glazed vitrified clay pipe, and PVC pipe.

and gravel, PVC pipe showed insignificant wear for a wide assortment of conditions (see Uni-Bell's UNI-TR-3, Maintenance of PVC Sewer Pipe).

Abrasion tests were performed on several piping products by the Institute for Hydromechanic and Hydraulic Structures of the Technical University of Darmstadt, Germany. Abrasion evaluation using river sand and gravel in unlined concrete pipe, lined concrete pipe, glazed vitrified clay pipe, and PVC pipe produced the following results (see Fig. 3.3):

- Concrete (unlined): measurable wear at 150,000 cycles.
- Concrete (lined): measurable wear at 150,000 cycles (less wear than unlined concrete).
- Vitrified clay (glazed): minimal wear at 260,000 cycles (accelerated wear after glazing wore off at 260,000 cycles).
- PVC: minimal wear at 260,000 cycles (about equal to glazed vitrified clay, but less accelerated than vitrified clay).

A second German abrasion investigation included an even broader range of pipe materials. The resultant values for specific abrasion are expressed in terms of wall thickness removed and in terms of relative increase in stress under loading (refer to Table 3.6). Relative abrasion values can be used to select appropriate pipe materials and to make pipe material longevity comparisons. For example, Table 3.6 can be used to compare the values of predicted wall thickness lost due to abrasion between piping materials. Assuming a

Table 3.6 Abrasion wear of different pipe materials

Pipe material	Specific abrasion (μm)	Relative increase in stress for same abrasive effect (%)
PVC	0.754	0.6
Steel	1.72	6
Cast iron	2.09	2
Stoneware (clay)	4.31	2
Concrete	15.90	5
Asbestos cement	17.28	9

time factor of 15, the concrete pipe would lose 75% (15 × 5%) of its available wall thickness to abrasion, while a PVC pipe would lose only 9% (15 × 0.6%) of its wall thickness.

Abrasion testing has also been conducted at California State University, Sacramento, where the performance of PVC profile wall pipe versus reinforced concrete pipe was evaluated, using velocities and aggregate materials to simulate very aggressive conditions. Additionally, acidity (pH) ranges were varied to simulate common in-service conditions.

PVC pipe exhibited minimal wear at 250,000 cycles. Conversely, identical tests on reinforced concrete pipes (RCP) had to be stopped prematurely at 165,000 cycles due to wall breaches of the samples (see Figs. 3.4 and 3.5 for comparison between RCP and PVC pipes).

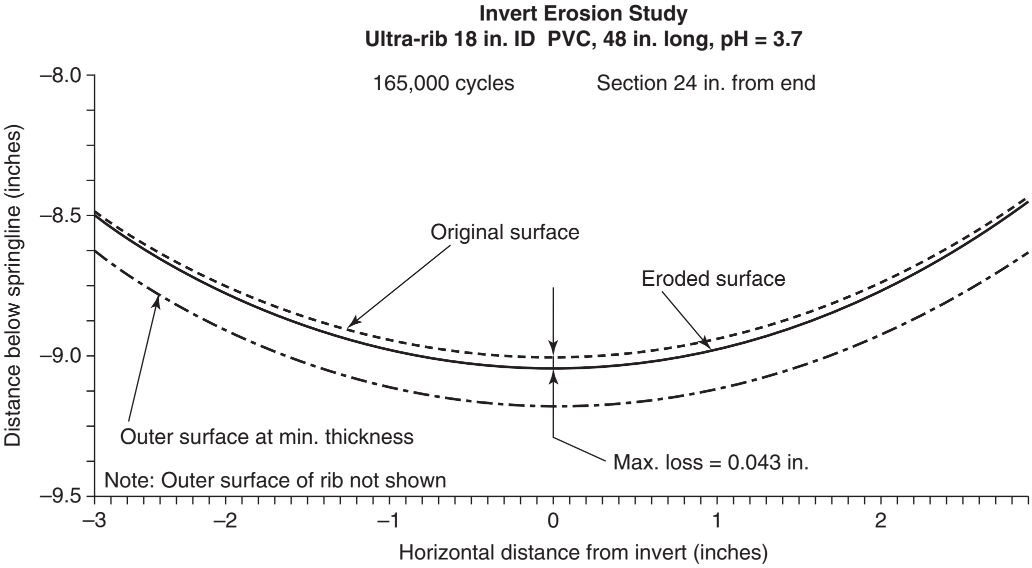

Fig. 3.4 PVC pipe invert erosion.

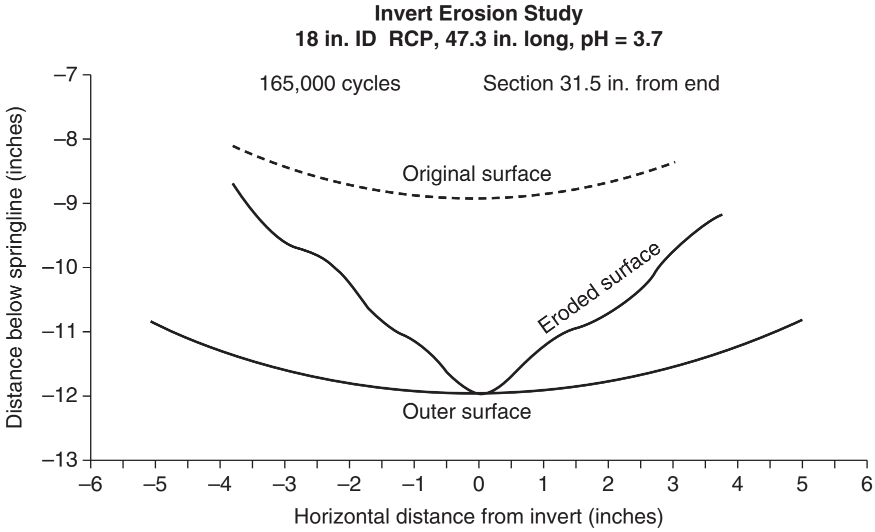

Fig. 3.5 RCP pipe invert erosion.

In this study, PVC profile pipe exhibited no measurable sensitivity or patterns of invert wear with increasing acidity of the water. Conversely, the reinforced concrete pipes (studied in parallel with the PVC pipes) were influenced by the acidity of the flowing water, with increasingly severe invert wear in response to increasing acidity.

In extremely abrasive exposures, wear must be considered. When compared with most other pipe materials, the use of PVC pipe can significantly reduce maintenance costs incurred due to abrasion and provide longer service life.

3.9 Soil Movement

While aggressive soils are often thought of in terms of the corrosion they cause, “aggressive” can also refer to their movement. Movements from expansion or contraction, frost heave, and earthquakes can turn soils into extremely aggressive environments for pipelines. If a pipeline has insufficient flexibility to allow movement, or if it has insufficient strength to resist it, the pipe will fail.

Because of their lack of flexibility, rigid pipes commonly experience beam breaks in expansive clays, shear failures due to manhole settlements, and shear and beam breaks as a result of earthquakes.

PVC pipe has longitudinal flexibility, which allows it to perform effectively while permitting relatively large movements, often making it the remedy for systems that have experienced failures due to soil movement. A survey of the San Francisco Bay Area’s water distribution systems immediately following the 1989 earthquake revealed that the PVC portions of these systems performed extremely well, displaying little to no effect from the quake.

3.10 Repetitive Fatigue

Repeated stress variation is known to shorten the life of many pipe materials through fatigue. PVC pipes have been evaluated under conditions of repetitive external live loads and repetitive internal pressure surges. In Chapter 5, Design Example 5.5 includes specific information for design that accommodates frequent internal surge pressures; in Chapter 7, Section 7.8.3 discusses PVC pipe performance under dynamic external wheel loadings. PVC pipe offers exceptional capabilities of fatigue-resistance.

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CHAPTER 4

Manufacturing and Testing of PVC Pipe and Fittings

Solid-Wall Pipe
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4.1 Introduction

Through research, development, and experience, the PVC pipe industry has advanced and matured since the product was introduced during the Second World War. A constantly evolving product, PVC pipe can be best evaluated and appreciated through an understanding of its technology. Ideally, the industry's stakeholders should possess comprehensive knowledge of the advantages and limitations of the piping systems they use. Toward this end, Chapter 4 reviews:

- manufacturing processes
- standard specifications
- testing requirements
- packaging
- shipping.

The technology of PVC pipe manufacturing processes is extensive and involved (Fig. 4.1). Well before a finished PVC product is ready for testing, inspection, and delivery, its beginnings can be traced from oil or gas wells, through petrochemical plants to PVC compounding operations, and finally to automated extrusion, molding, and fabrication operations.

As covered in Chapter 2, PVC pipe is produced from a blend of materials whose major ingredient is polyvinyl chloride resin. In the plastics industry, the word "resin" refers to the basic polymer used as a raw material and "compound" refers to a homogeneous blend of

Fig. 4.1 PVC pipe manufacturing facility.

resin and various additives. Polyvinyl chloride resin is a thermoplastic polymer produced by the polymerization of vinyl chloride monomer (VCM). Vinyl chloride is a colorless gas produced from chlorine and ethylene. In North America, the raw materials of vinyl chloride monomer are saltwater and natural gas.

The terms *thermoplasticity, polymer, monomer,* and *polymerization* are defined as follows:

- *Thermoplasticity* refers to the property that enables a material to be repeatedly softened by an increase in temperature and hardened by a decrease in temperature.
- A *polymer* is an organic material that contains a large number of the same chemical configurations, attached to each other like links in a chain. The long chains result in high molecular weight.
- A *monomer* is the simple, small molecule from which the polymer chain is made.
- *Polymerization* is the reaction that bonds monomers into the large structure of the polymer.

Polymers are not exclusively manmade; they are also found in a large variety of natural materials such as protein, cellulose, starch, and rubbers.

There are many polymerization processes that convert vinyl chloride monomer into polyvinyl chloride resin (polymer). Two processes are best suited to the manufacture of the type of high quality PVC resin needed for pipe. They are (1) suspension polymerization and (2) mass (sometimes termed “bulk”) polymerization. These are economical processes used in the production of virtually all PVC pipe-grade resins today.

After production and quality assurance, resin manufacturers ship the PVC resin (in powder form) to pipe producers. Product parameters commonly evaluated include molecular weight, particle size/dimension, volatiles content, bulk density, flow time, and residual VCM. Large 200,000-lb bulk railcars or 40,000-lb bulk trucks are normally used to transport the PVC resin. Upon arrival at a pipe manufacturer, the resin is pneumatically conveyed from the bulk transporters into the pipe production plant and stored in silos.

Other ingredients that are compounded with the PVC resin include stabilizers, pigments, lubricants, processing aids, and functional additives. Each ingredient is used to impart specific processing characteristics or to enhance specific finished product properties. For instance, functional additives may be used to increase the PVC compound’s modulus of elasticity. The proportions of these minor ingredients will vary from compound to compound. The formulations, which stipulate the percentages and actual ingredients used in a given PVC pipe compound, are developed to impart specific properties dictated by application. As described in Chapter 2, properties for rigid PVC compounds are established in ASTM D1784.

The process used to mix PVC resin with minor ingredients to produce PVC pipe extrusion compound is termed *dry-blend compounding* or *dry blending*. Dry blending is performed in a high-speed, intensive mixer. In the process, friction created by high-speed rotation of the mixer blades and intense movement of material particles generates substantial heat, elevating the temperature of the blending materials. As PVC particles are heated they expand, developing a porous, irregular appearance similar to that of popcorn. These particles then become uniformly coated with minor ingredients in proportions determined by the compound formulation (some ingredients, such as lubricants, melt at the elevated temperatures, permitting thorough dispersion and providing added homogeneity to the blend). After intensive mixing at elevated temperatures for several minutes, preparation of a PVC compound batch is complete. The batch is then cooled and transported to compound silos for storage and later use.

Upon demand, the extrusion compound is pneumatically conveyed to the pipe extrusion operation, where it is fed into hoppers. The compound is then metered into the extruders and pipe production commences.

4.2 Manufacturing of Solid-Wall Pipe

PVC *solid-wall pipe* takes the form of a cylinder with homogeneous walls of uniform thickness. Both the interior and exterior surfaces are smooth. Solid-wall manufacturing processes allow pipe to be produced in sizes from tiny 1/8-in. Schedule 40 tubing up to massive 60-in. municipal pressure pipe.

Almost all extruded plastic products are produced on two classes of extruders: (1) single-screw extruders (Fig. 4.2) or (2) multi-screw extruders (Fig. 4.3). Products made on single-screw extruders include garden hose, fishing line filament, and artificial wood molding. Also, most pipes made from thermoplastic materials other than PVC, such as styrene, polybutylene (PB), polyethylene (PE), and acrylonitrile butadiene styrene (ABS), are produced on single-screw extruders. Although single-screw machines can be used for

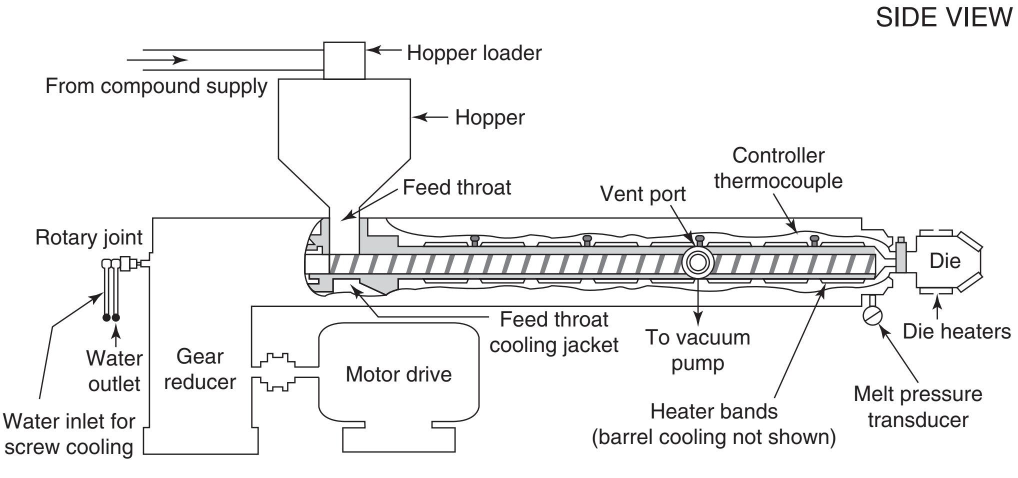

Fig. 4.2 Components of a single-screw extruder.

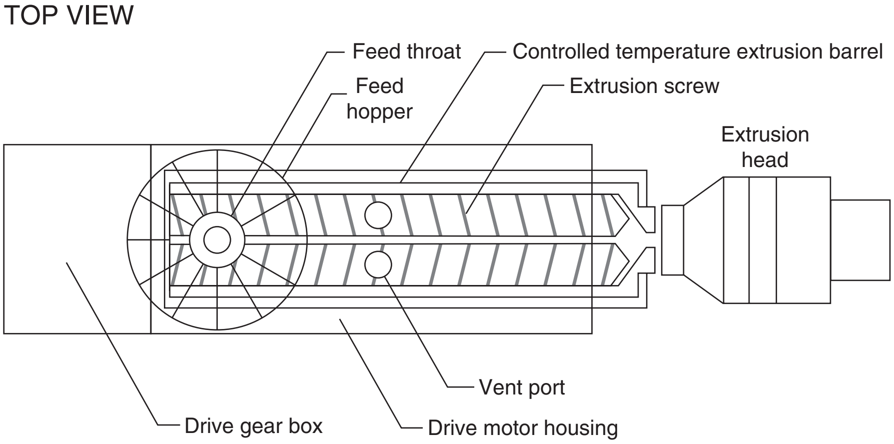

Fig. 4.3 Components of a multi-screw extruder.

PVC pipe, the bulk of PVC pipe produced in the world today is manufactured on multi-screw extruders.

The popularity of the multi-screw extruder for the production of PVC pipe can be attributed to the additional processing flexibility it offers over single-screw extruders. The same toughness and strength that makes PVC such an excellent pipe material also renders it a relatively difficult material to process. The multi-screw extruder's versatility allows processing at lower temperatures for excellent dimensional control, with smaller quantities of necessary compounding ingredients, providing PVC its full potential strength.

PVC compound in its powder form flows from the feed hopper through the feed throat into the extruder barrel, where it is received by rotating screws. The material is then conveyed with a pumping action by the intermeshing screw flights through the extruder. As the material passes through the extruder and is exposed to carefully controlled heat and pressure, it is converted from the dry powder into a viscous plastic mass. This process is carefully monitored and accurately controlled in order to guarantee the correct properties in the finished product.

When the plasticating (softening) process is complete and volatiles have been removed from the molten plastic, the material is properly prepared for final forming. The viscous, elastic mass of plastic is extruded into the pipe-forming die under high pressure (2,000–5,000 psi). In the pipe extrusion die the hot plastic material is formed into a cylindrical shape.

As it leaves the extrusion die at the exit orifice, the material is extremely hot (about 400°F), flexible, and pliable. In this state the hot plastic is formed with dimensional accuracy into a finished product and then cooled into a solid state. Outside diameter dimensional control is established by forcing the hot plastic through a sizing sleeve with a piece of equipment commonly called a *haul-off*, as it is drawn away from the extruder. Wall thickness control is established through proper synchronization of haul-off and extruder speeds.

Wall thickness is normally adjusted by varying the speed of the haul-off. Reduction of haul-off speed increases wall thickness, while increase in haul-off speed reduces wall thickness. When substantial changes in wall thickness are required, so too are changes in extrusion tooling dimensions. Upon completion of final forming, the extruded PVC pipe is drawn away from the extruder into cooling tanks, where it is cooled by chilled water. By the time the pipe emerges from the end of the cooling tanks, it has cooled to a temperature at which it can be handled without distortion.

After leaving the cooling station, the pipe travels through a printing station, where pertinent product and process information is printed on the pipe. Beyond the printer, the pipe is automatically cut to a correct length with chamfered ends, a process accomplished with a planetary saw that cuts and chamfers as it travels with the moving pipe. (See Fig. 4.4 for a flow chart of the manufacturing process.)

At this point the finished PVC pipe is transferred to a belling station, where an integral bell is formed on the end of the pipe. In this step of the process the portion of the pipe to be formed into a bell is reheated to a pliable state, which permits mechanical molding. The

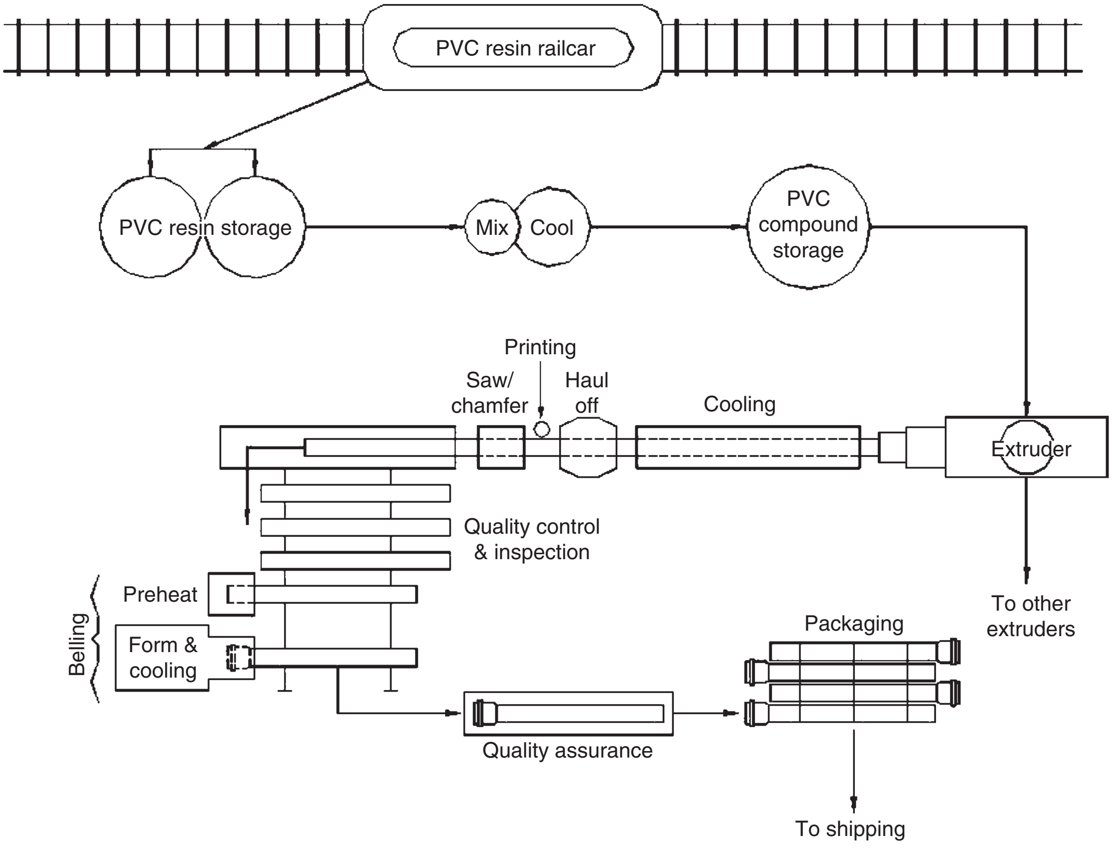

Fig. 4.4 Process flow chart—PVC pipe manufacturing.

integral bell is then formed by means of precision tooling, which may include an internal mandrel and various external dies. When the bell joint is properly formed, the plastic is cooled to a solid state and the tooling removed.

PVC pressure pipe standards require that bell-end dimensions conform to ASTM D3139. Integral bell-gasketed joints manufactured for nonpressure applications such as sewer pipe may be formed without special provisions for added wall thickness in the bell joints.

Throughout the manufacturing process, product is sampled on a predetermined frequency and subjected to quality control tests. In the case of American Water Works Association (AWWA) standards, each piece (unless the purchaser and the manufacturer agree to a different test frequency) is filled with water and individually pressure tested. Any pieces not tested must be so marked. Quality control testing is completed on finished lots to ensure the product meets company and industry specifications.

4.3 Manufacturing of Profile-Wall Pipe

PVC *profile-wall pipe* is pipe that has a smooth internal surface but a non-solid wall cross-sectional pattern perpendicular to the pipe axis. Wall patterns may be *open-profile* (such as concentric ribs or spiral ribs) or *closed-profile* (smooth inner and outer walls with internal ribs). The process of producing a profile-wall pipe is exemplary of PVC manufacturing technology combined with engineering design. Pipes with profile-wall characteristics provide cost-effective, material-efficient options that utilize durable profile designs, which resist impact and earth loads while maintaining the hydraulic excellence of a smooth interior.

Profile-wall pipes are not intended for pressure service. In North America, PVC profile pipes are manufactured with open profiles (ASTM F794 and F949), using either ribs or dual-wall corrugation, and with closed profiles (ASTM F1803) (see Fig. 4.5), using a pattern “sandwiched” between smooth internal and external walls. Diagrams of the common pipe wall profiles are provided with the pipe dimension tables in the Appendix of this handbook.

4.3.1 Concentric or Annular Ribbed

The manufacture of a concentric or annular ribbed profile involves the use of a continuous displacement molding machine immediately following the extruder. The machine employs longitudinally moving, semicircular extrusion blocks that simultaneously clamp around an extruded PVC pipe (see Fig. 4.6). The precisely machined interior cavity of these blocks displaces the exterior of the PVC pipe into a unique pipe profile, while a mandrel inside the pipe maintains a smooth interior. The end result is a seamless, continuously extruded product with ribs that provide structural reinforcement.

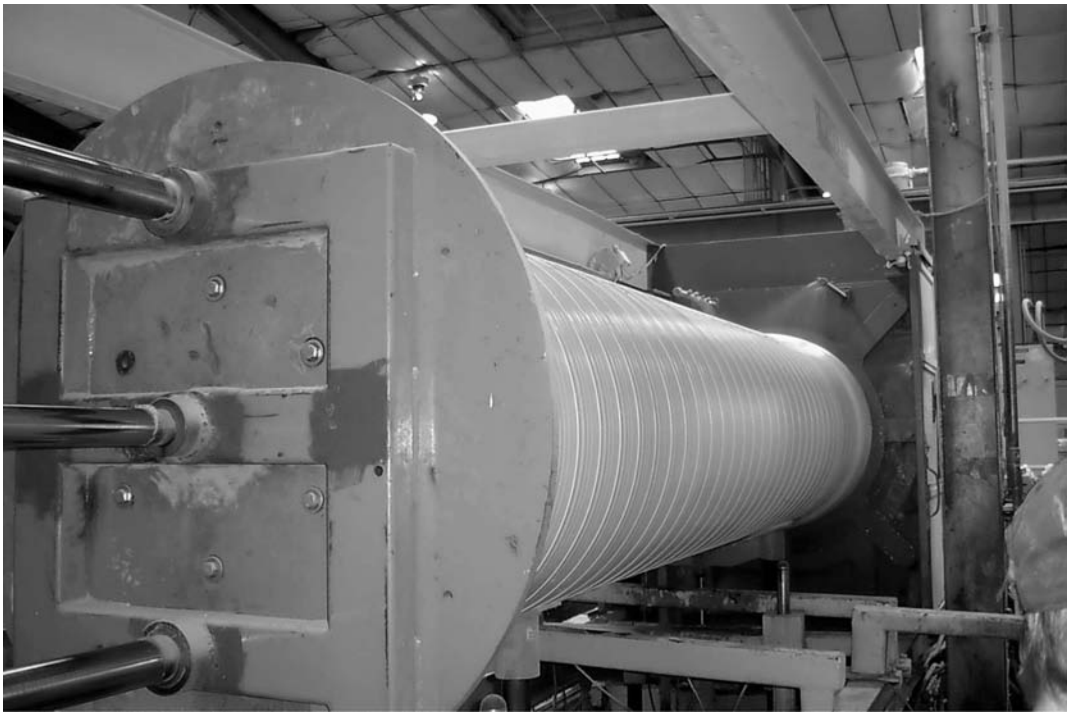

Fig. 4.5 Sewer pipe manufactured to ASTM F1803 undergoing required air test.

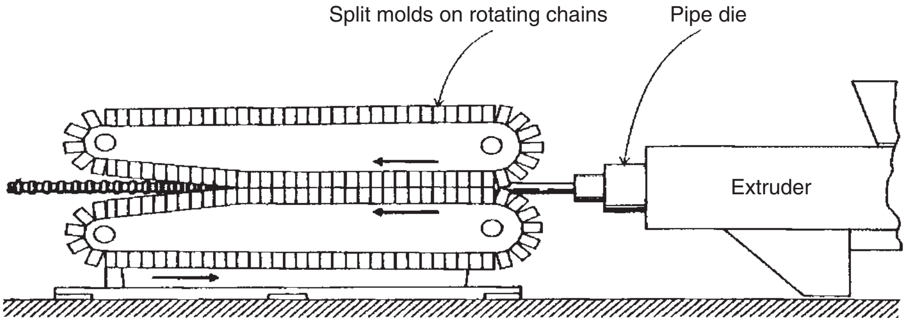

Fig. 4.6 Schematic of split molding process. Source: Modern Plastics Magazine

4.3.2 Dual-Wall Corrugated

In the extrusion of dual-wall corrugated profile (DWCP) pipe, two concentric tubes of hot PVC plastic simultaneously exit the extrusion die at the same speed. The inner flow is formed against a cooling mandrel to create a smooth interior wall, while the outer flow is disposed by a corrugator, which uses split-mold halves. In this process, the inner and outer walls are fused together using heat to create the dual-wall corrugation.

4.3.3 Helically Ribbed and Dual-Wall Closed Profile

Helically ribbed and dual-wall closed profile pipes do not utilize the split-mold halves described for dual-wall corrugated pipes. Instead, helical profile pipes are produced by extruding a profile strip, which is then helically wrapped onto a mandrel, providing a continuous profile with a helical heat-welded seam. The result is a pipe with smooth interior and exterior (closed profile) or smooth interior and open profile exterior (ribbed).

4.4 Manufacturing and Testing of Injection Molded PVC Fittings

4.4.1 Manufacturing Process

The injection molding of PVC fittings involves forcing PVC compound into a mold cavity, the inner surface of which is accurately defined by the core and the outer surface by the cavity itself (Fig. 4.7). This process is similar for both pressure-rated fittings and fittings for use in nonpressure systems. Injection molded fittings for use with PVC pipe meeting standard AWWA C900 Pressure Class 235 and Pressure Class 165 must conform

Fig. 4.7 The operator is demonstrating how a PVC Pressure Class 235 Tee would be positioned in the injection molding machine.

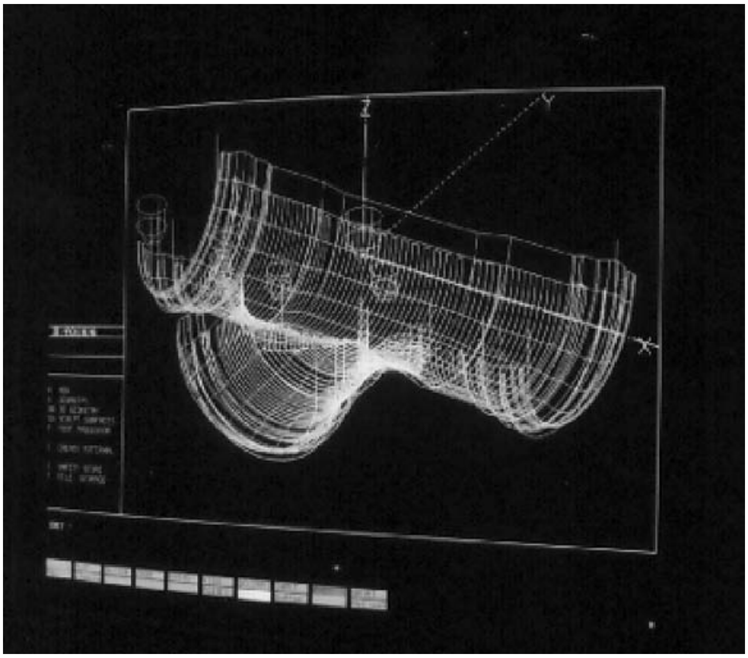

Fig. 4.8 CADD analysis of a PVC fitting design.

to AWWA C907 or to Canadian Standards Association (CSA) Standard B137.2. Molded sewer fittings conform to any of the standards ASTM F1336, CSA B182.1, B182.2, or B182.4.

The compounds used for injection molding these fittings are similar to those used in the manufacture of extruded pipe, although they may have lower molecular weights, which allow for better melt flow properties. These PVC compounds are typically in pellet form.

Molded PVC fittings are carefully analyzed and designed for the stresses they will encounter during service. Figure 4.8 shows a CADD analysis of a PVC pressure fitting design.

There are two major components of an injection molding machine: (1) an injection unit, which raises the temperature of the PVC compound to a fused state and injects the material into a mold; and (2) a set of platens capable of holding the two halves of a mold, which clamp together and permit the high-pressure injection of the fused PVC compound.

An extruder supplies the heat of fusion through heating bands on the extruder barrel and, more importantly, through frictional heat as the material is worked through the flights of the extruder screw. Preparing the compound for injection in this manner permits control of temperature, since the amount of time in the fused state is reduced.

There are injection machines that deposit a measured amount of fused PVC (referred to as the *shot*) into a cylinder and then force it into the mold by a mechanical plunger.

However, a much more common technique uses a reciprocating-screw process, which eliminates the injection plunger. In the reciprocating-screw injection molding machine, the rotating screw in the extruder barrel acts not only as a means of fusing the compound, but can also be retracted and pushed forward in the manner of a plunger, forcing the fused plastic into the mold. This reduces the time the fused plastic must be held at the injection temperature and also allows for a faster processing time.

For large shots such as those required for C907 fittings, very large machines are required. These machines may have clamping pressures of 2,500 tons or more. In this case, the opening and closing of the clamping unit is accomplished by variable-speed hydraulic rams. Regardless of the size of the machine, the two halves of the mold are mounted on the face of the two platens of the injection molding machine and separated a sufficient distance to permit manual inspection and cleaning at the end of each cycle.

The mold itself is precision-machined and may be made of aluminum, stainless steel, or chrome-plated steel. Required marking for the fitting is engraved on the surface of the tool and is thereby molded into the fitting during the injection process.

When the injection process is complete, the mold is separated and the fittings are lifted out for trimming and inspection. Afterwards, the fittings may be transferred to a water-cooling vat to reduce their temperature before further handling and quality control.

In addition to controls associated with the extrusion process, a number of controls must also be maintained in the injection process. The predetermined injection parameters are monitored by sensors located in the mold and on the machine, which are normally computer-controlled. Among the variables in the injection molding process are temperature (before, during, and after injection), pressure, and time. A successful shot is one in which the following occurs: (1) the temperature of the fused PVC and mold have been raised to the appropriate level; (2) the size of the orifice is appropriate for the rapid transfer of fused PVC to the mold cavity; (3) the mold is properly vented to remove gases; (4) the rate of cooling in the mold permits the smooth flow of material into all corners of the cavity prior to solidifying; and (5) the clamping/injection pressures permit the rapid packing of the mold.

Once machine controls have been established, the reliability of a process is high, with the fittings reflecting the precision of the carefully engineered mold and the automatic controls by which the sequence of operations is monitored and adjusted. Nevertheless, the quality levels of injection molded PVC pressure and sewer fittings are continually checked.

4.4.2 Testing

4.4.2.1 Quality Control (QC) Tests

Injection molded Class 235 PVC fittings are manufactured with gasketed joints and designed for use with Pressure Class 235 and Pressure Class 165 AWWA standards PVC pipes with cast iron outside diameter. These fittings are subject to the following quality control procedures:

Minimum burst pressure test: During the beginning of a production run and at intervals thereafter, fittings are subject to a quick burst test. The test requirement is 755 psi minimum, the same as Pressure Class 235 PVC pipe in the AWWA standard.

Dimensional checks: The minimum wall thickness of the molded fitting body must be at least 125% of the wall thickness of Pressure Class 235 AWWA standards pipe of the same size. The wall thickness at any point in the bell must be at least equivalent to the thickness determined by DR 18. Other minimum dimensions must conform to the published standards.

Heat reversion test: Selected fittings must pass the ASTM F610 heat reversion test to ensure that the PVC compound has been properly fused.

Gasketed and injection molded PVC fittings for sewer applications are tested for stiffness, joint performance, and dimensional accuracy. ASTM Standard F1336 also requires impact testing for molded sewer fittings.

4.4.2.2 Qualification Tests

For service with Pressure Class 235 AWWA standards PVC pipe, injection molded gasketed Pressure Class 235 PVC fittings are subjected to long-term stress rupture testing. At least ten specimens of each individual size and configuration of fitting are placed in a pressure manifold and raised to a variety of pressures calculated to cause failure within various time periods (a test very similar to the stress regression test performed on PVC compounds in the manufacture of extruded PVC pipe). Since injection molded fittings may exhibit individual reactions to long-term pressurization, it is important that each fitting be qualified individually to establish a pressure regression line specific to that fitting. The industry requirement is that the projected long-term pressure strength of each fitting be no less than 470 psi after 100,000 hours (11.4 years). This performance is the same requirement imposed on PVC compounds used in the manufacture of PVC pressure pipe; the 470-psi requirement for fittings corresponds to a nominal 4,000 psi circumferential hoop stress in Pressure Class 235 DR 18 PVC pressure pipe.

4.4.2.3 Quality Assurance (QA) Tests

Once a fitting has been qualified for service, it must be tested periodically to ensure that it retains this standing. The procedure used is known as the *accelerated regression test*, in which a group of fittings (of specific size and configuration) is subjected to stress-rupture testing. This provides the minimum number of data points required to extrapolate a stress regression line to the minimum long-term intercept of 470 psi.

The performance of a fittings gasketed joint must also be tested to ensure that it complies with the requirements of ASTM D3139 (for pressure fittings) or ASTM D3212 (for nonpressure fittings). This testing is the same as that used for qualifying a PVC pipe joint and is performed under both pressure and vacuum, with the components deflected.

4.5 Manufacturing and Testing of Fabricated PVC Fittings

4.5.1 Manufacturing Process

The fabrication process for PVC fittings described next applies to pressure fittings. The process used for PVC fittings for nonpressure applications is quite similar.

Fabricated PVC fittings are manufactured from straight lengths of pipe and are made for both pressurized and nonpressurized PVC pipe systems. An important advantage of fabricated fittings is that their constituent parts are exactly the same as the pipeline with which they will be used. The body of the fitting is extruded PVC pipe that has already passed the minimum testing requirements. The dimensions and performance of the joint are identical to those established for the pipe and will therefore exhibit identical performance characteristics. Although the process of fabricating a fitting is labor intensive, the step-by-step, hands-on manufacturing process and the quality control procedures that govern (and are an integral part of) the manufacture of fabricated fittings produce a high level of quality in the end product.

Fabricated fittings are available for any size or class of PVC pressure pipe or nonpressure pipe, including pipe with profiled walls. Fabricated pressure fittings may conform to AWWA standards or CSA B137.3. Meanwhile, CSA standards B182.2 and B182.4 and ASTM F1336 describe the requirements for fabricated fittings used in sewer systems.

PVC pipe and integral gasketed bells used for fabricating fittings will have the same or greater class or pressure rating as the PVC pipe to which they are joined. Pipes will have certifications or outside agency approvals required for the service. If PVC welding rod is used in production, it must be compatible with the material from which the pipe is manufactured.

4.5.2 Preparation of Segments

Elbows are manufactured from two or more segments of a straight length of pipe. In preparation for assembly, the segments are precision cut to provide intimate contact at the mating surfaces of the segments.

Legs of tees or wyes may be connected to the body of the fitting through face weld or by solvent cementing to an integral coupling, which is formed in the body wall by pulling a forming plug through the heated wall.

4.5.3 Fabrication

4.5.3.1 Welding

Joining segments of pipe edge-to-edge is accomplished with either a *welding* process or a *butt fusion* process. In welding, the edges of the mitered sections are machined to form a specific angle of groove on the outside surface. Using hot air, a rod of PVC is heated to the fusing temperature at the same time that the grooved edges of the segments are heated. The fused welding rod forms a homogeneous bond at the two faces of the segment edges. Continuous layers of welding rod applied in this way re-form the PVC wall thickness at the bond. After the first round of weld (the "root weld") has been placed and after the weld has been completed, an electrical arc test is performed to detect any voids. A grounding medium is placed on the inside of the weld and an electrode carrying a 25,000-volt charge is passed around the outside of the weld. At any point where the weld is not complete, a spark will jump across the gap.

4.5.3.1.1 Butt Fusion

In butt fusion, both mating surfaces of the segments are carefully aligned in a clamping device and then heated to the fusion temperature. Hydraulic rams bring the two faces together to form a homogeneous wall at the faces of the mitered segments. Figure 4.9 shows a 16-in. 45° PVC elbow for pressure applications being fabricated from two miter-cut segments using the butt fusion method. The fitting will then be overwrapped with fiberglass.

Fig. 4.9 Butt fusion method.

4.5.3.1.2 Solvent Welding

In solvent welding, a hole is drilled in the wall of a specialized coupling (tee-body). This area of the tee-body is then heated to the re-forming temperature and a sizing plug is drawn through the hole (from the inside of the body) to form a protruding socket, the inside dimensions of which are suitable for accepting the branch of the tee-body as a solvent cemented joint. Solvent-welded joints are restricted to this type of fitting because only in this way can the required minimum contact surfaces be assured.

4.5.3.1.3 Thermal Forming

Thermal forming may be used for fabricating bends. In this method, pipe is heated by radiant heaters or by immersion in a glycerin bath. Once the pipe is heated through, it is removed and immediately bent and belled.

4.5.4 Fiberglass Overwrap

Even though a properly bonded fitting using one of the above methods is essentially completed and ready for service, the joints of the fitting (or the entire fitting) are frequently overwrapped for pressure applications (or where additional mechanical strength is required) with fiberglass reinforced thermosetting plastics.

4.5.5 Quality Test Requirements

At each stage in the fabrication process, the dimensions are checked for conformity with the governing standard. The quality of seams where pipe segments are bonded together is verified by 25,000-volt electrical probe test or lap shear test. Fabricated fittings made under AWWA standards are routinely pressure-tested to twice the designated pressure class for a minimum duration of 2 hours. Furthermore, pressure fittings must qualify under the joint performance requirements of ASTM D3139, whereas nonpressure fittings must qualify under ASTM D3212. More details of quality control and qualification testing are provided in Section 4.7.

4.6 Standard Specifications

The following list of standard specifications is a partial summary of standard documents applicable to PVC pipe products. Those listed include: product specifications, test methods, joint specifications, system standards, recommended practices, terminology, plumbing codes, and design guides.

AASHTO	American Association of State Highway and Transportation Officials 444 North Capitol Street NW, Suite 249 Washington, DC 20001 (202) 624-5800 www.aashto.org
M278	Class PS 46 Polyvinyl Chloride (PVC) Pipe
M304	Polyvinyl Chloride (PVC) Profile Wall Drain Pipe and Fittings Based on Controlled Inside Diameter
Section 18	Soil-Thermoplastic Pipe Interaction Systems
ASABE (formerly ASAE)	American Society of Agricultural and Biological Engineers 2950 Niles Road St. Joseph, MI 49085 (269) 429-0300 www.asabe.org
S376.1	Design, Installation, and Performance of Underground Thermoplastic Irrigation Pipelines
ASTM	ASTM International 100 Barr Harbor Drive West Conshohocken, PA 19428-2959 (610) 832-9585 www.astm.org
D883	Terminology Relating to Plastics
D1598	Test Method for Time-to-Failure of Plastic Pipe under Constant Internal Pressure
D1599	Test Method for Short-Time Hydraulic Failure Pressure of Plastic Pipe, Tubing and Fittings
D1600	Terminology for Abbreviated Terms Relating to Plastics
D1784	Rigid Polyvinyl Chloride (PVC) Compounds and Chlorinated Polyvinyl Chloride (CPVC) Compounds
D1785	Polyvinyl Chloride (PVC) Plastic Pipe, Schedules 40, 80, and 120
D2122	Test Method for Determining Dimensions of Thermoplastic Pipe and Fittings
D2152	Test Method for Adequacy of Fusion of Extruded Polyvinyl Chloride (PVC) Pipe and Molded Fittings by Acetone Immersion

D2241	Polyvinyl Chloride (PVC) Pressure-Rated Pipe (SDR PR Series)
D2321	Practice for Underground Installation of Thermoplastic Pipe for Sewers and Other Gravity-Flow Applications
D2412	Test Method for Determination of External Loading Characteristics of Plastic Pipe by Parallel-Plate Loading
D2444	Test Method for Determination of the Impact Resistance of Thermoplastic Pipe and Fittings by Means of a Tup (Falling Weight)
D2464	Threaded Polyvinyl Chloride (PVC) Plastic Pipe Fittings, Schedule 80
D2466	Polyvinyl Chloride (PVC) Plastic Pipe Fittings, Schedule 40
D2467	Polyvinyl Chloride (PVC) Plastic Pipe Fittings, Schedule 80
D2564	Solvent Cements for Polyvinyl Chloride (PVC) Piping Systems
D2672	Joints for IPS PVC Pipe Using Solvent Cement
D2729	Polyvinyl Chloride (PVC) Sewer Pipe and Fittings
D2749	Standard Symbols for Dimensions of Plastic Pipe Fittings
D2774	Practice for Underground Installation of Thermoplastic Pressure Piping
D2837	Test Method for Obtaining Hydrostatic Design Basis for Thermoplastic Pipe Materials
D2855	Practice for Making Solvent-Cemented Joints with Polyvinyl Chloride (PVC) Pipe and Fittings
D2949	3.25-in. Outside Diameter Polyvinyl Chloride (PVC) Plastic Drain, Waste, and Vent Pipe and Fittings
D3034	Type PSM Polyvinyl Chloride (PVC) Sewer Pipe and Fittings
D3138	Solvent Cements for Transition Joints Between Acrylonitrile-Butadiene-Styrene (ABS) and Polyvinyl Chloride (PVC) Nonpressure Piping Components
D3139	Joints for Plastic Pressure Pipes Using Flexible Elastomeric Seals
D3212	Joints for Drain and Sewer Plastic Pipes Using Flexible Elastomeric Seals
D3915	Rigid Polyvinyl Chloride (PVC) and Chlorinated Polyvinyl Chloride (CPVC) Compounds for Plastic Pipe and Fittings Used in Pressure Applications

D4396	Rigid Polyvinyl Chloride (PVC) and Chlorinated Polyvinyl Chloride (CPVC) Compounds for Plastic Pipe and Fittings Used in Nonpressure Applications
F402	Practice for Safe Handling of Solvent Cements, Primers and Cleaners Used for Joining Thermoplastic Pipe and Fittings
F412	Standard Terminology Relating to Plastic Piping Systems
F441	Standard Specification for Chlorinated Polyvinyl Chloride (CPVC) Plastic Pipe, Schedules 40 and 80
F442	Standard Specification for Chlorinated Polyvinyl Chloride (CPVC) Plastic Pipe (SDR-PR)
F477	Elastomeric Seals (Gaskets) for Joining Plastic Pipe
F481	Practice for Installation of Thermoplastic Pipe and Corrugated Pipe in Septic Tank Leach Fields
F610	Test Method for Evaluating the Quality of Molded Polyvinyl Chloride (PVC) Plastic Pipe Fittings by the Heat Reversion Technique
F645	Guide for Selection, Design and Installation of Thermoplastic Water Pressure Piping
F656	Primers for Use in Solvent Cement Joints of Polyvinyl Chloride (PVC) Plastic Pipe and Fittings
F679	Polyvinyl Chloride (PVC) Large-Diameter Plastic Gravity Sewer Pipe and Fittings
F690	Practice for Underground Installation of Thermoplastic Pressure Piping Irrigation Systems
F758	Smooth-Wall Polyvinyl Chloride (PVC) Plastic Underdrain Systems for Highway, Airport, and Similar Drainage
F794	Polyvinyl Chloride (PVC) Profile Gravity Sewer Pipe and Fittings Based on Controlled Inside Diameter
F891	Coextruded Polyvinyl Chloride (PVC) Plastic Pipe with a Cellular Core
F948	Test Method for Time-to-Failure of Plastic Piping Systems and Components Under Constant Internal Pressure with Flow
F949	Polyvinyl Chloride (PVC) Corrugated Sewer Pipe with a Smooth Interior and Fittings

F1057	Practice for Estimating the Quality of Extruded Polyvinyl Chloride (PVC) Pipe by the Heat Reversion Technique
F1176	Practice for Design and Installation of Thermoplastic Irrigation Systems with Maximum Working Pressure of 63 psi
F1336	Polyvinyl Chloride (PVC) Gasketed Sewer Fittings
F1365	Test Method for Water Infiltration Resistance of Plastic Underground Conduit Joints which Use Flexible Elastomeric Seals
F1417	Test Method for Installation Acceptance of Plastic Gravity Sewer Lines Using Low-Pressure Air
F1429	Test Method for Assembly Force of Plastic Underground Conduit Joints that Use Flexible Elastomeric Seals Located in the Bell
F1483	Specification for Oriented Polyvinyl Chloride, PVCO, Pressure Pipe
F1674	Test Method for Joint Restraint Products for Use with PVC Pipe
F1688	Guide for Construction Procedures for Buried Plastic Pipe
F1732	Polyvinyl Chloride (PVC) Sewer and Drain Pipe Containing Recycled PVC Material
F1760	Coextruded Polyvinyl Chloride (PVC) Nonpressure Plastic Pipe Having Reprocessed Recycled Content
F1803	Standard Specification for Polyvinyl Chloride (PVC) Closed Profile Gravity Pipe and Fittings Based on Controlled Inside Diameter
AWWA	American Water Works Association 6666 West Quincy Avenue Denver, CO 80235 (303) 794-7711 www.awwa.org
AWWA C605	Underground Installation of Polyvinyl Chloride (PVC) Pressure Pipe and Fittings for Water
AWWA C651	Disinfecting Water Mains
AWWA C900	Polyvinyl Chloride (PVC) Pressure Pipe and Fabricated Fittings, 4 in. through 12 in. (100 mm through 300 mm), for Water Transmission and Distribution

AWWA C905	Polyvinyl Chloride (PVC) Pressure Pipe and Fabricated Fittings, 14 in. through 48 in. (350 mm through 1200 mm), for Water Transmission and Distribution
AWWA C907	Injection-Molded Polyvinyl Chloride (PVC) Pressure Fittings, 4 in. through 12 in. (100 mm through 300 mm), for Water, Wastewater, and Reclaimed Water Service
AWWA C909	Molecularly Oriented Polyvinyl Chloride (PVCO) Pressure Pipe, 4 in. through 24 in. (100 mm through 600 mm) for Water, Wastewater, and Reclaimed Water Service
M 23	PVC Pipe—Design and Installation
CSA	Canadian Standards Association 5060 Spectrum Way Mississauga, Ontario, L4W5N6 Canada (416) 747-4000 www.csa.ca
B137.0	Definitions, General Requirements and Methods of Testing for Thermoplastic Pressure Piping
B137.2	PVC Injection-Moulded Gasketed Fittings for Pressure Applications
B137.3	Rigid Polyvinyl Chloride (PVC) Pipe for Pressure Applications
B137.3.1	Molecularly Oriented Polyvinyl Chloride (PVCO) Pipe for Pressure Applications
B181.2	PVC Drain, Waste and Vent Pipe and Pipe Fittings
B182.1	Plastic Drain and Sewer Pipe and Pipe Fittings
B182.2	PVC Sewer Pipe and Fittings (PSM Type)
B182.4	Profile PVC Sewer Pipe and Fittings
B182.11	Recommended Practice for the Installation of Thermoplastic Drain, Storm and Sewer Pipe and Fittings
Dept. of Agriculture, U.S.	Department of Agriculture, U.S. Natural Resource Conservation Service PO Box 2890 Washington, DC 20013 (202) 720-4525 www.nrcs.usda.gov

SCS	National Handbook of Conservation Practices
SCS 430-DD	Irrigation Water Conveyance, Pipeline (High Pressure Underground Plastic)
SCS 430-EE	Irrigation Water Conveyance, Pipeline (Low Pressure Underground Plastic)
SCS 441	Irrigation System, Trickle
SCS 442	Irrigation System, Sprinkler
SCS 443	Irrigation System, Surface and Subsurface
SCS 447	Irrigation System, Tailwater Recovery
SCS 516	Pipeline
SCS 606	Subsurface Drain
SCS 620	Underground Outlet
SCS 636	Water Harvesting Catchment
SCS 642	Well
IAPMO	International Association of Plumbing and Mechanical Officials 5001 E. Philadelphia Street Ontario, CA 91761 (909) 472-4100 www.iapmo.org
IAPMO IS 1	Non-Metallic Building Sewers
IAPMO IS 8	PVC Cold Water Building Supply and Yard Piping
IAPMO IS 9	PVC Building Drain, Waste and Vent Pipe and Fittings
IAPMO	Uniform Plumbing Code
NFPA	National Fire Protection Association 1 Batterymarch Park Quincy, MA 02169 (617) 770-3000 www.nfpa.org
NFPA 24	Installation of Private Fire Service Mains and Their Appurtenances

NSF	NSF International 789 N. Dixboro Road Ann Arbor, MI 48105 (734) 769-8010 www.nsf.org
NSF 14	Plastic Piping Components and Related Materials
NSF 24	Plumbing System Components for Manufactured Homes and Recreational Vehicles
NSF 61	Drinking Water System Components—Health Effects
UL	Underwriters Laboratories, Inc. 333 Pfingsten Road Northbrook, IL 60062 (847) 272-8800 www.ul.com
UL 1285	Pipe and Couplings, Polyvinyl Chloride (PVC) for Underground Fire Service
Uni-Bell	Uni-Bell PVC Pipe Association 2711 LBJ Freeway, Suite 1000 Dallas, TX 75234 (972) 243-3902 www.uni-bell.org
UNI-B-1	Recommended Specification for Thermoplastic Pipe Joints, Pressure and Nonpressure Applications
UNI-B-6	Recommended Practice for Low-Pressure Air Testing of Installed Sewer Pipe
UNI-B-8	Recommended Practice for the Direct Tapping of Polyvinyl Chloride (PVC) Pressure Water Pipe
UNI-B-9	Recommended Performance Specification for Polyvinyl Chloride (PVC) Profile Wall Gravity Sewer Pipe and Fittings Based on Controlled Inside Diameter (Nominal Pipe Sizes 4-48 in.)
UNI-PUB-6	Installation Guide for PVC Solid-Wall Sewer Pipe (4-48 in.)
UNI-PUB-7	External Corrosion of Underground Water Distribution Piping Systems
UNI-PUB-8	Tapping Guide for PVC Pressure Pipe

UNI-PUB-9	Installation Guide for PVC Pressure Pipe
UNI-PUB-10	When Performance Counts
UNI-PUB-11	PVC Pipe—The Right Choice for Trenchless Projects
UNI-TR-1	Deflection: The Pipe/Soil Mechanism
UNI-TR-3	Maintenance of PVC Sewer Pipe
UNI-TR-5	The Effects of Ultraviolet Aging on PVC Pipe
UNI-TR-6	PVC Force Main Design
UNI-TR-7	Thermoplastic Pressure Pipe Design and Selection
UNI-V-1	Tapping PVC Pressure Pipe

4.7 Testing

The high level of reliability inherent in the manufacture of PVC pipe is clearly displayed in the sophisticated statistical sampling and testing programs enacted by the PVC pipe industry. The demands of modern piping systems have been met not only by advanced manufacturing technology but also by critically important testing technology—the final assurance to the consumer that PVC pipe will consistently serve long-term needs.

Testing in the PVC pipe industry is divided into three general categories:

- qualification testing
- quality control testing
- quality assurance testing.

It is vital that PVC pipe be tested in all categories to ensure it serves as intended throughout its lifetime.

4.7.1 Qualification Testing

Qualification testing is performed on piping product and materials from which piping products are produced to ensure that the finished product conforms to the requirements of applicable specifications. In ASTM F412, the qualification test is defined as "an evaluation, generally nonrepetitive, conducted on an existing, altered or new product to determine acceptability."

Qualification tests vary for pressure and nonpressure piping products, just as relative design properties vary. For example, toxicological testing, although critical to the qualification of raw materials for manufacture of potable water distribution pipe, is meaningless in the qualification of sanitary sewer pipe. In general, qualification tests evaluate the properties of raw materials and finished products to consistently attain specified design properties required in the finished product.

Different types of qualification tests are outlined in Sections 4.7.1.1 to 4.7.1.6.

4.7.1.1 Cell Classification Testing

ASTM Standard D1784 is the widely accepted standard for selection and identification of rigid PVC compounds used to manufacture PVC piping products (see Chapter 2 for more information on the raw materials of PVC pipe). PVC compounds are engineered to provide properties tailored to the requirements of specific pipe and fitting standards. The purpose of compound cell classification testing is to qualify compounds for use in the manufacture of PVC pipe and fittings.

Test specimens taken from pipe or fittings will not provide valid results and cannot be used to verify cell classification. According to ASTM D1784 Sec. 1.2: “The requirements in this specification are intended for the quality control of compounds used to manufacture finished products. These properties are based on data obtained using standard test specimens tested under specified conditions. They are not directly applicable to finished products.” The standard further directs the user to see the applicable ASTM standards that give requirements for finished products.

Specified requirements for PVC compounds include:

- impact strength (Izod)
- tensile strength
- tensile modulus of elasticity
- deflection temperature under load
- flammability.

4.7.1.2 Health Effects Evaluation

PVC pipe has the longest history of affirmation by NSF International (NSF) of its safety for potable water service. NSF’s program includes formulation review and testing, performed to verify the absence of chemicals in quantities that could cause toxic, carcinogenic, or mutagenic effects on humans who drink water conveyed within the pipe. These qualification tests are appropriate for all potable water system pipes and components.

NSF Standard 61, a voluntary consensus standard available for public use, covers indirect additives, including process media, sealing materials, gaskets, mechanical devices, pipes, and all water distribution and plumbing materials that come in contact with drinking water. When referenced by federal, state, or local health authorities in their specifications, piping manufacturers must have their products evaluated against Standard 61 to demonstrate compliance. Standard 61 and the registered trademark of the testing agency indicating certification should appear on PVC piping products intended for potable water.

To address concerns related to chemical contaminants added to drinking water from drinking water system components, most state plumbing codes and waterworks regulations require drinking water system components be certified by an American National Standards Institute (ANSI) accredited third party to NSF/ANSI Standard 61 Drinking Water System Components—Health Effects. This standard was developed in 1987 at the request of U.S. Environmental Protection Agency (EPA) to establish health-based maximum contaminant limits for chemicals migrating from products that contact public water supplies. The standard covers all types of materials used in drinking water systems, including PVC.

NSF International runs a third party testing, inspections, and certification program for drinking water system components. The program includes:

- A formulation review of any material in contact with drinking water to determine what possible contaminants could leach into the water as well as what type of chemical extraction testing is necessary on a product.
- A 17-day chemical extraction testing process on PVC products, in which the products are exposed to various formulated waters designed to extract specific types of contaminants. PVC products are tested for volatile organic compounds (VOCs), phenolics, residual vinyl chloride monomer (RVCM), regulated metals, and any other potential contaminant identified during the formulation review. Products are tested initially, prior to any major formulation changes, and at least once annually from each production facility.
- A toxicology evaluation on products tested. Any regulated contaminants found must be below EPA and Health Canada levels for regulated contaminants. Regarding nonregulated contaminants found, NSF/ANSI Standard 61 sets health-based pass/fail levels, established on review of available toxicity data using the risk assessment procedures in Annex A of the standard.
- At least two unannounced audits performed by NSF of each production facility annually. During the audit, NSF verifies that no modifications have been made to the product formulation, suppliers, or processing. NSF also collects samples for laboratory retesting of each product family on an annual basis.

NSF is frequently consulted about the following contaminants:

- *Lead*: NSF/ANSI 61 excludes lead as an intentional ingredient in PVC pipe and fittings. This is verified by NSF during formulation reviews, plant inspections, and chemical extraction testing.
- *Vinyl chloride monomer*: In addition to the chemical extraction testing referenced above, all PVC pipe, fittings, and materials are tested at least twice per year for

residual vinyl chloride. Samples are selected randomly by NSF auditors during unannounced inspections of each production facility.
- *Phthalates*: Rigid PVC pipe and fittings certified by NSF do not contain phthalates.

To verify products that have been tested and listed by NSF, products will bear the NSF 61 or NSF-pw (potable water) marks. Product listings can be verified on NSF's website, http://www.nsf.org/business/searchlistings/

4.7.1.3 Hydrostatic Design Basis (HDB) Testing

Long-term hydrostatic stress testing is conducted in accordance with the Plastics Pipe Institute (PPI) Technical Report PPI-TR3, Policies and Procedures for Developing Recommended Hydrostatic Design Stress for Thermoplastic Pipe Materials. The method for obtaining long-term hydrostatic test data is defined in ASTM Standard D2837, Standard Method for Obtaining Hydrostatic Design Basis for Thermoplastic Pipe Materials.

The hydrostatic design basis (HDB) for a given PVC pipe extrusion compound is established through long-term hydrostatic pressure testing of PVC pipe extruded from that compound. Testing of one lot of pipe for at least 10,000 hours and two additional lots of pipe from the same compound for 2,000 hours establishes the stress regression line from which the HDB is calculated, based on extrapolating data to 1,000,000 hours and 50 years. The HDB for PVC pressure pipe must be equal to or greater than 4,000 psi. As the response of PVC pipe to hoop stress caused by internal pressure is time-dependent, this qualification test to define long-term HDB for extrusion compounds is critical to ensuring proper long-term performance of PVC pressure pipe (see Chapter 5).

The hydrostatic design stress for a given PVC pipe compound—defined as the maximum allowable hoop (circumferential) tensile stress in the wall of PVC pipe (due to continuous internal pressure) that will provide a high level of certainty that failure of the pipe will not occur—is calculated by multiplying the established HDB by the desired design factor (DF) as defined in the specification for the specific pressure piping application. The hydrostatic design stress rating required for PVC pressure pipe is 2,000 psi, including a design factor of 0.5 (equivalent to a safety factor of 2.0).

4.7.1.4 Joining System Performance Testing

PVC pipe joint performance testing is recommended to ensure proper joint design in both pressure and nonpressure applications. Joining systems commonly used in the installation of PVC pipe are:

- integral bell gasketed joints
- integral bell solvent-cemented joints

- gasketed couplings
- solvent-cemented couplings
- gasketed fittings
- solvent-cemented fittings
- mechanically restrained gasketed joints.

Joining system performance testing is performed under laboratory conditions to verify a leak-free design of a specified pipe joint. Applicable qualification tests for PVC piping products joined by elastomeric gaskets are ASTM D3139 (for pressure pipe) and ASTM D3212 (for nonpressure sewer pipe); they are performed by manufacturers to ensure the joint or coupling design seal in the specified application.

Performance testing of gasketed joints done in accordance with these recommended standards subjects specific joint designs to both internal hydrostatic pressure and to internal vacuum. The joint design is evaluated through testing of a representative series of sample joints under the following conditions:

- assembled joint in straight alignment
- assembled joint in angular deflection
- assembled joint in diametric deflection (nonpressure pipe, see Fig. 4.10).

4.7.1.5 Sustained Pressure Test

PVC pressure pipe samples are periodically subjected to sustained hydrostatic pressure for 1,000 hours. At the sustained pressure, specified in the applicable product standard, the sample should not fail, balloon, burst, or weep. Sustained pressure testing is conducted in accordance with ASTM D1598.

4.7.1.6 Accelerated Regression Test

A number of specimens of pipe or fittings are pressurized to cause rupture at various time intervals. The results are extrapolated by methods outlined in ASTM D2837 to prove compliance with minimum design stress requirements.

4.7.2 Quality Control (QC) Testing

Quality control testing is routinely performed on a statistical sampling of PVC piping products during manufacture to ensure that proper production procedures and controls are consistently implemented, as required, to yield quality products that comply with

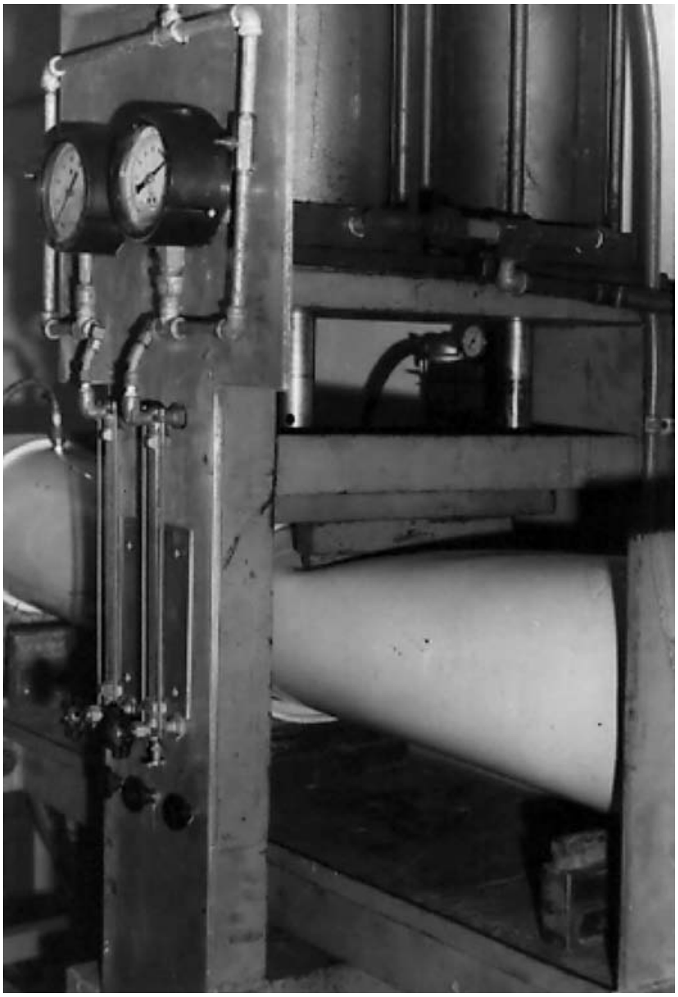

Fig. 4.10 10-in. sewer pipe (ASTM D3034) under 35% deflection and vacuum of 23 in. of mercury without losing vacuum (standard requires only 5% deflection).

applicable specifications. While many quality control tests and procedures are common to all PVC pipe products, there are others that apply only to certain products. One universal requirement in the manufacture of all pipe products is that the manufacturer take adequate measures to ensure full compliance with the applicable product standard. This is accomplished through quality control inspection and testing.

Quality control tests, as the term implies, are performed in the manufacturer's plant at the time of production and before shipment. Quality control testing must not be confused with field acceptance testing, as tests on pipes that have been shipped and rehandled are not always definitive for determination of compliance with standard specifications.

4.7.2.1 Quality Control Inspection

4.7.2.1.1 Proper Workmanship

Inspection is conducted to make certain that the PVC pipe is homogeneous throughout, free from voids, cracks, inclusions, and other defects, and reasonably uniform in color, density, and other physical properties. Pipe surfaces, including the joining surfaces of spigots and bells, are inspected to ensure that they are free from nicks, gouges, severe scratches, and other such blemishes.

4.7.2.1.2 Dimensions

Measurement of critical dimensions on a regular and systematic basis is essential. Failure to meet critical dimensional requirements is unacceptable, regardless of successes achieved in other inspections and tests. All dimensional measurements are made in accordance with ASTM D2122. Dimensional measurements commonly required include:

- pipe diameter
- pipe wall thickness
- out-of-roundness
- bell joint dimensions
- length.

Dimensional requirements are defined in product specifications. Some product specifications do not require all the above listed dimensional measurements.

4.7.2.1.3 Product Marking

Inspection should verify proper marking of the pipe as required in the applicable product specification. Marking of PVC pipe commonly includes:

- manufacturer name or trademark
- nominal pipe size and size base
- PVC cell classification or material code
- dimension ratio or standard dimension ratio
- product type, pressure class, or pressure rating
- standard specification designation
- production record code
- certification mark(s) (if required).

Inspection should also verify that identification markings remain legible during normal handling, storage, and installation.

4.7.2.1.4 Product Packaging

The finished package of PVC pipe prepared for shipment to the customer should be inspected to ensure pipe quantity is correct and that the pipe is adequately protected.

4.7.2.2 Quality Control Tests

4.7.2.2.1 Quick Burst Test

The PVC pipe sample will not fail when pressurized to the minimum burst pressure within a test time period of 60–70 seconds. Quick burst testing is conducted in accordance with ASTM D1599.

4.7.2.2.2 Extrusion Quality Tests

For an extrusion quality test, PVC pipe samples are immersed in anhydrous (dry) acetone for a specified duration. When removed from the acetone bath, the sample should not display evidence of flaking or disintegration. This test is conducted in accordance with ASTM D2152 and distinguishes between unfused and properly fused PVC pipe. An additional test for estimating extrusion quality is heat reversion in accordance with ASTM F1057.

4.7.2.2.3 Pipe Impact Test

In pipe impact testing, PVC pipe samples are placed on a specified holder and subjected to impact by a metal tup of defined geometry and weight falling from a specified height. Impact resistance by PVC pipe is reported in units of ft-lb (joules) of energy. Impact resistance testing is conducted in accordance with ASTM D2444 as a quality control procedure; it should not, however, be considered a field acceptance test.

4.7.2.2.4 Flattening Test

When a sample of PVC pipe is flattened between moving parallel plates, it should display no evidence of splitting, cracking, or breaking. See Fig. 4.11.

4.7.2.2.5 Pipe Stiffness Test

For a pipe stiffness test, the PVC pipe sample is flattened between parallel plates to 5% datum deflection, at which point the force required to achieve this deflection is accurately

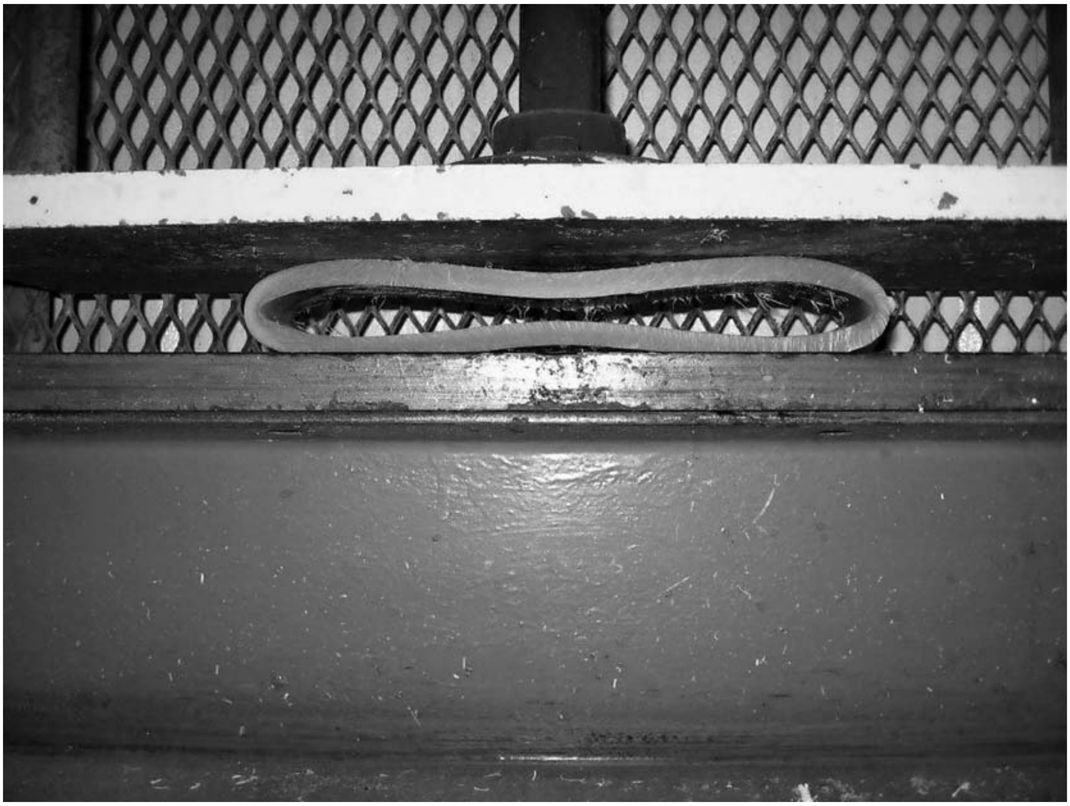

Fig. 4.11 PVC pipe undergoing a flattening test.

measured. This force per unit length divided by vertical deflection is expressed in units of pounds per lineal inch per inch (psi) (kPa) and is termed *pipe stiffness at 5% deflection datum*. Deflection datum bases other than 5% may be appropriate for some products. Pipe stiffness testing is conducted in accordance with procedures defined in ASTM D2412. The 5% measurement used in pipe stiffness testing should not be interpreted as a field performance limit. ASTM sewer pipe standards such as ASTM D3034 and F679 recommend a post-installation deflection limit of 7½%.

4.7.2.2.6 Hydrostatic Proof Test

The hydrostatic proof test is required in the manufacture of PVC municipal water mains in accordance with AWWA standards. (See Fig. 4.12.) In this test, every piece of PVC water main is proof-tested through application of hydrostatic pressure for a minimum dwell time of 5 seconds (unless purchaser and manufacturer agree to a different test frequency; any pipe not tested must be so marked).

Fig. 4.12 Hydrostatic proof test of PVC pressure pipe.

4.7.3 Quality Assurance (QA) Testing

Quality assurance testing is required by some standards and certifying agencies. Once a product has been qualified through qualification testing, QA testing is performed periodically to ensure continued adherence to design and performance requirements.

4.8 Test Certification and Warranty

4.8.1 Recognized Approval and Listing

Approval and listing by independent testing laboratories is common for PVC pressure pipe applications. Many PVC pipe products are marked with the seal of approval from various independent, third-party certification laboratories. Municipal water and fire mains are commonly listed by Underwriters Laboratories (UL). Potable water pipe and various other piping products are commonly certified for use in the United States by NSF and in Canada by CSA. The PPI lists recommended hydrostatic design stress ratings for many plastic pipe compounds. Other testing laboratories and organizations offer listing services for various PVC pipe compounds and products.

4.8.2 Manufacturer Warranty

Manufacturer warranty is a condition of sale specific to the agreement established between a manufacturer and customer regarding quality and performance of pipe products purchased. No standard warranty for PVC pipe products exists, although many warrantees are similar. Terms of warranty should not be assumed; rather, they should be obtained from the manufacturer.

4.9 Packaging and Shipping

At the conclusion of the production processes, inspection, and testing, PVC pipe products are prepared for shipment to the customer. Various acceptable methods of product packaging are used in the PVC pipe industry. Proper shipping and handling procedures should be provided by the manufacturer.

When a commercial carrier accepts PVC pipe with agreement to deliver to an established destination, the responsibility for the product is assumed by the carrier (see Chapter 10).

4.10 Sources

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CHAPTER 5

Pressure Pipe and Fittings Design and Selection

PVC Pressure Pipe and Fittings Design
•
PVC Pressure Pipe and Fittings Standards
•
Design Examples
•
PVC Pressure Pipe Longevity

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5.1 Notation

a = pressure wave velocity, ft/s
A = cross-sectional area, ft^2
C_L = number of cycles to failure, dimensionless
C' = number of cycles throughout design life, dimensionless
C = Hazen–Williams roughness flow coefficient, dimensionless
D_i = pipe inside diameter, in.
D_o = pipe outside diameter, in.
DF = design factor, dimensionless
DR = dimension ratio, dimensionless
E = modulus of elasticity of the pipe, psi
f = friction head, ft of water per 100 ft of pipe
F_T = temperature coefficient, dimensionless
g = acceleration due to gravity, ft/s^2
HDB = hydrostatic design basis, psi
k = fluid bulk modulus, psi
N = number of cycles per day, cycles/day
P = internal pressure, psi
$P_{amp(rs)}$ = pressure amplitude from recurring cyclic surges, psi
$P_{max(rs)}$ = maximum design pressure from recurring cyclic surges, psi
$P_{min(rs)}$ = minimum design pressure from recurring cyclic surges, psi
P_{os} = occasional surge pressure, psi
P_{rs} = recurring surge pressure, psi
P_s = pressure surge, psi
P_s' = pressure surge in response to a 1.0-ft/s change in velocity, psi
PC = pressure class, psi
Q_{cfs} = fluid flow, ft^3/s
Q_{gpm} = fluid flow, US gpm
r = pipe inside radius, in.
S = hoop stress, psi
S_a = allowable stress, psi
SF = safety factor, dimensionless

SDR = standard dimension ratio, dimensionless
STR = short-term rating, psi
STS = short-term strength, psi
t_{min} = minimum wall thickness, in.
V = fluid velocity, ft/s
WP = working pressure, psi
Y = design life, years
ΔV_{max} = maximum velocity change, ft/s
$\sigma_{amp(rs)}$ = hoop stress amplitude generated by recurring cyclic surges, psi
$\sigma_{avg(rs)}$ = average hoop stress generated by recurring cyclic surges, psi
$\sigma_{max(rs)}$ = maximum hoop stress generated by recurring cyclic surges, psi
$\sigma_{min(rs)}$ = minimum hoop stress generated by recurring cyclic surges, psi

5.2 Introduction

The performance of PVC pressure piping systems compared to other materials is well documented. A 1995 survey of 21 cities found that PVC had the lowest break rate of all commonly used water main piping materials (Fig. 5.1), thus quantifying the lower cost of maintaining PVC water systems.

A later study by Folkman was published in 2012. This extensive survey of 188 cities (representing about 10 percent of the municipal pipe in the United States and Canada) confirmed the results of the earlier work: PVC was again the material with the lowest break rate.

In the study, water main break rates were determined for the six major pipe materials used in the transmission and distribution of potable water:

- asbestos cement
- cast iron
- concrete
- ductile iron
- PVC
- steel.

Key findings of the report included:

- PVC pipe has the lowest overall failure rate.
- Corrosion is a major cause of water main breaks; 75% of all utilities have corrosive soil conditions.

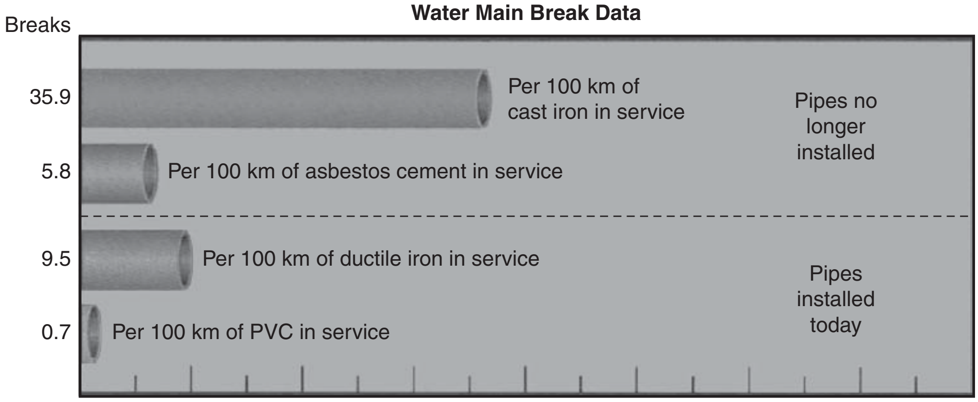

Fig. 5.1 Water main break data for various piping materials.

- Corrosion is ranked the second highest cause of water main pipe failure in the United States.
- Thinner-walled ductile iron is experiencing failures earlier in its design life than the older thick-walled cast iron.

The service reliability that PVC pipe offers can be achieved more consistently if engineers and designers understand product design principles. This chapter provides design theory and recommended approaches.

5.3 PVC Pressure Pipe and Fittings Design

Designers must consider both long-term and short-term hydrostatic strength. Depending on the application, cyclic pressures and operating temperatures might also need consideration.

5.3.1 The Stress Regression Line

The hydrostatic strength of visco-elastic materials like PVC and other plastics is described in a stress regression (SR) line. This approach differs from the one used for linear elastic materials like steel and other metals. Before specifics on the development of the SR line are presented, key variables and their relationships are defined.

Figure 5.2 shows a free-body diagram of a half-section of pipe subjected to internal pressure. Equation 5.1 shows the relationship between hoop stress (S) and internal pressure (P).

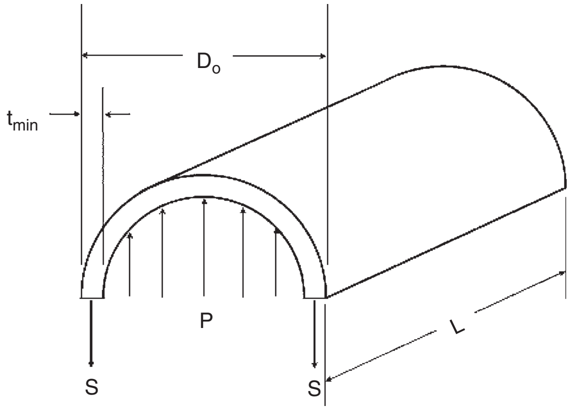

Fig. 5.2 Hoop stress due to internal pressure.

Equation 5.1

$$S = \frac{P(D_o - t_{min})}{2t_{min}}$$

where:

S = hoop stress, psi
t_{min} = minimum wall thickness, in.
P = internal pressure, psi
D_o = pipe outside diameter, in.

The terms *dimension ratio* and *standard dimension ratio* (abbreviated DR and SDR, respectively) are commonly used in the PVC pipe industry. They refer to the same dimensionless ratio, the quotient of average outside pipe diameter (D_o) divided by minimum pipe wall thickness (t_{min}) (Equation 5.2). SDRs are a series of DRs in 25% increments (13.5, 17, 21, 26, 32.5, 41, 51, …). For the remainder of the chapter, only the term DR is used.

Equation 5.2

$$SDR \equiv DR = \frac{D_o}{t_{min}}$$

where:

SDR = standard dimension ratio, dimensionless
DR = dimension ratio, dimensionless

A few points to remember about DR classifications:

- The lower the DR number, the thicker the pipe wall.
- Pressure capacity of a particular DR is constant, regardless of diameter.
- Structural strength of a particular DR is constant regardless of diameter (discussed further in Chapter 7).
- High DR pipe has a low pressure rating and low DR pipe has a high pressure rating.

Equation 5.3 expresses hoop stress (S) in terms of DR and internal pressure (P); it is derived from Equations 5.1 and 5.2.

Equation 5.3

$$S = \frac{P}{2}(DR - 1)$$

The first step in creating the SR line is collection of stress-rupture data, which is obtained by pressurizing PVC pipe samples to various hoop stresses until failure (rupture) occurs. Figure 5.3 shows a testing apparatus, and Table 5.1 details the number of samples needed at various stress levels to generate the range of data points desired. The pressure needed to generate the hoop stress in a DR 18 pipe is also listed.

Table 5.2 lists the data set generated from hydrostatic testing, taken from a 1981 article by Robert Hucks in the Journal of the AWWA. The pipe was manufactured from ASTM D1784 cell class 12454 pressure compound.

Figure 5.4 shows the data in Table 5.2 plotted on a linear scale using Cartesian coordinates as well as the best-fit curve, which in this case is the stress regression curve. This curve is a best-fit plot of stress versus time-to-failure data points; it does not represent a reduction of strength in a single pipe over time.

Fig. 5.3 Apparatus for collecting stress-rupture data.

Table 5.1 Typical set of test samples required for generating stress-rupture data set as applied to DR 18 PVC pipe

Number of samples	Hydrostatic pressure, psi	Hoop stress, psi
2	706	6,000
3	685	5,800
3	659	5,600
2	635	5,400
1	612	5,200
3	588	5,000
3	565	4,800
3	541	4,600

Table 5.2 Typical stress-rupture data for ASTM D1784 cell class 12454 PVC pressure pipe compound

Sample number	Hoop stress, psi	Time to rupture, hr
1	6,000	42
2	6,000	91
3	5,800	119
4	5,800	72
5	5,800	153
6	5,600	142
7	5,600	231
8	5,600	402
9	5,400	248
10	5,400	1,103
11	5,200	1,012
12	5,000	1,409
13	5,000	1,998
14	5,000	3,010
15	4,800	4,970
16	4,800	3,521
17	4,800	8,009
18	4,600	14,981
19	4,600	19,298
20	4,600	8,995

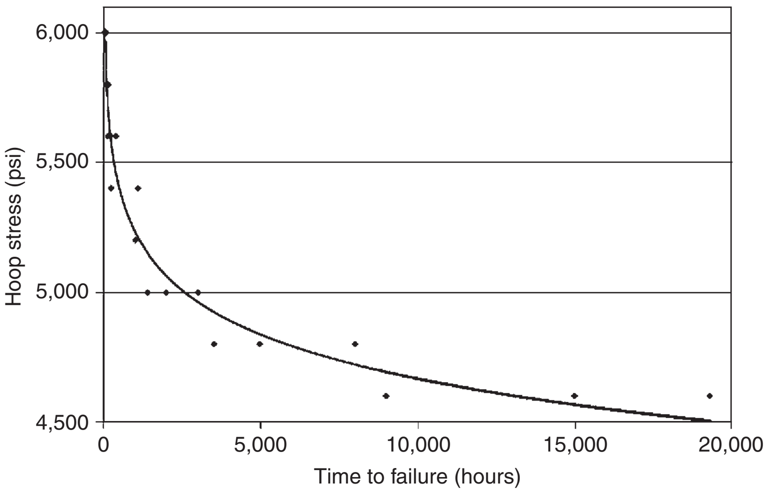

Fig. 5.4 Stress regression curve for PVC pressure pipe.

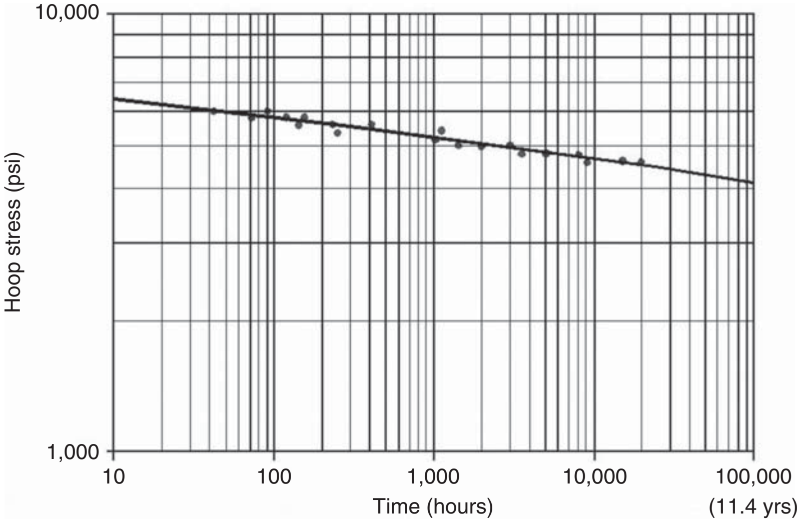

Fig. 5.5 Stress regression line for PVC pressure pipe.

Figure 5.5 shows the same data as Fig. 5.4, but plotted on a logarithmic scale, where the log-log plot of stress-rupture data for PVC pipe can be seen as a straight line. When plotted on a log-log graph, the data show little scatter and the line may be extrapolated to very long time frames with high levels of confidence.

All PVC pressure pipe manufactured in North America must be extruded from PVC compounds for which stress regression lines have been established. The SR line quantifies the time-dependence of PVC pipe's response to applied internal hydrostatic pressure.

5.3.2 Hydrostatic Design Basis

The reference time-to-failure selected in North American standards is 100,000 hours (11.4 years). This time frame makes sense when the typical SR line for PVC looks like the one shown Fig. 5.5, where the response of the PVC pipe to applied internal hydrostatic pressure or applied hoop stress has essentially stabilized at 100,000 hours. Moreover, when testing for the stress-rupture data set is performed in accordance ASTM D1598, Standard Test Method for Time-to-Failure of Plastic Pipe Under Constant Internal Pressure, and when those data are analyzed as required in ASTM D2837, Standard Method for Obtaining Hydrostatic Design Basis for Thermoplastic Materials, the response of the PVC pipe to applied hoop stresses can be determined with extreme accuracy for a design life in the 50- to 200-year time frame.

The long-term strength used in design is known as the *hydrostatic design basis* (HDB). For ASTM D1784 cell class 12454 PVC pressure pipe compounds, the HDB is 4,000 psi. Figure 5.6 illustrates the categories used in assigning PVC pressure pipe compound an HDB of 4,000 psi. First, the SR line is developed per the applicable ASTM standards. Next, the *long-term hydrostatic strength* (LTHS) at 100,000 hours is determined, which in this figure is 4,163 psi; this LTHS falls within a range qualifying it for an HDB of 4,000 psi. Figure 5.6 shows other LTHS ranges for HDB categories as low as 1,250 psi and as high as 7,100 psi.

ASTM D2837 has other requirements, some of which are statistical in nature and address items like confidence intervals, scatter, and minimum number of data points in each log cycle. Other requirements are material-related and specify requirements for the 50-year LTHS compared to the 100,000-hour LTHS.

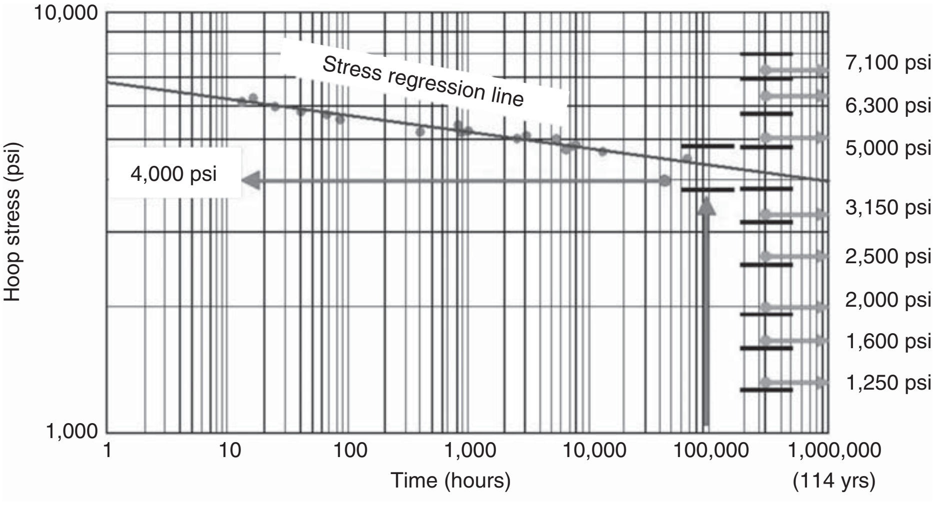

Fig. 5.6 Stress regression line showing HDB categories.

5.3.3 Short-Term Hydrostatic Strength

The SR line seen in Fig. 5.5 illustrates the ability of PVC pipe to withstand substantially higher hydrostatic pressure over short durations of application than over long periods of time. The product standards for PVC pressure pipe incorporate this concept in the required quality control testing. The pass/fail criterion for a short-term test (quick-burst) is significantly higher than the pass/fail level for the 1,000-hour test: hoop stress at burst must meet or exceed 6,400 psi for pipe to pass the quick-burst test. The quick-burst test is calibrated to raise the test pressure to burst in a 60- to 70-second time frame. However, to pass the 1,000-hour sustained pressure test, the sample must endure a constant hoop stress of 4,200 psi for 1,000 hours without failure, which is defined as ballooning, bursting, or weeping. The quick-burst test provides assurance of PVC extrusion quality and demonstrates the surge capacity of PVC pipe.

Quick-burst testing for quality control purposes provides for a short-term strength of over 6,400 psi hoop stress. Results of research conducted to verify that PVC pipe in service and under pressure maintains quick-burst strength are illustrated in Fig. 5.7.

The line labeled “4,000-psi applied long-term” in Fig. 5.7 denotes that the samples were subjected to a hoop stress of 4,000 psi for thousands of hours. To generate such a level of stress, a DR 18 product would need to be pressurized to 470 psi. The arrows pointing up from this line show the time at which the sample was taken off hydrostatic testing and subjected to quick-burst testing; the small squares plot the stress the specimen was undergoing when it burst. Of most interest is the last specimen tested, circled and labeled C. This sample had been under constant pressure for 87,867 hours (10 years), and it was drawing near the SR line

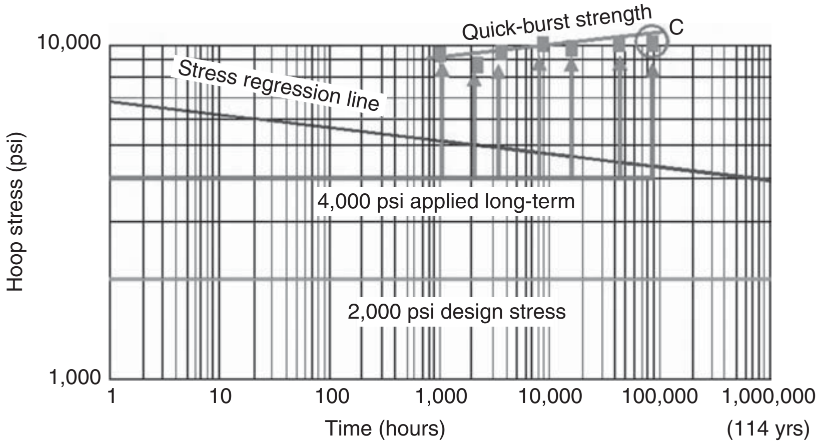

Fig. 5.7 Quick-burst strength of PVC pipe after being subjected to long-term hydrostatic pressure (Hucks).

and the end of its hydrostatic life. Creep rupture of the specimen is expected to occur at the time when the hoop stress intersects the SR line. Even though the majority of specimen C's hydrostatic life had been exhausted, the quick-burst strength was higher than that of new pipe at 10,178 psi. Also of significance is that the "Quick-burst line trends upward, which means quick-burst strength tends to increase the longer the pipe is in service and under pressure.

5.3.4 Temperature Effects on Hydrostatic Strength

In North America, PVC pipe is rated for pressure capacity at 73.4°F (23°C). As operating temperature falls below 73.4°F (23°C), pressure capacity of PVC pipe increases. This increase is treated as an unstated addition to the working safety factor, but it is not otherwise considered in the design process. Conversely, as the operating temperature rises above 73.4°F (23°C), the pressure capacity of PVC pipe decreases. Table 5.3 displays the response of PVC pressure pipe to changes in operating temperature.

Table 5.3 Thermal de-rating factors for PVC pressure pipes and fittings

Maximum service temperature °F (°C)	Multiply pressure class (PC) at 73.4°F (23°C) by factor shown
80 (27)	0.88
90 (32)	0.75
100 (38)	0.62
110 (43)	0.50
120 (49)	0.40
130 (54)	0.30
140 (60)	0.22

Notes:

1. The maximum recommended sustained temperature for the wall of PVC pressure pipe and fittings is 140°F (60°C).
2. Interpolate between the temperatures listed to calculate other factors.
3. Pipe gaskets are generally suitable for continuous use in water at the temperatures listed above.
4. The de-rating factors assume sustained elevated service temperatures. When the contents of a buried PVC pressure pipe are only intermittently and temporarily raised above the service temperature shown, de-rating may not be needed.

5.3.5 Hydrostatic Strength of PVC Fittings

Injection-molded and fabricated PVC fittings are manufactured from one of a number of compounds and employ a variety of machines and designs. The total effect of these

Table 5.4 Typical pressure-rupture data for AWWA C907 molded fittings equivalent to DR 18 AWWA C900 pipe

Sample number	Internal pressure, psi	Time to rupture, hr
1	706	42
2	706	91
3	685	119
4	685	72
5	685	153
6	659	142
7	659	231
8	659	402
9	635	248
10	635	1,103
11	612	1,012
12	588	1,409
13	588	1,998
14	588	3,010
15	565	4,970
16	565	3,521
17	565	8,009
18	541	14,981
19	541	19,298
20	541	8,995

manufacturing decisions is specific to each size and fitting configuration. Thus, each size of each fitting configuration is subjected to hydrostatic stress-regression testing in the same manner as pipe compounds, except that internal pressure is substituted for hoop stress. Table 5.4 gives a sample data set, and Fig. 5.8 shows the resulting regression line plotted on a log-log scale.

The standard requirement is that the fittings must have proven long-term pressure strength (LTPS) equivalent to that of the PVC pipe. The pressure strength of PVC pipe can be calculated using Equation 5.4.

Equation 5.4

$$P = \frac{2S}{DR - 1}$$

where:

P = internal pressure, psi
S = hoop stress, psi
DR = dimension ratio, dimensionless

When the hoop stress is set to the value of the HDB for ASTM D1784 cell class 12454 PVC pressure pipe compound, the LTPS for DR 18 is 470 psi:

$$P = \frac{2 \times 4{,}000}{18 - 1} = 470 \text{ psi}$$

In a DR 18 PVC pipe, therefore, an internal pressure of 470 psi is equivalent to a circumferential hoop stress of 4,000 psi, which is the HDB of the compound. This pressure is defined as the LTPS requirement for PVC fittings. Each size and configuration of PVC fitting must demonstrate its ability to sustain a pressure of 470 psi in excess of 100,000 hours. The analysis of test results is performed using the least squares method given in ASTM D2837.

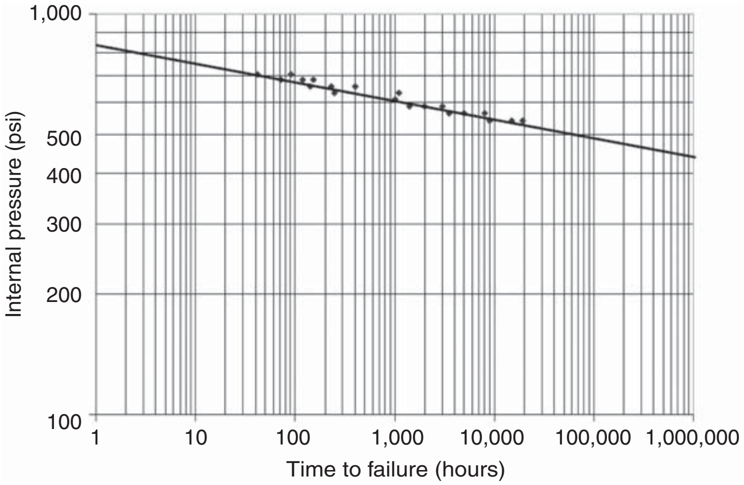

Fig. 5.8 Pressure regression line for PVC fittings.

5.3.6 Surge Pressure in PVC Pipe

In general, surge pressures are any deviation from the regular steady state hydrostatic pressure in a piping system. Normally, positive surges are the concern; however, negative surges to the vapor pressure of pipe's contents may occur. In both cases, the surges can be brought to acceptable levels through the use of suitable protection devices or operating procedures.

Surge pressures (commonly termed “water-hammer”) are generated in any pressurized piping system where the flowing liquid changes velocity. When flow velocity changes, part or all of the kinetic energy of the moving fluid must be converted to potential (stored) energy and ultimately dissipated through frictional losses in the fluid or in the pipe wall if the fluid is to return to its original pressure. Some of the more common causes of pressure surges are:

- opening and closing (full or partial) of valves
- starting and stopping of pumps
- changes in flow demand
- changes in reservoir elevation
- reservoir wave action
- liquid column separation
- entrapped air.

Entrapped air may be managed by installation of air-release valves or combination air-release and air/vacuum valves. Without these valves, air may accumulate at high points and severely reduce the flow capacity. Large pressure surges may occur as a result. The American Water Works Association (AWWA) Manual M51, entitled Air-Release, Air/Vacuum, and Combination Air Valves, provides recommendations for locating air valves along a pipeline.

Surges are divided into two categories: (1) *occasional* (*transient*) surges and (2) *recurring* (*cyclic*) surges. Transient surges, or “transients,” are intermediate conditions that exist in a system as it moves from one steady state condition to another. The closing of a single valve is a typical example. Design equations analyzing occasional surges are presented in Section 5.3.6.1. Recurring (cyclic) surging is a condition that recurs regularly over time. Surging of this type is often associated with the action of equipment such as reciprocating pumps and pressure-reducing valves. Any piping material, including PVC, may eventually fatigue if exposed to continuous cyclic surging at sufficiently high frequency and stress amplitude. If cyclic fatigue is design-limiting, it is often more economical to install surge control devices rather than increase the pipe wall thickness.

5.3.6.1 Occasional Surge Pressures

Occasional surge pressures are those caused by emergency operations—usually the result of a malfunction such as a power failure, sudden valve closure, or system component failure. The magnitude of occasional, or transient, surges is calculated using the elastic wave theory of surge analysis. The geometry and boundary conditions of many systems are complicated and require the use of refined techniques similar to those developed by Streeter and Wylie.

Maximum surge pressure is related to maximum rate of change of the flow and the rate at which the pressure wave travels. Wave velocity is given by Equation 5.5:

Equation 5.5

$$a = \frac{4{,}660}{\sqrt{1 + \frac{kD_i}{Et_{min}}}}$$

where:

a = pressure wave velocity, ft/s
k = fluid bulk modulus, psi (300,000 psi for water)
D_i = pipe inside diameter, in.
E = modulus of elasticity of the pipe, psi (400,000 psi for PVC water pipe)
t_{min} = minimum wall thickness, in.

The equation for pressure wave velocity can also be expressed in terms of dimension ratio, DR. Since $D_i = D_o - 2t_{min}$, substituting D_i for D_o in Equation 5.2 and rearranging gives $Di = (DR - 2)(t_{min})$. Equation 5.5 can then be expressed as:

Equation 5.6

$$a = \frac{4{,}660}{\sqrt{1 + \frac{k}{E}(DR - 2)}}$$

where:

DR = dimension ratio, dimensionless

Once pressure wave velocity has been determined, the maximum pressure surge may be calculated using Equation 5.7:

Equation 5.7

$$P_s = \frac{a(\Delta V_{max})}{2.31g}$$

where:

P_s = pressure surge, psi
ΔV_{max} = maximum velocity change, ft/s
g = acceleration due to gravity, 32.2 ft/s^2

Example 5.1

This example calculates the surge pressure in PC235 PVC pipe for a change in flow velocity of 2 ft/s. First the pressure wave velocity (a) is determined using Equation 5.6, and then the surge pressure (P_s) using Equation 5.7.

Knowns:

- Pipe: 6-in. PC235 PVC pipe
- DR = 18
- E = 400,000 psi for PVC
- k = 300,000 psi for water

Solution

$$a = \frac{4{,}660}{\sqrt{1 + \left(\frac{300{,}000}{400{,}000}\right)(18 - 2)}} = 1{,}292 \text{ ft/s}$$

$$P_s = \frac{(1{,}292)(2)}{(2.31)(32.2)} = 35 \text{ psi}$$

Example 5.2

This example calculates the surge pressure in PC350 DI pipe for a change in flow velocity of 2 ft/s. First the pressure wave velocity is determined using Equation 5.5 and then the surge pressure using Equation 5.7.

Knowns:

- Pipe: 6-in. PC350 DI pipe
- D_o = 6.90 in.
- t_{min} = 0.25 in.
- D_i = 6.40 in.
- E = 24,000,000 psi for ductile iron
- k = 300,000 psi for water

$$a = \frac{4{,}660}{\sqrt{1 + \left(\frac{300{,}000}{24{,}000{,}000}\right)\left(\frac{6.40}{0.25}\right)}} = 4{,}056 \text{ ft/s}$$

$$P_s = \frac{(4{,}056)(2)}{(2.31)(32.2)} = 109 \text{ psi}$$

Note in the above examples that for the same conditions of interrupted flow, pressure surge is significantly greater in pipes with high tensile moduli (e.g., ductile iron) than in pipes with lower moduli (PVC) with similar dimensions.

As the modulus of tensile elasticity for a pipe material increases, the resultant pressure surge (water hammer) caused by a change in flow velocity also increases. For example, an instantaneous 2.0-ft/s flow velocity change in a 14-in. water main will create different surge pressures for different pipe materials, as shown in Table 5.5.

Table 5.5 Pressure surges in 14-in. water main for a 2.0-ft/s (0.6-m/s) instantaneous change in velocity

Pipe product	Pressure surge, psi (kPa)
PC235 AWWA PVC pipe	34.8 (240)
PC250 AWWA DI pipe	97.3 (670)
Class 150 AWWA concrete cylinder pipe	96.4 (665)

Pressure surges (P_s') in PVC pipe (ASTM D1784 cell class 12454) of different dimension ratios in response to a 1.0-ft/s (0.3-m/s) instantaneous flow velocity change are shown in Table 5.6.

Table 5.6 Design table for PVC pipe pressure surge vs. dimension ratio for a 1.0-ft/s (0.3-m/s) instantaneous change in velocity

DR	Pressure surge P_s', psi (kPa)
51	10.8 (74)
41	11.4 (79)
32.5	12.8 (88)
26	14.4 (99)
25	14.7 (101)
21	16.0 (110)
18	17.4 (120)
14	19.8 (137)
13.5	20.2 (139)

5.3.6.2 Recurring Surges and Cyclic Design

Working pressures in full-flowing liquid transport piping systems (water distribution lines, sewer force mains, irrigation lines) are not hydrostatic pressures. Varying demand for liquid transport relating to pump and/or valve operation in the piping system will result in working pressure fluctuations. Inherent in the non-steady state operation of common piping systems is some measure of cyclic surging. Consequently, if cyclic surging of high frequency or magnitude is anticipated, the design of piping systems for liquid transport should not be based solely on hydrostatic pressure ratings assigned to pipe products.

Any pipe material can experience fatigue failure when exposed to severe cyclic surging that exceeds design limits. Fatigue failure due to cyclic surging is typically not a matter of concern in water distribution systems, as such systems rarely experience routine cyclic surging with frequency and magnitude high enough to influence pipe design. However, the design of some piping systems (i.e., sewer force mains, turf irrigation systems, and frost control systems) may be governed by severe cyclic surging. If cyclic surges are not controlled or designed out of the system, then all pipes, fittings, and appurtenances must be designed with sufficient allowance for cyclic surging to prevent fatigue failure.

A *cycle* is defined as *a change in operating pressure*. In a forcemain, for example, starting of a pump is considered a cycle and subsequent stoppage of the pump is also considered a cycle.

Empirical design methods recognize the effects of cyclic pressure surges on PVC pipe. Research performed by Moser has established two independent variables for cyclic analysis: average hoop stress (or mean hoop stress) and stress amplitude. Moser's design method is mathematically illustrated by the function $C_L = f\{\sigma_{avg(rs)}, \sigma_{amp(rs)}\}$, where:

C_L = cycles to failure (or cyclic life), dimensionless
$\sigma_{avg(rs)}$ = average hoop stress generated by recurring surges, psi
$\sigma_{amp(rs)}$ = hoop stress amplitude generated by recurring surges, psi

The functional relationships of various stresses are illustrated in Fig. 5.9, where:

$\sigma_{max(rs)}$ = maximum hoop stress generated by recurring surges, psi
$\sigma_{min(rs)}$ = minimum hoop stress generated by recurring surges, psi

In Europe, cyclic fatigue analysis for plastic pipe is based solely on stress amplitude. The European approach provides less conservative predictions. Although stress

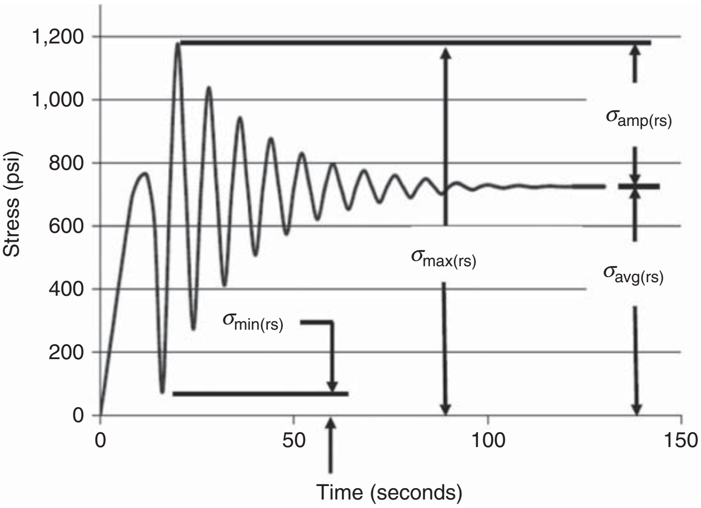

Fig. 5.9 Stress vs. time relationships in cyclic design.

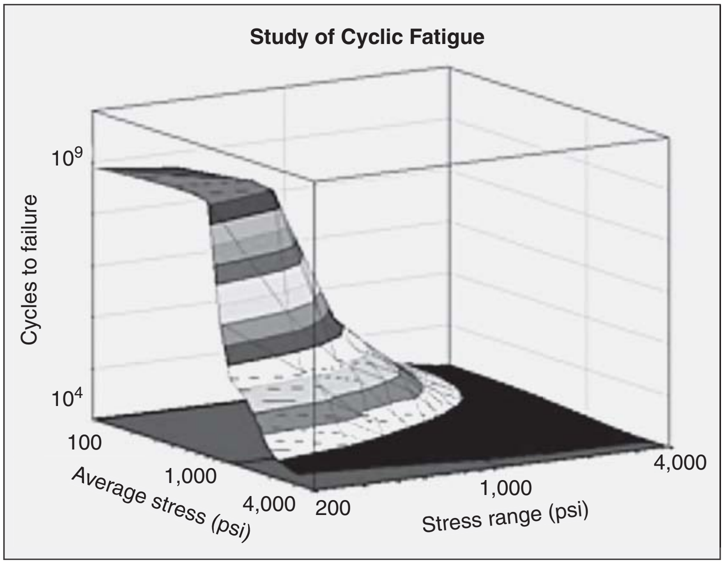

Fig. 5.10 Typical surface from cyclic data for PVC pipe by Moser.

amplitude is the more critical of the two variables, the concept arrived at by Moser takes into account the influences of both amplitude and average stress. A typical regression of stress rupture data for PVC pipe in terms of these two influences now takes the form of a three-dimensional failure surface, as shown in Fig. 5.10.

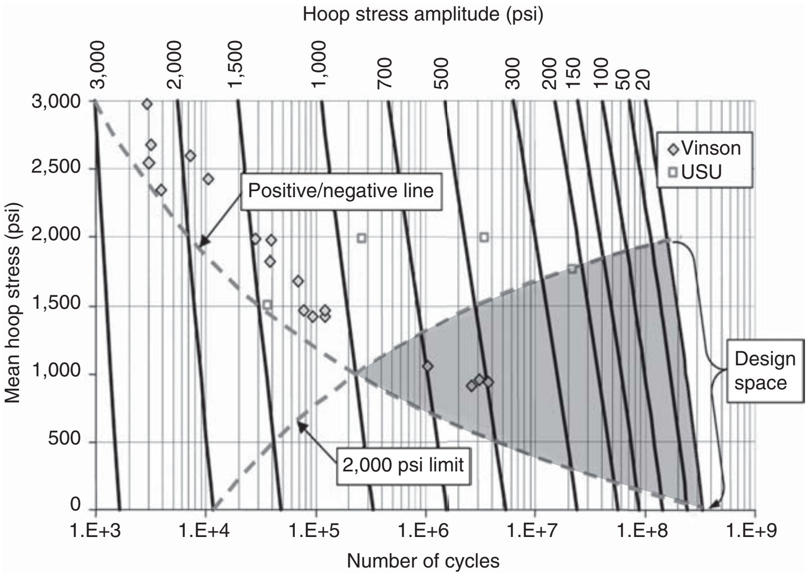

Fig. 5.11 Cyclic design curves for PVC pipe

A two-dimensional projection (such as a top view) of the three-dimensional surface reveals exponential decay curves, with each band representing a designated number of cycles to failure. Such curves can be represented in a more useful form when plotted on semi-logarithmic axes, with average stress given on a linear scale and cycles to failure on a logarithmic scale (Fig. 5.11). The resulting straight lines of the chart represent different hoop stress amplitudes.

Figure 5.11 is used as follows: first, the *y*-axis is read at the average (mean) stress under consideration; then, proceeding right, the appropriate stress amplitude line is reached; last, going down, the predicted cycles to failure is read.

The broken curve trending downward through the graph in Fig. 5.11 shows the boundary between positive and negative pressures. Negative pressures result where stress amplitude is greater than average stress. In these situations, the buckling resistance of the PVC pipe wall is usually strong enough to withstand a vacuum.

Successful cyclic design will result in a cyclic life (C_L) that exceeds the total number of cycles (C') that occur throughout the design life. Figure 5.11 is used to determine C_L, whereas Equation 5.8 is used to calculate C'. Note that Equation 5.8 uses the total number of cycles per day, not cycles per hour. By using a total daily number, one accounts for both heavy and light periods of flow. The worst-case design condition would be based on the design number of starts and stops per hour, which is part of the pump selection and wet well design process. The number of starts per hour should be limited to prevent the pump motor from short-cycling and overheating.

Equation 5.8

$$C' = (N)(365\ \text{days/year})(Y)$$

where

C' = number of cycles throughout design life, dimensionless
N = number of cycles per day, cycles/day
Y = design life, years.

If the pressure waves are simple, as shown in Fig. 5.12, determining the number of cycles per day is straightforward. However, if the waves are more complex, as shown in Fig. 5.13, additional analysis is required to calculate the number of cycles per day. This analysis converts the secondary and tertiary cycles into an equivalent number of primary cycles. In the case of the dampened sine wave shown in Fig. 5.13, the secondary and

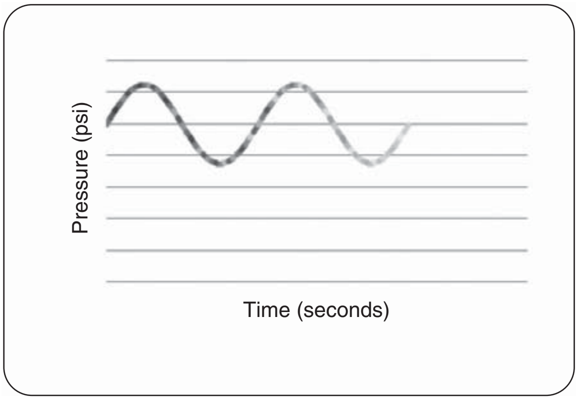

Fig. 5.12 Simple pressure waves.

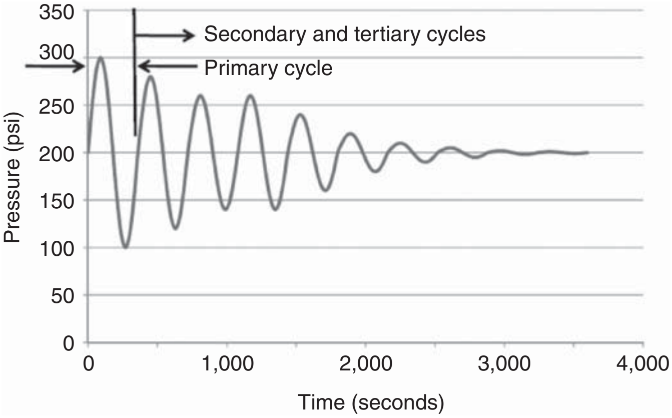

Fig. 5.13 Complex pressure waves.

tertiary waves have the fatigue equivalent of 0.55 primary wave. Appendix A of *Long-Term Cyclic Testing of PVC Pipe* (Moser) provides details on the derivation of the 0.55 multiplier using Miner's rule.

The experimental conditions upon which Fig. 5.11 is based will seldom be duplicated exactly in an installed pipeline, since pressure variation, cycle period, and temperature will vary. Nevertheless, if the calculated number of cycles to failure is critical in a proposed pipeline, the designer should moderate the maximum pressure, amplitude of surges, and/or cyclic frequency.

Once the approximate number of cycles is known, the next step is to select a PVC pipe dimension ratio (DR) and determine the average stress anticipated for that particular pipe. The minimum and maximum internal pressures are values that must be determined by the designer. (These are labeled $P_{min(rs)}$ and $P_{max(rs)}$ in Fig. 5.14.) If no effort is made to control surges, the maximum pressure should be the sum of the operating pressure and the maximum surge (Equation 5.7 calculates the maximum surge). However, using surge-control devices (soft-start pumps, expansion tanks, etc.) is generally more cost-effective than not using them. Where surge-control devices are used, the designer should use a value of peak pressure that accurately reflects the true value of recurring surges. It is important to recognize that proper maintenance of system appurtenances ensures that the controlled pressures remain appropriate. When the minimum and maximum pressures of the system design are known, average stress (σ_{avg}) can be determined with Equation 5.9.

Equations 5.9 and 5.10 relate to the cyclic pressure surges that are a result of system operation. $P_{max(rs)}$ and $P_{min(rs)}$ are the upper and lower boundaries, respectively, of the pressure fluctuations at a particular point in the system that result when the system moves from one operating condition to another. If the system has been modeled using one of the commercially available transient analysis software packages, the values for $P_{max(rs)}$ and $P_{min(rs)}$ may be taken from the output of the program.

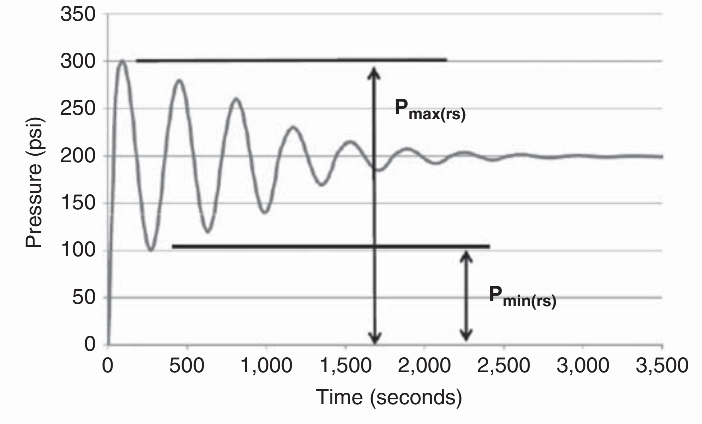

Fig. 5.14 Minimum and maximum pressures in cyclic design.

Equation 5.9

$$\sigma_{\mathrm{avg(rs)}} = \frac{(\mathrm{P}_{\mathrm{max(rs)}} + \mathrm{P}_{\mathrm{min(rs)}})(\mathrm{DR} - 1)}{4}$$

where:

$\sigma_{\mathrm{avg(rs)}}$ = average hoop stress generated by recurring surges, psi
$\mathrm{P}_{\mathrm{max(rs)}}$ = maximum design pressure from recurring surges, psi
$\mathrm{P}_{\mathrm{min(rs)}}$ = minimum design pressure from recurring surges, psi
DR = dimension ratio, dimensionless.

The hoop stress amplitude ($\sigma_{\mathrm{amp(rs)}}$) is similarly calculated.

Equation 5.10

$$\sigma_{\mathrm{amp(rs)}} = \frac{(\mathrm{P}_{\mathrm{max(rs)}} - \mathrm{P}_{\mathrm{min(rs)}})(\mathrm{DR} - 1)}{4}$$

where:

$\sigma_{\mathrm{amp(rs)}}$ = hoop stress amplitude generated by recurring cyclic surges, psi

When Fig. 5.11 is used to determine the number of cycles to failure (C), simply comparing this result to the needed number of cycles (C′) will determine whether the pipe DR is adequate. If C is greater than C′, then the selected DR will satisfy the cyclic criterion of the design. If not, then the design may be limited by the cyclic capacity of the pipe and, consequently, a lower DR should be selected. This process should be repeated until a DR has been selected that provides for a C that is greater than C′.

5.3.6.3 Common Surge-Control Techniques

A change in flow velocity within a closed conduit causes elastic waves to travel upstream and downstream from the point of origin, which causes an increase or decrease in pressure as the waves travel along the pipeline. Although pressure-control devices serve multiple purposes in a piping system, their primary function is to minimize pressure fluctuations created when this change in fluid velocity occurs.

Where either the magnitude or frequency of surges is judged to be the limiting parameter in a pipeline design, there are practical means of reducing the surges to acceptable levels. In general, the first objective is to keep the upsurge and downsurge (the maximum positive and negative surges) at minimum values. Within this minimized transient pressure envelope, even at a fixed-cycle frequency (i.e., where C is not a controllable variable), the operation of the pipeline may often proceed because the cyclic strength of the system is shown to be sufficient.

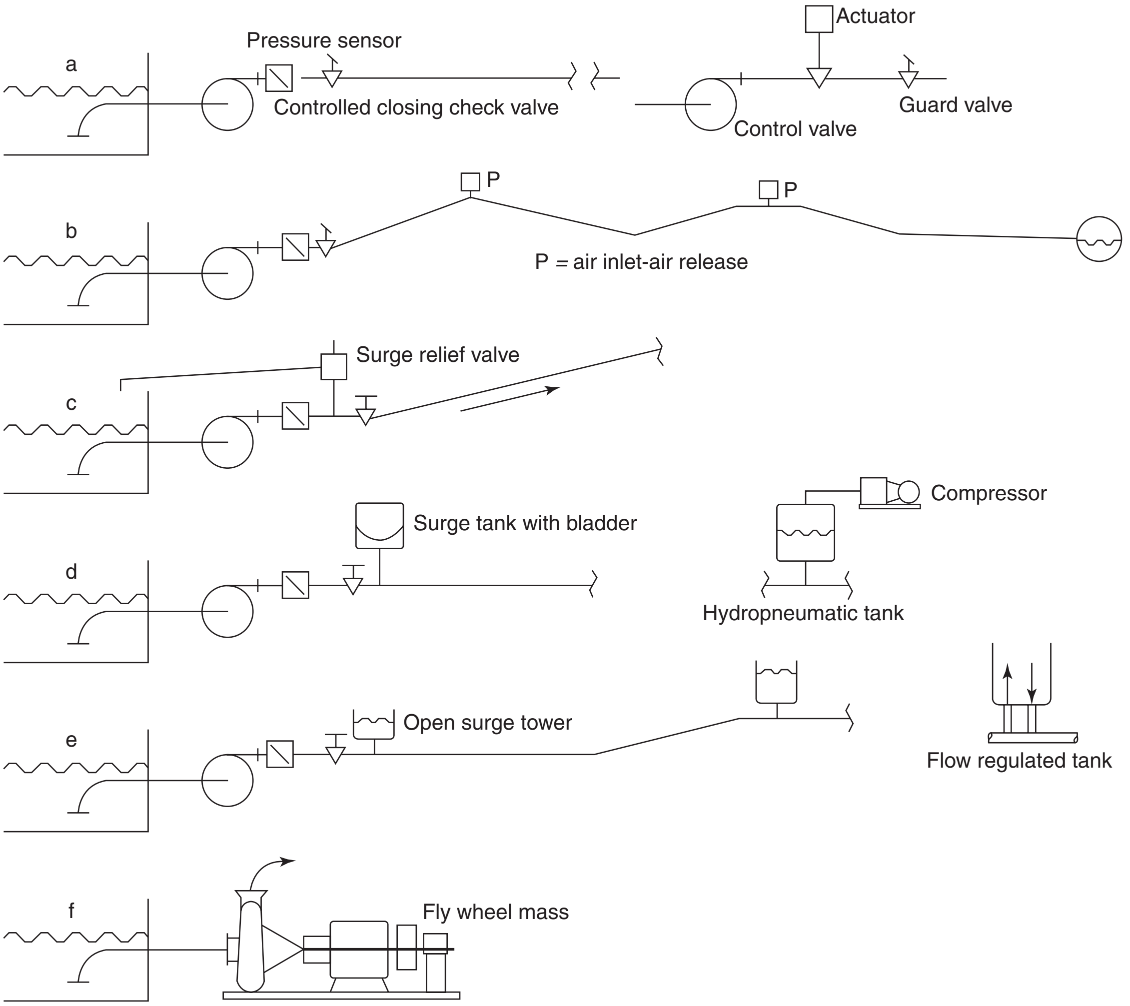

Fig. 5.15 Surge reduction methods.

Due to the wide variety of surge conditions possible (positive or negative pressures, occasional or recurring frequency) there is no one solution for controlling surge conditions. There are various means of controlling, reducing, or withstanding surge pressure in pressure systems. One method is to use variable speed pumps, which allow the pumping operation to be continuous for varying flow conditions, thereby greatly reducing the number of on/off cycles. Other options, as shown in Fig. 5.15, are described below:

a) *Controlled closing check or pump control valve:* The use of slow opening and closing check valves or pump control valves is an effective way to control pressure surges during normal pump starts and stops. (This arrangement is often referred to as a “soft start/soft stop” pump.) The rate of opening and closing will be a function of the pipe length. Another design factor is minimum flow required by volute-casing-centrifugal pumps. The pump manufacturer should be consulted for the flow required to relieve the high radial thrusts this type of pump generates.

b) *Air exhaust and air inlet valves:* Air exhaust valves serve two purposes: (1) venting air at the high points, when the line is slowly filled for its acceptance testing after installation; (2) venting entrapped air. When the pressure drops below atmospheric pressure, air inlet valves will admit air in order to prevent a vacuum from occurring.
c) *Pressure surge relief valves:* Spring-loaded valves vent pressures in excess of a preset value. When relief valves are activated, the fluid discharged is piped back to the wet well.
d) *Closed or pressurized surge tanks:* A closed unit containing air and the conveyance fluid, which is occasionally separated by a diaphragm or a bladder. The air is under pressure, allowing control of both positive and negative surges in high pressure systems by allowing flow into and out of the unit.
e) *Surge tower:* A tank open to the atmosphere that functions in a manner similar to a surge tank for low pressures.
f) *Pump and driver inertia:* Pumps that decelerate slowly in the event of a power outage, which minimizes the downsurge on the fluid column.

Note: Proper maintenance of surge control devices and other system appurtenances is necessary for the system to operate as designed.

PVC pressure systems can utilize some or all of the methods listed above and illustrated in Fig. 5.15. Additional discussion is provided in WEF Design of Wastewater and Stormwater Pumping Stations.

5.4 PVC Pressure Pipe and Fittings Standards

The first ASTM standard for PVC pressure pipe in North America was published in 1960. The publication of AWWA C900 in 1975 marked a new era in pipe materials, as it was the first thermoplastic piping standard for potable water distribution published by AWWA. This was followed by the publication of AWWA C905 in 1988 for water transmission, which included larger diameter pipes, 14 in. and above. For the next two decades, there were two design approaches for PVC pressure pipe: (1) the *pressure class approach*, as described in AWWA C900-97, and (2) the *pressure rated approach*, as described in AWWA C905. The former incorporated a built-in surge allowance as well as a safety factor of 2.5, whereas the latter did not have a built-in surge allowance and used a safety factor of 2.0. When the AWWA PVC Committee began its update of the 1997 versions of these two standards, it decided to harmonize them. The AWWA Research Foundation published the report *Long-Term Performance Prediction for PVC Pipe,* emphasizing that design stresses between standards be consistent and based upon a safety factor of 2.0.

5.4.1 Allowable Stress

Allowable stress (S_a) is the hoop stress used to determine the maximum recommended operating pressure of the pipe. Table 5.7 shows S_a values for common standards in North America.

Table 5.7 Allowable stresses used in North America for PVC

Standard	Design factor, DF	Safety factor, SF	Allowable stress, S_a (psi)
AWWA C900	0.5	NA	2,000
ASTM D2241	NA	2.0	2,000
CSA B137.3	0.5	NA	2,000

Allowable stress is calculated in Equation 5.11.

Equation 5.11

$$S_a = \frac{HDB}{SF} \quad \text{or} \quad S_a = (HDB)(DF)$$

where:

S_a = allowable stress, psi
HDB = hydrostatic design basis, psi (see Section 5.3.2)
SF = safety factor, dimensionless
DF = design factor, dimensionless.

Note: Safety factor is the inverse of design factor.

5.4.2 Sustained Pressure and Quick-Burst Capacities

PVC pressure capacity increases as duration of the applied pressure decreases. Table 5.8 illustrates this by showing the higher stresses applied as the test duration decreases.

Table 5.8 Applied stresses for various test methods and durations

Test and method	Test duration	Applied stress (psi)
HDB per ASTM D2837	100,000 hr	4,000
Sustained pressure per ASTM D1598	1,000 hr	4,200
Quick-burst per ASTM D1599	60–70 sec	6,400

Table 5.9 Sustained pressure test requirements (1,000-hr duration) for minimum hoop stress of 4,200 psi (29.0 MPa)

DR	Minimum sustained pressure, psi (MPa)
14	650 (4.48)
17	525 (3.62)
18	500 (3.44)
21	420 (2.89)
25	350 (2.41)
26	340 (2.34)
32.5	270 (1.86)
41	210 (1.44)
51	170 (1.17)

Table 5.10 Quick-burst requirements for minimum hoop stress of 6,400 psi (44.1 MPa)

DR	Minimum burst pressure, psi (MPa)
14	985 (6.79)
17	800 (5.52)
18	755 (5.21)
21	630 (4.34)
25	535 (3.69)
26	500 (3.45)
32.5	400 (2.76)
41	315 (2.17)
51	255 (1.76)

The pressures required to achieve the minimum 4,200-psi hoop stress for the sustained pressure test are listed in Table 5.9 and the pressures for the quick-burst test are shown in Table 5.10. Pressures have been rounded to the nearest multiple of 5 in both tables.

The quick-burst test provides assurance of PVC extrusion quality and demonstrates the surge capacity of the pipe.

5.4.3 Short-Term Rating

A surge pressure of short duration would have to exceed a pipe's quick-burst strength in order to fail the pipe. Since duration of transient surges is measured in fractions of a second, the 60–70-second quick-burst strength is a conservative measure of PVC's ability to handle sudden surges. The short-term rating (STR) is determined by dividing short-term strength (STS) by a safety factor. The STS is the minimum quick-burst strength given in Table 5.10.

Equation 5.12

$$\mathrm{STR} = \frac{\mathrm{STS}}{\mathrm{SF}} \quad \text{or} \quad \mathrm{STR} = (\mathrm{STS})(\mathrm{DF})$$

where:

STR = short-term rating, psi
STS = short-term strength, psi
SF = safety factor, dimensionless
DF = design factor, dimensionless

Table 5.11 lists STR and STS values for various DR. The STR is based on a safety factor of 2.0 and a hoop stress of 3,200 psi (see Equation 5.12).

Table 5.11 Short-term strengths and short-term ratings

DR	STS, psi (MPa)	STR, psi (MPa)
14	985 (6.79)	488 (3.40)
17	800 (5.52)	400 (2.26)
18	755 (5.21)	376 (2.11)
21	630 (4.34)	320 (2.17)
25	535 (3.69)	264 (1.85)
26	500 (3.45)	256 (1.73)
32.5	400 (2.76)	200 (1.38)
41	315 (2.17)	160 (1.08)
51	255 (1.76)	128 (0.88)

Note: The STR listed may not be exactly half the STS due to rounding of the STS to the nearest multiple of 5. The STR listed is calculated by multiplying the DR Pressure Class by 1.60.

Recall Fig. 5.5 and the log-log nature of applied stress versus time to failure. If PVC pipe were subjected to the STR, the predicted life would still be in the hundreds of years, as outlined further in Fig. 5.16.

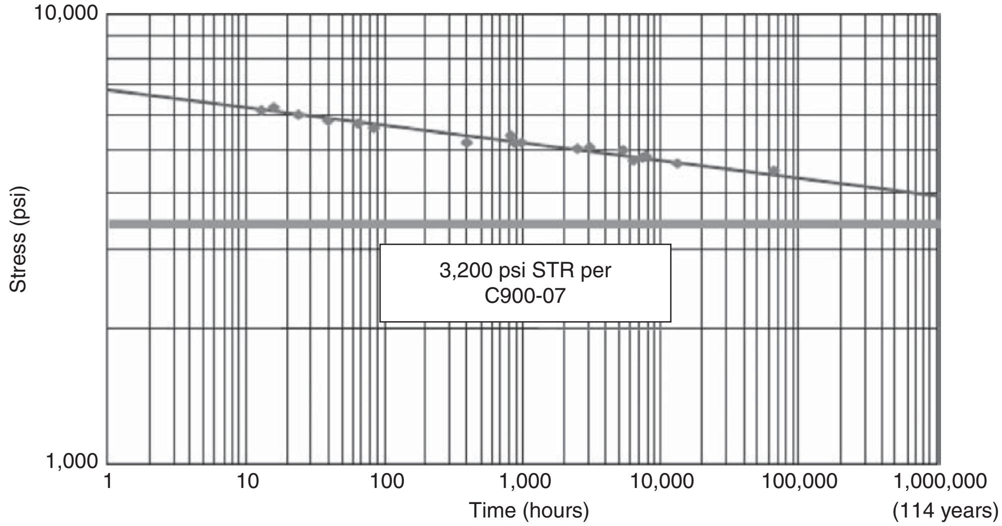

Fig. 5.16 Hydrostatic life when PVC pipe operates at its STR.

5.4.4 PVC Pressure Pipe Applications

There are four general types of pressure systems:

1. *Distribution:* A network of piping with frequent service connections. Surge pressure is typically not a governing factor for design.
2. *Transmission:* Piping that carries large volumes of water directly from one location to another, such as a supply line from a water source to a reservoir (which would then feed a distribution system). Surge pressure is typically not a governing factor for design.
3. *Sewer force main:* Piping that moves wastewater under pressure. Due to the cyclic nature of force main operations, surge pressures may be a governing factor for design.
4. *Irrigation:* Piping that moves water under pressure for agricultural and turf irrigation. Due to the cyclic nature of irrigation operations, surge pressures may be a governing factor for design.

The PVC piping used in North America for these applications is typically manufactured to standards developed by AWWA, ASTM, or CSA.

5.4.5 AWWA Pressure Pipe Design Approach

This section describes the AWWA design procedure for PVC pressure pipe and fittings. Pipe dimensions are found in the Appendix.

The formula for calculating the pressure class is Equation 5.13.

Equation 5.13

$$PC = \left(\frac{2}{DR - 1}\right)\left(\frac{HDB}{SF}\right) \quad \text{or} \quad PC = \left(\frac{2}{DR - 1}\right)(HDB)(DF)$$

where:

PC = pressure class, psi (see Table 5.12)
DR = dimension ratio, dimensionless (see Equation 5.2)
HDB = hydrostatic design basis, psi (see Section 5.3.2) (4,000 psi for PVC)
SF = safety factor, dimensionless
DF = design factor, dimensionless.

Table 5.12 AWWA pressure classes and short-term ratings

DR	Pressure Class (PC), psi (kPa)	Short-Term Rating (STR), psi (kPa)
14	305 (2,110)	488 (3,380)
18	235 (1,620)	376 (2,590)
21	200 (1,380)	320 (2,210)
25	165 (1,140)	264 (1,820)
26	160 (1,100)	256 (1,780)
32.5	125 (860)	200 (1,380)
41	100 (690)	160 (1,100)
51	80 (550)	128 (880)

The standard has three design checks (Equation 5.14, Equation 5.15, and Equation 5.16):

Equation 5.14

$$WP \leq PC \times F_T$$

Equation 5.15

$$WP + P_{rs} \leq PC \times F_T$$

Equation 5.16

$$WP + P_{os} \leq 1.6 \times PC \times F_T$$

where:

WP = working pressure, psi – the maximum operating pressure in a pipeline exclusive of surge pressure

PC = pressure class, psi (see Table 5.12)

F_T = temperature coefficient, dimensionless (see Table 5.3)

P_{rs} = recurring surge pressure, psi (see definition in Section 5.3.6)

P_{os} = occasional surge pressure, psi (see definition in Section 5.3.6).

When STR is substituted for 1.6 × PC in Equation 5.16, we arrive at Equation 5.17:

Equation 5.17

$$WP + P_{os} \leq STR \times F_T$$

where STR = short-term rating, psi (see Table 5.12).

Appendix B of the C900 and C905 standards provides the cyclic design approach for cases where frequent surges of large magnitude are present. C900 pipe uses cast iron pipe equivalent (CIOD) dimensions for outside diameters. C905 pipe uses both CIOD and steel-pipe equivalent (IPS) dimensions. Table 5.13 lists the actual outside diameters for each nominal pipe size.

Section 5.5 provides a design example that includes all the design checks. The cyclic design approach is illustrated in the force main design example.

5.4.6 AWWA Fabricated PVC Fittings

Fabricated fittings are included in AWWA PVC pipe standards. They are constructed from sections of PVC pipe and therefore the design of these fittings for internal pressure is identical to that of the pipe. If fabricated fittings are to be included in the design, they must be made from pipe meeting the requirements of the applicable AWWA standard.

5.4.7 AWWA C907 Molded Fittings

The development of gasketed injection-molded PVC pressure fittings designed for use with AWWA C900 PVC pressure pipes began in the 1980s. Their use in pressure-rated

Table 5.13 AWWA outside diameters

Pipe size, in.	Outside diameter (D_o) for CIOD pipe, in.	Outside diameter (D_o) for IPS pipe, in.
4	4.80	–
6	6.90	–
8	9.05	–
10	11.10	–
12	13.20	–
14	15.30	14.00
16	17.40	16.00
18	19.50	18.00
20	21.60	20.00
24	25.80	24.00
30	32.00	30.00
36	38.30	36.00
42	44.50	–
48	50.80	–

PVC pipe systems extended the benefits of PVC to those components of the system that might otherwise be metallic. These benefits include light weight, freedom from corrosion, and joint compatibility with the pipe system. Injection molded fittings are designed in accordance with AWWA C907.

5.4.8 ASTM Pressure Pipe Design Approach

The ASTM PVC pressure pipe ratings are calculated in the same manner as AWWA pressure classes (Equation 5.18). Both use Equation 5.13. ASTM pressure ratings and short-term ratings are found in Table 5.14. ASTM pipe is most often supplied with IPS diameters. However, Annex A of the ASTM D2241 standard also includes plastic irrigation pipe (PIP). Dimensions for ASTM D2241 products are provided in the Appendix.

Equation 5.18

$$\text{ASTM PR} = \text{AWWA PC}$$

Table 5.14 ASTM D2241 pressure ratings and short-term ratings

DR	Pressure Rating (PR), psi (kPa)	Short-Term Rating (STR), psi (kPa)
13.5	315 (2,170)	504 (3,480)
17	250 (1,725)	400 (2,750)
21	200 (1,380)	320 (2,210)
26	160 (1,100)	256 (1,780)
32.5	125 (860)	200 (1,380)
41	100 (690)	160 (1,100)
51	80 (550)	128 (880)
64	63 (435)	100 (695)

5.5 Design Examples

Example 5.3. *8-in. AWWA PVC water distribution pipe*

This example illustrates the use of the design checks required in AWWA PVC pipe standards. The design objective is to select the appropriate pressure class given the following project conditions:

- Pipe size: 8-in.
- Sustained operating temperature: 80°F
- Working pressure, WP: 100 psi
- Maximum fluid velocity: 6.0 ft/s
- Occasional surge, P_{os}: The surge resulting when water traveling at maximum velocity is instantaneously stopped
- Recurring surge, P_{rs}: 15 psi
- Cyclic fatigue: Assume fatigue is not a design-limiting criterion.

Solution

The design checks required by AWWA PVC pipe standards were given in Equations 5.14 through 5.16. Those checks are shown again below.

$$\mathrm{WP} \leq \mathrm{PC} \times F_T \qquad \text{(first design check)}$$

$$\mathrm{WP} + P_{rs} \leq \mathrm{PC} \times F_T \qquad \text{(second design check)}$$

$$\mathrm{WP} + P_{os} \leq 1.6 \times \mathrm{PC} \times F_T \qquad \text{(third design check)}$$

Step 1: Conduct the first design check. With an operating temperature of 80°F, a thermal de-rating factor needs to be applied. Referring to Section 5.3.4, F_T is 0.88. When there is a recurring surge and when the operating temperature is the same for the first two design checks, the first design check may be skipped.

Step 2: Conduct the second design check. First, sum WP and P_{rs}:

$$WP + P_{rs} = 100 \text{ psi} + 15 \text{ psi} = 115 \text{ psi}$$

Next, de-rate the three PCs available in AWWA C900 by F_T for 80°F:

DR	PC, psi	F_T	PC × F_T, psi
25	165	0.88	145
18	235	0.88	207
14	305	0.88	268

Now, select the lowest PC that satisfies the second design check. In this case, the thermally de-rated PC selected must be at least 115 psi. By referring to the table above, DR 25 satisfies the second design check.

Step 3: Calculate P_{os} by multiplying the fluid velocity by the surge response per ft/s given in Table 5.6. Continue working under the assumption that the DR 25/PC165 selected in Step 2 is adequate. The maximum occasional surge response is:

$$P_{os} = (6.0 \text{ ft/s})(14.7 \text{ psi/ft/s}) = 88.2 \text{ psi}$$

Step 4: Conduct the third design check. First, sum WP and P_{os}.

$$WP + P_{os} = 100 \text{ psi} + 88.2 \text{ psi} = 188.2 \text{ psi}$$

Next, find the STR for DR 25 when it operates continuously at 80°F.

$$STR = 1.6 \times PC \times F_T = 1.6 \times 165 \text{ psi} \times 0.88 = 232 \text{ psi}$$

Since the STR of DR 25 exceeds WP + P_{os}, DR 25 satisfies the third and final design check.

Summary: DR 25 satisfies the three design checks required in AWWA PVC standards.

Example 5.4. *20-in. AWWA transmission pipeline design*

This analysis of a relatively simple pipeline will illustrate the use of the design principles discussed in this chapter. PVC pipe standards offer a variety of pipe strengths and sizes. Ideally, the designer will make selections that minimize capital and operating costs, while maintaining adequate design safety factor.

Project conditions:

- Pipeline length: 20,000 ft
- Design flow: 4,000 US gpm (5.76 MGD)
- Sustained operating temperature: 60°F
- Occasional surge, P_{os}: The surge resulting when water traveling at maximum velocity is instantaneously stopped
- Recurring surge, P_{rs}: 10 psi
- Cyclic fatigue: Assume fatigue is not a design-limiting factor.

Solution

The profile of the proposed pipeline is shown in Fig. 5.17. Water is being pumped to a ground storage tank. The upsurge from the pump during startup is 10 psi over the system's steady state operating pressure. No other recurring surges are expected to exceed the upsurge from the pump startup. The maximum water level of the storage tank is 35 ft from the floor. The centerline of the discharge end of the main (point f in Fig. 5.17) at

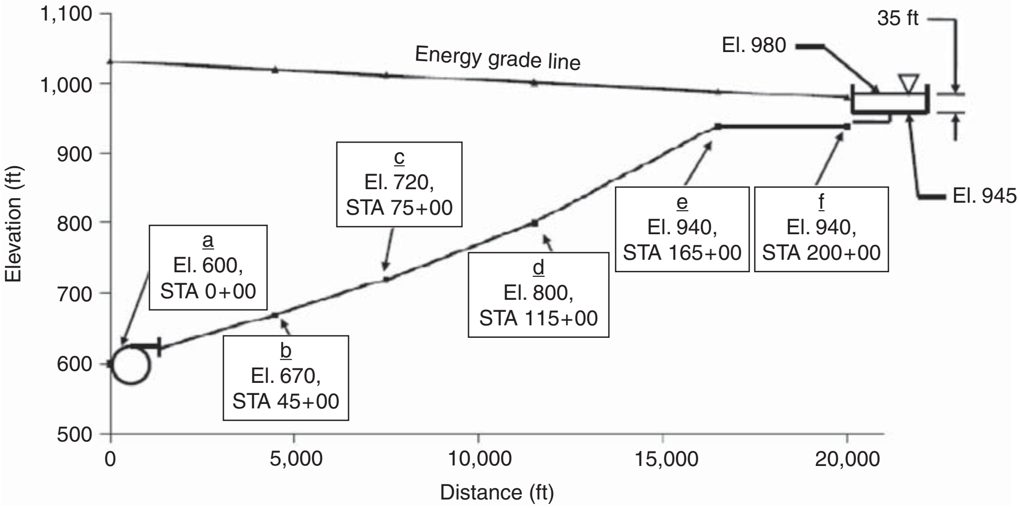

Fig. 5.17 20-in. AWWA transmission pipe design example.

the tie-in to the storage tank will be 5 ft below the tank floor. Key stations and elevations along the pipeline are:

Point	Station	Elevation at pipe centerline, ft
a	0 + 00	600
b	45 + 00	670
c	75 + 00	720
d	115 + 00	800
e	165 + 00	940
f	200 + 00	940

The objective of the design process is to select proper DRs of PVC pipe for the various zones of the pipeline. Also, an effort should be made to select a DR that not only meets the AWWA design criteria discussed in Section 5.4.5 but also provides optimum economic value for the utility or owner. For simplicity, the selection of PVC pipe in this example will be limited to four PCs in CIOD only: PC235, PC165, PC125, and PC100. To further simplify this design example, it is assumed that cyclic fatigue does not govern the system's design.

The total pressure in the pipeline at any point is the sum of the static head, the friction loss, and the pressure rise due to sudden velocity changes. The system must satisfy three design checks, which were given as Equations 5.14 through 5.16. The design checks are shown below.

$$\mathrm{WP} \leq \mathrm{PC} \times F_T \qquad \text{(first design check)}$$

$$\mathrm{WP} + P_{rs} \leq \mathrm{PC} \times F_T \qquad \text{(second design check)}$$

$$\mathrm{WP} + P_{os} \leq 1.6 \times \mathrm{PC} \times F_T \qquad \text{(third design check)}$$

The design steps are as follows:

Step 1: Calculate the maximum flow velocity.
Step 2: Calculate the maximum occasional surge pressure.
Step 3: Calculate the friction loss under full flow conditions.
Step 4: Calculate the pressures at key points in the pipeline.
Step 5: Conduct the first design check.
Step 6: Conduct the second design check.
Step 7: Conduct the third design check.
Step 8: Determine the appropriate DR for various sections of the pipeline.

Step 1: Determine the maximum flow velocity. An assumption will be made that 20-in. PVC pipe is used. In AWWA, the heaviest wall shown to be available for 20-in. pipe is DR 18. The assumption of the heaviest wall (i.e., the lowest DR) is recommended for most designs at the initial stage. The first assumption may be confirmed or revised as the design is developed.

Equations 5.19, 5.20, and 5.21 will be used to determine the maximum flow velocity. The inside diameter is given by Equation 5.19.

Equation 5.19

$$D_i = D_o - 2(t_{min} \times 1.06)$$

Note: The tolerance on the minimum wall thickness is approximately +12%. There is no minus tolerance.

Assume:

20-in. DR 18 per AWWA. Use the dimensions found in the Appendix.

$$D_i = 21.60 - 2(1.200 \times 1.06) = 19.05 \text{ in.}$$

Equation 5.20

$$V = \frac{Q_{cfs}}{A}$$

where:

V = fluid velocity, ft/s

Q_{cfs} = flow in ft^3/s (4,000 US gpm = 8.91 ft^3/s for this example)

A = cross-sectional area, ft^2.

Equation 5.21

$$A = \pi\left(\frac{D_i}{2}\right)^2 = \pi\left(\frac{19.05}{2}\right)^2 = 285 \text{ in}^2 = 1.98 \text{ ft}^2$$

Therefore,

$$V = \frac{8.91}{1.98} = 4.5 \text{ ft/s}$$

Step 2: In a transmission pipeline, the amplitude and location of the surge pressure envelope will often be analyzed by computer. For this example, the assumption has been made that the maximum occasional surge pressure will be equal to an instantaneous stoppage of flow at maximum velocity. In practice, the costs of pipe materials may be significantly reduced through the use of appropriate surge control devices and correct pipeline operating procedures.

The pressure rise resulting from a 4.5 ft/s instantaneous velocity change in PVC pressure pipes can be tabulated by multiplying the fluid velocity by the surge response per ft/s (P_s') given in Table 5.6. Using that approach, the maximum occasional surge responses are found to be:

DR	P_s' (from Table 5.6), psi	P_{os}, psi
41	11.4	51.3
32.5	12.8	57.6
25	14.7	66.2
18	17.4	78.3

Step 3: Determine the friction loss (f) under full flow conditions. Continue to assume DR 18 for this calculation because this pipe will produce slightly greater losses than the other pipe DRs under consideration. The result will be conservative for all design options. The Hazen–Williams equation is convenient for calculating the friction loss. It is given as Equation 5.22:

Equation 5.22

$$f = 0.2083\left(\frac{100}{C}\right)^{1.85}\frac{(Q_{gpm})^{1.85}}{(D_i)^{4.86}}$$

where:

f = friction head, feet of water per 100 ft of pipe
D_i = pipe inside diameter, in. (19.05 in. for this example)
Q_{gpm} = fluid flow, US gpm (4,000 gpm for this example)
C = Hazen–Williams roughness flow coefficient, dimensionless (150 for PVC pipe).

Substituting for 20-in. DR 18 pipe:

f = 0.273 ft of water/100 ft of pipeline = 0.118 psi per 100 ft of pipeline.

Step 4: Determine the pressures at key points in the pipeline under steady state, full-flow conditions. This pressure is the sum of the static head due to elevation and friction loss. The pressure is listed in both feet of water and in psi. The conversion factor is provided in the Appendix. Referring to Fig. 5.17, the pressure at key points can be calculated as follows:

Starting at the storage tank:

Point f, Station 200 + 00

Elevation head = 980 − 940 = 40 ft
To convert feet of water to psi, multiply by 0.43346 = 17.3 psi

Point e, Station 165 + 00

Elevation head = (980 − 940)(0.43346) = 17.3 psi
Friction head = (20,000 ft − 16,500 ft)(0.118 psi/100 ft) = 4.1 psi
Total head = 21.4 psi

Point d, Station 115 + 00

Elevation head = (980 − 800)(0.43346) = 77.4 psi
Friction head = (20,000 ft − 11,500 ft)(0.118 psi/100 ft) = 10.0 psi
Total head = 87.4 psi

Point c, Station 75 + 00

Elevation head = (980 − 720)(0.43346) = 111.8 psi
Friction head = (20,000 ft − 7,500 ft)(0.118 psi/100 ft) = 14.8 psi
Total head = 126.6 psi

Point b, Station 45 + 00

Elevation head = (980 − 670)(0.43346) = 133.3 psi
Friction head = (20,000 ft − 4,500 ft)(0.118 psi/100 ft) = 18.3 psi
Total head = 151.6 psi

Point a, Station 0 + 00

Elevation head = (980 − 600)(0.43346) = 163.4 psi
Friction head = (20,000 ft − 0 ft)(0.118 psi/ft) = 23.6 psi
Total head = 187.0 psi

Working pressure (WP) at key points in the line is summarized in the following table:

Station	Point	Elevation head, psi	Friction head, psi	Working pressure (WP), psi
200 + 00	f	17.3	0	17.3
165 + 00	e	17.3	4.1	21.4
115 + 00	d	77.4	10.0	87.4
75 + 00	c	111.8	14.8	126.6
45 + 00	b	133.3	18.3	151.6
0 + 00	a	163.4	23.6	187.0

Step 5: Conduct the first design check, which is:

$$\mathrm{WP} \leq \mathrm{PC} \times F_T \qquad \text{(first design check)}$$

With an operating temperature of 60°F, no thermal de-rating factor needs to be applied (see Section 5.3.4 for additional discussion on thermal de-rating factors). When there is a recurring surge, and when the operating temperature is the same for first two design checks, the first design check may be skipped.

Step 6: Conduct the second design check, which is:

$$\mathrm{WP} + P_{rs} \leq \mathrm{PC} \times F_T \qquad \text{(second design check)}$$

As discussed in Step 5, no thermal de-rating is required. Thus, a simpler version of this design check may be used.

$$\mathrm{WP} + P_{rs} \leq \mathrm{PC} \qquad \text{(second design check, simplified)}$$

Next, determine which DRs are appropriate for various segments of the pipeline. That is, PC100 (DR 41) would be used at the discharge and upstream until the combined pressures of WP and P_{rs} exceed 100 psi. At that point, PC125 (DR 32.5) would be used until the combined pressures exceed 125 psi, and so on. Before doing this analysis, the last design check will be conducted to see which one governs. To conduct the last design check, the maximum WP for each DR is needed. That value is given as follows:

$$\mathrm{WP} \leq \mathrm{PC} - P_{rs} \qquad \text{(second design check, rearranged)}$$

Using the above equation, the maximum WP from the second design check is used.

DR	PC, psi	P_{rs}, psi	WP = PC − P_{rs}, psi
41	100	10	90
32.5	125	10	115
25	165	10	155
18	235	10	225

Step 7: Conduct the third design check, which is:

$$WP + P_{os} \leq 1.6 \times PC \times F_T \qquad \text{(third design check)}$$

The table below uses the maximum WP to determine the greatest combination of WP and P_{os}. In all cases, the STR exceeds the maximum combination of WP and P_{os}. Thus, the second design check governs the design of this system for each of the proposed DRs.

DR	WP, psi	P_{os}, psi	WP + P_{os}, psi	STR = 1.6 × PC × F_T, psi
41	90	51.3	141.3	160
32.5	115	57.6	172.6	200
25	155	66.2	221.2	264
18	225	78.3	303.3	376

Step 8: Determine the appropriate DR of pipe for various sections of the pipeline. From calculations in Step 3, WP required at key points along the pipeline was determined. In Step 6, the maximum WP for each DR was calculated.

The WP required at the pump house (point a) is 187.0 psi. The WP required at point b is 151.6 psi. To satisfy design check two, the WP in DR 18 may not exceed 225 psi and the WP in DR 25 may not exceed 155 psi. Thus, a WP of 187.0 psi is acceptable for DR 18 but not for DR 25. When the WP drops below 155 psi, DR 25 then becomes acceptable. This occurs between points a and b. To pinpoint the exact location, the pressure gradient for section a-b must be calculated:

$$\Delta P_{a-b} = \frac{P_a - P_b}{\text{distance}} = \frac{(187 - 151.6)\ \text{psi}}{(0 - 4{,}500)\ \text{ft}} = -0.0079\ \text{psi/ft}$$

The length beyond STA 0 + 00 (point a) where DR 25 becomes acceptable is calculated as follows:

$$\text{Length} = \frac{\text{WP}_{\text{max for DR 25}} - \text{WP}_{\text{point a}}}{\Delta \text{P}_{\text{a}-\text{b}}}$$

$$= \frac{(155 - 187)\ \text{psi}}{-\ 0.0079\ \text{psi/ft}} = 4{,}051\ \text{ft} = \text{STA } 40 + 51$$

Subsequent calculations determine the starting points for DR 32.5 and DR 41. The working pressures become acceptable for DR 32.5 in section c-d. The pressure gradient for Section c-d is:

$$\Delta \text{P}_{\text{c}-\text{d}} = \frac{\text{P}_\text{c} - \text{P}_\text{d}}{\text{distance}} = \frac{(126.6 - 87.4)\,\text{psi}}{(7{,}500 - 11{,}500)\,\text{ft}} = -0.0098\,\text{psi/ft}$$

The length beyond STA 75 + 00 (point c) where DR 32.5 becomes acceptable can be calculated as follows:

$$\text{Length} = \frac{\text{WP}_{\text{max for DR 32.5}} - \text{WP}_{\text{point c}}}{\Delta \text{P}_{\text{c}-\text{d}}} = \frac{(115 - 126.6)\ \text{psi}}{-0.0098\ \text{psi/ft}} = 1{,}184\ \text{ft}$$

DR 32.5 may be used starting at a distance of 1,184 beyond STA 75 + 00. Therefore, begin using DR 32.5 at STA 86 + 84. (86 + 84 is the sum of 75 + 00 and 11 + 84.)

The working pressures become acceptable for DR 41 in section c-d as well. The pressure gradient for section c-d has already been calculated. The length beyond STA 75 + 00 (point c) where DR 41 becomes acceptable is found as follows:

$$\text{Length} = \frac{\text{WP}_{\text{max for DR 41}} - \text{WP}_{\text{point c}}}{\Delta \text{P}_{\text{c}-\text{d}}} = \frac{90 - 126.6\ \text{psi}}{-0.0098\ \text{psi/ft}} = 3{,}735\ \text{ft}$$

DR 41 may be used starting at a distance of 3,735 beyond STA 75 + 00. Therefore, begin using DR 41 at STA 112 + 35 (112 + 35 is the sum of 75 + 00 and 37 + 35).

Summary: The design for internal pressure of the 20-in. pipeline may be summarized as follows:

Distance from pump house, ft	Use DR	Pressure gradient, psi
0 to 4,051	18	187 to 155
4,051 to 8,684	25	155 to 115
8,684 to 11,235	32.5	115 to 90
11,235 to 20,000	41	90 to 17.3

In this example of a 20,000 ft (3.8-mi pipeline), the designer has the opportunity to achieve significant cost savings through the use of several PVC pipe pressure ratings.

The design is essentially complete. In some cases, two further elaborations will be needed to check the design. If the pipeline is operated in a cyclic mode (e.g., sewage force main), an analysis of fatigue life should be conducted using the methods of Section 5.3.6. Both present and future modes of operation should be examined. The effect of external loads (earth and live loads) is seldom a design consideration for pressure pipes. The height of cover is usually minimized and the internal pressure far exceeds the external pressure. However, the effect of external loads can be readily determined using methods given in Chapter 7.

Example 5.5. *14-in. AWWA forcemain*

This example will demonstrate the various design checks for PVC pressure pipe subjected to frequent surges from the starting and stopping of pumps. The pipe under consideration is a 14-in. DR 41 AWWA pipe, with a CIOD diameter regimen and the following knowns/specifications:

- The design flow is 3.03 ft^3/s.
- The operating temperature of the wastewater is 65°F.
- It is estimated that the pump will have 58 starts and 58 stops each day.
- Once the steady state operating flow has been achieved, the working pressure is 27 psi.
- During startup or shutdown, the pressure amplitude may be as large as 20 psi.
- The forcemain discharges into a manhole at atmospheric pressure at the upstream end.
- The desired design life is 100 years.
- An analysis of transients using design software has not been conducted.

Solution

The system must satisfy four design checks. These checks are shown below:

$$\mathrm{WP} \le \mathrm{PC} \times F_T \qquad \text{(first design check)}$$

$$\mathrm{WP} + P_{rs} \le \mathrm{PC} \times F_T \qquad \text{(second design check)}$$

$$\mathrm{WP} + P_{os} \le 1.6 \times \mathrm{PC} \times F_T \qquad \text{(third design check)}$$

$$C_L \le C' \qquad \text{(fourth design check)}$$

The design steps are as follows:

Step 1: Calculate the maximum flow velocity.
Step 2: Calculate the maximum recurring surge pressure.
Step 3: Conduct the first design check.
Step 4: Conduct the second design check.
Step 5: Calculate the maximum occasional surge pressure.
Step 6: Conduct the third design check.
Step 7: Calculate the number of cycles required to meet the design life required.
Step 8: Calculate the average stress and stress amplitude generated by recurring surges.
Step 9: Find the cyclic strength of the DR 41 pipe.
Step 10: Conduct the fourth design check.
Step 11: Determine the forcemain's predicted life.

Step 1: Equations 5.19, 5.20, and 5.21 will be used to determine the maximum flow velocity. The inside diameter is given by Equation 5.19.

$$D_i = D_o - 2(t_{min} \times 1.06)$$

Note: The tolerance on the minimum wall thickness is approximately +12%. There is no minus tolerance.

Use the dimensions found in the Appendix.

$$D_i = 15.30 - 2(0.373 \times 1.06) = 14.5 \text{ in.}$$

$$V = \frac{Q_{cfs}}{A}$$

where:
V = fluid velocity, ft/s
Q_{cfs} = fluid flow, ft^3/s = 3.03 ft^3/s

A = cross-sectional area, ft^2 $= \pi\left(\frac{D_i}{2}\right)^2 = \pi\left(\frac{14.5}{2}\right)^2 = 166 \text{ in}^2 = 1.15 \text{ ft}^2$

Therefore,

$$V = \frac{3.03\ \mathrm{ft}^3/_{\mathrm{s}}}{1.15\ \mathrm{ft}^2} = 2.64\ \mathrm{ft/s}$$

Step 3: Conduct the first design check, which is:

$$WP \leq PC \times F_T \qquad \text{(first design check)}$$

With an operating temperature of 65°F, no thermal de-rating factor need be applied (see Section 5.3.4 for additional discussion on thermal de-rating factors). When there is a recurring surge and when the operating temperature is the same for the first two design checks, the first design check may be skipped.

Step 4: Conduct the second design check, which is:

$$WP + P_{rs} \leq PC \times F_T \qquad \text{(second design check)}$$

As discussed in Step 3, no thermal de-rating is required. Thus, a simpler version of this design check may be used.

$$WP + P_{rs} \leq PC \qquad \text{(second design check, simplified)}$$

Substituting 100 psi for the PC of DR 41 as well as the values for WP and P_{rs} results in:

$$20 + 27 \leq 100\ \mathrm{psi}$$

$$47 \leq 100\ \mathrm{psi}$$

The second design check is satisfied with the DR 41.

Step 5: Calculate the maximum occasional surge pressure. The pressure rise resulting from a 2.64-ft/s instantaneous velocity change in a DR 41 PVC pressure pipe can be calculated by multiplying the fluid velocity and the surge response per ft/s given in Table 5.6. Using this approach, the maximum occasional surge response is found to be:

$$P_{os} = \Delta V_{max}\,(P_s')$$

$$P_{os} = (2.64)(11.4) = 30.1\ \mathrm{psi}$$

Step 6: Conduct the third design check, which is:

$$\mathrm{WP} + \mathrm{P}_{\mathrm{os}} \leq 1.6 \times \mathrm{PC} \times \mathrm{F}_{\mathrm{T}} \qquad \text{(third design check)}$$

The WP is 20 psi. The P_{os} is 30.1 psi. The PC for DR 41 is 100 psi. The thermal de-rating factor is unity.

$$20 + 30.1 \leq 1.6 \times (100)(1.0)$$

$$50.1 \text{ psi} \leq 160 \text{ psi}$$

The third design check is satisfied with the DR 41.

Step 7: Calculate the number of cycles (C′) required to meet the design life specified. The number of cycles per day (N) may be determined from the known information. Equation 5.8 can be used to determine C′.

$$\mathrm{N} = 58 \text{ starts} + 58 \text{ stops} = 116 \text{ cycles/day}$$

$$\mathrm{C}' = (116 \text{ cycles/day})\ (365 \text{ days/year})(100 \text{ years}) = 4.23 \times 10^{6} \text{ cycles}$$

Note from the product of the first two factors that the system experiences 42,340 cycles per year.

Step 8: Calculate the average stress and stress amplitude generated by recurring surges. From the known data, the routine pressures the forcemain experiences are:

$$\mathrm{WP} = \text{working pressure} = 27 \text{ psi} \qquad \text{(known)}$$

$$\mathrm{P}_{\mathrm{amp(rs)}} = \text{pressure amplitude} = 20 \text{ psi} \qquad \text{(known)}$$

$$\mathrm{P}_{\mathrm{max(rs)}} = 27 + 20 = 47 \text{ psi}$$

$$\mathrm{P}_{\mathrm{min(rs)}} = 27 - 20 = 7 \text{ psi}$$

Hoop stresses from the routine pressures may now be calculated using Equations 5.9 and 5.10.

$$\sigma_{\mathrm{avg(rs)}} = \frac{(47 + 7)(41 - 1)}{4} = 540 \text{ psi}$$

$$\sigma_{\mathrm{amp(rs)}} = \frac{(47 - 7)(41 - 1)}{4} = 400 \text{ psi}$$

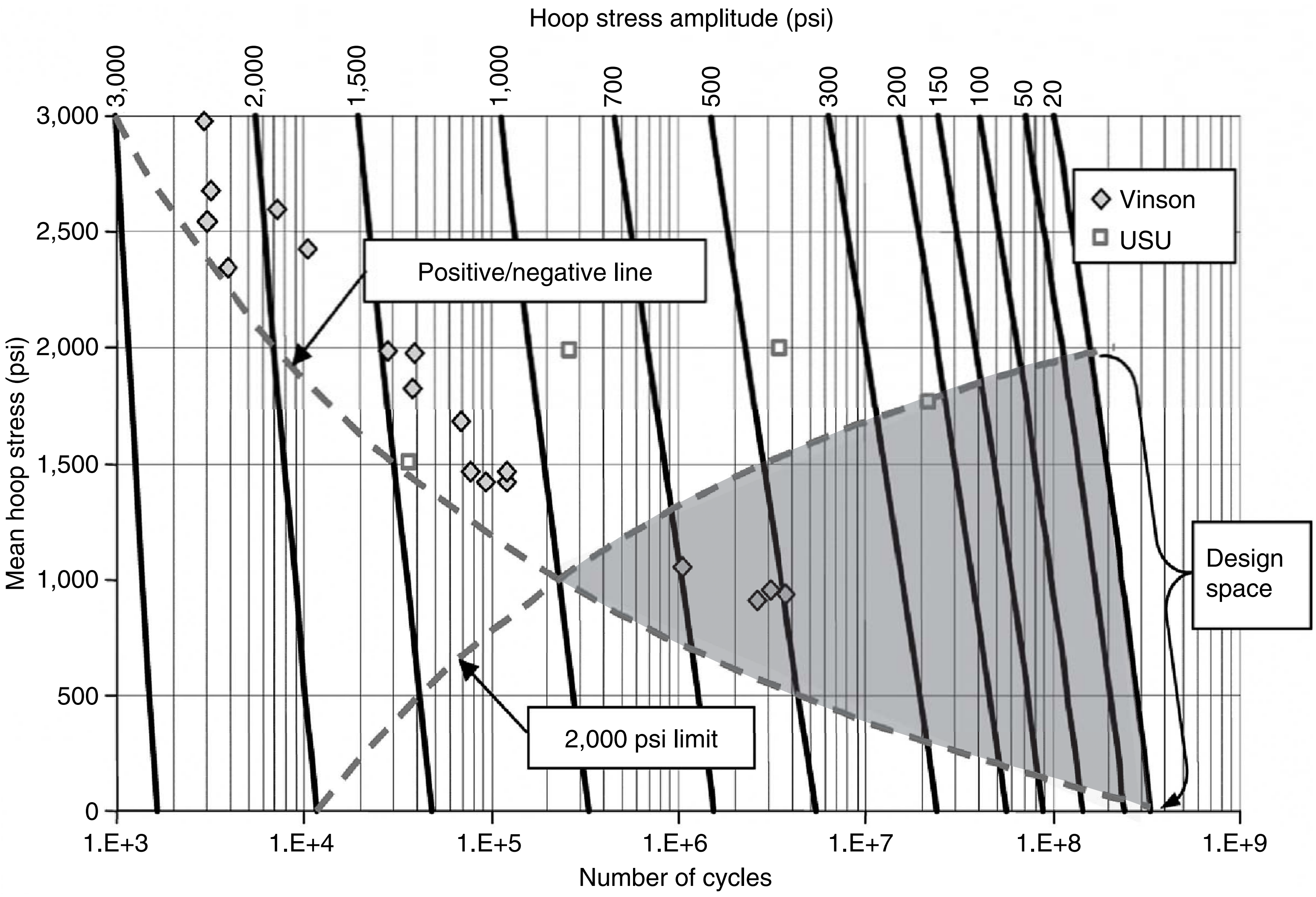

Fig. 5.11 (repeated) Cyclic design curves for PVC pipe.

Step 9: Find the cyclic strength (C_L) of the DR 41 pipe. Using Fig. 5.11 (repeated above), with a $\sigma_{avg(rs)}$ of 540 psi and a $\sigma_{amp(rs)}$ of 400 psi, C_L equals 9×10^6.

Step 10: Conduct the fourth design check, which is:

$$C_L \leq C' \qquad \text{(fourth design check)}$$

C' was calculated in Step 7, and C_L was determined in Step 9. Substituting:

$C' = (116 \text{ cycles/day}) (365 \text{ days/year}) (100 \text{ years}) = 4.23 \times 10^6$ cycles
4.23×10^6 cycles (required) $< 9 \times 10^6$ cycles (provided)

Thus, DR 41 satisfies the cyclic requirements.

Step 11: Determine the forcemain's predicted life by dividing DR 41 cyclic strength (9×10^6 cycles) by the annual number of cycles.

$$\begin{aligned} \text{Predicted life} &= \text{cycles provided} \div \text{annual number of cycles} \\ &= 9 \times 10^6 \div 42{,}340 \\ &= 213 \text{ years} \end{aligned}$$

In this example, an efficient forcemain design was achieved by verifying the suitability of DR 41. The example also demonstrated an extremely satisfactory predicted life span of PVC in a cyclic environment.

5.6 PVC Pressure Pipe Longevity

In order to examine longevity and durability of PVC pressure pipe, a number of studies have been conducted on pipe that has been in service for many years, tested to new pipe performance standards.

In 1986, pipe from a 1964 installation in Texas was excavated and sent to an independent lab for testing. After 22 years of service, the 4-in. SDR 21 PVC pressure pipe met the quick-burst pressure, accelerated stress regression, extrusion quality, flattening, and impact resistance requirements as specified in ASTM D2241 for new pipe.

A similar study was conducted on AWWA PVC pipe in 1994 in Alberta, Canada. The AWWA PVC pipe was first installed in 1977. Seventeen years after the original installation, 24 ft of 8-in. DR 18 and 10-in. DR 18 pipe were excavated and tested. The pipes met the quick-burst pressure, extrusion quality, flattening, and joint performance requirements specified in AWWA PVC standards for new pipe, and also met the impact resistance requirements of CSA B137.3. Ten years later, a follow-up investigation was conducted. The 27-year-old AWWA PVC pipe once again met the quick-burst pressure, extrusion quality, flattening, and joint performance requirements of new pipe, as specified in AWWA.

In 2007, a Water Research Foundation report confirmed the longevity of PVC pipe to be in excess of 110 years. Water utility managers and engineering firms cited corrosion resistance, longevity, and durability as reasons for choosing PVC above other materials.

An extensive evaluation of the long-term physical properties of PVC pressure pipe was performed in the Netherlands; pipe samples ranging in age from 10 to 35 years were collected from 15 sites. A variety of tests were conducted to collect historical data to supplement extrapolated laboratory data. Tests included tensile strength and elongation at break, stiffness (ISO 9969), E modulus, three-point bending test, and tensile impact (DIN 53448). Additionally, 37-year-old pipe from the Flevoland Potable Water Company was burst pressure-tested in accordance with ISO 1167. The conclusion was that a life expectancy much greater than the value currently used for PVC pressure pipe in Europe should be adopted. Another European study determined PVC pipe's minimum expected life to be 170 years.

5.7 Sources

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CHAPTER 6

External Loads on Buried Pipe

Earth Loads

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Live Loads

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AASHTO Design Method

•

Design Software—External Load Design for Flexible Conduits

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6.1 Notation

A = area of load distribution under truck dual-tire, ft^2
B_c = pipe outside diameter, ft
B_d = width of trench at top of pipe, ft
C_c or C_d = load coefficient for pipes installed in trenches, dimensionless
C_L = live load coefficient per foot of effective length, 1/ft
D_o = pipe outside diameter, ft
h = distance from ground surface to any horizontal plane in backfill, ft
h_e = distance from plane of equal settlement to any horizontal plane in backfill, ft
H = height of fill above top of pipe, ft
H_e = distance from top of pipe to plane of equal settlement, ft
I_f = impact factor, dimensionless
K = Rankine's ratio of active lateral pressure to vertical pressure, dimensionless
L_T = length of truck dual-tire, ft
p = projection ratio, dimensionless
P = vertical soil pressure due to prism load, psi
P_v = vertical soil pressure due to prism load, lb/ft^2
P_{vT} = vertical soil load due to prism load, lb/ft
P_w = wheel load, lb
R = pipe radius, ft
r_{sd} = settlement ratio, dimensionless
S_f = settlement of bottom of pipe, ft
S_g = settlement of natural ground adjacent to pipe, ft
S_m = compression of columns of soil of height pB_c, ft
w = unit weight of soil, lb/ft^3
W_c = soil load on pipe, lb/ft
W_L = live load, lb/in.
W_T = width of truck dual-tire, ft
V = vertical soil pressure on any horizontal plane in the backfill, lb/ft
Δh = change in h, ft
Δh_e = change in h_e, ft
ΔV = incremental change in V, lb/ft
Δy = pipe deflection, ft
μ' = coefficient of friction between backfill material and sides of trench, dimensionless

6.2 Introduction

External loads on buried PVC pipe fall into two categories: *earth loads* and *live loads*. Both types of external loads must be considered in the design of buried piping systems. In accordance with common design practices, earth loads and live loads are treated as separate scenarios.

6.3 Earth Loads

The first solution to the problem of soil-induced loads on buried pipe was published by Professor Anson Marston at Iowa State University in 1913. Since then, the Marston theory of loads on underground conduits has been used to determine loads on buried pipe. Much of the work done on earth loading technology for buried conduits throughout the world is based, in part, on Marston's load theory. Its fundamental concept is that the load from the weight of the soil above a buried pipe is modified by the response of the pipe. This is seen in Fig. 6.1 for rigid pipe. However, the theory relates to both *rigid* and *flexible* pipe, as we will see.

In Fig. 6.1, the expression

$$K\mu'\frac{V\Delta h}{B_d}$$

represents the frictional force resisting settlement, and

$$\frac{KV\Delta h}{B_d}$$

represents the force against the trench wall due to active lateral pressure. In these expressions, the variables are defined as:

V = vertical pressure on any horizontal plane in the backfill, lb/ft
B_c = pipe outside diameter, ft
B_d = width of trench at top of pipe, ft
h = distance from ground surface to any horizontal plane in backfill, ft
C_d = load coefficient for pipes installed in trenches, dimensionless
K = Rankine's ratio of active lateral pressure to vertical pressure, dimensionless
μ' = coefficient of friction between backfill material and sides of trench, dimensionless
Δh = change in h, ft
ΔV = change in V, lb/ft

Rankine's ratio (K) is a function of the angle of internal friction for each soil.

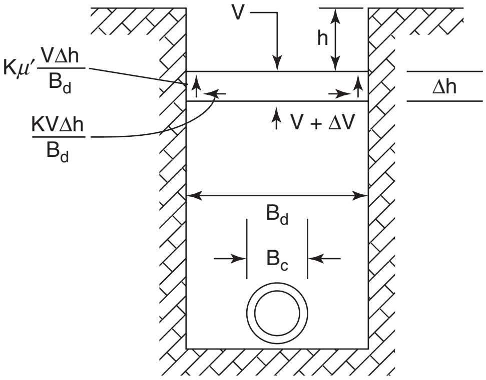


Fig. 6.1 Development of loads on rigid pipe in trenches.

When the embedment material between the pipe and the trench wall is more compressible than the pipe (rigid pipe), the pipe assumes a load generated across the width of the trench as shown in Fig. 6.2. In contrast, when the pipe has the ability to deflect without cracking (flexible pipe), an arching effect is produced that transfers some of the load to the adjacent embedment (i.e., between the pipe and the trench wall). This arching effect reduces the load on a flexible pipe to an amount less than the weight of the central prism over the pipe. As soil in the trench settles or moves downward relative to the trench sidewall, the side prisms produce shearing forces that act to reduce the weight of the

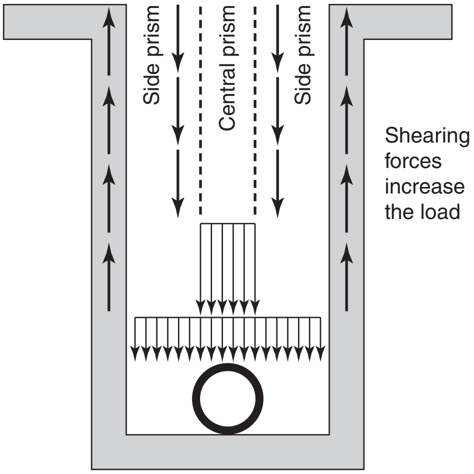


Fig. 6.2 Downward shearing forces over rigid pipe.

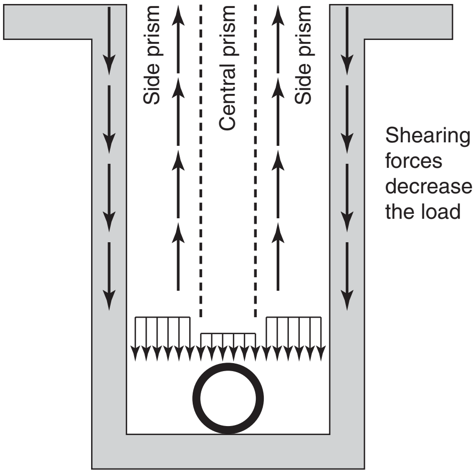


Fig. 6.3 Upward shearing forces over flexible pipe.

trench-wide soil column (i.e., soil arching action) as shown in Fig. 6.3. Marston's load theory predicts and accounts for these shearing forces.

The Marston load theory can be modeled as three springs supporting a load. Loads are transferred through the path(s) of greatest resistance, i.e., the stiffest spring(s). Since rigid pipe is not compressible and does not deflect, it acts as a very stiff spring and carries the majority of the load. In the case of flexible pipes, the embedment material acts as the stiffer spring(s) and carries the majority of the load, i.e., flexible pipe transfers most of the load to the side prisms. This contrast is shown in Figs. 6.4 and 6.5.

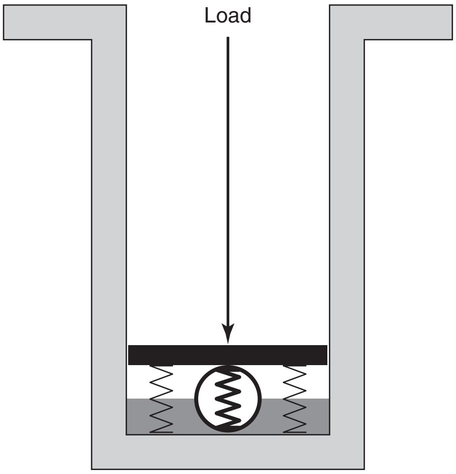


Fig. 6.4 Trench load conceptualization with rigid pipe.

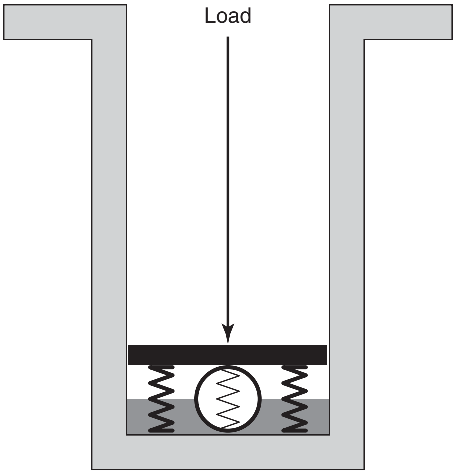


Fig. 6.5 Trench load conceptualization with flexible pipe.

Marston recognized that for most flexible conduits, load imposed on pipe is less than the weight of the prism of soil over the pipe (called the *prism load*). Pipe flexibility ensures that the relative prism settlement above the pipe will be greater than what occurs in the *side column* in nearly all cases. The load on rigid conduits such as concrete pipes is greater. The lack of flexibility in rigid conduit dictates that the relative backfill settlement is greater on the pipe sides than over the pipe.

The inherent differences in pipe load for the two types of pipe are expressed in the formulas of Equations 6.1 and 6.2. Marston developed these to calculate earth loads imposed on pipe buried in a trench. The *Marston equations* are as follows:

Equation 6.1

Rigid pipe load $W_c = C_d w B_d B_d$

Equation 6.2

Flexible pipe load $W_c = C_d w B_d B_c$

where:

W_c = soil load on pipe, lb/ft
w = unit weight of soil, lb/ft^3
B_c = pipe outside diameter, ft
B_d = width of trench at top of pipe, ft
C_d = load coefficient for pipes installed in trenches, dimensionless.

Analysis of the two equations reveals that the ratio of the load on a rigid pipe (or conduit) to the load on a flexible pipe (or conduit) is equal to the ratio of pipe diameter to trench width for identical conditions of installation. Equation 6.3 expresses this relationship.

Equation 6.3

$$\frac{W_c\,(\text{rigid})}{W_c\,(\text{flexible})} = \frac{C_d w B_d B_d}{C_d w B_d B_c} = \frac{B_d}{B_c}$$

Therefore, if a trench is twice as wide as the pipe being buried (e.g., a 12-in. pipe in a 24-in.-wide trench), the load imposed on a rigid pipe will be twice the load imposed on a flexible pipe, as indicated by the Marston equations.

For loads on buried pipe, the load coefficient term (C_d) is determined by installation conditions (see Equation 6.4). C_d is computed as follows:

Equation 6.4

$$C_d = \frac{1 - e^{-2K\mu' H/B_d}}{2K\mu'}$$

where:

C_d = load coefficient for pipes installed in trenches, dimensionless
e = natural logarithm base
K = Rankine's ratio of active lateral pressure to vertical pressure, dimensionless
μ' = coefficient of friction between backfill material and sides of trench, dimensionless
H = height of fill above top of pipe, ft
B_d = width of trench at top of pipe, ft

A diagram has been developed (Fig. 6.6) for various values of $K\mu'$ and ratios H/B_d. In most cases, this diagram eliminated the need for computation of load coefficient C_d. According to Marston's equations, the width of the trench directly affects the loads imposed on flexible and rigid pipe. Height of the backfill material and trench width appear again in C_d computations.

Although load imposed on a pipe increases with trench width, this increase is limited. *Transition width* is trench width for a given depth and size of pipe beyond which no additional load may be imposed on the pipe. It is a limiting value for calculating loads, which is based on Marston's trench formulas. At the transition width and beyond, loads can be calculated using Marston's positive projecting conduit, or "embankment," equations. Embankment installation is realized if the top of a pipe projects above the natural ground surface or is in a relatively wide trench (beyond the transition width). The maximum loads imposed on a pipe are those obtained in the embankment mode of installation.

Marston developed the *embankment load formula* (Equation 6.5) for computing loads on both flexible and rigid positive-projecting conduits (embankment installation).

Equation 6.5

$$W_c = C_c w B_c B_c$$

where:

C_c = load coefficient for pipes installed in trenches, dimensionless

Equation 6.5 is similar to Equation 6.1 with C_c replacing C_d as load coefficient and B_c replacing B_d.

The load coefficient C_c in this case depends on projection ratio (p), settlement ratio (r_{sd}), and ratio of fill height (H) to pipe width (not trench width) (B_c).

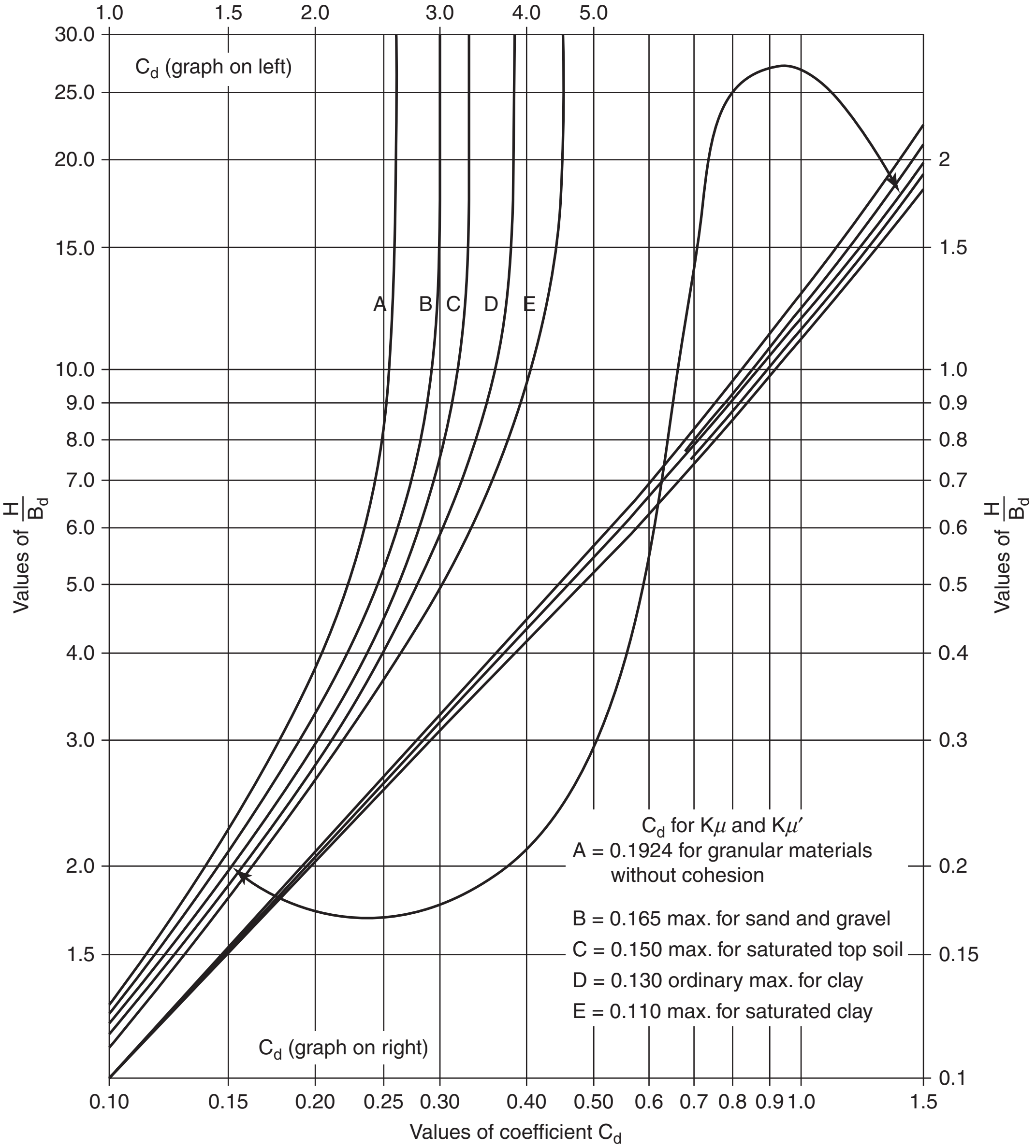


Fig. 6.6 Values of C_d. Computation diagram for earth loads on trench conditions (completely buried in trenches). Sources: Gravity, Sanitary Design and Construction. Manuals & Report on Engineering Practice No. 60, ASCE; and Manual of Practice FD-5, Water Pollution Control Federation, 1982.

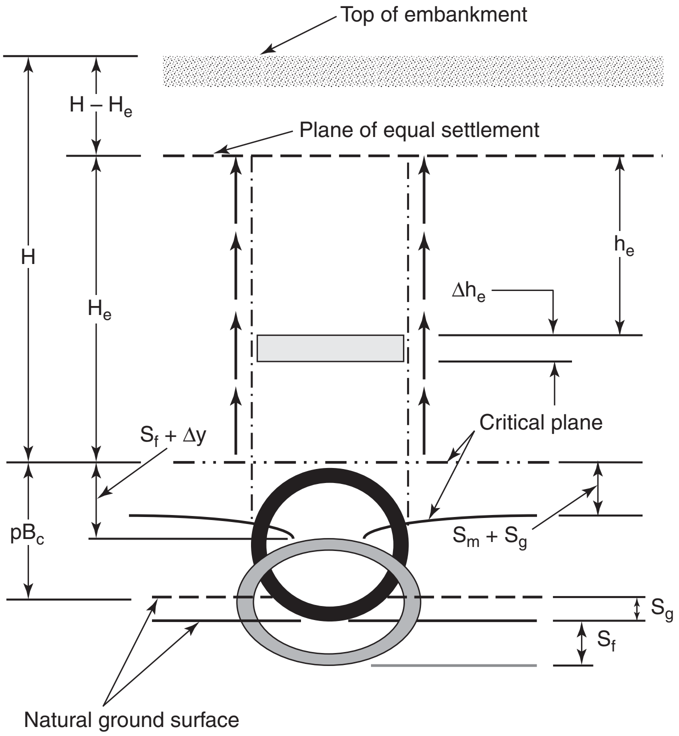


Fig. 6.7 Settlements that influence loads on positive-projecting conduits. Sources: Gravity Sanitary Design and Construction. Manuals & Report on Engineering Practice No. 60, ASCE, and Manual of Practice FD-5, Water Pollution Control Federation, 1982.

In Figs. 6.7 and 6.8, the relevant variables are as follows:

B_c = pipe outside diameter, ft
C_c = load coefficient for pipes installed in trenches, dimensionless
H = height of fill above top of pipe, ft
H_e = distance from top of pipe to plane of equal settlement, ft
h_e = distance from plane of equal settlement to any horizontal plane in backfill, ft
K = Rankine's ratio of active lateral pressure to vertical pressure, dimensionless
p = projection ratio, dimensionless
r_{sd} = settlement ratio, dimensionless $= \dfrac{(S_m + S_g) - (S_f + \Delta y)}{S_m}$
S_f = settlement of bottom of pipe, ft
S_g = settlement of natural ground adjacent to pipe, ft
S_m = compression of columns of soil of height, pB_c, ft

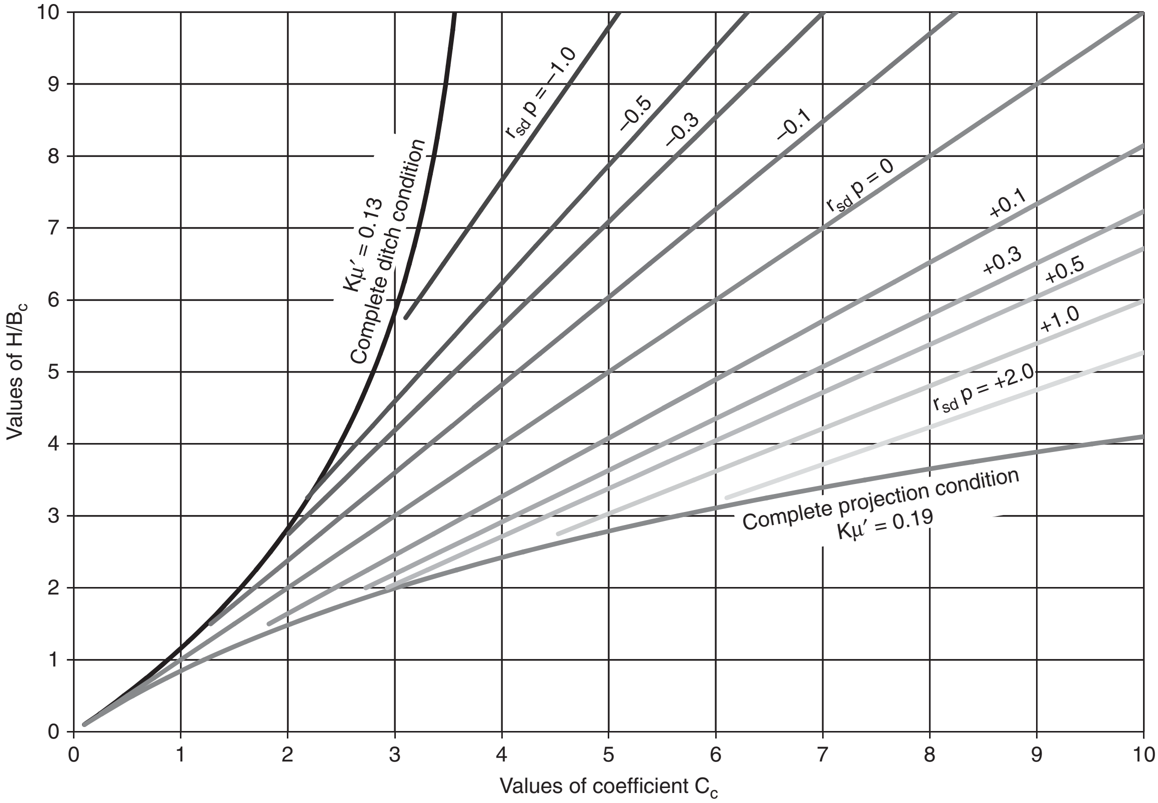


Fig. 6.8 Diagram for coefficient C_c for positive-projecting conduits. Sources: Gravity Sanitary Design and Construction. Manuals & Report on Engineering Practice No. 60, ASCE, and Manual of Practice FD-5, Water Pollution Control Federation, 1982.

Δh_e = change in h_e, ft
Δy = pipe deflection, ft
μ' = coefficient of friction between backfill material and sides of trench, dimensionless

The *projection ratio* is the vertical distance from the natural ground surface to the top of the pipe (prior to any deflection or settlement) divided by the pipe outside diameter.

For flexible pipe under most conditions, the product $r_{sd}p$ is less than zero (i.e., negative). A value of $r_{sd}p$ that is greater than zero is found only in flexible pipe of very high pipe stiffness. Therefore, allowing for negative $r_{sd}p$ is a conservative design approach for most buried flexible pipe installation. This is shown in Fig. 6.8, the computation graph for C_c. In this figure, $r_{sd}p = 0$ and $C_c = H/B_c$.

In flexible pipe, prism load represents maximum soil load on flexible pipe, and it dictates design in virtually all cases. Thus, conservative pipe design uses prism load.

Replacing C_c in Equation 6.5 (Marston's embankment load formula) with H/B_c yields the load formula for flexible pipe:

Equation 6.6

$$W_c = HwB_c$$

where:

W_c = soil load on pipe, lb/ft
H = height of fill above top of pipe, ft
w = unit weight of soil, lb/ft^3
B_c = pipe outside diameter, ft

Prism load may also be expressed in terms of *soil pressure* as follows:

Equation 6.7

$$P_v = wH = \frac{W_c}{B_c}$$

where:

P_v = vertical soil pressure due to the prism load, lb/ft^2

Calculation of soil pressure on rigid and flexible pipes of the same diameter under the same burial conditions demonstrates the difference between load on flexible conduit in trench and embankment conditions and load on rigid conduit in trench conditions.

Example 6.1

Find the trench load for a rigid pipe and a flexible pipe given the following information:

Pipe outside diameter (B_c)	12 in. = 1 ft
Height of fill above top of pipe (H)	12 ft
Width of trench at top of pipe (B_d)	3 ft
Rankine's ratio (K)	0.33
Unit weight of soil (w)	120 lb/ft^3
Coefficient of friction between backfill material and sides of trench (μ')	0.5

Rigid pipe load (trench condition); use Equation 6.1:

$$C_d = \frac{1 - e^{-2(0.33)(0.5)(12/3)}}{2(0.33)(0.5)} = 2.221$$

$$W_c = 2.221(120)(3)(3) = 2{,}400 \text{ lb/ft}$$

Flexible pipe load (trench condition); use Equation 6.2:

$$W_c = 2.221(120)(3)(1) = 800 \text{ lb/ft}$$

Flexible pipe load (assume prism condition); use Equation 6.6

$$W_c = (12)(120)(1) = 1{,}440 \text{ lb/ft}$$

Research and actual long-term data have confirmed that prism load provides a conservative, simplified approach for designing flexible PVC piping systems to accommodate earth load. In a trench, friction forces can reduce the load on the pipe through arching action of the soil. However, frost and water action may dissipate these forces, and in the long run the load may approach the prism load.

The following tables were developed for use in determining Marston earth loads on PVC sewer pipe:

- Table 6.1: Prism earth loads are listed in lb/ft. This table is dependent on outside-diameter dimensions and can be used with any flexible pipe of similar outside diameter. Actual diameters appear on the final page of the table.
- Table 6.2: Prism earth loads are listed in psi.

Both tables include the most common ranges for height of fill (H) and unit weight of soil (w).

Table 6.1 Prism load

$P_{VT} = wHD_o/12$ (lb/ft)

Height of fill, ft	Unit weight of soil, lb/ft^3	Pipe outside diameter, in.															
		4	6	8	10	12	15	18	21	24	27	30	36	42	48	54	60
3	100	105	157	210	263	313	383	468	551	620	699	787	984	1109	1264	1424	1584
	110	116	173	231	289	344	421	514	606	682	769	866	1083	1220	1391	1566	1742
	120	126	188	252	315	375	459	561	661	744	839	945	1181	1331	1517	1709	1901
	130	137	204	273	341	406	497	608	717	806	908	1024	1280	1442	1644	1851	2059
4	100	141	209	280	350	417	510	623	735	827	932	1050	1312	1479	1686	1899	2112
	110	155	230	308	385	458	561	686	808	909	1025	1155	1444	1627	1854	2089	2323
	120	169	251	336	420	500	612	748	882	992	1118	1260	1575	1775	2023	2278	2534
	130	183	272	364	455	542	663	810	955	1075	1211	1365	1706	1923	2191	2468	2746
6	100	211	314	420	525	625	765	935	1102	1240	1398	1575	1969	2219	2529	2848	3168
	110	232	345	462	578	688	842	1029	1213	1364	1537	1732	2165	2441	2781	3133	3485
	120	253	377	504	630	750	918	1122	1323	1488	1677	1890	2362	2663	3034	3418	3802
	130	274	408	546	683	813	995	1216	1433	1612	1817	2047	2559	2884	3287	3702	4118
8	100	281	418	560	700	833	1020	1247	1470	1654	1864	2100	2625	2958	3371	3797	4224
	110	309	460	616	770	917	1122	1371	1617	1819	2050	2310	2887	3254	3708	4177	4646
	120	337	502	672	840	1000	1224	1496	1764	1984	2236	2520	3150	3550	4046	4557	5069
	130	365	544	728	910	1083	1326	1621	1911	2150	2423	2730	3412	3846	4383	4937	5491
10	100	351	523	700	875	1042	1275	1558	1837	2067	2329	2625	3281	3698	4212	4747	5280
	110	386	575	770	963	1146	1403	1714	2021	2274	2562	2887	3609	4068	4636	5221	5808
	120	422	628	840	1050	1250	1530	1870	2205	2480	2795	3150	3937	4438	5057	5696	6336
	130	457	680	910	1138	1354	1685	2026	2388	2687	3028	3412	4265	4807	5478	6171	6864

where:

P_{VT} = vertical soil load due to the soil prism load, lb/ft
w = unit weight of soil, lb/ft^3
H = height of fill above top of pipe, ft
D_o = pipe outside diameter, in.

Note: Termination of the table at H = 50 ft does not imply a depth-of-bury limit.

Table 6.1 Prism load (*continued*)

$P_{VT} = wHD_o/12$ (lb/ft)

Height of fill, ft	Unit weight of soil, lb/ft^3	Pipe outside diameter, in.															
		4	6	8	10	12	15	18	21	24	27	30	36	42	48	54	60
12	100	422	628	840	1050	1250	1530	1870	2205	2480	2795	3150	3937	4438	5057	5696	6336
	110	464	690	924	1155	1375	1683	2057	2425	2728	3075	3465	4331	4881	5563	6266	6970
	120	506	753	1008	1260	1500	1836	2244	2646	2976	3354	3780	4724	5325	6068	6835	7603
	130	548	816	1092	1365	1625	1989	2431	2866	3224	3634	4094	5118	5769	6574	7405	8237
14	100	492	732	980	1225	1458	1785	2182	2572	2894	3261	3675	4593	5177	5900	6645	7392
	110	541	805	1078	1348	1604	1964	2400	2829	3138	3587	4042	5052	5695	6490	7310	8131
	120	590	879	1176	1470	1750	2142	2618	3087	3472	3913	4409	5512	6213	7080	7974	8870
	130	639	952	1274	1593	1896	2321	2836	3344	3762	4240	4777	5971	6730	7670	8639	9610
16	100	562	837	1120	1400	1667	2040	2493	2940	3307	3727	4199	5249	5917	6743	7595	8448
	110	618	920	1232	1540	1833	2244	2743	3234	3638	4100	4619	5774	6508	7417	8354	9293
	120	674	1004	1344	1680	2000	2448	2992	3528	3968	4472	5039	6299	7100	8091	9114	10138
	130	731	1088	1456	1820	2167	2652	3242	3821	4299	4845	5459	6824	7692	8765	9873	10982
18	100	632	941	1260	1575	1875	2295	2805	3307	3720	4193	4724	5906	6656	7586	8544	9504
	110	695	1035	1386	1733	2063	2525	3086	3638	4092	4612	5197	6496	7322	8344	9398	10454
	120	759	1130	1512	1890	2250	2754	3366	3968	4465	5032	5669	7087	7988	9103	10253	11405
	130	822	1224	1638	2048	2438	2984	3647	4299	4837	5451	6142	7677	8653	9861	11107	12355
20	100	703	1046	1400	1750	2083	2550	3117	3675	4134	4659	5249	6562	7396	8428	9493	10560
	110	773	1150	1540	1925	2292	2805	3429	4042	4547	5125	5774	7218	8135	9271	10443	11616
	120	843	1255	1680	2100	2500	3060	3740	4409	4961	5591	6299	7874	8875	10114	11392	12672
	130	913	1360	1820	2275	2708	3315	4052	4777	5374	6056	6824	8530	9615	10957	12341	13782
22	100	773	1150	1540	1925	2292	2805	3429	4042	4547	5125	5774	7218	8135	9271	10443	11616
	110	850	1265	1694	2118	2521	3086	3771	4446	5002	5637	6352	7940	8949	10198	11487	12778
	120	927	1381	1848	2310	2750	3366	4114	4850	5457	6150	6929	8661	9763	11125	12531	13939
	130	1005	1496	2002	2503	2979	3647	4457	5255	5911	6662	7507	9383	10576	12053	13575	15101
24	100	843	1255	1680	2100	2500	3060	3740	4409	4961	5591	6299	7874	8875	10114	11392	12672
	110	927	1381	1848	2310	2750	3366	4114	4850	5457	6150	6929	8661	9763	11125	12531	13939
	120	1012	1506	2016	2520	3000	3672	4488	5291	5953	6709	7559	9449	10650	12137	13670	15206
	130	1096	1632	2184	2730	3250	3978	4862	5732	6449	7268	8189	10236	11538	13148	14810	16474

Table 6.1 Prism load (*continued*)

$P_{VT} = wHD_o/12$ (lb/ft)

Height of fill, ft	Unit weight of soil, lb/ft^3	Pipe outside diameter, in.															
		4	6	8	10	12	15	18	21	24	27	30	36	42	48	54	60
26	100	913	1360	1820	2275	2708	3315	4052	4777	5374	6056	6824	8530	9615	10957	12341	13728
	110	1005	1496	2002	2503	2979	3647	4457	5255	5911	6662	7507	9383	10576	12053	13575	15101
	120	1096	1632	2184	2730	3250	3978	4862	5732	6449	7268	8189	10236	11538	13148	14810	16474
	130	1187	1767	2366	2958	3521	4310	5267	6210	6986	7873	8871	11089	12499	14244	16044	17846
28	100	984	1464	1960	2450	2917	3570	4364	5144	5787	6522	7349	9186	10354	11800	13291	14784
	110	1082	1611	2156	2695	3208	3927	4800	5659	6366	7175	8084	10105	11390	12980	14620	16262
	120	1180	1757	2352	2940	3500	4284	5236	6173	6945	7827	8819	11024	12425	14160	15949	17741
	130	1279	1903	2548	3185	3792	4641	5673	6688	7524	8479	9554	11942	13460	15340	17278	19219
30	100	1054	1569	2100	2625	3125	3825	4675	5512	6201	6988	7874	9843	11094	12643	14240	15840
	110	1159	1726	2310	2888	3438	4208	5143	6063	6821	7687	8661	10827	12203	13907	15664	17424
	120	1265	1883	2520	3150	3750	4590	5610	6614	7441	8386	9449	11811	13313	15171	17088	19008
	130	1370	2039	2730	3413	4063	4973	6078	7165	8061	9085	10236	12795	14422	16435	18512	20592
32	100	1124	1673	2240	2800	3333	4080	4987	5879	6614	7454	8399	10499	11833	13485	15189	16896
	110	1236	1841	2464	3080	3667	4488	5486	6467	7276	8200	9239	11549	13017	14834	16708	18586
	120	1349	2008	2688	3360	4000	4896	5984	7055	7937	8945	10079	12598	14200	16182	18227	20275
	130	1461	2175	2912	3640	4333	5304	6483	7643	8698	9690	10919	13648	15383	17531	19746	21965
34	100	1194	1778	2380	2975	3542	4335	5299	6247	7028	7920	8924	11155	12573	14328	16139	17952
	110	1314	1956	2618	3273	3896	4769	5828	6871	7730	8712	9816	12270	13803	15761	17753	19747
	120	1433	2134	2856	3570	4250	5202	6358	7496	8433	9504	10709	13386	15088	17194	19366	21542
	130	1553	2311	3094	3868	4604	5636	6888	8121	9136	10296	11601	14501	16345	18627	20980	23338

where:

P_{VT} = vertical soil load due to the soil prism load, lb/ft
w = unit weight of soil, lb/ft^3
H = height of fill above top of pipe, ft
D_o = pipe outside diameter, in.

Note: Termination of the table at H = 50 ft does not imply a depth-of-bury limit.

Table 6.1 Prism load (*continued*)

$P_{VT} = wHD_o/12$ (lb/ft)																	
Height of fill, ft	Unit weight of soil, lb/ft^3	Pipe outside diameter, in.															
		4	6	8	10	12	15	18	21	24	27	30	36	42	48	54	60
36	100	1265	1883	2520	3150	3750	4590	5610	6614	7441	8386	9449	11811	13313	15171	17088	19008
	110	1391	2071	2772	3465	4125	5049	6171	7276	8185	9224	10394	12992	14644	16688	18797	20909
	120	1517	2259	3024	3780	4500	5508	6732	7937	8929	10063	11339	14173	15975	18205	20506	22810
	130	1644	2447	3276	4095	4875	5967	7293	8598	9673	10902	12283	15354	17306	19722	22214	24710
38	100	1335	1987	2660	3325	3958	4845	5922	6982	7854	8852	9974	12467	14052	16014	18037	20064
	110	1468	2186	2926	3658	4354	5330	6514	7680	8640	9737	10971	13714	15457	17615	19841	22070
	120	1602	2385	3192	3990	4750	5814	7106	8378	9425	10622	11968	14961	16863	19217	21645	24077
	130	1735	2583	3458	4323	5146	6299	7699	9076	10211	11507	12966	16207	18268	20818	23449	26038
40	100	1405	2092	2800	3500	4167	5100	6234	7349	8268	9318	10499	13123	14792	16857	18987	21220
	110	1546	2301	3080	3850	4583	5610	6857	8084	9094	10249	11549	14436	16271	18542	20885	23232
	120	1686	2510	3360	4200	5000	6120	7480	8819	9921	11181	12598	15748	17750	20228	22784	25344
	130	1827	2719	3640	4550	5417	6630	8104	9554	10748	12113	13648	17060	19229	21914	24683	27546
42	100	1475	2196	2940	3675	4375	5355	6545	7716	8681	9784	11024	13780	15531	17700	19936	22176
	110	1623	2416	3234	4043	4813	5891	7200	8488	9549	10762	12126	15157	17084	19469	21930	24394
	120	1770	2636	3528	4410	5250	6426	7854	9260	10417	11740	13228	16535	18638	21239	23923	26611
	130	1918	2855	3822	4778	5688	6962	8509	10031	11285	12719	14331	17913	20191	23009	25917	28829
44	100	1546	2301	3080	3850	4583	5610	6857	8084	9094	10249	11549	14436	16271	18542	20885	23232
	110	1700	2531	3388	4235	5042	6171	7543	8892	10004	11274	12703	15879	17898	20397	22974	25555
	120	1855	2761	3696	4620	5500	6732	8228	9701	10913	12299	13858	17323	19525	22251	25062	27878
	130	2009	2991	4004	5005	5958	7293	8914	10509	11823	13324	15013	18766	21152	24105	27151	30202
46	100	1616	2405	3220	4025	4792	5865	7169	8451	9508	10715	12073	15092	17010	19385	21835	24288
	110	1777	2646	3542	4428	5271	6452	7886	9296	10459	11787	13281	16601	18711	21324	24018	26717
	120	1939	2887	3864	4830	5750	7038	8602	10142	11409	12858	14488	18110	20413	23262	26202	29146
	130	2100	3127	4186	5233	6229	7625	9319	10987	12360	13930	15969	19619	22114	25201	28385	31574
48	100	1686	2510	3360	4200	5000	6120	7480	8819	9921	11181	12598	15748	17750	20228	22784	25344
	110	1855	2761	3696	4620	5500	6732	8228	9701	10913	12299	13858	17323	19525	22251	25062	27878
	120	2023	3012	4032	5040	6000	7344	8976	10583	11905	13417	15118	18898	21300	24274	27341	30413
	130	2192	3263	4368	5460	6500	7956	9725	11464	12898	14536	16378	20472	23075	26296	29619	32947

Table 6.1 Prism load (*continued*)

$P_{VT} = wHD_o/12$ (lb/ft)

Height of fill, ft	Unit weight of soil, lb/ft^3	Pipe outside diameter, in.															
		4	6	8	10	12	15	18	21	24	27	30	36	42	48	54	60
50	100	1756	2615	3500	4375	5208	6375	7792	9186	10335	11647	13123	16404	18490	21071	23733	26400
	110	1932	2876	3850	4813	5729	7013	8571	10105	11368	12812	14436	18045	20339	23178	26107	29040
	120	2108	3138	4200	5250	6250	7650	9351	11024	12402	13977	15748	19685	22188	25285	28480	31680
	130	2283	3399	4550	5688	6771	8288	10130	11942	13435	15141	17060	21325	24036	27392	30853	34320

where:

P_{VT} = vertical soil load due to the soil prism load, lb/ft
w = unit weight of soil, lb/ft^3
H = height of fill above top of pipe, ft
D_o = pipe outside diameter, in.

Note: Termination of the table at H = 50 ft does not imply a depth-of-bury limit.

The following values are used for D_o:

4 in. = 4.215 in.
6 in. = 6.275 in.
8 in. = 8.400 in.
10 in. = 10.500 in.
12 in. = 12.500 in.
15 in. = 15.300 in.
18 in. = 18.701 in.
21 in. = 22.047 in.
24 in. = 24.803 in.
27 in. = 27.935 in.
30 in. = 31.496 in.
36 in. = 39.370 in.
39 in. = 41.385 in.
42 in. = 44.375 in.
45 in. = 47.370 in.
48 in. = 50.570 in.
54 in. = 56.960 in.
60 in. = 63.360 in.

Table 6.2 Prism load soil pressure

P = wH/144 (psi)				
Height of fill, ft	Unit weight of soil, lb/ft^3 100	110	120	130
1	0.69	0.76	0.83	0.90
2	1.39	1.53	1.67	1.81
3	2.08	2.29	2.50	2.71
4	2.78	3.06	3.33	3.61
5	3.47	3.82	4.17	4.51
6	4.17	4.58	5.00	5.42
7	4.86	5.35	5.83	6.32
8	5.56	6.11	6.67	7.22
9	6.25	6.88	7.50	8.13
10	6.94	7.64	8.33	9.03
11	7.64	8.40	9.17	9.93
12	8.33	9.17	10.00	10.83
13	9.03	9.93	10.83	11.74
14	9.72	10.69	11.67	12.64
15	10.42	11.46	12.50	13.54
16	11.11	12.22	13.33	14.44
17	11.81	12.99	14.17	15.35
18	12.50	13.75	15.00	16.25
19	13.19	14.51	15.83	17.15
20	13.89	15.28	16.67	18.06
21	14.58	16.04	17.50	18.96
22	15.28	16.81	18.33	19.86
23	15.97	17.57	19.17	20.76

where:

P = vertical soil pressure due to the prism load, psi
w = unit weight of soil, lb/ft^3
H = height of fill above top of pipe, ft

Table 6.2 Prism load soil pressure (*continued*)

P = wH/144 (psi)				
Height of fill, ft	Unit weight of soil, lb/ft^3			
	100	110	120	130
24	16.67	18.33	20.00	21.67
25	17.36	19.10	20.83	22.57
26	18.06	19.86	21.67	23.47
27	18.75	20.63	22.50	24.38
28	19.44	21.39	23.33	25.28
29	20.14	22.15	24.17	26.18
30	20.83	22.92	25.00	27.08
31	21.53	23.68	25.83	27.99
32	22.22	24.44	26.67	28.89
33	22.92	25.21	27.50	29.79
34	23.61	25.97	28.33	30.69
35	24.31	26.74	29.17	31.60
36	25.00	27.50	30.00	32.50
37	25.69	28.26	30.83	33.40
38	26.39	29.03	31.67	34.31
39	27.08	29.79	32.50	35.21
40	27.78	30.56	33.33	36.11
41	28.47	31.32	34.17	37.01
42	29.17	32.08	35.00	37.92
43	29.86	32.85	35.83	38.82
44	30.56	33.61	36.67	39.72
45	31.25	34.38	37.50	40.63

where:

P = vertical soil pressure due to the prism load, psi
w = unit weight of soil, lb/ft^3
H = height of fill above top of pipe, ft

Table 6.2 Prism load soil pressure (*continued*)

$P = wH/144$ (psi)				
Height of fill, ft	Unit weight of soil, lb/ft^3			
	100	110	120	130
46	31.94	35.14	38.33	41.53
47	32.64	35.90	39.17	42.43
48	33.33	36.67	40.00	43.33
49	34.03	37.43	40.83	44.24
50	34.72	38.19	41.67	45.14

where:

P = vertical soil pressure due to the prism load, psi
w = unit weight of soil, lb/ft^3
H = height of fill above top of pipe, ft

Note: Termination of the table at $H = 50$ ft does not imply a depth-of-bury limit.

6.4 Live Loads

In addition to earth loads, underground PVC pipe may be subjected to *live loads* from sources such as highways and railways. Design for shallow pipe burial must take these loads into account; for deep burial, the effect of live loads diminishes and can be ignored.

Several methods exist for calculating live loads. The design approach presented here is based on the Boussinesq formula for a point load at the surface of a semi-infinite elastic soil (Equation 6.8).

Equation 6.8

$$W_L = \frac{C_L P_w I_f}{12}$$

where:

W_L = live load, lb/in.
C_L = live load coefficient per ft effective length, 1/ft
P_w = wheel load, lb
I_f = impact factor, dimensionless

For H between 1 ft and 2 ft, $I_f = 1.35$; for H between 2 ft and 3 ft, $I_f = 1.15$; for H greater than 3 ft, $I_f = 1.00$, where: H = height of fill above top of pipe, ft.

Table 6.3 Live load coefficients for single-wheel load

Pipe size, in.	Height of fill above top of pipe (H), ft								
	2	4	6	8	10	12	14	16	18
	Live load coefficient C_L, 1/ft								
8	0.055	0.018	0.008	0.005	0.003	0.002	0.002	0.001	0.001
10	0.068	0.022	0.010	0.006	0.004	0.003	0.002	0.002	0.001
12	0.080	0.026	0.013	0.007	0.005	0.003	0.002	0.002	0.001
14	0.092	0.031	0.015	0.008	0.005	0.004	0.003	0.002	0.002
16	0.104	0.035	0.017	0.010	0.006	0.004	0.003	0.002	0.002
18	0.114	0.039	0.019	0.011	0.007	0.005	0.004	0.003	0.002
20	0.125	0.043	0.021	0.012	0.008	0.005	0.004	0.003	0.002
24	0.143	0.051	0.025	0.014	0.009	0.007	0.005	0.004	0.003
30	0.165	0.062	0.030	0.018	0.012	0.008	0.006	0.005	0.004
36	0.183	0.072	0.036	0.021	0.014	0.010	0.007	0.006	0.004
42	0.196	0.082	0.041	0.024	0.016	0.011	0.008	0.006	0.005
48	0.206	0.090	0.046	0.028	0.018	0.013	0.009	0.007	0.006
54	0.214	0.097	0.051	0.031	0.020	0.014	0.011	0.008	0.007
60	0.219	0.104	0.055	0.034	0.022	0.016	0.012	0.009	0.007

Notes:

1. An effective length of 3.0 ft of pipe is assumed.
2. The formula for live load coefficient is:

$$C_L = \frac{1}{3} - \frac{2}{3\pi}\sin^{-1}\left[H\sqrt{\frac{R^2 + H^2 + 1.5^2}{(R^2 + H^2)(H^2 + 1.5^2)}}\right] + \frac{RH\left[\left(\frac{1}{R^2 + H^2} + \frac{1}{H^2 + 1.5^2}\right)\right]}{\pi\sqrt{R^2 + H^2 + 1.5^2}}$$

where
H = height of fill above top of pipe, ft
R = pipe radius, ft = $D_o/2$

3. $\sin^{-1}$(argument) is in radians.

Note: AASHTO H20 truck loading results in an effective single-wheel load of 16,000 lb.

Table 6.3 lists live load coefficients, C_L, for a single-wheel load; Table 6.4 lists C_L for two passing trucks. The design approach taken in these tables conservatively represents a

Table 6.4 Live load coefficients for two passing trucks

Pipe size, in.	Height of fill above top of pipe (H), ft								
	2	4	6	8	10	12	14	16	18
	Live load coefficient C_L, 1/ft								
8	0.0523	0.0296	0.0169	0.0112	0.0081	0.0062	0.0049	0.0039	0.0032
10	0.0654	0.0369	0.0211	0.0140	0.0101	0.0077	0.0061	0.0049	0.0041
12	0.0785	0.0443	0.0253	0.0168	0.0122	0.0093	0.0073	0.0059	0.0049
14	0.0916	0.0517	0.0295	0.0196	0.0142	0.0108	0.0085	0.0069	0.0057
16	0.1047	0.0591	0.0338	0.0224	0.0162	0.0124	0.0098	0.0079	0.0065
18	0.1177	0.0665	0.0380	0.0252	0.0182	0.0139	0.0110	0.0089	0.0073
20	0.1308	0.0739	0.0422	0.0279	0.0203	0.0155	0.0122	0.0099	0.0081
24	0.1570	0.0887	0.0506	0.0335	0.0243	0.0186	0.0147	0.0118	0.0097
30	0.1962	0.1108	0.0633	0.0419	0.0304	0.0232	0.0183	0.0148	0.0122
36	0.2355	0.1330	0.0760	0.0503	0.0365	0.0279	0.0220	0.0178	0.0146
42	0.2747	0.1552	0.0886	0.0587	0.0426	0.0325	0.0256	0.0207	0.0171
48	0.3140	0.1773	0.1013	0.0671	0.0486	0.0371	0.0293	0.0237	0.0195
54	0.3532	0.1995	0.1139	0.0755	0.0547	0.0418	0.0330	0.0266	0.0219
60	0.3925	0.2217	0.1266	0.0838	0.0608	0.0464	0.0366	0.0296	0.0244

Notes:

1. An effective length of 3.0 ft of pipe is assumed.
2. Coefficients are for 6-ft axle widths, 3.0 ft between passing wheels.
3. The formula for live load coefficient is:

$$C_L = \frac{3D_o}{\pi H^2}\left\{\left[\cos\left(\tan^{-1}\frac{1.5}{H}\right)\right]^5 + \left[\cos\left(\tan^{-1}\frac{7.5}{H}\right)\right]^5\right\}$$

where:

D_o = pipe outside diameter, ft
H = height of fill above top of pipe, ft

4. cos (argument) is unitless; $\tan^{-1}$(argument) is in radians.

wheel load as a point load. Below the tables, analytical expressions for C_L in terms of pipe diameter (or radius) and height of cover are presented.

As mentioned above, the influence of live loads on PVC pipe performance is significant only at shallow depths. This is graphically demonstrated in Figs. 6.9 and 6.10,

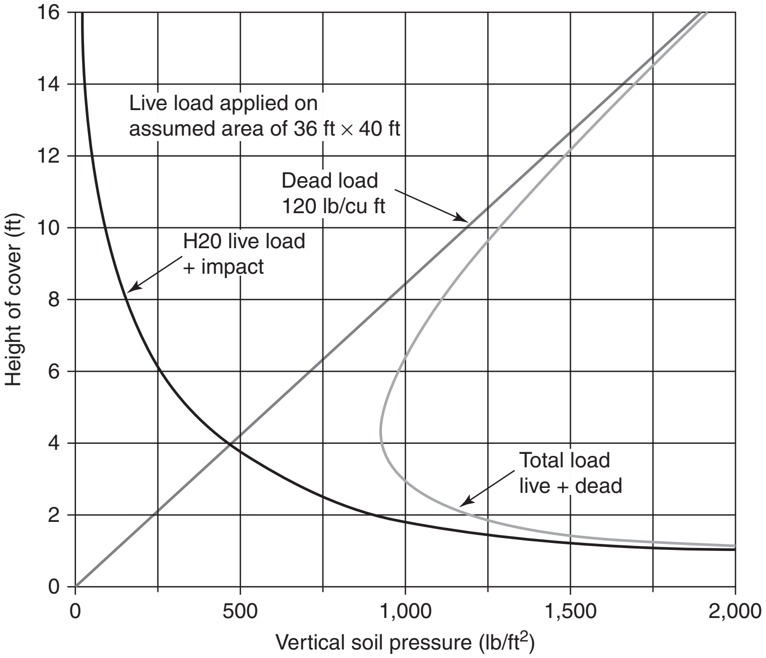


Fig. 6.9 H20 highway loading. Source: American Iron and Steel Institute, Washington, DC.

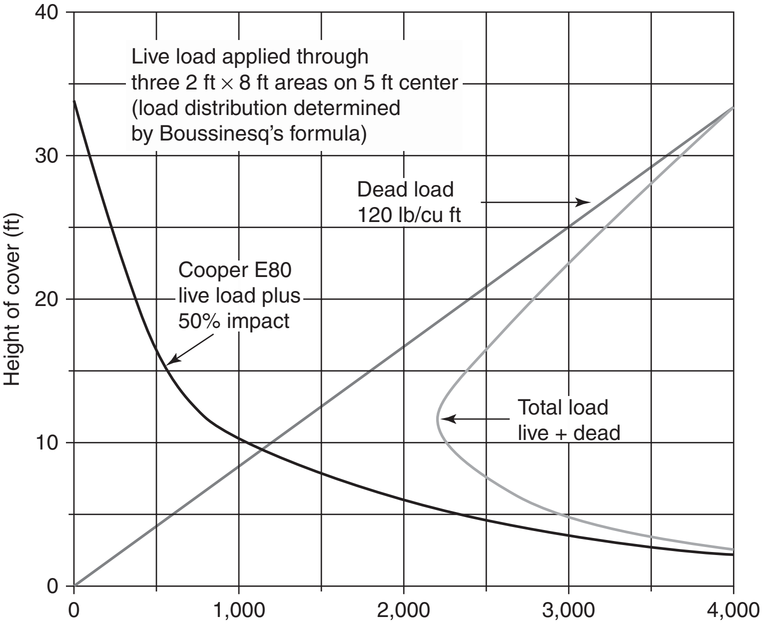


Fig. 6.10 Cooper E80 live loading. Source: American Iron and Steel Institute, Washington, DC.

Table 6.5 Live loads on pipe

	Live load transferred to pipe, psi				Live load transferred to pipe, psi		
Height of cover, ft	Highway H20[1]	Railway E80[2]	Airport[3]	Height of cover, ft	Highway H20[1]	Railway E80[2]	Airport[3]
1	12.50			14	*	4.17	3.06
2	5.56	26.39	13.14	16	*	3.47	2.29
3	4.17	23.61	12.28	18	*	2.78	1.91
4	2.78	18.40	11.27	20	*	2.08	1.53
5	1.74	16.67	10.09	22	*	1.91	1.14
6	1.39	15.63	8.79	24	*	1.74	1.05
7	1.22	12.15	7.85	26	*	1.39	*
8	0.69	11.11	6.93	28	*	1.04	*
10	*	7.64	6.09	30	*	0.69	*
12	*	5.56	4.76	35	*	*	*

[1] Simulates 20-ton truck traffic + impact (Source: ASTM A796)

[2] Simulates 80,000 lb railway load + impact (Source: ASTM A796)

[3] 180,000-lb dual tandem gear assembly.
26-in. spacing between tires and 66-in. center-to-center spacing between fore and aft tires under a rigid pavement 12in. thick + impact.

*Negligible live load influence.

which show total load on a pipe exposed to live loads and earth loads for highway and railway traffic. Both graphs show that as depth of cover increases, influence of live load diminishes rapidly. This illustrates that at a certain depth of cover, total load is minimal. This depth is approximately 5 ft for an H20 truck and 13 ft for an E80 railway load.

The influence of live loads on PVC pipe as projected for highway, railroad, and airport installations is shown in Table 6.5. The values shown account for impact and loading factors and can be converted to live load per unit length (as used in Equation 6.8 for W_L) by multiplying table values by pipe outside diameter.

With an AASHTO H20 live load, a 20-ton truckload is simulated in which 80% (32,000 lb) is distributed to the rear axle, evenly divided into two 16,000-lb wheel loads. The remaining 20% (8,000 lb) is divided over the front axle into two 4,000-lb wheel loads. The distance between the front and rear axles is assumed to be 14 ft, with two dual-tire wheel loads on each axle. One is centered over the point in question and the other located 6 ft away. With impact, the AASHTO LRFD Bridge Design Specification distribution of the tire footprint is taken as 1.5 ft × 1.67 ft. Similarly, the AREMA (2000) Cooper E80 live load simulates the effect of four 80,000-lb axles, located 5 ft apart. Each axle load is assumed to be distributed over a 2-ft × 8-ft area.

6.5 AASHTO Design Method

The American Association of State Highway and Transportation Officials (AASHTO) currently has two design documents providing specifications for estimation of live load effects: (1) Section 3 in the LRFD Bridge Specifications Manual, titled Loads and Load Factors, and (2) Standard Specifications for Highway Bridges, Division 1, Section 3, titled Loads. A summary of the method of the former reference, the more recent of the two, is offered below.

The contact area of a dual-tire is assumed to be a single rectangle with a width (W) of 20 in. and a length (L) of 10 in. The equivalent area of loading distribution, realized at pipe depth, can be calculated as follows:

Equation 6.9

$$A = (W_T + \alpha H)(L_T + \alpha H)$$

where:

A = area of load distribution under fill, ft^2
W_T = width of truck dual-tire, ft
L_T = length of truck dual-tire, ft
$\alpha = 1.15$ for granular soils; $\alpha = 1.0$ for all other soil types
H = height of cover, ft

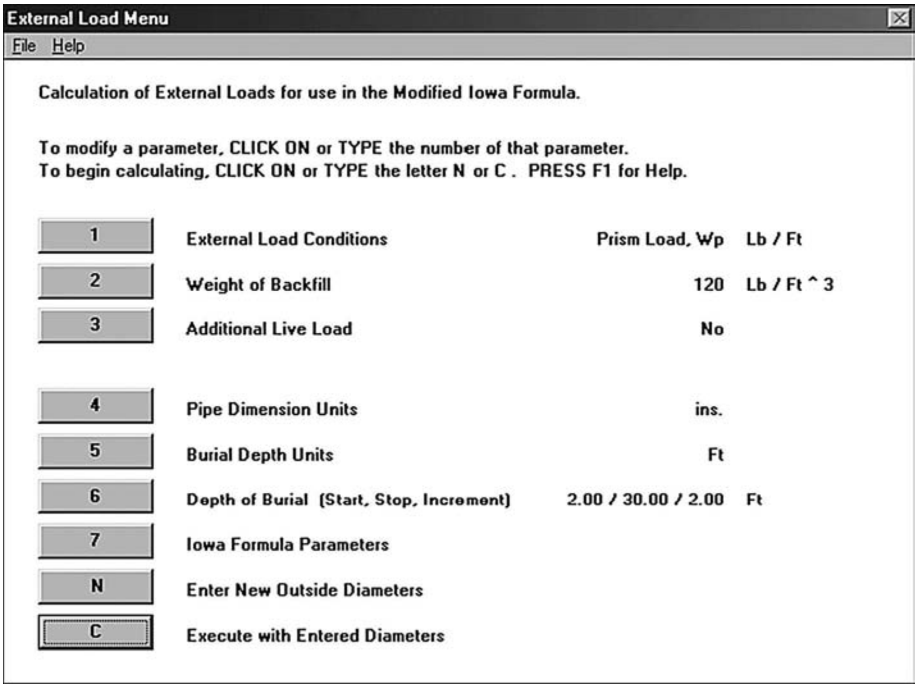
Similar to the 60°rule often found in soil mechanics texts, the equation above applies for burial depths between 2 and 8 ft (the distributive effect of the fill can be ignored at cover depths less than 2 ft, and live loads can be neglected where depth of fill is more than 8 ft). The enlarged contact area, defined in Equation 6.9, is used to compute distributed load experienced at the pipe surface, which is simply wheel load divided by area of load distribution.

6.6 Design Software—External Load Design for Flexible Conduits

The Uni-Bell PVC Pipe Association offers design software that can calculate the loads described in this chapter as well as apply the loadings to estimation of long-term deflection, which is discussed in Chapter 7, Design of Buried PVC Pipe.

The program can account for either of the earth-loading scenarios described in this chapter. The Marston earth load (Equation 6.2) and the prism earth load options (Equation 6.6) are both available to the program user. Through interactive screens such as those shown in Figs. 6.11 and 6.12, design specifics are obtained (backfill material, height of cover, compaction effort, etc.), in which the user is prompted to input data or select from a listing of typical values. Furthermore, units for input and output are user-defined, allowing for either metric or English units.

With regard to live loads, several options are available: The software has the capability to simulate standard highway (H20), railway (E80), and airport live loads, as well as provide for custom live load situations. Single-wheel, two-trucks-passing, and custom live loads (in which load and pattern are user-defined) are all computed using a method similar to the Boussinesq method, presented earlier in this chapter. The software determines the

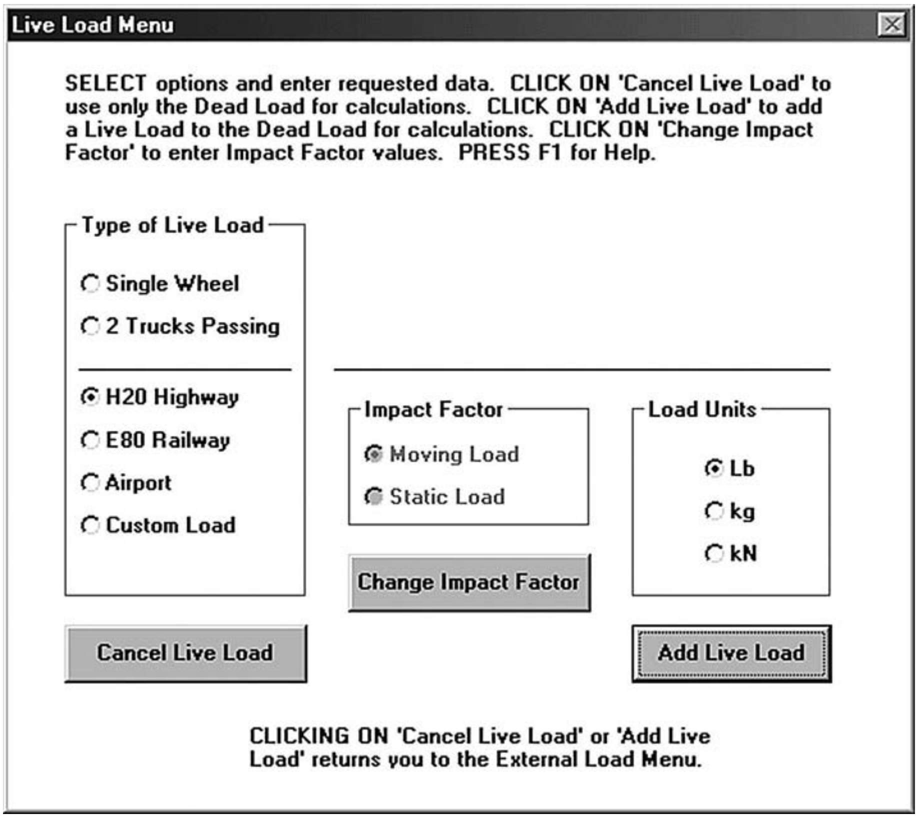


Calculation of External Loads for use in the Modified Iowa Formula.

To modify a parameter, CLICK ON or TYPE the number of that parameter.
To begin calculating, CLICK ON or TYPE the letter N or C . PRESS F1 for Help.

1	External Load Conditions	Prism Load, Wp	Lb / Ft
2	Weight of Backfill	120	Lb / Ft ^ 3
3	Additional Live Load	No	
4	Pipe Dimension Units	ins.	
5	Burial Depth Units	Ft	
6	Depth of Burial (Start, Stop, Increment)	2.00 / 30.00 / 2.00	Ft
7	Iowa Formula Parameters		
N	Enter New Outside Diameters		
C	Execute with Entered Diameters		

Fig. 6.11 Design software sample input screen.



SELECT options and enter requested data. CLICK ON 'Cancel Live Load' to use only the Dead Load for calculations. CLICK ON 'Add Live Load' to add a Live Load to the Dead Load for calculations. CLICK ON 'Change Impact Factor' to enter Impact Factor values. PRESS F1 for Help.

Type of Live Load
○ Single Wheel
○ 2 Trucks Passing
● H20 Highway
○ E80 Railway
○ Airport
○ Custom Load

Impact Factor
● Moving Load
● Static Load

Load Units
● Lb
○ kg
○ kN

CLICKING ON 'Cancel Live Load' or 'Add Live Load' returns you to the External Load Menu.

Fig. 6.12 Live load menu screen.

live loads at user-defined depths using Holl and Newmark's integration of the Boussinesq formula. Furthermore, the software can be used to calculate long-term deflection for flexible pipe using principles explained in Chapter 7.

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CHAPTER 7

Design of Buried PVC Pipe

Table of Contents

7.1 Notation

A = area of pipe wall longitudinal cross-section, in.^{2}/in.
b = trench width, in.
C = reduction factor, dimensionless
C_{max} = distance from neutral axis to extreme fiber, in.
D = mean pipe diameter, in. = $D_o - t$
D_L = deflection lag factor, dimensionless
D_o = pipe outside diameter, in.
DR = dimension ratio, dimensionless
e = modulus of passive resistance of the side fill, psi
E = modulus of elasticity of pipe material, psi
E′ = modulus of soil reaction, psi
E_2 = modulus of soil reaction of soil around pipe, psi
E_3 = modulus of soil reaction of trench wall, psi
$E_S = P/\varepsilon$, = psi slope of stress-strain curve for given soil in one-dimensional consolidation test
F = force, lb/in. of sample length
FF = flexibility factor from AASHTO ring strength design, in./lb
H = height of fill above top of pipe, ft

I = moment of inertia of wall cross-section per unit length of pipe, in.^{4}/in.
K = bedding constant, dimensionless
M_s = constrained soil modulus, psi
P = vertical soil pressure due to prism load, psi
P_b = buckling pressure in a given soil, psi
P_c = circumferential pressure, psi
P_{cr} = critical buckling pressure, psi
P_v = vertical soil pressure due to the prism load, lb/ft^2
PS = pipe stiffness, psi
r = mean pipe radius, in.
R_S = stiffness ratio, dimensionless
T = wall thrust, lb/in.
t = pipe wall thickness, in.
W = load on pipe per unit length, lb/in.
W' = live load, psi
w = soil unit weight, lb/ft^3
W_c = Marston's load per unit length of pipe, lb/in.
zeta = in ATV design method, adjustment factor for modulus of soil reaction (to account for native trench wall soil stiffness), dimensionless
ΔX = horizontal deflection, in.
ΔY = vertical deflection, in.
ε = vertical soil strain, in./in.
ε_c = maximum combined strain in pipe wall, in./in.
ε_f = maximum strain in pipe wall due to ring deflection or flexure, in./in.
ε_h = maximum strain in pipe wall due to hoop stress, in./in.
ν = Poisson's ratio, dimensionless = unit lateral contraction/unit axial elongation = 0.38 for PVC pipe
σ_c = compressive stress, psi
$\%\Delta Y/D$ = percent pipe deflection, dimensionless

7.2 Introduction

By definition, a flexible pipe is a conduit that *deflects* (ovalizes) at least 2% without signs of structural distress, such as injurious cracking. In practice, for a conduit to truly behave as a flexible pipe when it is buried, it must yield more than the embedment soil that surrounds it.

Flexible pipe derives its external load-carrying capacity from its flexibility. Under vertical load, pipe tends to deflect, developing passive soil support along its sides. At the same time, ring deflection relieves the pipe of the greater portion of the vertical load, which is then carried by surrounding soil through the mechanism known as *soil arching action* over the pipe. (See Chapter 6 for full discussion.)

The effective strength of the pipe/soil system is remarkably high. For example, tests at Utah State University indicate that a rigid pipe with a three-edge bearing strength of 3,300 lb/ft (48.15 kN/m) buried in Class C bedding fails under a vertical load of 5,000 lb/ft (72.95 kN/m). However, under identical soil conditions and loading, PVC sewer pipe with minimum pipe stiffness of 46 psi deflects only 5%, far below an amount that could cause damage to PVC pipe. So, in this scenario, rigid pipe failed while flexible pipe performed successfully.

Of course, in flat-plate or three-edge loading, rigid pipe will support much more than flexible pipe. This seeming anomaly can be misleading, as users often relate the lower flat-plate supporting strength for flexible pipe to in-soil load capacity. It should be noted, then, that flat-plate or three-edge loading is an appropriate measure of load-bearing strength for rigid pipe, but not for flexible pipe.

7.3 Pipe Stiffness

7.3.1 Definition

Pipe stiffness (PS) is the inherent resistance of flexible pipe to deflect under load. It is measured according to ASTM D2412, Standard Test Method for External Loading Properties of Plastic Pipe by Parallel-Plate Loading at a 5% deflection. Note: 5% deflection is not a performance limit for PVC pipe.

Pipe stiffness is defined in Equation 7.1.

Equation 7.1

$$PS = \frac{F}{\Delta Y} = \frac{EI}{0.149r^3} = \frac{6.71\,EI}{r^3}$$

where:

PS = pipe stiffness, psi
F = force, lb/in. of sample length
ΔY = vertical deflection, in.
E = modulus of elasticity of pipe material, psi

I = moment of inertia of wall cross-section per unit length of pipe, in.^{4}/in.
r = mean pipe radius, in.

Thus, pipe stiffness increases as moment of inertia (I) of wall cross-section increases.

For solid wall pipe, moment of inertia per unit length is equal to $t^3/12$ in.^{4}/in.; the center of gravity is at the midpoint of the pipe wall. Equation 7.1 can thus be rewritten as:

Equation 7.2

$$PS = \frac{F}{\Delta Y} = \frac{6.71Et^3}{12r^3} = 0.559E\left(\frac{t}{r}\right)^3$$

where:
t = pipe wall thickness, in.

For solid wall PVC pipe with outside (rather than inside) diameter controlled dimensions, Equation 7.2 can be further simplified:

Equation 7.3

$$PS = 4.47\frac{E}{(DR - 1)^3}$$

where:
$DR = D_o/t$, dimensionless
D_o = pipe outside diameter, in.

Because pipe stiffness is measured at only one prescribed deflection, it provides little information relative to overall structural performance of a product. That is, pipe stiffness defines only the flat-plate loading necessary for a particular deflection. The resulting PS values for various dimension ratios and modulus of elasticity (E) values of PVC pipe are shown in Table 7.1.

7.3.2 Optimum Pipe Stiffness

The way plastic pipe responds to load is a very important consideration in underground pipeline design. Furthermore, the way plastic pipe stiffness influences in-ground deflection is important both in terms of performance and economics.

Table 7.1 Minimum PVC pipe stiffness (psi)

DR	Min. E = 400,000 psi	Min. E = 440,000 psi	Min. E = 500,000 psi
64	7	8	9
51	14	16	18
42	26	29	32
41	28	31	35
35	46	50	57
33.5	52	57	65
32.5	57	63	71
28	91	100	114
26	115	126	144
25	129	142	161
23.5	157	173	196
21	224	246	279
18	364	400	455
17	437	480	546
14	815	895	1,019
13.5	916	1,007	1,145

Results of a Utah State University research project undertaken to address the relationship between pipe stiffness and in-ground deflection are shown in Fig. 7.1. Points in this graph were taken from load deflection curves of plastic pipe buried in medium dense sand. The curves show a marked increase in pipe deflection for pipe stiffness values below 35 psi. Furthermore, the curves are nearly flat for pipe stiffness values greater than 39 psi, indicating that pipe stiffness above 39 psi has little or no effect on in-ground deflections.

The study concluded that pipe stiffness of approximately 37 psi (independent of both soil compaction and height of cover) resulted in the least deflection and could be considered optimum. The study further concluded that this optimum pipe stiffness yields a ring flexibility that interacts best with the pipe's enveloping soils to limit ring deflection.

A common pipe stiffness value for PVC gravity sewer pipe is 46 psi. At typical summer installation temperatures, this stiffness is very near the optimum value (see Fig. 7.2). Pipes with lower stiffness may be used as long as proper attention is paid to selection and placement of embedment material.

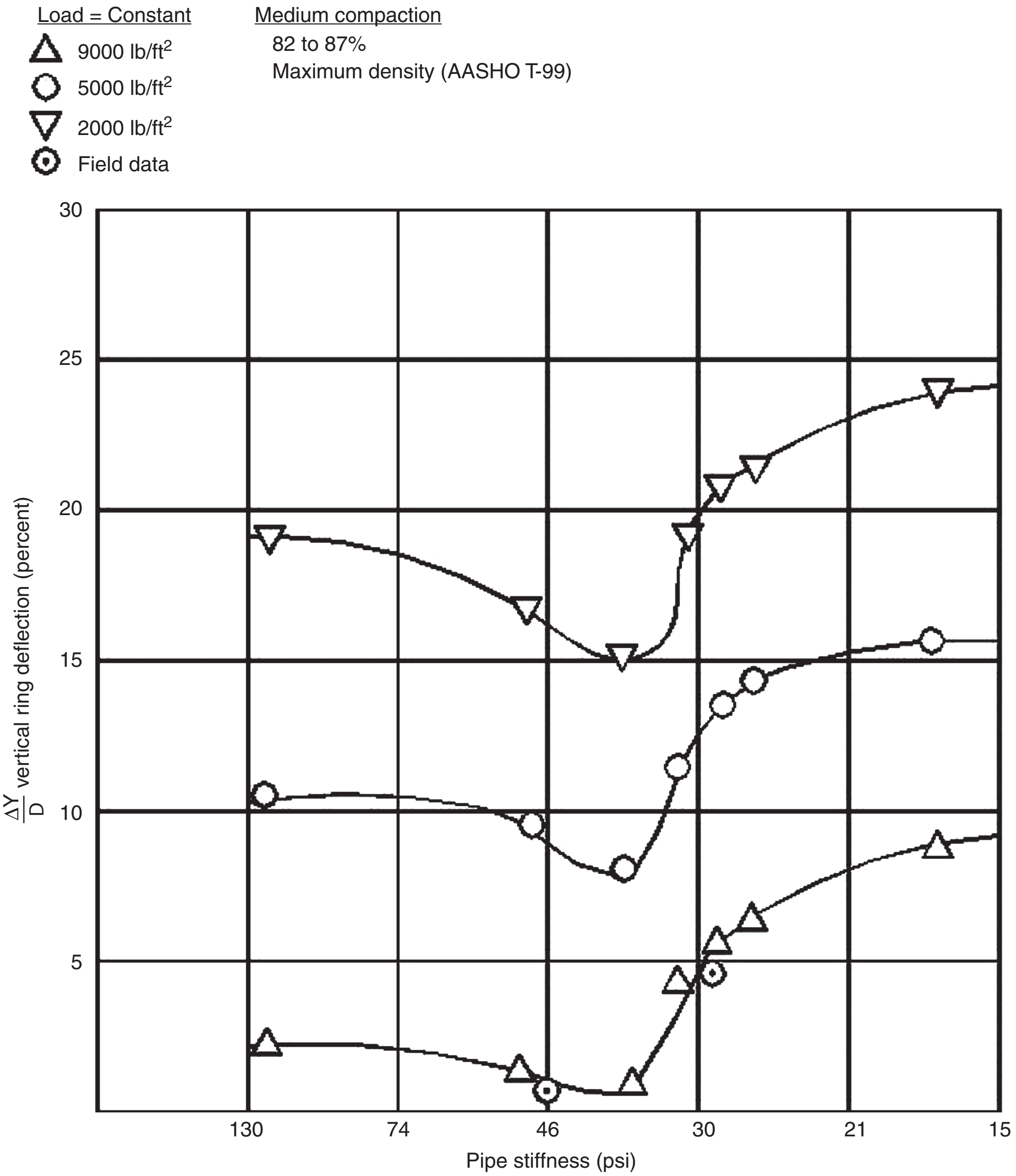


Fig. 7.1 Vertical ring deflection in buried plastic pipe.

Pipe stiffness is affected by DR and pipe wall geometry. More efficient design allows for a variety of profile wall PVC pipe products to be used for gravity sanitary and storm sewer applications. Users are thus afforded the economy of a pipe with stiffness comparable to that of a solid wall product, but containing less raw material per unit length and greater freedom of design.

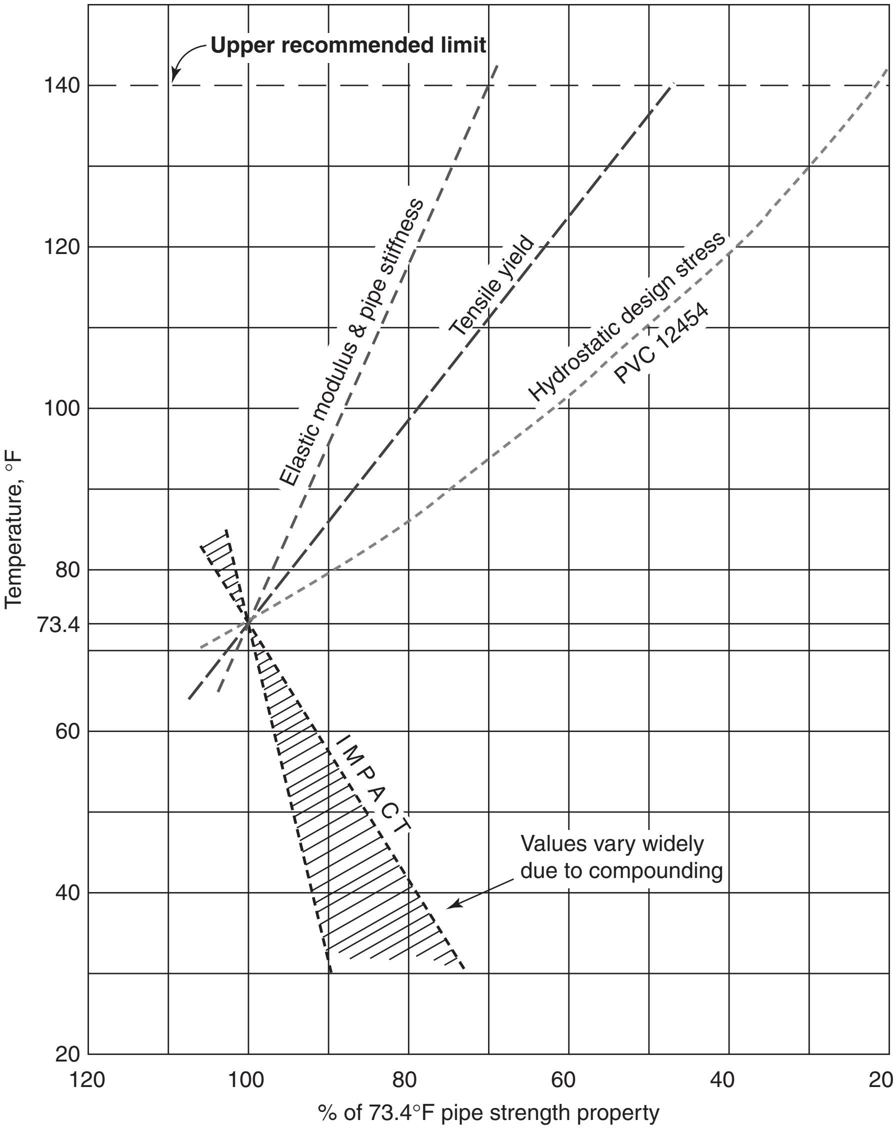


Fig. 7.2 Approximate relationship for 12454 PVC flexible pipe strength properties vs. temperature.

In the case of profile wall pipe (i.e., ASTM F794, F949, F1803, and AASHTO M304), calculation of moment of inertia is more complex than it is for solid wall pipe. For profile wall pipe, the center of gravity (or centroid) for the profile must be computed first, then the parallel axis theorem must be applied to determine composite moment of inertia. It is the location of a pipe's center of gravity, rather than its overall thickness, that has the greatest effect on moment of inertia and gives profile wall pipe its high stiffness-to-weight ratio.

7.4 Soil/Structure Interaction

7.4.1 Description

Because flexible conduit interacts with surrounding soil to support vertical loads, the properties of soil are very important. Just as bedding is important in limiting soil-pressure concentrations on rigid pipes (e.g., clay, concrete, asbestos-cement, cast iron), soil compaction is essential in limiting ring deflection in flexible pipes. Thus, soil selection and soil placement as well as pipe properties are important in the design of any buried pipe installation.

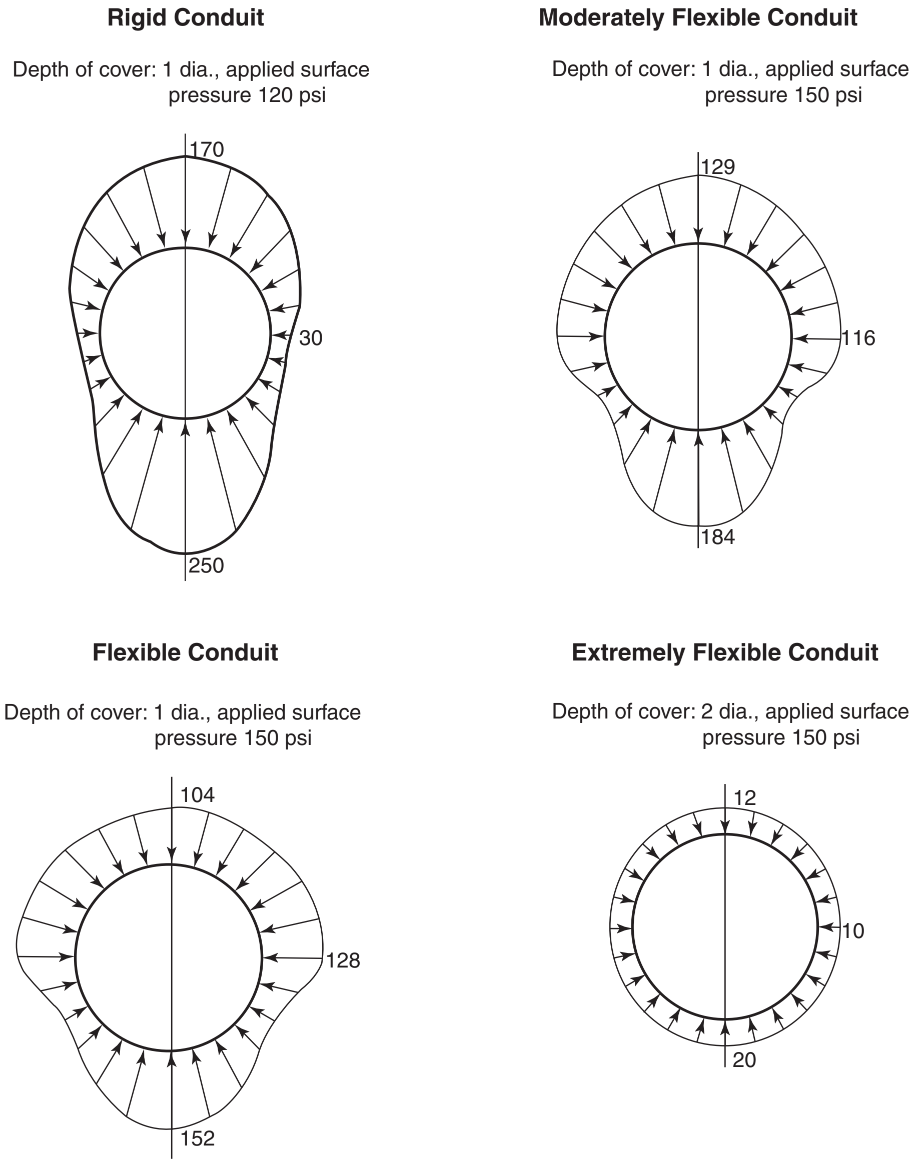
To understand how flexible pipe performance differs from rigid pipe performance, one must first understand each pipe's response to applied load: In a rigid pipe system, applied vertical load must be carried completely by the inherent strength of the unyielding rigid pipe, since soil at the pipe sides tends to compress and deform away from the load; in a flexible pipe system, applied earth load is largely carried by the soil at the sides of the pipe, since the flexible pipe deflects away from the load (see Chapter 6). That portion of the load carried by the flexible pipe—a vertical vector of force—is transferred principally through the deflection mechanism into approximately horizontal force vectors resisted by the compressed soil at the sides of the pipe. Flexible pipe's ability to redistribute vertical load into near horizontal vectors is an advantage that diminishes with increasing pipe stiffness.

Rigid pipes have very limited strain capacity, as do some thermoset and composite plastic pipes. These pipes experience early structural damage, which inhibits their ability to resist loading. For this reason such pipe products must be designed and limited to very small allowable deflections.

7.4.2 Quantifying Soil/Structure Interaction

In 1968, Dr. Kaare Hoeg reported research conducted on buried conduits of different stiffness surrounded by dense sand. In his project, contact-pressure distributions around the circumference of pipes of varying stiffness were measured and reported. His report on a series of four tests demonstrated the relative benefits derived through distribution of load force vectors into surrounding embedment soils.

Dr. Hoeg installed pipe of different stiffness values at depths of cover of one or two pipe diameters. He then applied uniformly distributed loads on the ground surface to create the effect of deep burial. The first diagram (at the upper left) in Fig. 7.3 shows the response of a rigid conduit to an applied ground-surface load of 120 psi. The image also illustrates the contact pressure on the external surface of the rigid pipe, which is not uniformly distributed but is relatively extreme at the top and bottom portions of its circumference—lateral soil



Rigid Conduit

Depth of cover: 1 dia., applied surface pressure 120 psi

Moderately Flexible Conduit

Depth of cover: 1 dia., applied surface pressure 150 psi

Flexible Conduit

Depth of cover: 1 dia., applied surface pressure 150 psi

Extremely Flexible Conduit

Depth of cover: 2 dia., applied surface pressure 150 psi

Fig. 7.3 Load distribution as a function of stiffness.

support is negligible. In the other three diagrams in Fig. 7.3, the response of more flexible conduits to applied loads indicates that pipe flexibility reduces extreme contact pressures, resulting in a better distribution of these contact pressures around pipe circumference.

Through the deflection mechanism, the applied vertical load on a flexible pipe is carried principally by the surrounding soil envelope and, to a lesser extent, by the pipe itself. Consequently, the strength provided by most buried flexible pipe is derived through the deflection mechanism from the combined strength provided by the pipe-soil system.

7.4.3 Spangler's Iowa Deflection Formula

M. G. Spangler noted that flexible pipes may provide little inherent strength in comparison to above-ground rigid pipes. When buried, however, these same pipes derive a significant ability to support vertical loads from the passive pressures induced as the sides of the pipe move outward against the earth. This fact, coupled with the idea that ring deflection may also be a basis for flexible-pipe design, prompted Spangler to publish his *Iowa formula* in 1941.

Spangler first defined flexible pipe's capacity to resist ring deflection when not buried in soil. Applying the elastic theory of flexure to thin rings for deflections less than 10%, he established the following relationships:

Equation 7.4

$$\Delta Y = 0.149 \frac{Wr^3}{EI}$$

Equation 7.5

$$\Delta X = 0.136 \frac{Wr^3}{EI}$$

Equation 7.6

$$\Delta X = 0.913 \Delta Y$$

where:

ΔY = vertical deflection, in.
ΔX = horizontal deflection, in.
W = load on pipe per unit length, lb/in.
r = mean pipe radius, in.
E = modulus of elasticity of pipe material, psi
I = moment of inertia of the wall cross-section per unit length of pipe, $\text{in.}^4/\text{in.}$

Spangler next incorporated the effects of the surrounding soil on pipe deflection. This was accomplished by assuming that Marston's theory of loads applied and that this load would be uniformly distributed over a plane at the top of the pipe. He also assumed a uniform pressure over a portion of the pipe bottom, depending on bedding angle. On the sides he assumed the horizontal pressure on each side would be proportional to the deflection of the pipe in the soil. He called the constant of proportionality the “modulus of passive resistance” of the soil. The modulus would presumably be a constant for a given soil and could be measured in a simple lab test. Through his analysis Spangler derived the Iowa formula:

Equation 7.7

$$\Delta X = D_L \frac{KW_c r^3}{EI + 0.061\,er^4}$$

where:

ΔX = horizontal deflection or change in diameter, in.
D_L = deflection lag factor, dimensionless
K = bedding constant, dimensionless
W_c = Marston’s load per unit length of pipe, lb/in.
E = modulus of elasticity of pipe material, psi
I = moment of inertia of the wall cross-section per unit length of pipe, in.^{4}/in.
e = modulus of passive resistance of the side fill, psi
r = mean pipe radius, in.

The basis of the Iowa formula is illustrated in Fig. 7.4.

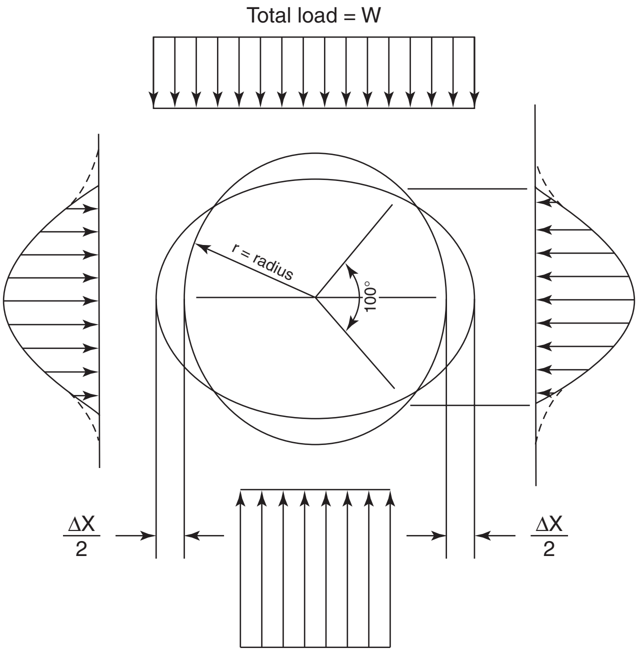


Fig. 7.4 Basis of Spangler’s derivation of the Iowa formula for deflection of buried pipes.

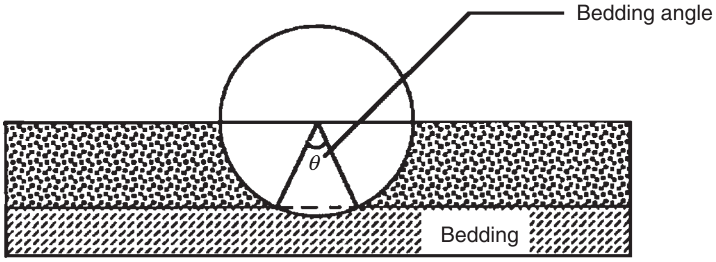


Fig. 7.5 Bedding angle.

Table 7.2 Values of bedding constant K

Bedding angle	K
0°	0.110
30°	0.108
45°	0.105
60°	0.102
90°	0.096
120°	0.090
180°	0.083

Equation 7.7 can be used to predict deflections of buried flexible pipe if the three empirical constants K, D_L, and e are known. The bedding constant (K) accommodates the response of the buried flexible pipe to the opposite and equal reaction of the load force, derived from the bedding under the pipe. The bedding constant varies with the width and angle of the bedding achieved in installation. The bedding angle is shown in Fig. 7.5, and Table 7.2 contains a list of bedding factors (K) dependent upon the bedding angle. These were determined theoretically by Spangler and published in 1941. As a general rule, a value of $K = 0.1$ is assumed.

7.4.4 Watkins's Contribution to Deflection Calculation

In 1955, Reynold Watkins, a graduate student of Spangler, investigated the modulus of passive resistance (e) through model studies and examined the Iowa formula dimensionally. The analysis determined that e could not be a true property of the soil because its dimensions were not like those of a true modulus. As a result of Watkins's effort, another soil parameter was identified: the "modulus of soil reaction," given by $E' = e \times r$. From it, the *modified Iowa formula* was developed, using the variables of the Iowa formula and the substitution:

Equation 7.8

$$\Delta X = D_L \frac{KW_c r^3}{EI + 0.061E' r^3}$$

where:

E' = modulus of soil reaction, psi

Two other observations from Watkins's work are of particular note: (1) There is little point in evaluating E′ by a model test and then using the modulus to predict ring deflection, as the model gives ring deflection directly. (2) Ring deflection may not be the only performance limit.

7.4.5 Modulus of Soil Reaction (Soil Stiffness)

Many researchers have quantified values of E′ by measuring deflections for pipes under which other conditions were known, followed by a back-calculation through the modified Iowa formula. This quantification requires assumptions regarding load, bedding factor, and deflection lag factor, leading to a variation in reported values of E′.

The most often cited work toward development of appropriate values of E′ was conducted by Amster K. Howard of the U.S. Bureau of Reclamation. Howard reviewed both laboratory and field data from many sources; using information from over 100 laboratory and field tests, he compiled a table of average E′ values for various soil types and densities, as seen in Table 7.3. He did this by assuming values of E′, K, and W_c and using the modified Iowa formula to calculate a theoretical value of deflection. This theoretical deflection was then compared with actual measurements. By assuming E′ values in Table 7.3, a bedding constant $K = 0.1$, and deflection lag factor $D_L = 1.0$, Howard was able to correlate the theoretical and empirical results to within ±2% deflection when using the prism load. For example, if theoretical deflections using values in Table 7.3 were approximately 5%, measured deflection would range from 3% to 7%. Study data were taken from tests on PVC, steel, reinforced plastic mortar, and other types of pipe. The study provides guidance to designers of all kinds of flexible pipe, including PVC.

Table 7.3 Average values of modulus of soil reaction E′ (for initial flexible pipe deflection)

Soil type-pipe bedding material (Unified Classification System[a])	E′ for degree of compaction of bedding, psi			
	Dumped	Slight, <85% Proctor, <40% relative density	Moderate, 85–95% Proctor, 40%–70% relative density	High, >95% Proctor, >70% relative density
Fine-grained soils (LL > 50)[b] Soils with medium to high plasticity, CH, MH, CH-MH	No data available; consult a competent soils engineer; otherwise, use E′ = 0			
Fine-grained soils (LL < 50) Soils with medium to no plasticity, CL, ML, ML-CL, with less than 25% coarse-grained particles	50	200	400	1,000
Fine-grained soils (LL < 50) Soils with medium to no plasticity, CL, ML, ML-CL, with more than 25% coarse-grained particles Coarse-grained soils with fines GM, GC, SM, SC[c] contain more than 12% fines	100	400	1,000	2,000
Coarse-grained soils with little or no fines GW, GP, SW, SP[c] contain less than 12% fines	200	1,000	2,000	3,000
Crushed rock	1,000	3,000	3,000	3,000
Accuracy in terms of percentage deflection[d]	±2	±2	±1	±0.5

[a] ASTM Designation D2487, USBR Designation E-3.
[b] LL = Liquid limit.
[c] Or any borderline soil beginning with one of these symbols (i.e., GM-GC, GC-SC).
[d] For ±1% accuracy and predicted deflection of 3%, actual deflection would be between 2 and 4%.

Note: Values applicable only for fills less than 50 ft (15 m). Table does not include any safety factor. For use in predicting initial deflections only, appropriate deflection lag factor must be applied for long-term deflections. If bedding falls on the borderline between two compaction categories, select lower E′ value or average the two values. Percentage Proctor based on laboratory maximum dry density from test standards using about 12,500 ft-lb/cu ft (598,000 J/m^3) (ASTM D698, AASHTO T-99, USBR Designation E-11). 1 psi = 6.9 kPa.

Source: *Soil Reaction for Flexible Pipe*, A.K. Howard, U.S. Bureau of Reclamation, Denver, CO. Reprinted with permission from ASCE.

7.4.6 Deflection Lag Factor

The remaining parameter in the Iowa formula to consider in deflection calculations is *deflection lag factor* D_L. Spangler recognized that in pipe-soil systems, as with all engineering systems involving soil, soil consolidation at the sides of the pipe continues with time after maximum load reaches the top of the pipe. His experience had shown that deflections could increase by as much as 30% over a period of 40 years. For this reason, he recommended the incorporation of a deflection lag factor of 1.5 as a conservative design value.

An alternative to lag factor with Marston's predicted load is *ultimate load* (i.e., prism load) with lag factor equal to unity. Time lag is discussed in much greater detail in Section 7.6.

Under most soil conditions, flexible PVC pipe tends to deflect into a nearly elliptical shape, and horizontal and vertical deflections may be considered equal for small deflections. Since most PVC pipe is described by either pipe stiffness (F/ΔY) or outside diameter-to-thickness ratio (DR), Equation 7.8, the modified Iowa equation, can be transposed and rewritten as follows:

Equation 7.9

$$\% \frac{\Delta Y}{D} = \frac{(D_L KP + KW')100}{0.149PS + 0.061E'}$$

where:

$\% \frac{\Delta Y}{D}$ = % pipe deflection, dimensionless
D_L = deflection lag factor, dimensionless
K = bedding constant, dimensionless
P = vertical soil pressure due to the prism load, psi
W′ = live load, psi
PS = pipe stiffness, psi
E = modulus of elasticity of the pipe material, psi
E′ = modulus of soil reaction, psi

For solid wall pipes the equation becomes:

Equation 7.10

$$\% \frac{\Delta Y}{D} = \frac{(D_L KP + KW')(100)}{[(2E/3)/(DR - 1)^3] + 0.061E'}$$

where:

DR = dimension ratio = D_o/t, dimensionless

7.5 Deflection Calculation Examples

Deflection calculations are performed using equations 7.9 and 7.10 in conjunction with the values for the empirical constants E′ and K, as found in Tables 7.2 and 7.3. In addition, Uni-Bell offers software for calculating pipe deflection.

Example 7.1

Find the predicted long-term deflection of a DR 35 PVC pipe buried on a flat-bottom trench in a slightly compacted fine-grained soil, given the following project conditions:

- Modulus of elasticity: 400,000 psi
- Pipe stiffness: 46 psi
- Soil unit weight: 120 lb/ft^3
- Liquid limit: less than 50%
- Burial depth: 10 ft.

Solution

From Table 7.3, $E' = 200$ psi. Bedding constant $K = 0.1$. Assume prism load, along with a deflection lag factor $D_L = 1.0$; the following results are obtained:

$$\%\frac{\Delta Y}{D} = \frac{(D_L KP + KW')100}{2E/[3(DR - 1)^3] + 0.061E'}$$

Given $P = wH$ and $W' = 0$ at a depth of 10 ft, calculate values of P and $\dfrac{2E}{3(DR - 1)^3}$

where:

w = soil unit weight, lb/ft^3
H = height of fill above top of pipe, ft

$$P = 120\,\frac{\text{lb}}{\text{ft}^3} \times 10\text{ ft} \times \frac{1\text{ ft}^2}{144\text{ in}^2} = 8.33\text{ in.}^2$$

$$\frac{2E}{3(DR - 1)^3} = \frac{2(400{,}000)}{3(35 - 1)^3} = 6.78\text{ psi}$$

$$\%\frac{\Delta Y}{D} = \frac{(1.0)(0.1)(8.33)(100)}{6.78 + (0.061)(200)} = 4.4\%$$

Now calculate deflection for an inside diameter-controlled profile pipe of the same stiffness (PS = 46 psi) and identical installation.

$$\%\frac{\Delta Y}{D} = \frac{(D_L KP + KW')100}{2E/[3(DR - 1)^3] + 0.061E'} = \frac{(1.0)(0.1)(8.33)(100)}{0.149(46) + 0.061(200)} = 4.4\%$$

When applicable, live loads should be added to the earth load to determine total load at the depth being considered.

In Table 7.4, results of calculations for deflections of buried AWWA PVC pipe are presented for cases in which live loads are present in combination with earth loads (prism load). In Table 7.5, similar results are shown for ASTM D3034 DR 35 PS46 sewer pipe.

Example 7.2

Suppose PVC sewer pipe (ASTM D3034 DR 35) with a minimum pipe stiffness of 46 psi is to be installed where the native soil is Class IV clay. Ninety percent of the line will be at depths as great as 20 ft. The engineer has selected 7.5% deflection as the design limit, consistent with the maximum identified in the Appendix of ASTM D3034.

Solution

Using Table 7.5, at a depth of 16 ft and an E′ = 200 psi, the calculated deflection is 7.02% (less than the maximum allowable deflection of 7.50%). Thus the native Class IV material could be used if it were compacted to 80% Proctor density. (Per Table 7.3, E′ = 200 psi for fine-grained soils with less than 25% coarse-grained particles and slight compaction.) However, groundwater conditions might make compaction difficult or impossible. If this is the case, imported material may be used with proper embedment procedures to limit deflection to less than 7.50%.

For the deeper portion of the line, Class III material could be imported and compacted to 80% Proctor density. (Again per table 7.3, E′ = 400 psi for fine-grained soils with more than 25% coarse-grained particles and slight compaction.) Expected maximum deflection at a depth of 20 ft would be 5.34%, considerably less than the allowable deflection.

7.6 Deflection Time Lag, Creep, and Stress Relaxation

Deflection time lag is the length of time that a buried flexible pipe will continue to deflect after the maximum imposed load is realized; it is a function of soil density in the pipe zone. As soil density at the sides of a pipe increases, the time during which the pipe will continue to deflect decreases, and so total deflection in response to load decreases.

Table 7.4 Calculated deflections of buried PVC pressure pipe; deflection (%) for prism, highway H20, and railway E80 loads

Height of cover, ft	**2**			**4**			**6**			**8**			**10**		
Load type	**Prism**	**H20**	**E80**	**Prism**	**H20**	**E80**	**Prism**	**H20**	**E80**	**Prism**	**H20**	**E80**	**Prism**	**H20**	**E80**
E′, psi	**DR 14**														
50	0.13	0.58	2.25	0.27	0.49	1.75	0.40	0.51	1.66	0.54	0.59	1.43	0.67	0.67	1.28
200	0.12	0.54	2.10	0.25	0.46	1.63	0.37	0.48	1.54	0.50	0.55	1.33	0.62	0.62	1.20
400	0.11	0.50	1.92	0.23	0.42	1.49	0.34	0.44	1.42	0.46	0.50	1.22	0.57	0.57	1.10
1000	0.09	0.40	1.54	0.18	0.34	1.19	0.27	0.35	1.13	0.37	0.40	0.97	0.45	0.46	0.88
2000	0.07	0.30	1.13	0.14	0.25	0.89	0.21	0.25	0.85	0.27	0.30	0.73	0.34	0.34	0.66
E′, psi	**DR 18**														
50	0.29	1.26	4.89	0.53	1.07	3.79	0.87	1.11	3.60	1.16	1.28	3.10	1.45	1.45	2.79
200	0.25	1.09	4.22	0.50	1.34	4.77	0.75	0.96	3.10	1.00	1.11	2.67	1.25	1.25	2.40
400	0.21	0.92	3.57	0.58	1.06	3.76	0.64	0.81	2.62	0.85	0.94	2.26	1.06	1.06	2.03
1000	0.14	0.63	2.43	0.35	0.65	2.30	0.43	0.55	1.79	0.58	0.64	1.54	0.72	0.72	1.39
2000	0.09	0.41	1.59	0.21	0.39	1.40	0.28	0.36	1.17	0.38	0.42	1.01	0.47	0.47	0.91
E′, psi	**DR 21**														
50	0.46	1.99	7.71	0.92	1.68	5.97	1.37	1.76	5.67	1.83	2.02	4.89	2.29	2.29	4.39
200	0.37	1.59	6.16	0.73	1.34	4.77	1.10	1.40	4.53	1.46	1.62	3.90	1.83	1.83	3.51
400	0.29	1.25	4.86	0.58	1.06	3.76	0.87	1.11	3.57	1.15	1.27	3.08	1.44	1.44	2.77
1000	0.18	0.77	2.97	0.35	0.65	2.30	0.53	0.68	2.19	0.71	0.78	1.88	0.88	0.88	1.69
2000	0.11	0.47	1.81	0.21	0.39	1.40	0.32	0.41	1.33	0.43	0.47	1.14	0.54	0.54	1.03
E′, psi	**DR 25**														
50	0.75	3.23	12.56	1.49	2.74	9.73	2.24	2.86	9.23	2.98	3.29	7.96	3.73	3.73	7.15
200	0.53	2.29	8.91	1.06	1.94	6.90	1.59	2.03	6.55	2.12	2.34	5.65	2.65	2.65	5.07
400	0.38	1.65	6.42	0.76	1.40	4.97	1.14	1.46	4.72	1.53	1.68	4.07	1.91	0.91	3.66
1000	0.21	0.90	3.49	0.42	0.76	2.71	0.62	0.80	2.57	0.83	0.92	2.21	1.04	1.04	1.99
2000	0.12	0.51	1.99	0.24	0.43	1.54	0.35	0.45	1.46	0.47	0.52	1.26	0.59	0.59	1.13

Table 7.4 Calculated deflections of buried PVC pressure pipe; deflection (%) for prism, highway H20, and railway E80 loads (*continued*)

Height of cover, ft	**2**			**4**			**6**			**8**			**10**		
Load type	**Prism**	**H20**	**E80**	**Prism**	**H20**	**E80**	**Prism**	**H20**	**E80**	**Prism**	**H20**	**E80**	**Prism**	**H20**	**E80**
E′, psi	**DR 26**														
50	0.83	3.59	13.95	1.66	3.04	10.80	2.49	3.18	10.26	3.31	3.66	8.84	4.14	4.14	7.94
200	0.57	2.47	9.59	1.14	2.09	7.43	1.71	2.18	7.05	2.28	2.51	6.07	2.85	2.85	5.46
400	0.40	1.74	6.77	0.80	1.47	5.24	1.21	1.54	4.98	1.61	1.77	4.29	2.01	2.01	3.85
1000	0.21	0.93	3.59	0.43	0.78	2.78	0.64	0.82	2.64	0.85	0.94	2.28	1.07	1.07	2.05
2000	0.12	0.52	2.02	0.24	0.44	1.56	0.36	0.46	1.48	0.48	0.53	1.28	0.60	0.60	1.15
E′, psi	**DR 32.5**														
50	1.44	6.24	24.22	2.88	5.28	18.77	4.32	5.52	17.81	5.76	6.35	15.35	7.20	7.20	13.79
200	0.80	3.49	13.53	1.61	2.95	10.48	2.41	3.08	9.95	3.22	3.55	8.57	4.02	4.02	7.70
400	0.51	2.19	8.52	1.01	1.86	6.60	1.52	1.94	6.26	2.02	2.23	5.40	2.53	2.53	4.85
1000	0.24	1.04	4.04	0.48	0.88	3.13	0.72	0.92	2.97	0.96	1.06	2.56	1.20	1.20	2.30
2000	0.13	0.55	2.15	0.26	0.47	1.66	0.38	0.49	1.58	0.51	0.56	1.36	0.64	0.64	1.22
E′, psi	**DR 41**														
50	2.31	10.01	38.88	4.62	8.47	20.12	6.93	8.85	28.59	9.24	10.19	24.63	11.55	11.55	22.13
200	1.02	4.42	17.14	2.04	3.74	13.28	3.05	3.90	12.60	4.07	4.49	10.86	5.09	5.09	9.76
400	0.58	2.53	9.82	1.17	2.14	7.61	1.75	2.24	7.22	2.33	2.58	6.22	2.92	2.92	5.59
1000	0.26	1.11	4.31	0.51	0.94	3.34	0.77	0.98	3.17	1.02	1.13	2.73	1.28	1.28	2.45
2000	0.13	0.57	2.22	0.26	0.48	1.72	0.40	0.51	1.64	0.53	0.58	1.41	0.66	0.66	1.27
E′, psi	**DR 51**														
50	3.22	13.94	54.13	6.43	11.79	41.93	9.65	12.33	39.80	12.86	14.19	34.30	16.06	16.06	30.82
200	1.16	5.04	19.57	2.33	4.27	15.16	3.49	4.46	14.39	4.65	5.13	12.40	5.81	5.81	11.14
400	0.63	2.72	10.57	1.26	2.30	8.19	1.88	2.41	7.78	2.51	2.77	6.70	3.14	3.14	6.02
1000	0.26	1.14	4.44	0.53	0.97	3.44	0.79	1.01	3.27	1.06	1.17	2.82	1.32	1.32	2.53
2000	0.13	0.58	2.26	0.27	0.49	1.75	0.40	0.51	1.66	0.54	0.59	1.43	0.67	0.67	1.29

Table 7.4 Calculated deflections of buried PVC pressure pipe; deflection (%) for prism, highway H20, and railway E80 loads (*continued*)

Height of cover, ft	**12**			**14**			**16**			**18**			**20**		
Load type	**Prism**	**H20**	**E80**	**Prism**	**H20**	**E80**	**Prism**	**H20**	**E80**	**Prism**	**H20**	**E80**	**Prism**	**H20**	**E80**
E′, psi	**DR 14**														
50	0.80	0.80	1.25	0.94	0.94	1.27	1.07	1.07	1.35	1.21	1.21	1.43	1.34	1.34	1.51
200	0.75	0.75	1.16	0.87	0.87	1.19	1.00	1.00	1.26	1.12	1.12	1.33	1.25	1.25	1.40
400	0.69	0.69	1.07	0.80	0.80	1.09	0.91	0.91	1.15	1.03	1.03	1.22	1.14	1.14	1.29
1000	0.55	0.55	0.85	0.64	0.64	0.87	0.73	0.73	0.92	0.82	0.82	0.97	0.91	0.91	1.03
2000	0.41	0.41	0.64	0.48	0.48	0.65	0.55	0.55	0.69	0.62	0.62	0.73	0.68	0.68	0.77
E′, psi	**DR 18**														
50	1.74	1.74	2.71	2.04	2.04	2.76	2.33	2.33	2.93	2.62	2.62	3.10	2.91	2.91	3.27
200	1.50	1.50	2.34	1.75	1.75	2.38	2.01	2.01	2.53	2.26	2.26	2.67	2.51	2.51	2.82
400	1.27	1.27	1.98	1.48	1.48	2.01	1.69	1.69	2.14	1.91	1.91	2.26	2.12	2.12	2.38
1000	0.87	0.87	1.35	1.01	1.01	1.37	1.16	1.16	1.46	1.30	1.30	1.54	1.45	1.45	1.63
2000	0.57	0.57	0.88	0.66	0.66	0.90	0.76	0.76	0.95	0.85	0.85	1.01	0.95	0.95	1.06
E′, psi	**DR 21**														
50	2.75	2.75	4.28	3.21	3.21	4.35	3.66	3.66	4.62	4.12	4.12	4.89	4.58	4.58	5.15
200	2.20	2.20	3.42	2.56	2.56	3.48	2.93	2.93	3.59	3.29	3.29	3.90	3.66	3.66	4.12
400	1.73	1.73	2.70	2.02	2.02	2.74	2.31	2.31	2.91	2.60	2.60	3.08	2.89	2.89	3.25
1000	1.06	1.06	1.65	1.24	1.24	1.68	1.41	1.41	1.78	1.59	1.59	1.88	1.77	1.77	1.99
2000	0.64	0.64	1.00	0.75	0.75	1.02	0.86	0.86	1.08	0.97	0.97	1.14	1.07	1.07	1.21
E′, psi	**DR 25**														
50	4.48	4.48	6.97	5.22	5.22	7.09	5.97	5.97	7.52	6.71	6.71	7.96	7.46	7.46	8.39
200	3.18	3.18	4.94	3.70	3.70	5.03	4.23	4.23	5.34	4.76	4.76	5.65	5.29	5.29	5.95
400	2.29	2.29	3.56	2.67	2.67	3.62	3.05	3.05	3.85	3.43	3.43	4.07	3.81	3.81	4.29
1000	1.25	1.25	1.94	1.45	1.45	1.97	1.66	1.66	2.09	1.87	1.87	2.21	2.08	2.08	2.33
2000	0.71	0.71	1.10	0.83	0.83	1.12	0.94	0.94	1.19	1.06	1.06	1.26	1.18	1.18	1.33

Table 7.4 Calculated deflections of buried PVC pressure pipe; deflection (%) for prism, highway H20, and railway E80 loads (*continued*)

Height of cover, ft	**12**			**14**			**16**			**18**			**20**		
Load type	**Prism**	**H20**	**E80**	**Prism**	**H20**	**E80**	**Prism**	**H20**	**E80**	**Prism**	**H20**	**E80**	**Prism**	**H20**	**E80**
E′, psi	**DR 26**														
50	4.97	4.97	7.73	5.80	5.80	7.87	6.63	6.63	8.35	7.46	7.46	8.84	8.29	8.29	9.32
200	3.42	3.42	5.32	3.99	3.99	5.41	4.56	4.56	5.74	5.13	5.13	6.08	5.69	5.69	6.41
400	2.41	2.41	3.75	2.81	2.81	3.82	3.22	3.22	4.05	3.62	3.62	4.29	4.02	4.02	4.52
1000	1.28	1.28	1.99	1.49	1.49	2.03	1.71	1.71	2.15	1.92	1.92	2.28	2.13	2.13	2.40
2000	0.72	0.72	1.12	0.84	0.84	1.14	0.96	0.96	1.21	1.08	1.08	1.28	1.20	1.20	1.35
E′, psi	**DR 32.5**														
50	8.63	8.63	13.43	10.07	10.07	13.67	11.51	11.51	14.51	12.95	12.95	15.35	14.39	14.39	16.19
200	4.82	4.82	7.51	5.63	5.63	7.64	6.43	6.43	8.11	7.24	7.24	8.58	8.04	8.04	9.04
400	3.04	3.04	4.72	3.54	3.54	4.81	4.05	4.05	5.10	4.55	4.55	5.40	5.06	5.06	5.69
1000	1.44	1.44	2.24	1.68	1.68	2.28	1.92	1.92	2.42	2.16	2.16	2.56	2.40	2.40	2.70
2000	0.77	0.77	1.19	0.89	0.89	1.21	1.02	1.02	1.29	1.15	1.15	1.36	1.28	1.28	1.44
E′, psi	**DR 41**														
50	13.86	13.86	21.56	16.17	16.17	21.94	18.48	18.48	23.28	20.79	20.79	24.64	23.09	23.09	25.98
200	6.11	6.11	9.5	7.13	7.13	9.68	8.15	8.15	10.27	9.16	9.16	10.86	10.18	10.18	11.45
400	3.50	3.50	5.45	4.08	4.08	5.54	4.67	4.67	5.88	5.25	5.25	6.22	5.83	5.83	6.56
1000	1.53	1.53	2.39	1.79	1.79	2.43	2.05	2.05	2.58	2.30	2.30	2.73	2.56	2.56	2.88
2000	0.79	0.79	1.23	0.92	0.92	1.26	1.06	1.06	1.33	1.19	1.19	1.41	1.32	1.32	1.49
E′, psi	**DR 51**														
50	19.29	19.29	30.02	22.51	22.51	30.55	25.72	25.72	32.42	28.94	28.94	34.30	32.15	32.15	36.17
200	6.98	6.98	10.86	8.14	8.14	11.05	9.30	9.30	11.72	10.47	10.47	12.40	11.63	11.63	13.08
400	3.77	3.77	5.86	4.40	4.40	5.97	5.03	5.03	6.33	5.65	5.65	6.70	6.28	6.28	7.07
1000	1.58	1.58	2.46	1.85	1.85	2.51	2.11	2.11	2.66	2.38	2.38	2.82	2.64	2.64	2.97
2000	0.81	0.81	1.25	0.94	0.94	1.28	1.07	1.07	1.35	1.21	1.21	1.43	1.34	1.34	1.51

Table 7.5 Calculated deflections of buried PVC gravity pipe; deflection (%) for prism, highway H20, and railway E80 loads

Height of cover, ft	**2**			**4**			**6**			**8**			**10**		
Load type	**Prism**	**H20**	**E80**	**Prism**	**H20**	**E80**	**Prism**	**H20**	**E80**	**Prism**	**H20**	**E80**	**Prism**	**H20**	**E80**
E′, psi	**Pipe Stiffness 46 psi**														
50	1.69	7.35	28.53	3.39	6.22	22.10	5.08	6.50	20.98	6.78	7.48	18.08	8.47	8.47	16.24
200	0.88	3.81	14.78	1.76	3.22	11.45	2.63	3.37	10.87	3.51	3.88	9.36	4.39	4.39	8.41
400	0.53	2.32	9.00	1.07	1.96	6.97	1.60	2.05	6.62	2.14	2.36	5.70	2.67	2.67	5.12
1000	0.25	1.07	4.14	0.49	0.90	3.21	0.74	0.94	3.04	0.98	1.09	2.62	1.23	1.23	2.36
2000	0.13	0.56	2.18	0.26	0.47	1.69	0.39	0.50	1.60	0.52	0.57	1.38	0.65	0.65	1.24
E′, psi	**Pipe Stiffness 75 psi**														
50	1.17	5.08	19.74	2.35	4.30	15.29	3.52	4.50	14.51	4.69	5.18	12.51	5.86	5.86	11.24
200	0.71	3.09	12.01	1.43	2.62	9.30	2.14	2.74	8.83	2.85	3.15	7.61	3.57	3.57	6.84
400	0.47	2.03	7.89	0.94	1.72	6.11	1.41	1.80	5.80	1.87	2.07	5.00	2.34	2.34	4.49
1000	0.23	1.00	3.89	0.46	0.85	3.01	0.69	0.89	2.86	0.92	1.02	2.46	1.15	1.15	2.21
2000	0.13	0.54	2.11	0.25	0.46	1.63	0.38	0.48	1.55	0.50	0.55	1.33	0.63	0.63	1.20
E′, psi	**Pipe Stiffness 115 psi**														
50	0.83	3.59	13.95	1.66	3.04	10.80	2.49	3.18	10.26	3.31	3.66	8.84	4.14	4.14	7.94
200	0.57	2.47	9.59	1.14	2.09	7.43	1.71	2.18	7.05	2.28	2.51	6.07	2.85	2.85	5.46
400	0.40	1.74	6.77	0.80	1.47	5.24	1.21	1.54	4.98	1.61	1.77	4.29	2.01	2.01	3.85
1000	0.21	0.93	3.59	0.43	0.78	2.78	0.64	0.82	2.64	0.85	0.94	2.28	1.07	1.07	2.05
2000	0.12	0.52	2.02	0.24	0.44	1.56	0.36	0.46	1.48	0.48	0.53	1.28	0.60	0.60	1.15

Table 7.5 Calculated deflections of buried PVC gravity pipe; deflection (%) for prism, highway H20, and railway E80 loads (*continued*)

Height of cover ft	**12**			**14**			**16**			**18**			**20**		
Load type	**Prism**	**H20**	**E80**	**Prism**	**H20**	**E80**	**Prism**	**H20**	**E80**	**Prism**	**H20**	**E80**	**Prism**	**H20**	**E80**
E′, psi	**Pipe Stiffness 46 psi**														
50	10.17	10.17	15.82	11.86	11.86	16.10	13.56	13.56	17.09	15.25	15.25	18.08	16.95	16.95	19.06
200	5.27	5.27	8.20	6.15	6.15	8.34	7.02	7.02	8.85	7.90	7.90	9.37	8.78	8.78	9.87
400	3.21	3.21	4.99	3.74	3.74	5.08	4.28	4.28	5.39	4.81	4.81	5.70	5.34	5.34	6.01
1000	1.48	1.48	2.30	1.72	1.72	2.34	1.97	1.97	2.48	2.21	2.21	2.62	2.46	2.46	2.77
2000	0.78	0.78	1.21	0.91	0.91	1.23	1.04	1.04	1.30	1.16	1.16	1.38	1.29	1.29	1.46
E′, psi	**Pipe Stiffness 75 psi**														
50	7.04	7.04	10.95	8.21	8.21	11.14	9.38	9.38	11.82	10.55	10.55	12.51	11.73	11.73	13.19
200	4.28	4.28	6.66	4.99	4.99	6.78	5.71	5.71	7.19	6.42	6.42	7.61	7.13	7.13	8.02
400	2.81	2.81	4.38	3.28	3.28	4.45	3.75	3.75	4.72	4.22	4.22	5.00	4.69	4.69	5.27
1000	1.39	1.39	2.16	1.62	1.62	2.19	1.85	1.85	2.33	2.08	2.08	2.46	2.31	2.31	2.60
2000	0.75	0.75	1.17	0.88	0.88	1.19	1.00	1.00	1.26	1.13	1.13	1.34	1.25	1.25	1.41
E′, psi	**Pipe Stiffness 115 psi**														
50	4.97	4.97	7.73	5.80	5.80	7.87	6.63	6.63	8.35	7.46	7.46	8.84	8.29	8.29	9.32
200	3.42	3.42	5.32	3.99	3.99	5.41	4.56	4.56	5.74	5.13	5.13	6.08	5.69	5.69	6.41
400	2.41	2.41	3.75	2.81	2.81	3.82	3.22	3.22	4.05	3.62	3.62	4.29	4.02	4.02	4.52
1000	1.28	1.28	1.99	1.49	1.49	2.03	1.71	1.71	2.15	1.92	1.92	2.28	2.13	2.13	2.40
2000	0.72	0.72	1.12	0.84	0.84	1.14	0.96	0.96	1.21	1.08	1.08	1.28	1.20	1.20	1.35

In fact, after trench load reaches a maximum, the pipe-soil system continues to deflect only as long as the soil around the pipe is in the process of consolidation. Once the granular pipe embedment soil has reached the density required to support the load, the pipe will not deflect further.

The full load on any buried pipe is not reached immediately after installation unless the final backfill is compacted to a high density. For a pipe with good flexibility, long-term load will not exceed the prism load. The increase in load with time is the largest contribution to increasing deflection. Therefore, for design, prism load should be used, thus effectively compensating for increased trench consolidation load over time and resulting in increased deflection. When deflection calculations are based on prism loads, deflection lag factor (D_L) should be 1.0.

Creep is normally defined as continuing deformation with time when a material is subjected to a constant load. Most plastics exhibit creep to some extent, and as temperature increases so too does creep rate under a given load. Similarly, as stress increases, so too does creep rate for a given temperature. As PVC creeps, it also relaxes with time. *Stress relaxation* may be defined as the decrease in stress with time in a material held at constant deformation.

Figure 7.6 shows stress relaxation curves for PVC pipe samples held in a constant deflection condition, showing that PVC pipe does relax with time. The highest stress in buried PVC nonpressure pipe is encountered at the equilibrium deflection condition. The behavior demonstrated in Fig. 7.6 results in a decrease in the actual pipe stress at that deflection.

Figure 7.7 shows long-term deflection data for PVC pipe buried in a soil box. The data were obtained in long-term deflection tests by imposition of a given soil load, held constant throughout the duration of the test. Results show that PVC pipe material creep properties have little influence on deflection lag, but soil properties (such as density) exert great influence.

The physical properties of PVC pipe vary with temperature. For PVC pipe, the approximate relationships of pipe strength properties vs. temperature are shown in Fig. 7.8. (Note: This figure is the same as Fig. 7.2.)

Temperature controlled tests on buried PVC pipe were conducted to determine the effect of temperature on long-term piping system behavior. Figure 7.9 illustrates this test, in which pipe was placed in a load cell, embedded in soil, and compacted to a specified percentage of Proctor density. The load on the soil was then increased until the desired starting vertical deflection of the pipe was reached. At this point, the load as well as temperature were held constant and the resulting time-dependent deflection was determined.

Data from the tests illustrated in Fig. 7.9 are shown in graphical form in Fig. 7.10. Four tests were initiated at approximately 5% deflection, an arbitrary amount, and two were started between 9 and 9.5% deflection. The loads required to produce these deflections were different in each case. The limiting deflection and the time required to reach

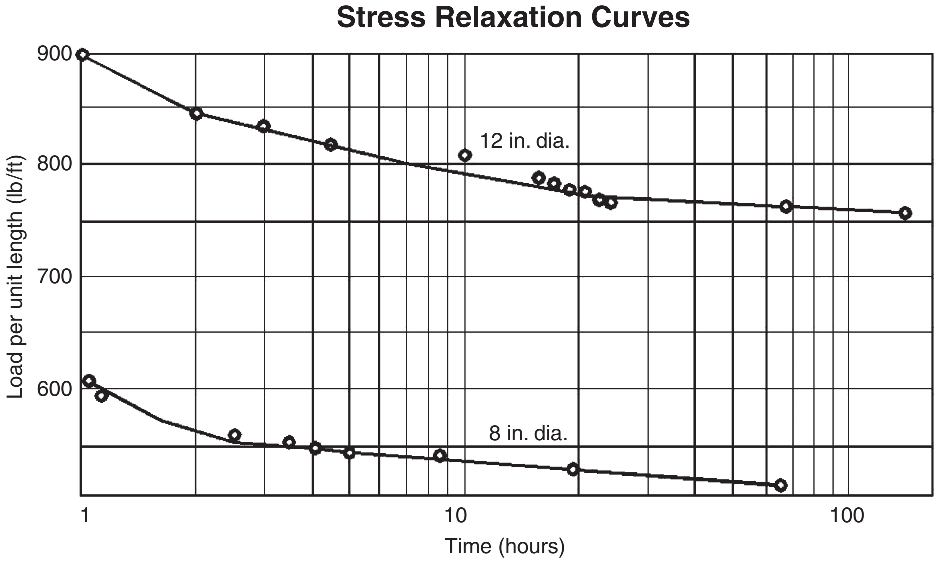


Fig. 7.6 Stress relaxation curves (load as a function of time for a constant ring deflection of 20%). Source: Utah State University

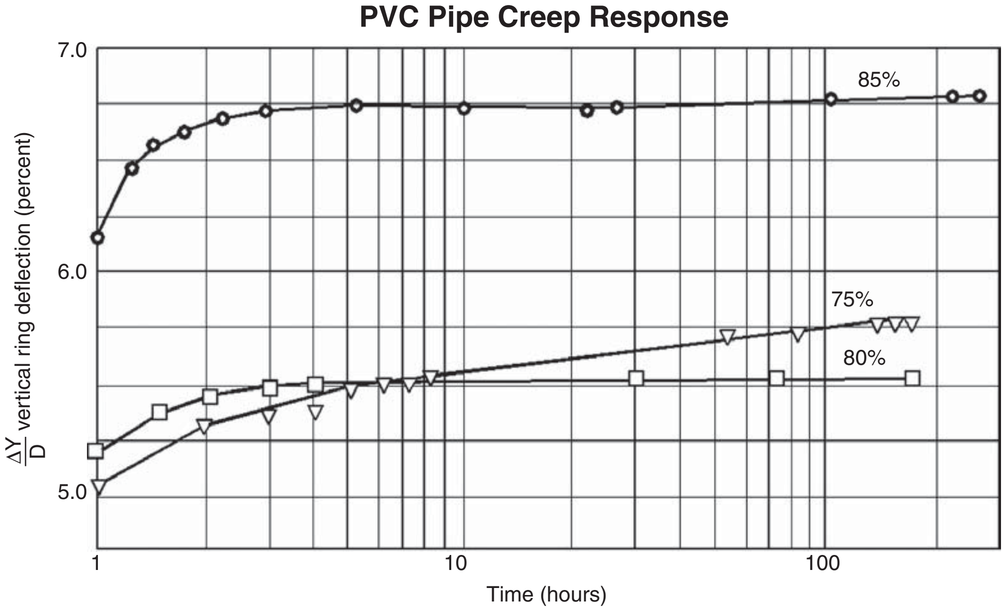


Fig. 7.7 PVC pipe creep response: time vs. vertical ring deflection for three soil densities, as percent of standard Proctor density. Source: Utah State University

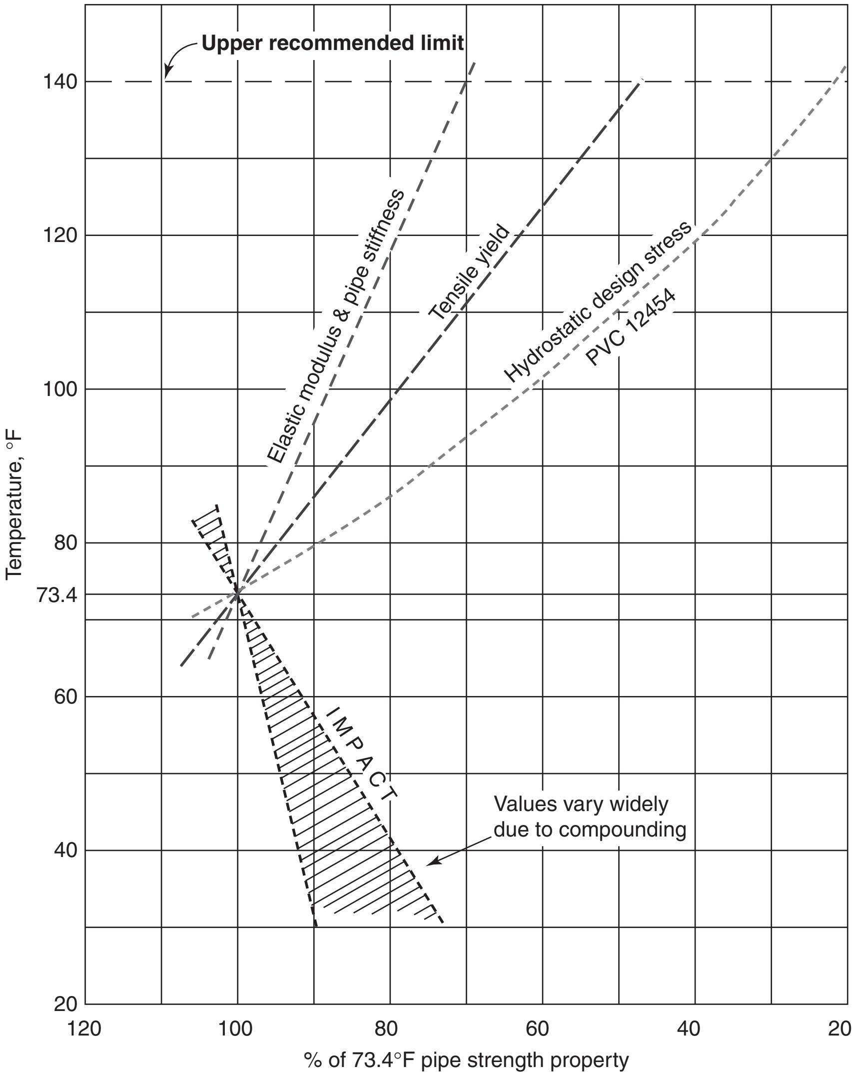


Fig. 7.8 Approximate relationship for 12454 PVC flexible pipe strength properties vs. temperature.

it were largely controlled by the soil density. It is interesting to note for tests at different temperatures with the same soil density that:

- equilibrium deflection is slightly larger for higher temperatures because effective pipe stiffness is lower;
- time for equilibrium to be reached is shorter for higher temperatures, since the soil-pipe system can interact at a faster rate to achieve it;
- an equilibrium deflection is reached in all cases; for the temperature range tested, an equilibrium state was reached and the pipe did not deflect beyond it.

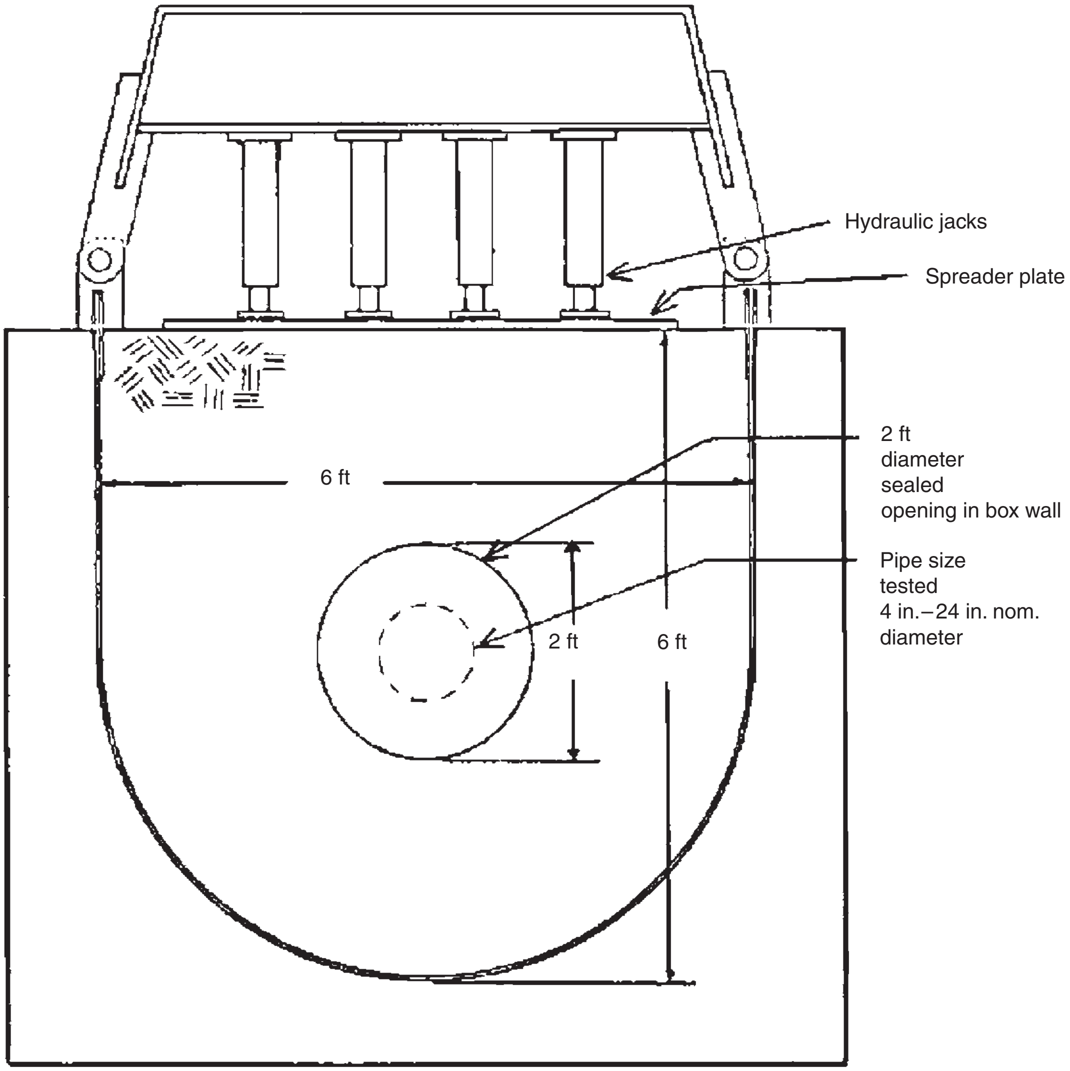


Fig. 7.9 Cell cross-section. Source: Utah State University

Long-term tests were carried out in a soil cell, where imposed load on a pipe is almost instantaneous due to the fact that the loading plane is only about 30 in. (760 mm) above the pipe. This provides a significant advantage over tests in either trench or embankment conditions, in which a substantial amount of time is needed for the full load to reach the pipe—as much as days, months, or years. When long-term tests are carried out in trenches or embankments, change in deflection with time is due to increasing loads and soil consolidation. Change in deflection with time in embankment condition is greater than what is measured in soil cell tests because the latter are constant load tests. The essential point

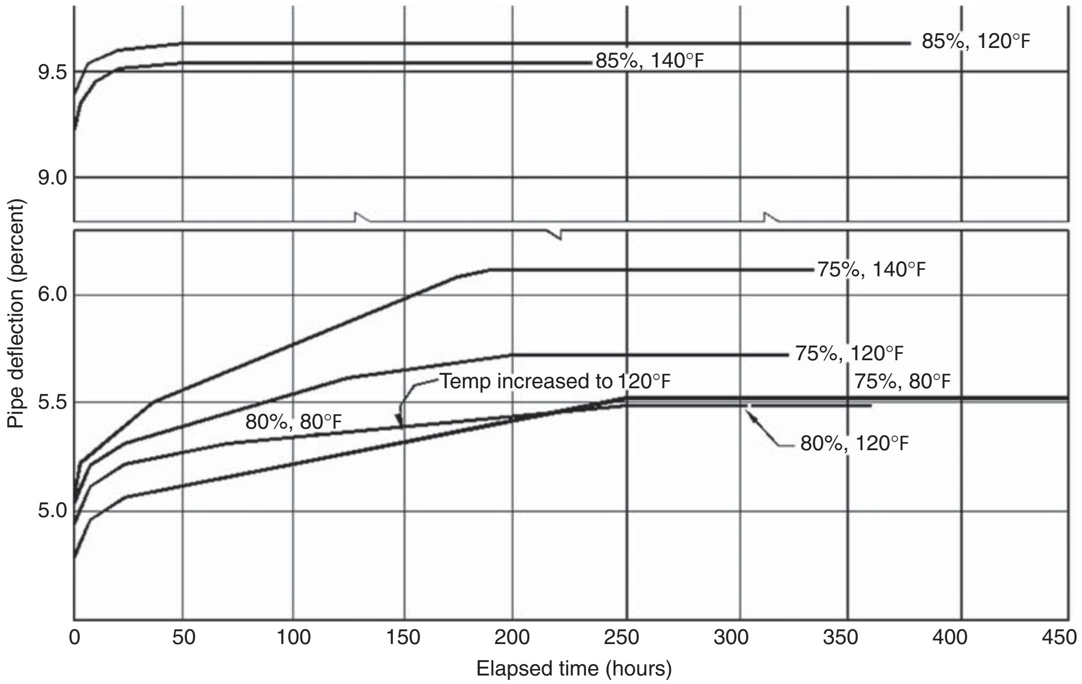


Fig. 7.10 Time-deflection curves in temperature-controlled soil cell test.

is that equilibrium deflections are the same for embankment conditions as they are for soil cell conditions.

Other factors, either manmade (such as live loads) or environmental (such as groundwater) can result in load increases after initial deflection equilibrium. The result is an incremental deflection increase until side-soil consolidation is sufficient to reestablish equilibrium. Figure 7.11 represents deflection vs. time results over a 15-year period for 10-in. diameter PVC nonpressure pipe. The deflection increase at 150 days (3.6×10^3 hours) after installation was due to the spring groundwater table reaching the pipe zone. Note that incremental increase is followed by renewed equilibrium.

Figure 7.12 depicts long-term deflection data obtained for PVC pipes over a 5-year period. All significant deflection occurs in the first few weeks while load and embedment stiffness reach equilibrium.

Extensive research has established that any buried flexible pipe (e.g., steel, fiberglass, thermoplastics, ductile iron) will continue to deflect as long as the surrounding soil consolidates. Thus, as previously stated, creep properties of pipe materials have little effect on long-term deflection behavior of flexible pipe buried in soil. In most cases a deflection lag factor (DL) of 1.5 conservatively accounts for long-term effects of soil consolidation. Alternatively, design can be based upon the anticipated prism load and a D_L of 1.0.

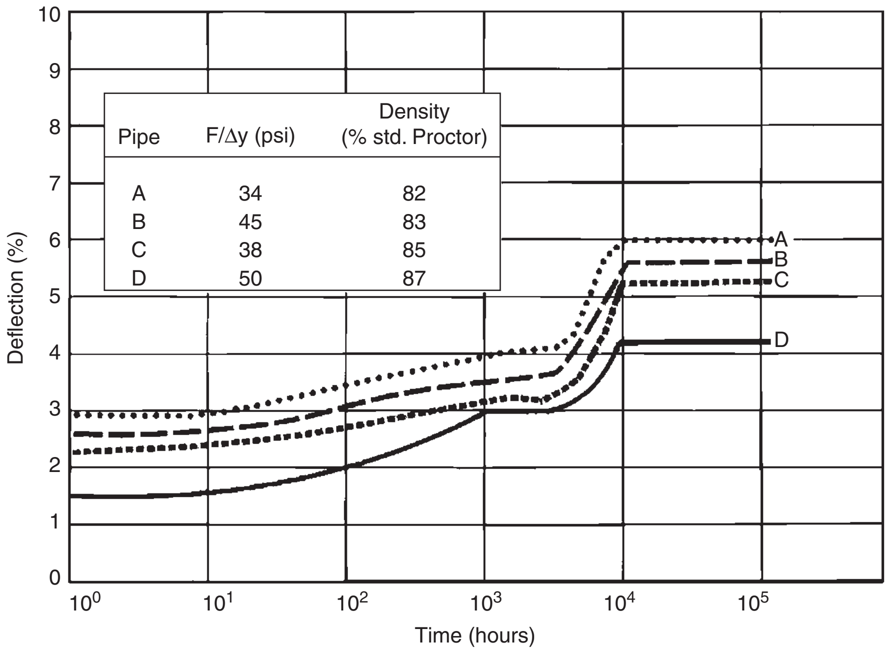


Fig. 7.11 Deflection vs. time for 10-in. diameter PVC sewer pipe (22-ft deep embankment, installed September 1975).

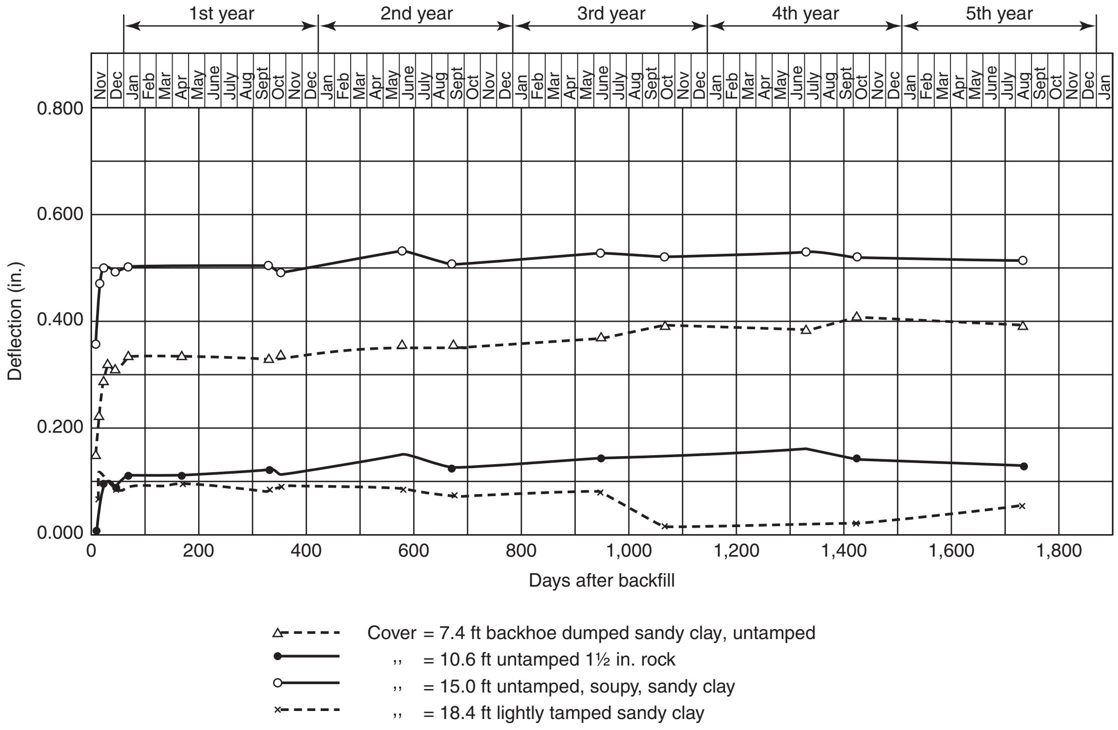


Fig. 7.12 Deflection vs. time for buried PVC pipes.

7.7 Empirical Methods

Methods discussed so far for determining load and deflection require experimental investigation to determine any unknown constants. When a pipe with good flexibility is buried, static pressure will not be greater than the prism load pressure applied. Calculation of actual pressure loading frustrated researchers for years; but when pipe was installed and tested in a known loaded condition (i.e., soil cell), the resulting deformation could be monitored without the actual static pressure being calculated.

Since the 1970s, this procedure has been validated in laboratory and field tests by Utah State University, the U.S. Bureau of Reclamation, and elsewhere. The data obtained in this manner can be used directly in the design of pipe-soil systems and in the prediction of overall performance. Ring buckling and over-deflection are evaluated simultaneously by actual tests. No explanation of the pipe-soil interaction phenomenon is necessary, and the results leave nothing to be estimated on the basis of judgment.

For example, if tests show that for a given soil compaction at 25 ft (7.6 m) of cover, a flexible pipe deflects 3% and in every other way performs well, actual load on the pipe and soil modulus are academic. Thus, a pipe installation can be designed with a known safety factor, provided that enough empirical test data are available.

In the collection of data, pipe was installed in a manner similar to that used in actual practice and height of cover was increased until performance levels were exceeded. The procedure was repeated many times and a reliable empirical curve of pipe performance versus height of fill was plotted. The use of such empirical curves or data eliminates the need to determine actual soil pressure, since pipe performance as a function of cover height is determined directly. Alternate empirical approaches to deflection mechanism study are:

- study of actual field installations;
- simulation of an earth cover in a soil test box large enough to exceed performance limits of the pipe.

It would be difficult to generate data for the wide variety of installation conditions found in the field. One alternative is to carefully choose design bases to cover the governing installed-pipe parameters. Critical design bases are:

- Embankment condition—results are conservative for any other scenario.
- Long-term deflection—time-lag factors are included.

An added advantage of this approach is that performance limits such as ring crushing, ring deflection, and strain and wall buckling can be analyzed by means of a single test.

Figures 7.13 and 7.14 compare the expected pipe deflection for two PVC pipe stiffnesses. Note the advantage of a higher stiffness pipe in poor soils. These graphs were developed using Uni-Bell's software for calculating deflection.

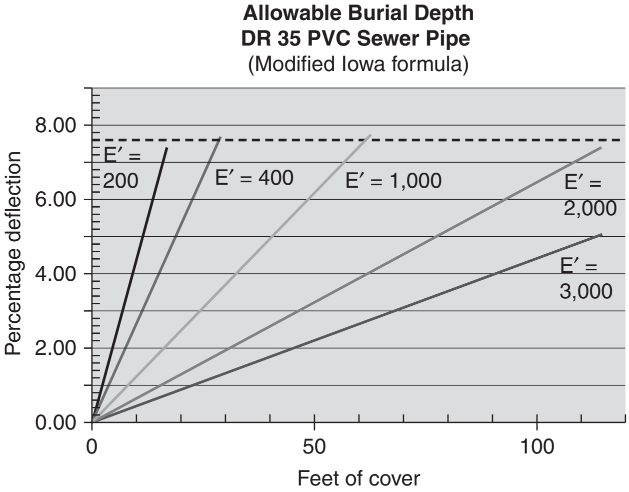


Fig. 7.13 Allowable burial depth for DR 35 PVC sewer pipe.

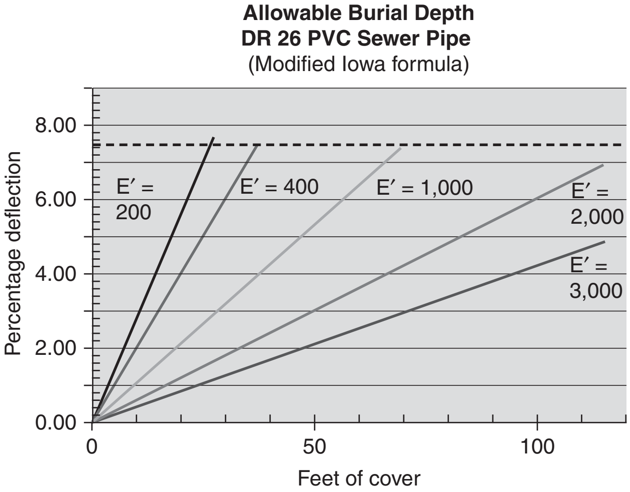


Fig. 7.14 Allowable burial depth for DR 26 PVC sewer pipe.

7.8 Performance Limits

7.8.1 Overview

Performance limits are established to prevent those conditions which may jeopardize the effective operation of a pipeline. The following is a list of performance limits considered in pipeline design:

- stress
- fatigue

- reverse curvature
- longitudinal bending
- ring buckling
- localized profile buckling
- wall crushing
- strain.

7.8.2 Stress Performance Limit

Stress performance limit describes any internal pressure application in which hoop stresses in pipe wall due to applied pressure exceeds pipe design strength. Stress performance limit for PVC pipe is discussed in Chapter 5.

7.8.3 Fatigue Performance Limit

Although *fatigue performance limit* may be a consideration in both pressure and gravity flow pipe applications, most potable water distribution systems and gravity flow sanitary systems function under conditions that do not warrant consideration of fatigue as a performance limit. PVC is similar to most materials in that it can fail at stresses lower than its material strength otherwise indicates if a repeating stress application occurs at a sufficiently high frequency and magnitude on a continuous basis over a period of time. Cyclic stress variations can be induced internally by surge pressures and water hammer effects, or stress cycles can be caused from external loads such as traffic loadings on pipelines at shallow burial depths.

Performance of PVC sewer pipe exposed to dynamic loadings at shallow depths was evaluated at the Geotechnical Laboratory, U.S. Army Engineer Waterways Experiment Station. Figure 7.15 shows results typical of the evaluation; from these it was concluded that PVC (DR 35) pipe performed very well under a range of loadings representative of highway and light to medium aircraft traffic. All tests were performed under a flexible bituminous road surface.

A minimum cover height of 12 in. is recommended for PVC (DR 35) pipe subjected to highway loads of up to 18 kip axle. Under light to medium aircraft loads of up to 320,000-lb gross weight, a minimum burial depth of 2 ft is recommended. To prevent cracking of the road surface special attention should be given to the selection, placement, and compaction of backfill material around shallow buried flexible pipe (such as PVC pipe) lying underneath rigid pavement (see Chapter 12).

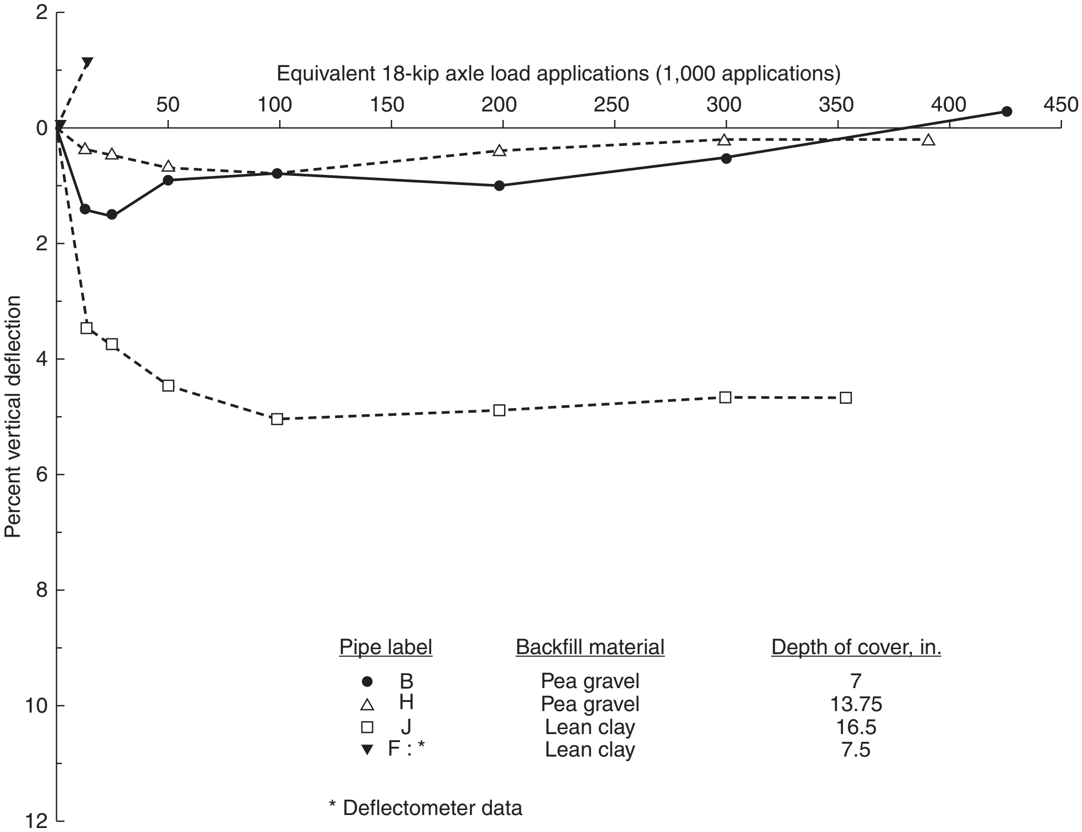


Fig. 7.15 Permanent deflection of a 12-in. PVC pipe as a function of traffic. Source: FAA-RD-79-86

7.8.4 Reverse Curvature Performance Limit

A *reverse curvature performance limit* for flexible steel pipe was established shortly after publication of the Iowa formula, when it was determined that corrugated steel pipe would begin reverse curvature at a deflection of about 20%. Design at that time called for a limit of 5% deflection, thereby providing a structural safety factor of 4.0.

Buried PVC sewer pipe (ASTM D3034 DR 35), deflecting in response to external loading, may develop the beginnings of recognizable reversal of curvature at 30% deflection. This level of deflection has been commonly designated as a conservative performance limit for PVC sewer pipe. Research has demonstrated that load-carrying capacity of PVC sewer pipe continues to increase even when deflection increases substantially beyond the point of curvature reversal. Considering this performance characteristic of PVC sewer pipe, engineers generally consider the 7.5% deflection limit recommended in the Appendix of ASTM D3034 as providing a very conservative factor of safety against structural failure. Similar to the methodology applied to steel pipe, the resulting structural safety factor for PVC sewer pipe is 4.0.

7.8.5 Longitudinal Bending Performance Limit

Whether intentional or unintentional, longitudinal bending of a pipeline should always be controlled. Unlike "rigid pipes" PVC pipe will not break in flexure, but it will bend. Such bending does not impair PVC pipeline performance, and only short radius bends should be considered performance-limiting for PVC pipe. See Chapter 8 for more on longitudinal bending.

7.8.6 Ring Buckling Performance Limit

Ring buckling may govern design of flexible pipes under conditions of internal vacuum, subaqueous installation, or loose soil burial. For a circular ring subjected to uniform external pressure or internal vacuum, *critical buckling pressure* (P_{cr}) is defined by Timoshenko as:

Equation 7.11

$$P_{cr} = \frac{3EI}{r^3} = 0.447\,PS$$

where:

P_{cr} = critical buckling pressure, psi

E = modulus of elasticity of pipe material, psi

I = moment of inertia of wall cross-section per unit length of pipe, in.^{4}/in.

r = mean pipe radius, in.

PS = pipe stiffness, psi

With moment of inertia (I) defined as $t^3/12$ for solid wall pipe, Equation 7.11 becomes:

Equation 7.12

$$P_{cr} = \frac{2E}{[(D_o - t)/t]^3} = \frac{2E}{(DR - 1)^3}$$

where:

D_o = pipe outside diameter, in.

t = pipe wall thickness, in.

DR = dimension ratio, dimensionless

For long tubes (pipelines) under combined stress, E is replaced by $E/(1 - \nu^2)$, where ν = Poisson's ratio: the ratio of unit lateral contraction to unit axial elongation. In this case, critical buckling pressure is:

Equation 7.13

$$P_{cr} = \frac{3EI}{(1 - \nu^2)r^3} = \frac{0.447\,PS}{(1 - \nu^2)}$$

where:

ν = Poisson's ratio, dimensionless = 0.38 for PVC pipe

For solid wall pipes:

Equation 7.14

$$P_{cr} = \frac{2E}{(1 - \nu^2)(DR - 1)^3} = \frac{2E}{(1 - \nu^2)}\left(\frac{t}{D_o - t}\right)^3 = \frac{2E}{(1 - \nu^2)(D/t)^3}$$

where:

D = mean pipe diameter, in. = $D_o - t$.

Since mean pipe radius (r) is equal to D/2, Equation 7.14 can be expressed as:

Equation 7.15

$$P_{cr} = \frac{E}{4(1 - \nu^2)}\left(\frac{t}{r}\right)^3$$

Pipes that are significantly out-of-round or deflected have less buckling resistance than round pipes. Critical buckling pressure for these elliptical shapes can be determined by using a reduction factor ("C"), shown graphically in Fig. 7.16, in order to account for the pipe's in-service shape. Here, critical buckling pressure is given by:

Equation 7.16

$$P_{cr} = C\frac{3EI}{(1 - \nu^2)r^3} = C\frac{0.447\,PS}{(1 - \nu^2)}$$

where:

C = reduction factor, dimensionless

For solid wall pipes, critical buckling pressure is:

Equation 7.17

$$P_{cr} = \frac{2CE}{(1 - \nu^2)\left(\frac{D}{t}\right)^3} = \frac{CE}{4(1 - \nu^2)}\left(\frac{t}{r}\right)^3$$

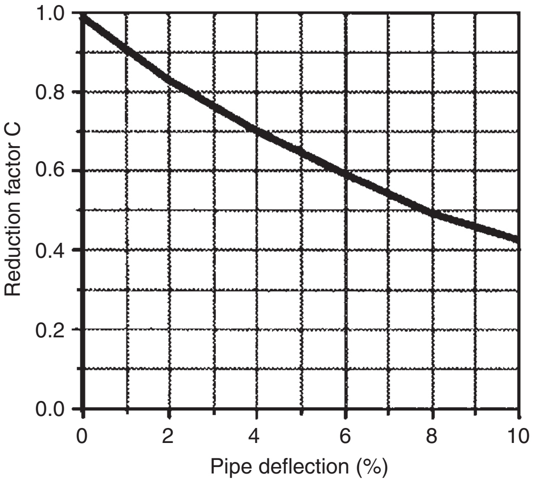


Fig. 7.16 Critical buckling pressure reduction factor C for shape.

According to Janson, when pipes are buried or installed in a way that allows soil or surrounding medium to provide some resistance against buckling or deflection, the buckling pressure (P_b) in the soil is found to be:

Equation 7.18

$$P_b = 1.15\sqrt{P_{cr}E'}$$

where:

P_b = buckling pressure in a given soil, psi
E' = modulus of soil reaction, psi

Example 7.3

If a DR 35 PVC sewer pipe with a 400,000 psi modulus of elasticity is confined in a saturated soil providing $E' = 800$ psi, what height (H) of the saturated soil with density 120 lb/ft^3 (w) would cause buckling? What maximum cover height ensures that deflection $\%\Delta Y/D$ does not exceed 7.5%? Assume bedding angle of zero ($K = 0.11$).

Solution

Find first the critical buckling pressure, using Equation 7.14:

$$P_{cr} = \frac{2E}{(1-\nu^2)(DR-1)^3} = \frac{2(400{,}000)}{[1-(0.38)^2](35-1)^3} = 23.8 \text{ psi}$$

Then, determine the buckling pressure in this soil:

$$P_b = 1.15\sqrt{(23.8)(800)} = 158.7 \text{ psi} = 22{,}850 \text{ lb/ft}^2$$

This is, then, the prism load (P_v), which is used to find maximum cover height H:

$$H = P_v/w = 22{,}850/120 = 190 \text{ ft}$$

where:

H = height of fill above top of pipe, ft

P_v = vertical soil pressure due to the prism load, lb/ft^2

To limit deflection %ΔY/D to 7.5%, maximum cover height (H) is found via prism load pressure (i.e., pressure of vertical column of soil) using Eq 7.9 with W′ = 0:

$$w = \text{Soil unit weight, lb/ft}^3$$

$$\%\Delta Y/D = \frac{KP_v(100)}{0.149\,PS + 0.061E'}$$

$$P_v = \frac{\%\Delta Y/D(0.149\,PS + 0.061E')}{100K} = \frac{7.5[(0.149)(46) + (0.61)(800)]}{(100)(0.11)}$$

$$= 37.9 \text{ psi} = 5{,}464 \text{ lb/ft}^2$$

Thus,

$$H \text{ (to limit deflection)} = 5{,}464/120 = 45.5 \text{ ft}$$

Maximum cover is limited by the allowable deflection, not by buckling. Therefore, the safety factor for the critical failure mode by buckling of DR 35 PVC pipe is ample.

7.8.7 Localized Profile Buckling Performance Limit

Localized profile buckling is known to be a design-limiting issue for some thermoplastic pipes. Evaluations of profile PVC pipe have shown that localized buckling is not a factor.

7.8.8 Wall-Crushing Performance Limit

Research has established that flexible steel pipe walls can buckle at deflections considerably less than 20% if load is large and the soil surrounding the pipe is extremely compacted. Based on these observations, H. L. White and J. P. Layer proposed the *ring compression* *theory* for the design of buried flexible pipes. This theory assumed that the backfill was highly compacted, that deflection would be negligible, and that the performance limit was wall-crushing. The design concept is expressed by the following equations:

Equation 7.19

$$T = P \times \frac{D_o}{2}$$

where:

T = wall thrust, lb/in.
P = vertical soil pressure due to prism load, psi
D_o = pipe outside diameter, in.

Equation 7.20

$$\sigma_c = \frac{T}{A}$$

where:

σ_c = compressive stress, psi
A = area of the pipe wall longitudinal cross-section, in.^{2}/in.

Example 7.4

A profile wall PVC pipe ($D_o = 19.15$ in., $A = 2.503$ in^2/ft) is concrete-cradled. At what vertical soil pressure or depth of cover (H) could failure be expected by ring compression? ($w = 120$ lb/ft^3)

$$\sigma_c = \frac{T}{A}, \qquad P = wH$$

Solution

Conservatively, assume σ_c = hydrostatic design basis = hoop tensile = 4,000 psi.

$$P = \frac{2\sigma_c A}{D_o} = \frac{(2)(4{,}000)(2.503/12)}{19.15} = 87.1 \text{ psi} = wH$$

Hence,

$$H = \frac{P}{w} = \frac{87.1 \text{ lb/in}^2}{120 \text{ lb/ft}^3} \times \frac{144 \text{ in}^2}{\text{ft}^2} = 104.5 \text{ ft}$$

This example easily illustrates that ring compression is not a governing factor in design of either PVC water or sewer pipe systems.

7.8.9 Strain Performance Limits

Strain is generally not a performance-limiting factor for buried PVC pipe. Total strain in a pipe wall can be caused by two actions: (1) hoop stress in the pipe wall; (2) flexure of the pipe as it deforms. Determination of strains due to hoop stress is straightforward: If a homogeneous wall is assumed and pressure concentrations are neglected, the formula for strain due to hoop stress is:

Equation 7.21

$$\varepsilon_h = \frac{P_c D}{2AE}$$

where:

ε_h = maximum strain in pipe wall due to hoop stress, in./in.
P_c = circumferential pressure (internal and/or external, with appropriate sign), psi
D = mean pipe diameter, in.
E = modulus of elasticity of pipe material, psi

For solid wall pipe, Equation 7.21 becomes:

Equation 7.22

$$\varepsilon_h = \frac{P_c D}{2tE}$$

where:

t = pipe wall thickness, in.

Maximum strain due to ring deflection or *flexure* may be determined if the assumption is made that the pipe remains ellipsoidal during deflection. The resulting equation for *flexural strain* is:

Equation 7.23

$$\varepsilon_f = \frac{C_{max}}{r}\left(\frac{3\Delta Y/D}{1 - 2\Delta Y/D}\right)$$

where:

ε_f = maximum strain in pipe wall due to ring deflection or flexure, in./in.
C_{max} = distance from the neutral axis to the extreme fiber, in.
r = mean pipe radius, in.
ΔY = vertical deflection, in.

Again, for solid wall pipes, Equation 7.23 becomes:

Equation 7.24

$$\varepsilon_f = \frac{t}{D}\left(\frac{3\Delta Y/D}{1 - 2\Delta Y/D}\right) = \frac{1}{DR}\left(\frac{3\Delta Y/D}{1 - 2\Delta Y/D}\right),$$

where:

DR = dimension ratio, dimensionless

In a buried pipeline, the ε_h and ε_f strain components act simultaneously. The *maximum combined strain* (denoted by ε_c) in the pipe wall is determined by summing both components (Equation 7.25):

Equation 7.25

$$\varepsilon_c = \varepsilon_f + \varepsilon_h$$

where:

ε_c = maximum combined strain in pipe wall, in./in.

PVC pipe is more tolerant of compression strains than tension strains, as the latter, when extensive, can cause PVC pipe to crack. Hoop tension strain from applied internal pressure, if any, should be added to maximum flexure strain from ring deflection in calculations of maximum combined strain. Conversely, ring compression strains from external soil loads should be subtracted to obtain the maximum combined strain.

In extensive investigations of PVC sewer pipe subjected to constant strain caused by deflection, it was found that the strain in the pipe material caused by deflections up to 20% did not give rise to failure within a 50-year period. In fact, the ultimate test—history—has demonstrated PVC pipe to be successful in sanitary sewer conditions where it has been in continuous use since 1962.

In the Janson investigation, 16 samples of PVC sewer pipe were deflected as much as 25%, corresponding to a relative strain in the pipe wall of 0.025 in./in. (2.5%). None of the 16 pipe samples, which were stored in both pure water and water with 2% detergent, showed failures or cracks after a loading exposure time of more than 22 years.

In the Moser investigation, strips and rings of PVC obtained from PVC pipe in both the longitudinal and the circumferential direction were tested under severe uniform-strain conditions (which are more critical than the bending strain associated with deflected buried pipe). After more than 22 years of observation, there was no indication that any of the circumferential samples strained to 5, 10, 15, 25, 40, or 50% deflection would fail in the future. In fact, longitudinal specimens were able to withstand constant strains approaching 100%. It is thus concluded that strain is not a practical design-limiting criterion for PVC pipelines.

7.9 Sewer Pipe Longevity

The design life of a PVC sewer is a direct result of the many advantages afforded by a durable plastic piping material. As a durable plastic, PVC provides chemical resistance and immunity to corrosion—properties that ultimately enhance the lifespan of a properly designed and installed system (see Chapter 3). In practice, PVC pipe has performed better than other traditional piping materials. In fact, to verify PVC's durability, in-service pipes have been unearthed in Europe and North America to determine the effect of aging on physical properties and joint performance.

PVC sewer pipes in Europe, some of which had been in service for 28 years, were uncovered in locations where installation had been done poorly or in conditions where the pipe had been overloaded. Thus, most samples were pipes that had been performing beyond design limits. The deflections were measured as high as 22% at test sites. In most cases these extreme deflections were the result of large rocks within the backfill, which had acted as point loads on the pipe. Test results verified that even though the majority of pipes had been loaded in such a severe manner, none had sustained structural damage or experienced failure. The tests performed on the samples included pipe stiffness, strain ability, abrasion, and joint performance.

Similar research was commissioned by Uni-Bell in 1990, in which a sample of 10-in. DR 35 sewer pipe was excavated and tested. Despite the fact that the pipe had been in service for 15 years and testing standards had changed within that time frame, the pipe was tested according to current requirements, and it proved to be in compliance with all requirements except outside diameter, which was found to be below the listed dimensional tolerance by 0.002 in.

These studies demonstrate that PVC pipes maintain their excellent structural characteristics and watertight joints in less than ideal conditions, affirming the suitability of PVC sewer pipe as a long-life product.

7.10 Alternative Design Methods

Several other methods for the design of flexible nonpressure pipes have been proposed, the more notable of which are included in this section in a general overview. Any design check using these alternatives may require more detailed information.

7.10.1 Watkins's Soil Strain Theory

A number of variations of the Iowa deflection formula have been developed, any of which can be described as:

$$\text{deflection} = \frac{\text{load}}{\text{pipe stiffness} + \text{soil stiffness}}$$

Upon analyzing data from many tests, Watkins rewrote the Iowa formula in terms of dimensionless ratios as follows:

Equation 7.26

$$\%\frac{\Delta Y}{D} = \frac{PR_s}{E_s(AR_s + B)}$$

where:

$\%\Delta Y/D$ = percent pipe deflection, dimensionless

A, B = empirical constants, which include terms such as D_L and K of the Iowa formula, dimensionless

P = vertical soil pressure due to the prism load, psi

R_S = stiffness ratio, dimensionless

R_S includes all properties of materials, soil as well as pipe:

$$R_s = \frac{E_s}{EI/D^3}$$

where:

$E_S = P/\varepsilon$, psi = slope of the stress-strain curve for soil at load in question in one-dimensional consolidation test

ε = vertical soil strain, in./in.

E = modulus of elasticity of pipe material, psi

I = moment of inertia of wall cross-section per unit length of pipe, $\text{in.}^4/\text{in.}$

D = mean pipe diameter, in.

For a solid wall pipe of constant cross-section, $I = t^3/12$. Then, the stiffness ratio is:

$$R_s = \frac{12E_sD^3}{Et^3}$$

where:

t = pipe wall thickness, in.

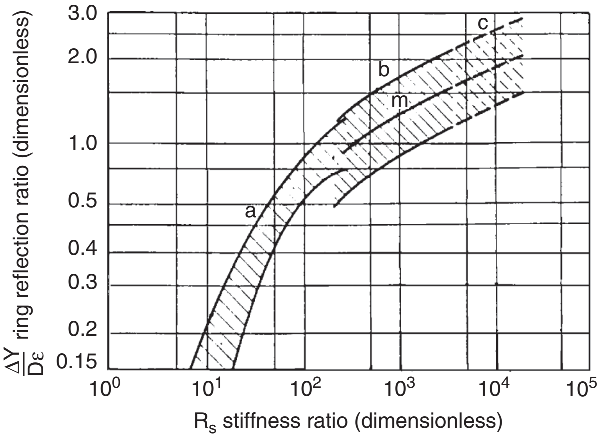


Fig. 7.17 Extended Watkins graph. a = region for steel pipe according to Watkins; b = region for thermoplastic pipe; c = extrapolated region; m = mean curve. Source: Hoechst Plastic Pipes, 1980

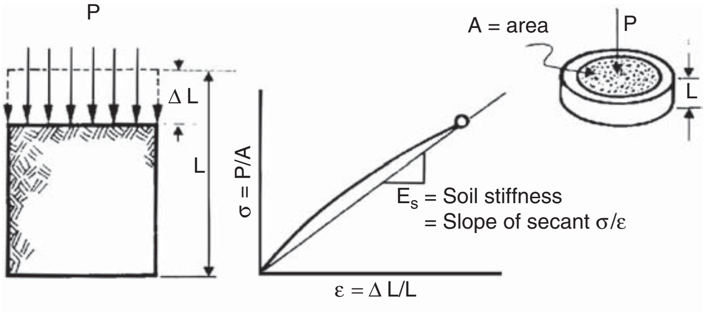


Fig. 7.18 Concept for predicting settlement of soil by means of stress-strain compression data from field or laboratory. Source: Utah State University

Through division by ε and substitution, Equation 7.26 becomes:

Equation 7.27

$$\frac{\Delta Y}{D\varepsilon} = \frac{R_s}{AR_s + B}$$

Equation 7.27 represents a simple relationship between two dimensionless variables: (1) ring deflection ratio ($\Delta Y/D\varepsilon$) and (2) stiffness ratio (R_s). Figure 7.17 represents the design curve that can be used for predicting ring deflection. As seen in this graph, Hoechst Plastic Pipes extended Watkins's work to cover stiffness range of PVC and other thermoplastic pipes.

Vertical soil strain in this fill depends upon soil compressibility and nominal load. Soil mechanics laboratory curves such as the one shown in Fig. 7.18 relate strain to soil pressure.

With these methods, using soil strain to predict pipe deflection becomes a simple exercise. The ratio of pipe deflection to soil strain can be determined from Fig. 7.17. Pipe load is then calculated using the prism (embankment) load theory, and soil strain can be determined from soil modulus data. Soil modulus can be determined from simple laboratory tests for a specific backfill. Alternatively, constrained soil modulus values found in Table 7.6, from AASHTO's Section 12, may be used.

Table 7.6 Design values for constrained soil modulus, M_s (psi)

	Soil type and compaction condition			
Stress level (lb/ft^2)	Sn-100	Sn-95	Sn-90	Sn-85
150	2,350	2,000	1,275	470
750	3,450	2,600	1,500	520
1,500	4,200	3,000	1,625	570
3,000	5,500	3,450	1,800	650
6,000	7,500	4,250	2,100	825
9,000	9,300	5,000	2,500	1,000
Stress level (lb/ft^2)		Si-95	Si-90	Si-85
150	—	1,415	600	360
750	—	1,670	740	390
1,500	—	1,770	750	400
3,000	—	1,880	790	430
6,000	—	2,090	900	510
Stress level (lb/ft^2)		Cl-95	Cl-90	Cl-85
150	—	530	255	130
750	—	625	320	175
1,500	—	690	355	200
3,000	—	740	395	230
6,000	—	815	460	285
9,000	—	895	525	345

Note: The soil types are defined by a two-letter designation, which indicates general soil classification: Sn for sands and gravels, Si for silts, and Cl for clays.

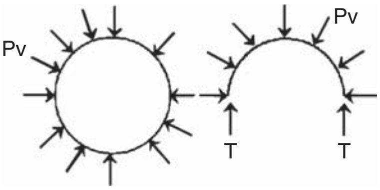


Fig. 7.19 Radial loads acting on the pipe.

7.10.2 AASHTO Design Method

AASHTO currently has two design documents that provide nearly identical specifications for flexible pipe/culvert design:

1. Standard Specification for Highway Bridges, Division 1, Section 18, Soil—Thermoplastic Pipe Interaction Systems. This was AASHTO's first design document for PVC pipe. The manual used the working stress design (WSD) philosophy. Design procedures closely paralleled Section 12 of the same document, which covers corrugated metal piping. (The Bridge Specification document was revised for the final time in 2002—the Soil-Thermoplastic Pipe portion was changed to be Section 17.)
2. LFRD Bridge Specifications Manual, Section 12, Buried Structures and Tunnel Liners. This manual employs the load-factor and resistance design (LFRD) method, which has replaced the WSD method. This document includes a subsection devoted exclusively to thermoplastic pipes.

Due to the origin of AASHTO Section 12, the design concept incorporates procedures both familiar and unfamiliar to designers of PVC pipe. In the AASHTO design, a properly backfilled pipe is assumed to act as a compression ring, and the overburden and live load pressures act radially around the pipe, as shown in Fig. 7.19. This loading on buried pipe is the reverse of that experienced by pressure pipe.

The complete AASHTO design method analysis includes checks for adequate:

- wall crushing
- buckling
- deflection
- installation stiffness.

Ring buckling and wall crushing criteria for PVC pipe are addressed in Sections 7.8.6 and 7.8.8. However, the AASHTO approach for these items is slightly different because it covers all thermoplastic materials.

In addition to allowable pipe deflection limit, AASHTO further indicates that long-term ring shrinkage due to creep should not exceed 5%. This is not design-limiting for PVC but may be for other thermoplastic materials.

The installation stiffness check is unique to AASHTO. The flexibility factor (FF) is applied to measure pipe wall stiffness; the larger the flexibility factor, the more flexible (less stiff) the pipe. Derived from the pipe stiffness equation, flexibility factor is expressed as:

Equation 7.28

$$FF = \frac{D^2}{EI} = \frac{4r^2}{EI}$$

where:

FF = flexibility factor from AASHTO ring strength design, in./lb
D = mean pipe diameter, in.
E = modulus of elasticity of pipe material, psi
I = moment of inertia of wall cross-section per unit length of pipe, in.^{4}/in.
r = mean pipe radius, in.

For solid wall pipe, the equation is as follows:

Equation 7.29

$$FF = \frac{48r^2}{Et^3}$$

where:

t = pipe wall thickness, in.

Installation-induced loads are independent of the diameter of the pipe to be installed. Reaction to that load, measured in percent deflection, will be greater in small diameter pipes than in larger diameter pipes of equal stiffness. A constant flexibility factor will produce an equal reaction (percent deflection) regardless of pipe diameter. Pipe stiffness (PS) and flexibility factor (FF) can be directly related as:

Equation 7.30

$$FF = \frac{53.69}{(PS)D} \qquad \text{or} \qquad PS = \frac{53.69}{(FF)D}$$

where:

PS = pipe stiffness, psi.

Flexibility factor is determined in the laboratory by first measuring pipe stiffness (ASTM D2412) and converting it through use of Equation 7.30. Table 7.7 provides a direct comparison of stiffness and flexibility factor.

Table 7.7 Pipe stiffness vs. flexibility factor

Diameter	PS (psi)	FF (in/lb)	PS (psi)	FF (in/lb)
18	28	0.1065	46	0.0648
24	28	0.0799	46	0.0486
30	28	0.0639	46	0.0389
36	28	0.0533	46	0.0324
42	28	0.0456	46	0.0277
48	28	0.0399	46	0.0243

7.10.3 Finite Element Analysis

The computational technique known as *finite element analysis* (FEA) was developed with the advance of digital computers; it was needed for the analysis of complex structural systems. Over the years, this technique has been applied to several other types of problems in subjects as diverse as thermodynamics, fluid mechanics, aerodynamics, and geotechnical engineering. Specifically, the case of buried flexible pipe has been treated by a number of researchers, who have produced pipe FEA computer programs such as CANDE (Culvert Analysis and Design), produced by Port Hueneme Naval Station; NUPIPE (New Pipe), produced by Northwestern University; and PIPE (Pipe Design), produced by Utah State University. The latest versions of these computational programs have contributed to the research of special pipe and installation conditions, and they have aided in the creation of pipe and installation design.

Data obtained by the PIPE program have been compared extensively to results of physical tests on plastic pipe, which has led to numerous enhancements of and improved correlation with actual pipe performance. Nonlinear soil model, stress-dependent soil parameters, large-deflection theory, compaction simulation, and other features are among the enhancements required for accurate prediction of soil-pipe interaction and performance. A full description of the application of FEA to buried pipe analysis is found in Moser's *Design of Buried Pipe*.

7.10.4 ATV Method

The *ATV method* of designing buried pipe is a regulation developed in Germany by the Waste-Water Engineers Association (ATV), in collaboration with the Union of Communal City Purification Plants (VKS). Since its finalization in Germany in 1984, the ATV method has been more widely used in Europe and in ISO work than the methods of the previous sections.

Although the ATV method provides a more rigorous treatment of deflection and load calculation than the Spangler or Watkins formulation, it is much more complex and time-consuming to apply; there is not enough difference in the results to justify its use, except in low stiffness pipe (PS ≤ 10 psi). However, there is an area addressed by the ATV method that is not addressed in other analytical techniques, except FEA. It is the inclusion of a factor, *zeta*, which modifies soil modulus in the pipe zone to account for different soils or modulus materials in the undisturbed trench wall.

7.10.5 Zeta Correction Factor

If unstable or soft soil conditions are encountered in the pipe zone, there is a method to find the modulus of soil reaction around the pipe. The effectiveness of a higher modulus pipe zone material may be influenced by the undisturbed trench wall. This situation is depicted in Fig. 7.20.

The *zeta correction factor* is a function of the ratio of trench width to pipe diameter (b/D_o) and the ratio of pipe zone modulus to trench sidewall modulus (E_2/E_3). The following equations show this.

Equation 7.31

$$\text{zeta} = \frac{1.44}{f + (1.44 - f)(E_2/E_3)}$$

where:

zeta = adjustment factor for modulus of soil reaction (to account for native trench wall soil stiffness), dimensionless

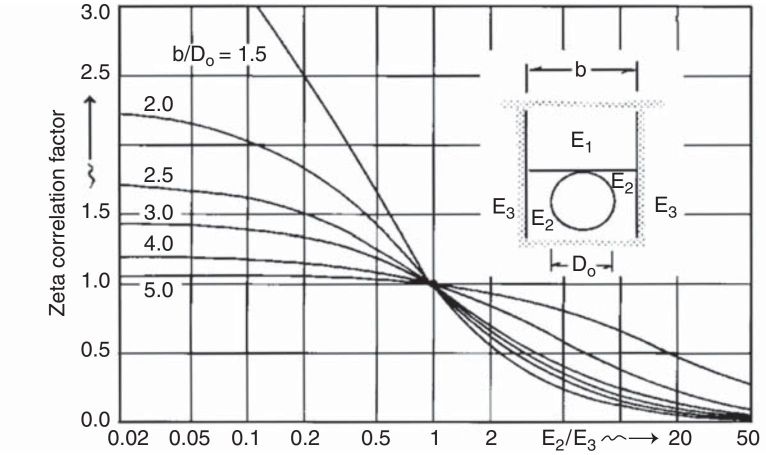


Fig. 7.20 Zeta correction factor.

$$f = \frac{b/D_o - 1}{1.154 + 0.444(b/D_o - 1)}$$

b = trench width, in.
D_o = pipe outside diameter, in.
E_2 = modulus of soil reaction of soil around pipe, psi
E_3 = modulus of soil reaction of trench wall, psi

Applying the zeta factor directly to a Spangler deflection calculation (Equation 7.9) quickly demonstrates the factor's effect. As expected, zeta = 1.0 when $E_2 = E_3$. Zeta also goes to 1.0 as trench width increases relative to pipe diameter. However, at a narrow trench width and ratio $b/D_O = 1.5$, zeta is about 1.6 for $E_2/E_3 = 0.5$. Applying these equations, adjustments to pipe zone soil moduli are made that account for weakening or strengthening, based on an undisturbed trench modulus and trench width.

Example 7.5

This example demonstrates the effect of native trench soil on pipe deflection. Three values for E_3 (modulus of soil reaction of trench wall) are considered:

Case 1: $E_3 = 400$ psi
Case 2: $E_3 = 100$ psi
Case 3: $E_3 = 600$ psi

Conditions:

- Pipe diameter, $D_o = 12$ in.
- Pipe stiffness, PS = 46 psi
- Height of cover, H = 15 ft
- Unit soil weight, $w = 120\ \text{lb/ft}^3$
- Trench width, b = 36 in.
- Modulus of soil reaction of soil around pipe, $E_2 = 400$ psi
- Live load: none

Prism load calculation:

$$P = wH/144\ \text{in}^2/\text{ft}^2 = (120\ \text{lb/ft}^3)(15\ \text{ft})/144\ \text{in}^2/\text{ft}^2 = 12.5\ \text{psi}$$
$$b/D_o = 36\ \text{in.}/12\text{in.} = 3.0$$

For deflection calculations, use Equation 7.9 with bedding constant K = 0.1 and deflection lag factor $D_L = 1.0$.

Solution

Case 1: $E_3 = 400$ psi

$$E_2/E_3 = 400/400 = 1 \therefore \text{ no zeta correction } (E_2 = E_3)$$

$$\frac{\Delta Y}{D} = \frac{(0.1)(1.0)(12.5)(100)}{(0.149)(46) + (0.061)(400)} = 4.02\% \text{ (without zeta adjustment).}$$

Case 2: $E_3 = 600$ psi

$$E_2/E_3 = 400/600 = 0.667 \therefore \text{ zeta} = 1.12$$

(from Fig. 7.17 or Equation 7.32).

$$\%\frac{\Delta Y}{D} = \frac{(0.1)(1.0)(12.5)(100)}{(0.149)(46) + (0.061)(400)(1.12)} = 3.67\% \text{ (when } E_3 = 600 \text{ psi).}$$

Case 3: $E_3 = 100$ psi

$$E_2/E_3 = 400/100 = 4.0 \therefore \text{ zeta} = 0.51$$

$$\%\frac{\Delta Y}{D} = \frac{(0.1)(1.0)(12.5)(100)}{(0.149)(46) + (0.061)(400)(0.51)} = 6.48\% \text{ (when } E_3 = 100 \text{ psi).}$$

The difference between the extremes is 6.48% − 3.67% = 2.81% deflection (case 2 compared to case 3).

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CHAPTER 8

Installation-Specific Design Applications

Changes in Direction
•
Support Spacing
•
Expansion and Contraction
•
Flotation

Table of Contents

8.1 Notation

A = offset at free end, in.

c = distance from extreme fiber to neutral axis, in.

C = chord length, in.

C_T = coefficient of thermal expansion, in./in./°F

D = original pipe outside diameter, in.

D_m = mean pipe diameter, in.

D_i = pipe inside diameter, in.

D_o = pipe outside diameter, in.

E = modulus of elasticity of the pipe material, psi

F = safety factor, dimensionless

HDB = hydrostatic design basis, psi

I = moment of inertia, in.^4

L = pipe length, in.

L_S = support spacing or span length, in.

M = bending moment, in.-lb

P = internal pipe pressure, psi

P_L = lateral offset force, lb

R_b = bending radius of pipe, in.

S = hydrostatic design stress, psi

S' = stress, psi

S_b = allowable flexural stress from longitudinal bending, psi

s_b = flexural stress from longitudinal bending, psi

S_t = tensile stress from longitudinal thrust, psi

t = pipe wall thickness, in.

t_1 = highest pipe wall temperature, °F

t_0 = lowest pipe wall temperature, °F

t_{avg} = average pipe wall thickness, in.

t_{min} = minimum pipe wall thickness, in.

T = thermal de-rating factor, dimensionless

w = load on pipe per unit length, lb/in.

W_w = weight of pipe filled with water, lb/in.

y = midspan vertical displacement (sag), in.

α = angle of lateral deflection, degrees

β = allowable bending deflection angle, degrees

ΔY = reduction in outside diameter, in.

δ = diametric (ring) deflection, dimensionless

ε_b = bending strain, in./in.

λ_1, λ_2 = intermediate variables used to simplify equations

ν = Poisson's ratio, dimensionless = 0.38 for PVC pipe

8.2 Changes in Direction

Controlled changes in direction may be accomplished by longitudinal bending of the pipe barrel (Fig. 8.1) or by angular deflection of the pipe joint. Fittings may also be used to effect direction change.

8.2.1 Longitudinal Bending

Allowable bending of PVC pipe is based on its long-term flexural stress limit. For PVC cell class 12454, the stress limit is conservatively assumed to be the hydrostatic design basis (HDB) of 4,000 psi (27.6 MPa).

Fig. 8.1 24-in. DR 18 fused PVC pipe longitudinally deflected horizontally and vertically during trenchless pull-in.

Table 8.1 Thermal de-rating factors for PVC pressure pipes and fittings

Maximum service temperature °F (°C)	Multiply pressure class (PC) at 73.4°F (23°C) by factor shown
80 (27)	0.88
90 (32)	0.75
100 (38)	0.62
110 (43)	0.50
120 (49)	0.40
130 (54)	0.30
140 (60)	0.22

Notes:

1. The maximum recommended sustained temperature for the wall of PVC pressure pipe and fittings is 140°F (60°C).
2. Interpolate between the temperatures listed to calculate other factors.
3. Pipe gaskets are generally suitable for continuous use in water at the temperatures listed above.
4. The de-rating factors assume sustained elevated service temperatures. When the contents of a buried PVC pressure pipe are only intermittently and temporarily raised above the service temperature shown, de-rating may not be needed.

Stresses are highest in restrained-joint systems, and therefore these stresses are used in design. PVC pipeline longitudinal stress is conservatively assumed to be half of the HDB. By this rationale, the equation for allowable flexural or bending stress may be given as:

Equation 8.1

$$S_b = (HDB - S_t)\frac{T}{F}$$

where:

S_b = allowable flexural stress from longitudinal bending, psi
HDB = hydrostatic design basis, psi
S_t = tensile stress from longitudinal thrust, psi = HDB/2
F = safety factor, dimensionless = 2.0 for bending of pressure-rated and nonpressure pipe; 2.5 for bending of pressure class pipe
T = thermal de-rating factor, dimensionless (see Table 8.1)

Notes:

1. Longitudinal stress from thermal expansion and contraction can be ignored in buried gasketed-joint PVC piping, which is able to accommodate these changes.
2. Longitudinal stress from thermal expansion and contraction must be considered in restrained-joint pipes.

Stress calculations for restrained-joint piping systems are performed as follows:

Equation 8.2

$$S' = EC_T(t_1 - t_0)$$

where:

S' = stress, psi
E = modulus of elasticity of the pipe material, psi
C_T = coefficient of thermal expansion, in./in./°F
t_1 = highest pipe wall temperature, °F
t_0 = lowest pipe wall temperature, °F

Maximum allowable flexural stresses (S_b) for PVC pipe at 73.4°F (23°C) are shown in Table 8.2. Values are calculated using Equation 8.1.

The geometry of a longitudinal bend is shown in Fig. 8.2.

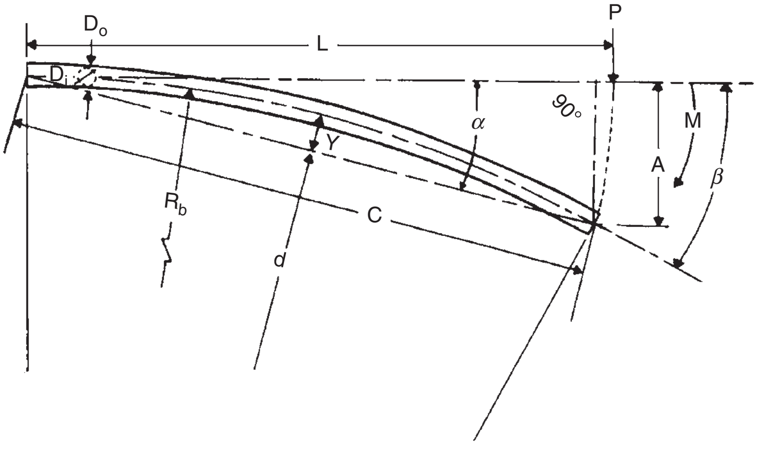

Fig. 8.2 Longitudinal bending diagram.

Table 8.2 Allowable flexural stresses at 73.4°F (23°C)

Pressure class pipe: $\left(4{,}000 - \dfrac{4{,}000}{2}\right)\dfrac{1.0}{2.5} = 800\text{ psi}\quad(5.51\text{ MPa})$

Pressure rated pipe: $\left(4{,}000 - \dfrac{4{,}000}{2}\right)\dfrac{1.0}{2.0} = 1{,}000\text{ psi}\quad(6.89\text{ MPa})$

Note: Allowable bending stresses above are based on restrained-joint systems and therefore are conservative for gasketed pressure pipe.

Nonpressure pipe:

PVC 12454: $(4{,}000 - 0)\dfrac{1.0}{2.0} = 2{,}000\text{ psi}\quad(13.79\text{ MPa})$

PVC 12364: $(3{,}200 - 0)\dfrac{1.0}{2.0} = 1{,}600\text{ psi}\quad(11.72\text{ MPa})$

The mathematical relationship between stress and the moment induced by longitudinal bending of pipes is represented by Equation 8.3.

Equation 8.3

$$M = \frac{S_b I}{c}$$

where:

M = bending moment, in.-lb
S_b = allowable flexural stress from longitudinal bending, psi (see Table 8.2)
c = distance from neutral axis to extreme fiber, in. = $D_o/2$
I = moment of inertia, in.^{4} (see Equation 8.4)
D_o = pipe outside diameter, in.

The moment of inertia needed to solve Equation 8.3 can be calculated using Equation 8.4:

Equation 8.4

$$I = \frac{\pi}{64}(D_o^4 - D_i^4) = 0.0491(D_o^4 - D_i^4)$$

where:

D_i = pipe inside diameter, in. = $D_o - 2t_{avg}$
t_{avg} = average wall thickness, in. = $t_{min} + 6\%\ t_{min}$
t_{min} = minimum wall thickness, in.

Note: This equation does not apply to profile wall products; due to the complex geometry, the manufacturer should be consulted for appropriate values of I or for allowable bending radius.

Assuming that a length of pipe with a longitudinal bend conforms to a circular arc after backfilling and installation, the minimum radius (R_b) in inches of the bending circle can be found by *Timoshenko's equation* (Equation 8.5):

Equation 8.5

$$R_b = \frac{EI}{M}$$

where:

R_b = pipe bending radius, in.

Combining Equations 8.3 and 8.5 gives:

Equation 8.6

$$R_b = \frac{ED_o}{2S_b}$$

The *allowable bending deflection angle* subtended by a pipe length is given in the next equation.

Equation 8.7

$$\beta = \frac{360L}{2\pi R_b} = \frac{57.3L}{R_b}$$

where:

β = allowable bending deflection angle, degrees

L = pipe length, in.

The *angle of lateral deflection* (α) of the curved pipe from a tangent to the circle is:

Equation 8.8

$$\alpha = \beta/2$$

where:

α = angle of lateral deflection, degrees

The *distance offset* (A) at the end of a pipe from point of tangency to circle is defined by Equation 8.9:

Equation 8.9

$$A = 2R_b \sin^2\left(\frac{\beta}{2}\right) = 2R_b \sin^2\alpha$$

where:

A = offset at free end, in.

Assuming that during installation a pipe is temporarily fixed at one end and acts as a cantilevered beam, the lateral force required at the free end to achieve offset A can be determined with Equation 8.10:

Equation 8.10

$$P_L = \frac{3EIA}{L^3}$$

where:

P_L = lateral offset force, lb
E = modulus of elasticity of the pipe material, psi
I = moment of inertia, in.^{4} (see Equation 8.4)

Modulus of elasticity (E) changes with temperature (see Table 8.3).

Table 8.3 Temperature corrections for modulus of elasticity

Temperature		Correction factor for modulus of elasticity
°F	°C	
90	32	0.93
100	38	0.88
110	43	0.84
120	49	0.79
130	54	0.75
140*	60	0.70

Notes:
*The maximum recommended temperature for wall of PVC pipe and fitting is 140°F (60°C).
Interpolate between the temperatures listed to calculate other correction factors.
The factors in this table assume sustained elevated service temperatures. When contents of PVC pipe are only intermittently and temporarily raised above service temperature shown, a multiplier (correction factor) may not be needed.

The mathematical relationship between bending deflection angle (α), offset (A), lateral offset force (P), and minimum bending radius (R_b) was defined in Equation 8.1. These and other quantities, shown in Fig. 8.2, are calculated by the equations that follow.

Equation 8.11

$$L = R_b\left(\frac{2\pi\alpha}{180}\right)$$

Equation 8.12

$$d = R_b \cos\left(\frac{\beta}{2}\right)$$

where:

d = as shown in Fig. 8.2, in.

Equation 8.13

$$Y = R_b - d$$

where:

Y = as shown in Fig. 8.2, in.

Equation 8.14

$$C = 2R_b \sin\left(\frac{\beta}{2}\right) \approx L$$

$$C \sin\left(\frac{\beta}{2}\right) = L \tan\alpha = A$$

where:

C = chord length, in.

Longitudinal bending of PVC pipe without allowance for joint deflection should not exceed limits given in Tables 8.4 through 8.8. In the tables:

- maximum bend allowable is defined in terms of minimum bending radius;
- maximum pipe end offset is measured from the tangent to the circle;
- angle of longitudinal deflection is measured from a circular tangent by pipe bending;
- lateral offset force is the force needed to effect bending.

Profile wall pipe may not duplicate the longitudinal bending performance of solid wall PVC pipe. Pipes with an open profile can typically be bent to the same radii as solid wall pipes with similar pipe stiffness; however, the lateral offset force (P_L) may be lower. Pipes

Table 8.4 Allowable longitudinal bending for AWWA C900 pipe in 20-ft lengths

$S_b = 800$ psi, $E = 400{,}000$ psi					
Pipe size, in.	4	6	8	10	12
DR 14 (PC 305)					
D_o, in.	4.800	6.900	9.050	11.100	13.200
t_{avg}, in.	0.363	0.522	0.685	0.840	0.999
D_i, in.	4.07	5.86	7.68	9.42	11.20
I, in.^{4}	12.5	53.5	158	358	716
M, in.-lb	4,170	12,400	28,000	51,600	86,800
R_b, in.*	1,200	1,730	2,260	2,780	3,300
R_b, ft*	100	144	188	232	275
β, degrees	11.5	7.9	6.1	4.9	4.2
α, degrees	5.7	4.0	3.0	2.5	2.1
A, in.	24	17	13	10	9
P_L, lb	26	77	170	320	540
Ratio R_b/D_o	250	250	250	250	250
DR 18 (PC 235)					
D_o, in.	4.800	6.900	9.050	11.100	13.200
t_{avg}, in.	0.283	0.406	0.533	0.654	0.777
D_i, in.	4.23	6.09	7.98	9.79	11.65
I, in.^{4}	10.3	43.8	130	293	586
M, in.-lb	3,420	10,200	22,900	42,300	71,100
R_b, in.*	1,200	1,730	2,260	2,780	3,300
R_b, ft*	100	144	188	232	275
β, degrees	11.5	7.9	6.1	4.9	4.2
α, degrees	5.7	4.0	3.0	2.5	2.1
A, in.	24	17	13	10	8.7
P_L, lb	21	63	140	260	440
Ratio R_b/D_o	250	250	250	250	250

*Minimum.

Note: Larger diameters of pipe are not shown because the high forces required for bending pipes of this size would make longitudinal bending impractical. The allowable bending stresses above are based on restrained joint system and are conservative for gasketed pipe.

Table 8.4 Allowable longitudinal bending for AWWA C900 pipe in 20-ft lengths (*continued*)

S_b = 800 psi, E = 400,000 psi					
Pipe size, in.	4	6	8	10	12
DR 25 (PC 165)					
D_o, in.	4.800	6.900	9.050	11.100	13.200
t_{avg}, in.	0.204	0.293	0.384	0.471	0.560
D_i, in.	4.39	6.31	8.28	10.16	12.08
I, in.^{4}	7.76	33.1	98.1	222	444
M, in.-lb	2,590	7,700	17,300	32,000	53,800
R_b, in.*	1,200	1,730	2,260	2,780	3,300
R_b, ft*	100	144	188	232	275
β, degrees	11.5	7.9	6.1	4.9	4.2
α, degrees	5.7	4.0	3.0	2.5	2.1
A, in.	24	17	13	10	9
P_L, lb	16	48	110	200	340
Ratio R_b/D_o	250	250	250	250	250

*Minimum.

Note: Larger diameters of pipe are not shown because the high forces required for bending pipes of this size would make longitudinal bending impractical. The allowable bending stresses above are based on restrained joint system and are conservative for gasketed pipe.

Table 8.5 Allowable longitudinal bending for CIOD butt-fusible PVC pipe in 40-ft lengths

S_b = 800 psi, E = 400,000 psi						
Pipe size, in.	D_o, in.	R_b, in.*	R_b, ft*	β, degrees	α, degrees	A, in.
4	4.800	1,200	100	22.9	11.5	95
6	6.900	1,725	144	15.9	8.0	66
8	9.050	2,263	189	12.2	6.1	51
10	11.100	2,775	231	9.9	5.0	41
12	13.200	3,300	275	8.3	4.2	35
14	15.300	3,825	319	7.2	3.6	30
16	17.400	4,350	363	6.3	3.2	26
18	19.500	4,875	406	5.6	2.8	24
20	21.600	5,400	450	5.1	2.5	21
24	25.800	6,450	538	4.3	2.1	18
30	32.000	8,000	667	3.4	1.7	14
36	38.300	9,575	798	2.9	1.4	12

*Minimum.

Notes:

1. Butt-fusible PVC is joined with fully restrained fusion joints, allowing uniform bending through all sizes.
2. The ratio of R_b to D_o is 250.
3. Information provided is applicable for all DRs available in the listed diameters.

Table 8.6 Allowable longitudinal bending for IPS OD butt-fusible PVC pipe in 40-ft lengths

S_b = 800 psi, E = 400,000 psi						
Pipe size, in.	D_o, in.	R_b, in.*	R_b, ft*	β, degrees	α, degrees	A, in.
3	3.500	875	73	31.4	15.7	128
4	4.500	1,125	94	24.4	12.2	101
6	6.625	1,656	138	16.6	8.3	69
8	8.625	2,156	180	12.8	6.4	53
10	10.750	2,688	224	10.2	5.1	43
12	12.750	3,188	266	8.6	4.3	36
14	14.000	3,500	292	7.9	3.9	33
16	16.000	4,000	333	6.9	3.4	29
18	18.000	4,500	375	6.1	3.1	26
20	20.000	5,000	417	5.5	2.8	23
24	24.000	6,000	500	4.6	2.3	19

*Minimum.

Notes:

1. Butt-fusible PVC is joined with fully restrained fusion joints, allowing uniform bending through all sizes.
2. The ratio of R_b to D_o is 250.
3. Information provided is applicable for all DRs available in the listed diameters.

with a closed profile are typically limited to larger bending radii. Individual pipe manufacturers should be consulted for specific recommendations and limits.

It is recommended that manual force alone be used to bend PVC pipe. Mechanical means could easily cause maximum recommended wall stresses to be exceeded.

When PVC pipe is bent longitudinally, its joint must be blocked or braced to ensure its straight alignment and to prevent axial deflection in the gasketed or mechanical joint (Fig. 8.3); excessive axial-joint deflection may result in damaging stresses. If bending requirements are followed, diameters larger than those shown in Tables 8.4 through 8.8 may be longitudinally bent; however, the forces this would require typically make such bending impractical.

When the desired change of direction in a PVC pipeline exceeds the allowable bending deflection angle (β) for a given length of pipe, the longitudinal bending required should

Table 8.7 Allowable longitudinal bending for pressure-rated pipe (ASTM D2241, DR = 21, 26, 32.5, 41) in 20-ft lengths. S_b = 1,000 psi, E = 400,000 psi

DR 21				
Pipe size, in.	3	4	5	6
D_o, in.	3.500	4.500	5.563	6.625
t_{avg}, in.	0.177	0.227	0.281	0.334
D_i, in.	3.15	4.05	5.00	5.96
I, in.4	2.55	6.97	16.27	32.7
M, in.-lb	1,460	3,100	5,850	9,880
R_b, in.*	700	900	1,110	1,330
R_b, ft*	58.3	75.0	92.5	111
β, deg	19.6	15.3	12.4	10.3
α, deg	9.8	7.6	6.2	5.2
A, in.	41	32	26	22
P_L, lb	9.0	19	36	61
Ratio R_b/D_o	200	200	200	200

DR 21			
Pipe size, in.	8	10	12
D_o, in.	8.625	10.750	12.750
t_{avg}, in.	0.435	0.543	0.644
D_i, in.	7.75	9.66	11.46
I, in.4	94.0	227	449
M, in.-lb	21,800	42,200	70,400
R_b, in.*	1,730	2,150	2,550
R_b, ft*	144	179	213
β, deg	7.9	6.4	5.4
α, deg	4.0	3.2	2.7
A, in.	17	13	11
P_L, lb	140	260	440
Ratio R_b/D_o	200	200	200

*Minimum.

Note: Larger diameters of pipe are not shown because the high forces required for bending pipes of this size would make longitudinal bending impractical. The allowable bending stresses above are based on restrained joint systems and are conservative for gasketed pipe.

Table 8.7 Allowable longitudinal bending for pressure-rated pipe (ASTM D2241, DR = 21, 26, 32.5, 41) in 20-ft lengths. S_b = 1,000 psi, E = 400,000 psi (*continued*)

DR 26				
Pipe size, in.	3	4	5	6
D_o, in.	3.500	4.500	5.563	6.625
t_{avg}, in.	0.143	0.183	0.227	0.270
D_i, in.	3.21	4.13	5.11	6.08
I, in.^{4}	2.12	5.79	13.5	27.2
M, in.-lb	1,210	2,580	4,870	8,220
R_b, in.*	700	900	1,110	1,330
R_b, ft*	58.3	75.0	92.5	111
β, deg	19.6	15.3	12.4	10.3
α, deg	9.8	7.6	6.2	5.2
A, in.	41	32	26	22
P_L, lb	7.5	16	30	51
Ratio R_b/D_o	200	200	200	200

DR 26			
Pipe size, in.	8	10	12
D_o, in.	8.625	10.750	12.750
t_{avg}, in.	0.352	0.438	0.520
D_i, in.	7.92	9.87	11.71
I, in.^{4}	78.2	189	373
M, in.-lb	18,100	35,100	58,600
R_b, in.*	1,730	2,150	2,550
R_b, ft*	144	179	213
β, deg	7.9	6.4	5.4
α, deg	4.0	3.2	2.7
A, in.	17	13	11
P_L, lb	110	220	370
Ratio R_b/D_o	200	200	200

Table 8.7 Allowable longitudinal bending for pressure-rated pipe (ASTM D2241, DR = 21, 26, 32.5, 41) in 20-ft lengths. S_b = 1,000 psi, E = 400,000 psi (*continued*)

DR 32.5				
Pipe size, in.	3	4	5	6
D_o, in.	3.500	4.500	5.563	6.625
t_{avg}, in.	0.114	0.147	0.181	0.216
D_i, in.	3.27	4.21	5.20	6.19
I, in.^{4}	1.74	4.75	11.10	22.3
M, in.-lb	990	2,110	3,990	6,740
R_b, in.*	700	900	1,110	1,330
R_b, ft*	58.3	75.0	92.5	111
β, deg	19.6	15.3	12.4	10.3
α, deg	9.8	7.6	6.2	5.2
A, in.	41	32	26	22
P_L, lb	6.1	13	25	42
Ratio R_b/D_o	200	200	200	200

DR 32.5			
Pipe size, in.	8	10	12
D_o, in.	8.625	10.750	12.750
t_{avg}, in.	0.281	0.351	0.416
D_i, in.	8.06	10.05	11.92
I, in.^{4}	64.1	155	306
M, in.-lb	14,900	28,800	48,000
R_b, in.*	1,730	2,150	2,550
R_b, ft*	144	179	213
β, deg	7.9	6.4	5.4
α, deg	4.0	3.2	2.7
A, in.	16.6	13.4	11.3
P_L, lb	93	180	300
Ratio R_b/D_o	200	200	200

*Minimum.

Note: Larger diameters of pipe are not shown because the high forces required for bending pipes of this size would make longitudinal bending impractical. The allowable bending stresses above are based on restrained joint systems and are conservative for gasketed pipe.

Table 8.7 Allowable longitudinal bending for pressure-rated pipe (ASTM D2241, DR = 21, 26, 32.5, 41) in 20-ft lengths. S_b = 1,000 psi, E = 400,000 psi (*continued*)

DR 41				
Pipe size, in.	3	4	5	6
D_o, in.	3.500	4.500	5.563	6.625
t_{avg}, in.	0.090	0.116	0.144	0.171
D_i, in.	3.32	4.27	5.28	6.28
I, in.^{4}	1.41	3.84	8.98	18.1
M, in.-lb	800	1,710	3,230	5,450
R_b, in.*	700	900	1,110	1,330
R_b, ft*	58.3	75.0	92.5	111
β, deg	12.9	10.0	8.1	6.8
α, deg	6.4	5.0	4.1	3.4
A, in.	18	14	11	9.3
P_L, lb	2.2	4.6	8.7	15
Ratio R_b/D_o	200	200	200	200

DR 41			
Pipe size, in.	8	10	12
D_o, in.	8.625	10.750	12.750
t_{avg}, in.	0.223	0.278	0.330
D_i, in.	8.18	10.19	12.09
I, in.^{4}	51.9	125	248
M, in.-lb	12,000	23,300	38,900
R_b, in.*	1,730	2,150	2,550
R_b, ft*	144	179	213
β, deg	5.2	4.2	3.5
α, deg	2.6	2.1	1.8
A, in.	7.2	5.8	4.9
P_L, lb	32	63	105
Ratio R_b/D_o	200	200	200

Table 8.8 Allowable longitudinal bending for DR 35 sewer pipe in 14- and 20-ft lengths (S_b = 1,600 psi, E = 500,000 psi)

Pipe size, in.	4	6	8	10	12	15
14-ft lengths						
D_o, in.	4.215	6.275	8.400	10.500	12.500	15.300
t_{avg}, in.	0.128	0.190	0.254	0.318	0.379	0.463
D_i, in.	3.96	5.89	7.89	9.86	11.74	14.374
I, in.^{4}	3.42	16.8	54.0	132	265	594.4
M, lb-in.	2,600	8,570	20,600	40,100	67,700	124,317
R_b, in.*	659	980	1,310	1,640	1,950	2,391
R_b, ft*	54.9	81.7	109	137	163	199.0
β, deg	14.6	9.8	7.3	5.9	4.9	4.0
α, deg	7.3	4.9	3.7	2.9	2.5	2.0
A, in.	21	14	11	8.6	7.2	5.9
P_L, lb	23	76	184	359	606	1,110
Ratio R_b/D_o	156	156	156	156	156	156
20-ft lengths						
D_o, in.	4.215	6.275	8.400	10.500	12.500	15.300
t_{avg}, in.	0.128	0.190	0.254	0.318	0.379	0.463
D_i, in.	3.96	5.89	7.89	9.86	11.74	14.374
I, in.^{4}	3.42	16.8	54.0	132	265	594.4
M, lb-in.	2,600	8,570	20,600	40,100	67,700	124,317
R_b, in.*	659	980	1,310	1,640	1,950	2,391
R_b, ft*	54.9	81.7	109	137	163	199.0
β, deg	20.9	14.0	10.5	8.4	7.1	5.8
α, deg	10.4	7.0	5.2	4.2	3.5	2.9
A, in.	43	29	22	18	15	12
P_L, lb	16	53	130	250	420	780
Ratio R_b/D_o	156	156	156	156	156	156

*Minimum.

Note: Larger diameters of sewer pipe are not shown because the high forces required would make longitudinal bending impractical. The values shown are conservative for sewer pipe manufactured with lower modulus materials.

Fig. 8.3 6-in. Class 235 PVC pipe (per AWWA C900 standard) with one length curved in the barrel to required alignment.

be made throughout a number of pipe lengths. Calculation of required distribution of longitudinal bending in PVC pipe is demonstrated in the following example.

Example 8.1

Calculate the number of pieces of pipe and total offset (A) required to achieve a 10-degree change in pipeline direction using only longitudinal bending of the pipe barrel. Do so for pipeline using AWWA C900 8-in. PVC DR 18 pipe in 20-ft lengths. Refer to Fig. 8.2 and Table 8.4.

Solution

$$R_b = 2{,}260 \text{ in. or } 188 \text{ ft}$$

$$\text{Circumference} = 2\pi R_b = 2\,(3.14)\,(188) = 1{,}181 \text{ ft}$$

$$L = (1{,}181)\,(10^\circ/360^\circ) = 33 \text{ ft}$$

$$20 \text{ ft} < 33 \text{ ft} < 40 \text{ ft}$$

Hence, we need two 8-in. × 20-ft lengths to achieve the change in pipeline direction, as stated. Then,

$$L = 2 \times 20 \text{ ft} = 40 \text{ ft} = 480 \text{ in.}$$

Now find the resultant total offset for the pipeline over these two pipe lengths. Assume:

$$L \approx C$$

Then, by using Equation 8.14:

$$A = C \sin(\beta/2) = 480 \sin(10°/2) = 480\ (0.087) = 41.8 \text{ in.}$$

8.2.1.1 Bending Strain

Longitudinal bending strain (ε_b) and longitudinal bending stress (s_b) for PVC pipe at different degrees of axial flexure are shown in Table 8.9, from Equation 8.15. The bending stresses calculated are the initial stresses, which decrease over time when the strain stays constant.

Equation 8.15

$$\varepsilon_b = \frac{s_b}{E} = \frac{D_o}{2R_b}$$

where:

ε_b = longitudinal bending strain, in./in.
s_b = flexural stress from longitudinal bending, psi
E = modulus of elasticity of pipe material, psi
D_o = pipe outside diameter, in.
R_b = bending radius of pipe, in.

Table 8.9 Longitudinal bending stress and strain in PVC pipe

Bending radius ratio R_b/D_o	Bending strain ε_b (in./in.)	Bending stress, s_b (psi)		
		E = 400,000	E = 440,000	E = 500,000
25	0.0200	8,000	8,800	10,000
50	0.0100	4,000	4,400	5,000
100	0.0050	2,000	2,200	2,500
200	0.0025	1,000	1,100	1,250
250	0.0020	800	880	1,000
300	0.0017	667	748	833
350	0.0010	400	440	500

8.2.1.2 Bending Ovalization (Diametric or Ring Deflection)

As a thin tube is bent longitudinally, it "ovalizes" into an approximately elliptical shape; in this chapter this effect has been ignored and deemed insignificant in the longitudinal bending equations so far. Ring deflection (δ) is usually expressed as:

Equation 8.16

$$\text{ring deflection} = \delta = \frac{\Delta Y}{D}$$

where:

δ = diametric (ring) deflection, dimensionless
ΔY = reduction in outside diameter, in.
D = original pipe outside diameter, in.

or:

Equation 8.17

$$\%\ \text{ring deflection} = 100\delta = 100\,\frac{\Delta Y}{D}$$

For thin pressurized tubes, the mathematical relationship between ring deflection and axial bending was derived by Reissner as follows:

Equation 8.18

$$\delta = \frac{\Delta Y}{D} = \lambda_2\left[\frac{2}{3} + \left(\frac{71 + 4\lambda_1}{135 + 9\lambda_1}\right)\lambda_2\right]$$

with λ_1 and λ_2 defined as:

Equation 8.19

$$\lambda_1 = \frac{12(1 - \nu^2)PD_m^3}{8Et^3}$$

Equation 8.20

$$\lambda_2 = \frac{1}{16}\left[\frac{18(1 - \nu^2)}{12 + 4\lambda}\right]\frac{D_m^4}{R_b t^2}$$

where:

λ_1, λ_2 = intermediate variables used to simply equations
D_m = mean pipe diameter, in.

ν = Poisson's ratio, dimensionless = 0.38 for PVC pipe
P = internal pipe pressure, psi
E = modulus of elasticity of the pipe material, psi
t = pipe wall thickness, in. (use $t_{avg} = 1.06 \times t_{min}$)
R_b = bending radius of pipe, in.

Example 8.2

Calculate the percent ring deflection δ that results from bending a 15-in. DR 35 PVC sewer pipe with a 400,000 psi modulus of elasticity to a minimum bending radius of 156 times the pipe diameter, as shown in Table 8.8.

Solution

Since P = 0, then $\lambda_1 = 0$ for sewer pipe. So,

$$\lambda_2 = \frac{1}{16}\left[\frac{18(1 - 0.38^2)}{12 + 4\lambda}\right]\frac{D_m^4}{R^2t^2}$$

$$= \frac{1}{16}\left(\frac{18}{12} \times 0.86\right)\frac{(15.3 - 0.463)^4}{(2{,}387^2)(0.463^2)}$$

$$= \frac{0.080(48{,}460)}{(5.597 \times 10^6)(0.214)} = 0.00324$$

$$\delta = 0.00324\left[\frac{2}{3} + \left(\frac{71 + 0}{135 + 0}\right)(0.00324)\right]$$

$$= 0.00324\ (0.667 + 0.00170)$$
$$= 0.002$$
$$= 0.2\%\ \text{ring deflection}$$

Example 8.3

Calculate the percent ring deflection after pressurization to 100 psi that results from bending a 4-in. DR 14 PVC pressure pipe to a minimum bending radius of 250 times its diameter, as shown in Table 8.4.

Solution

$$\lambda_1 = \frac{12(1 - 0.38^2)100(4.800 - 0.363)^3}{8(400{,}000)(0.363^3)} = \frac{1{,}200(0.86)(87.29)}{3{,}200{,}000(0.0482)} = 0.584$$

$$\lambda_2 = \frac{1}{16}\left[\frac{18(1 - 0.38^2)}{12 + 4(0.584)}\right]\frac{(4.800 - 0.363)^4}{(1{,}200^2)(0.363^2)}$$

$$= \frac{1}{16}\left(\frac{18 \times 0.86}{12 + 2.32}\right)\frac{387.2}{(1{,}440{,}000)(0.132)} = 0.000138$$

$$\delta = 0.000138\left[\left(\frac{2}{3}\right) + \frac{71 + 4(0.584)}{135 + 9(0.584)} \times 0.000138\right]$$

$$= 0.000138\left(\frac{2}{3} + 0.000722\right)$$

$$= 0.000092$$

$$= 0.009\% \text{ ring deflection}$$

An analysis of the above examples determines that a good approximation of ring deflection δ can be calculated at the recommended minimum bending radius for 4- to 15-in. PVC pressure pipe and nonpressure pipe. The following equation handles this approximation:

Equation 8.21

$$\delta = \frac{\Delta Y}{D_m} = \frac{2}{3}(\lambda_2) = \frac{(1 - \nu^2)D_m^4}{16R_b t^2}$$

Analysis of these relationships also establishes that the amount of deflection resulting from bending is negligible in the case of pressure pipes, and the amount has very little significance in the case of nonpressure pipes.

8.2.2 Axial Joint Deflection

When longitudinal bending of PVC pipe barrel is not practical, such as is the case in large-diameter pipeline, axial deflection in pipe joints may be possible. The pipe manufacturer should be contacted for joint deflection recommendations.

The recommended axial joint-deflection β is shown in Fig. 8.4.

For vertical changes in direction, joint deflection of one degree is equivalent to a change in slope of 1.75 percent.

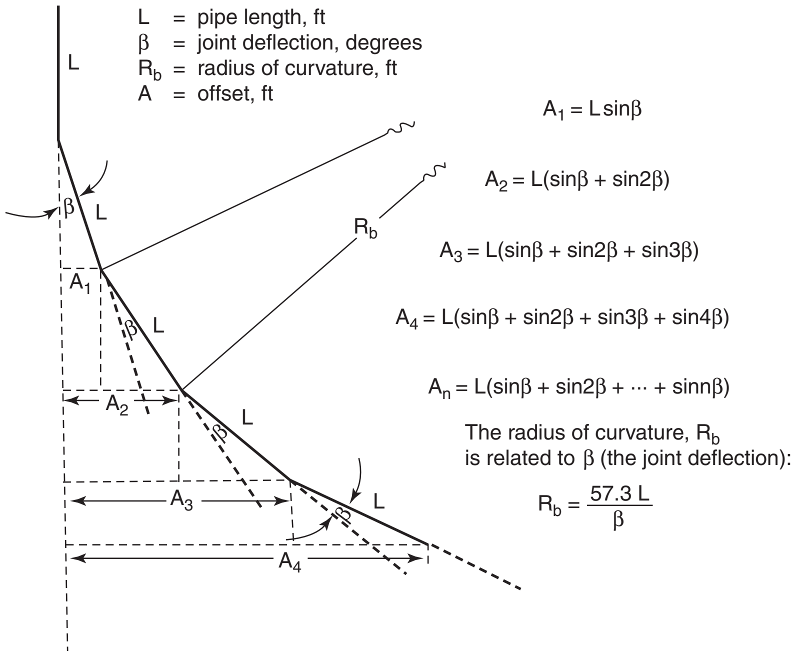

Fig. 8.4 Alignment change from offsetting multiple pipes.

8.3 Support Spacing

PVC pipe installed above ground must be suspended from properly spaced supports. These supports are called “hangers” or “brackets.” Proper spacing of pipe supports prevents excessive bending stress, eliminates excessive stress concentration due to load bearing, and limits pipe displacement or “sag” between supports to acceptable tolerances. Recommended support spacing or length of pipe spanning between supports for PVC pipe in above-ground applications is shown in Table 8.10.

PVC pipe that conveys fluids while suspended in horizontal configuration by rigid supports responds to load in accordance with design theory for suspended beams. For two supports per continuous length of pipe (one span), maximum span vertical displacement (sag) may be calculated as:

Equation 8.22

$$y = \frac{0.0130\,W_w L_s^4}{EI}$$

where:

y = mid-span vertical displacement (sag), in.
W_W = weight of pipe filled with water, lb/in.

L_s = support spacing or span length, in.
E = modulus of elasticity of the pipe material, psi
I = moment of inertia, $in.^4$ (see Equation 8.4)

Note: The use of two supports (one span) is the most conservative case.

Equation 8.22 for vertical displacement can be rearranged in order to calculate maximum support spacing to allow for a maximum long-term mid-span deflection (sag) of 0.2% of span length.

Equation 8.23

$$L_s = \left(\frac{0.154\,EI}{W_w}\right)^{1/3}$$

Since the modulus of elasticity of PVC is temperature-dependent, a multiplier should be applied to the room temperature modulus for applications at higher temperatures. The modulus for PVC at 73.4°F is simply multiplied by the correction factor shown in Table 8.3 to obtain an accurate E value, which can be used in vertical displacement and support spacing calculations.

The weight of PVC pipe when filled with water is calculated as follows:

Equation 8.24

$$W_w = 0.0113(3.5D_o^2 - D_i^2)$$

where:

D_o = pipe outside diameter, in.
D_i = pipe inside diameter, in.

The derivation of Equation 8.24 is based on *specific gravity* (SG). Specific gravity (or *relative density*) is a ratio of the density of a substance to water's density (62.4 lb/ft^3 or 1 g/ml) at a given temperature. The SG of water is defined as its density relative to itself and is thus 1.0. PVC's specific gravity is 1.4. That is,

$$SG_{H_2O} = 1.0$$
$$SG_{PVC} = 1.4$$

Typically, the specific gravity of sewage can be assumed to be 1.0. If higher specific gravities are anticipated, Equation 8.24 should be factored by the particular fluid specific gravity.

Maximum bending stress in the pipe wall may be calculated as follows:

Equation 8.25

$$S_b = \frac{MD_o}{2I}$$

where:

S_b = allowable flexural stress from longitudinal bending, psi
M = bending moment, in.-lb

Moment for an end-supported simple beam with single span may be calculated as follows:

Equation 8.26

$$M = \frac{wL_s^2}{8}$$

where:

w = load on pipe per unit length, lb/in.
L_s = support spacing or span length, in.

Substituting Equation 8.26 for M and Equation 8.4 for I in Equation 8.25 results in the equation for maximum bending stress:

Equation 8.27

$$S_b = \frac{1.27\,wL_s^2D_o}{D_o^4 - D_i^4}$$

A brief list of best practices for support spacing is as follows:

- A support should be placed within 2 ft of both sides of each pipe joint.
- Pipe supports should provide a smooth bearing surface conforming closely to the pipe contour.
- The bearing surface in contact with the pipe should provide adequate support.
- Supports should permit longitudinal pipe movement in expansion and contraction without abrasion, cutting, or restriction.
- Supports should be mounted rigidly to prevent lateral or vertical pipe movement perpendicular to longitudinal axis in response to thrust from internal pressure.
- Changes in pipe line size and direction should be adequately anchored.

Table 8.10 Support spacing for suspended horizontal PVC pipe filled with water (see *Notes* at end of table)

Modulus of elasticity of 400,000 psi					
Pipe size, in.	Product standard	Dimension ratio	PVC pipe support spacing, ft (m)		
			73.4°F (23°C)	120°F (49°C)	140°F (60°C)
4	AWWA C900	14	8.3 (2.5)	7.7 (2.3)	7.4 (2.2)
		18	7.8 (2.3)	7.3 (2.2)	7.0 (2.1)
		25	7.2 (2.1)	6.7 (2.0)	6.4 (1.9)
6	AWWA C900	14	10.6 (3.2)	9.9 (3.0)	9.4 (2.8)
		18	10.0 (3.0)	9.3 (2.8)	8.9 (2.4)
		25	9.2 (2.8)	8.5 (2.5)	8.1 (2.4)
8	AWWA C900	14	12.8(3.9)	11.8 (3.5)	11.3 (3.4)
		18	12.0 (3.6)	11.1 (3.3)	10.6 (3.2)
		25	11.0 (3.3)	10.2 (3.1)	9.8 (2.9)
10	AWWA C900	14	14.6 (4.4)	13.6 (4.1)	13.0 (3.9)
		18	13.8 (4.2)	12.8 (3.9)	12.2 (3.7)
		25	12.6 (3.8)	11.7 (3.5)	11.2 (3.4)
12	AWWA C900	14	16.4 (4.9)	15.2 (4.6)	14.6 (4.4)
		18	15.4 (4.6)	14.3 (4.3)	13.7 (4.1)
		25	14.2 (4.3)	13.1 (3.9)	12.6 (3.8)

Note: Support spacing recommendations shown in this table are based on the following design limitations:

1. Initial pipe vertical displacement (sag) limited to 0.2% of span length based on calculations using Equation 8.22, so that long-term sag is limited to approximately 0.5%.
2. Pipe bending stress values limited to values defined in Table 8.2.
3. All calculated values greater than 20.0 ft have been reduced to 20.0 ft. Pipe supplier should be consulted for spacing recommendations for pipe longer than 20 ft.
4. Support spacing is based on single-span simply supported beams. These values are conservative when used for multiple spans.
5. Due to the various profile designs that are available, manufacturers of profile wall pipe should be contacted concerning the recommended support spacing of their products.

Table 8.10 Support spacing for suspended horizontal PVC pipe filled with water (see *Notes* at end of table) (*continued*)

Modulus of elasticity of 400,000 psi					
			PVC pipe support spacing, ft (m)		
Pipe size, in.	Product standard	Dimension ratio	73.4°F (23°C)	120°F (49°C)	140°F (60°C)
14	AWWA C905	18	17.3 (5.3)	16.0 (4.9)	15.3 (4.7)
		21	16.7 (5.1)	15.4 (4.7)	14.8 (4.5)
		25	15.8 (4.8)	14.7 (4.5)	14.1 (4.3)
		32.5	14.7 (4.5)	13.6 (4.2)	13.1 (4.0)
		41	13.8 (4.2)	12.8 (3.9)	12.3 (3.7)
16	AWWA C905	18	18.8 (5.7)	17.4 (5.3)	16.7 (5.1)
		21	18.2 (5.5)	16.8 (5.1)	16.1 (4.9)
		25	17.3 (5.3)	16.0 (4.9)	15.3 (4.7)
		32.5	16.1 (4.9)	14.8 (4.5)	14.3 (4.3)
		41	15.0 (4.6)	13.9 (4.2)	13.4 (4.1)
18	AWWA C905	18	20.0 (6.1)	18.8 (5.7)	18.0 (5.5)
		21	19.5 (5.9)	18.0 (5.5)	17.3 (5.3)
		25	18.6 (5.7)	17.2 (5.3)	16.5 (5.0)
		32.5	17.3 (5.3)	16.0 (4.9)	15.4 (4.7)
		41	16.2 (4.9)	15.0 (4.6)	14.4 (4.4)
		51	15.3(4.6)	14.4 (4.3)	13.5 (4.1)
20	AWWA C905	18	20.0 (6.1)	20.0 (6.1)	19.3 (5.9)
		21	20.0 (6.1)	19.3 (5.9)	18.5 (5.7)
		25	19.9 (6.1)	18.4 (5.6)	17.7 (5.4)
		32.5	17.3 (5.3)	16.0 (4.9)	15.4 (4.7)
		41	17.4 (5.3)	16.1 (4.9)	15.4 (4.7)
		51	16.4 (5.0)	15.1(4.6)	14.5 (4.4)

Table 8.10 Support spacing for suspended horizontal PVC pipe filled with water (see *Notes* at end of table) (*continued*)

Modulus of elasticity of 400,000 psi					
Pipe size, in.	Product standard	Dimension ratio	PVC pipe support spacing, ft (m)		
			73.4°F (23°C)	120°F (49°C)	140°F (60°C)
24	AWWA C905	18	20.0 (6.1)	20.0 (6.1)	20.0 (6.1)
		21	20.0 (6.1)	20.0 (6.1)	20.0 (6.1)
		25	20.0 (6.1)	20.0 (6.1)	19.9 (6.1)
		32.5	20.0 (6.1)	19.3 (5.9)	18.5 (5.6)
		41	19.6 (6.0)	18.1 (5.5)	17.4 (5.3)
		51	18.4 (5.6)	17.0 (5.2)	16.3 (5.0)
30	AWWA C905	21	20.0 (6.1)	20.0 (6.1)	20.0 (6.1)
		25	20.0 (6.1)	20.0 (6.1)	20.0 (6.1)
		32.5	20.0 (6.1)	20.0 (6.1)	20.0 (6.1)
		41	20.0 (6.1)	20.0 (6.1)	20.0 (6.1)
		51	20.0 (6.1)	19.7 (6.0)	18.9 (5.7)
36	AWWA C905	21	20.0 (6.1)	20.0 (6.1)	20.0 (6.1)
		25	20.0 (6.1)	20.0 (6.1)	20.0 (6.1)
		32.5	20.0 (6.1)	20.0 (6.1)	20.0 (6.1)
		41	20.0 (6.1)	20.0 (6.1)	20.0 (6.1)
		51	20.0 (6.1)	20.0 (6.1)	20.0 (6.1)

Note: Support spacing recommendations shown in this table are based on the following design limitations:

1. Initial pipe vertical displacement (sag) limited to 0.2% of span length based on calculations using Equation 8.22, so that long-term sag is limited to approximately 0.5%.
2. Pipe bending stress values limited to values defined in Table 8.2.
3. All calculated values greater than 20.0 ft have been reduced to 20.0 ft. Pipe supplier should be consulted for spacing recommendations for pipe longer than 20 ft.
4. Support spacing is based on single-span simply supported beams. These values are conservative when used for multiple spans.
5. Due to the various profile designs that are available, manufacturers of profile wall pipe should be contacted concerning the recommended support spacing of their products.

Table 8.10 Support spacing for suspended horizontal PVC pipe filled with water (see *Notes* at end of table) (*continued*)

Modulus of elasticity of 400,000 psi					
			PVC pipe support spacing, ft (m)		
Pipe size, in.	Product standard	Dimension ratio	73.4°F (23°C)	120°F (49°C)	140°F (60°C)
42	AWWA C905	25	20.0 (6.1)	20.0 (6.1)	20.0 (6.1)
		32.5	20.0 (6.1)	20.0 (6.1)	20.0 (6.1)
		41	20.0 (6.1)	20.0 (6.1)	20.0 (6.1)
		51	20.0 (6.1)	20.0 (6.1)	20.0 (6.1)
48	AWWA C905	32.5	20.0 (6.1)	20.0 (6.1)	20.0 (6.1)
		41	20.0 (6.1)	20.0 (6.1)	20.0 (6.1)
		51	20.0 (6.1)	20.0 (6.1)	20.0 (6.1)
1.5	ASTM D2241	21	4.2 (1.3)	3.8 (1.2)	3.7 (1.1)
		26	3.9 (1.2)	3.6 (1.1)	3.5 (1.1)
2	ASTM D2241	21	4.8 (1.5)	4.5 (1.4)	4.3 (1.3)
		26	4.6 (1.4)	4.2 (1.3)	4.0 (1.2)
2.5	ASTM D22415	21	5.5 (1.7)	5.1 (1.5)	4.9 (1.5)
		26	5.2 (1.6)	4.8 (1.5)	4.6 (1.4)
3	ASTM D2241	21	6.3 (1.9)	5.8 (1.8)	5.6 (1.7)
		26	5.9 (1.8)	5.5 (1.7)	5.2 (1.6)
4	ASTM D2241	21	7.4 (2.3)	6.8 (2.1)	6.6 (2.0)
		26	7.0 (2.1)	6.5 (2.0)	6.2 (1.9)
5	ASTM D2241	21	8.5 (2.6)	7.9 (2.4)	7.6 (2.3)
		26	8.0 (2.5)	7.4 (2.3)	7.1 (2.2)
6	ASTM D2241	21	9.6 (2.9)	8.8 (2.7)	8.5 (2.6)
		26	9.0 (2.8)	8.4 (2.5)	8.0 (2.4)
8	ASTM D2241	21	11.4 (3.5)	10.5 (3.2)	10.1 (3.1)
		26	10.8 (3.3)	10.0 (3.0)	9.6 (2.9)
		32.5	10.1 (3.1)	9.4 (2.9)	9.0 (2.7)
		41	9.5 (2.9)	8.7 (2.7)	8.4 (2.6)

Table 8.10 Support spacing for suspended horizontal PVC pipe filled with water (see *Notes* at end of table) (*continued*)

Modulus of elasticity of 400,000 psi					
			PVC pipe support spacing, ft (m)		
Pipe size, in.	Product standard	Dimension ratio	73.4°F (23°C)	120°F (49°C)	140°F (60°C)
10	ASTM D2241	21	13.2 (4.0)	12.2 (3.7)	11.7 (3.6)
		26	12.5 (3.8)	11.5 (3.5)	11.1 (3.4)
		32.5	11.7 (3.6)	10.8 (3.3)	10.4 (3.2)
		41	11.0 (3.3)	10.1 (3.1)	9.7 (3.0)
12	ASTM D2241	21	14.8 (4.5)	13.7 (4.2)	13.1 (4.0)
		26	14.0 (4.3)	12.9 (3.9)	12.4 (3.8)
		32.5	13.1 (4.0)	12.1 (3.7)	11.7 (3.6)
		41	12.3 (3.7)	11.4 (3.5)	10.9 (3.3)
14	ASTM D2241	21	16.5 (4.8)	14.5 (4.4)	13.9 (4.2)
		26	14.8 (4.5)	13.7 (4.2)	13.1 (4.0)
		32.5	13.9 (4.2)	12.8 (3.9)	12.3 (3.8)
		41	13.0 (4.0)	12.0 (3.7)	11.6 (3.5)
16	ASTM D2241	21	17.1 (5.2)	15.8 (4.8)	15.2(4.6)
		26	16.2 (4.9)	14.9 (4.6)	14.3 (4.4)
		32.5	15.2 (4.6)	14.0 (4.3)	13.5 (4.1)
		41	14.2 (4.3)	13.2 (4.0)	12.6 (3.9)

Note: Support spacing recommendations shown in this table are based on the following design limitations:

1. Initial pipe vertical displacement (sag) limited to 0.2% of span length based on calculations using Equation 8.22, so that long-term sag is limited to approximately 0.5%.
2. Pipe bending stress values limited to values defined in Table 8.2.
3. All calculated values greater than 20.0 ft have been reduced to 20.0 ft. Pipe supplier should be consulted for spacing recommendations for pipe longer than 20 ft.
4. Support spacing is based on single-span simply supported beams. These values are conservative when used for multiple spans.
5. Due to the various profile designs that are available, manufacturers of profile wall pipe should be contacted concerning the recommended support spacing of their products.

Table 8.10 Support spacing for suspended horizontal PVC pipe filled with water (see *Notes* at end of table) (*continued*)

Modulus of elasticity of 400,000 psi					
			PVC pipe support spacing, ft (m)		
Pipe size, in.	Product standard	Dimension ratio	73.4°F (23°C)	120°F (49°C)	140°F (60°C)
18	ASTM D2241	21	18.5 (5.6)	17.1 (5.2)	16.4 (5.0)
		26	17.5 (5.3)	16.3 (4.9)	15.5 (4.7)
		32.5	16.4 (5.0)	15.2 (4.6)	14.6 (4.4)
		41	15.4 (4.7)	14.2 (4.3)	13.7 (4.2)
20	ASTM D2241	21	19.8 (6.0)	18.3 (5.6)	17.6 (5.4)
		26	18.7 (5.7)	17.3 (5.3)	16.6 (5.1)
		32.5	17.6 (5.4)	16.3 (5.0)	15.6 (4.8)
		41	16.5 (5.0)	15.3 (4.7)	14.7 (4.5)
24	ASTM D2241	21	20.0 (6.1)	19.6 (6.0)	18.8 (5.7)
		26	20.0 (6.1)	19.6 (6.0)	18.8 (5.7)
		41	18.6 (5.7)	17.2 (5.3)	16.6 (5.0)
4	ASTM D3034	26	6.7 (2.0)	6.2 (1.9)	5.9 (1.8)
		35	6.1 (1.9)	5.7 (1.7)	5.5 (1.7)
6	ASTM D3034	26	8.7 (2.7)	8.1 (2.5)	7.7 (2.4)
		35	8.0 (2.4)	7.4 (2.3)	7.1 (2.2)
8	ASTM D3034	26	10.6 (3.2)	9.8 (3.0)	9.4 (2.9)
		35	9.7 (3.0)	9.0 (2.7)	8.6 (2.6)
10	ASTM D3034	26	12.3 (3.7)	11.4 (3.5)	10.9 (3.3)
		35	11.3 (3.4)	10.4 (3.2)	10.0 (3.1)
12	ASTM D3034	26	13.8 (4.2)	12.8 (3.9)	12.2 (3.7)
		35	12.7 (3.9)	11.8 (3.6)	11.3 (3.3)
15	ASTM D3034	26	15.8 (4.8)	14.6 (4.4)	14.0 (4.3)
		35	14.5 (4.4)	13.4 (4.1)	12.9 (3.9)

Table 8.10 Support spacing for suspended horizontal PVC pipe filled with water (see *Notes* at end of table) (*continued*)

Modulus of elasticity of 400,000 psi					
			PVC pipe support spacing, ft (m)		
Pipe size, in.	Product standard	Dimension ratio	73.4°F (23°C)	120°F (49°C)	140°F (60°C)
18	ASTM F679		16.5 (5.0)	15.3 (4.7)	14.7 (4.5)
21	ASTM F679		18.4 (5.6)	17.0(5.2)	16.4 (5.0)
24	ASTM F679		19.9 (6.1)	18.4 (5.6)	17.7 (5.4)
27	ASTM F679		20.0 (6.1)	19.9 (6.1)	19.2 (5.8)
30–48	ASTM F679		20.0 (6.1)	20.0 (6.1)	20.0 (6.1)

Modulus of elasticity of 500,000 psi					
			PVC pipe support spacing, ft (m)		
Pipe size, in.	Product standard	Dimension ratio	73.4°F (23°C)	120°F (49°C)	140°F (60°C)
4	ASTM D3034	35	6.5 (1.9)	6.0 (1.8)	5.7 (1.7)
6	ASTM D3034	35	8.4 (2.5)	7.8 (2.3)	7.5 (2.2)
8	ASTM D3034	35	10.2 (3.1)	9.5 (2.8)	9.1 (2.7)
10	ASTM D3034	35	11.9 (3.6)	11.0 (3.3)	10.6 (3.2)
12	ASTM D3034	35	13.4 (4.0)	12.4 (3.7)	11.9 (3.6)
15	ASTM D3034	35	15.3 (4.6)	14.2 (4.3)	13.6 (4.1)

Note: Support spacing recommendations shown in this table are based on the following design limitations:

1. Initial pipe vertical displacement (sag) limited to 0.2% of span length based on calculations using Equation 8.22, so that long-term sag is limited to approximately 0.5%.
2. Pipe bending stress values limited to values defined in Table 8.2.
3. All calculated values greater than 20.0 ft have been reduced to 20.0 ft. Pipe supplier should be consulted for spacing recommendations for pipe longer than 20 ft.
4. Support spacing is based on single-span simply supported beams. These values are conservative when used for multiple spans.
5. Due to the various profile designs that are available, manufacturers of profile wall pipe should be contacted concerning the recommended support spacing of their products.

8.4 Expansion and Contraction

All pipe products expand and contract with temperature change. Variation in pipe length due to thermal expansion or contraction depends on coefficient of thermal expansion of pipe material and variation in temperature (ΔT). It should be noted that change in pipe diameter or wall thickness, with pipe material properties remaining constant, does not affect rates of thermal expansion or contraction. Typical coefficients of thermal expansion for different pipe materials are presented in Table 8.11.

Table 8.12 displays typical length variation of PVC pipe due to thermal expansion and contraction.

A good rule of thumb in the design of PVC piping systems is to allow 3/8 in. of length variation for every 100 ft of pipe for each 10ºF change in temperature (5.4 mm/10 m/10ºC).

Table 8.11 Coefficients of thermal expansion

Piping material	Coefficient in./in./°F	Expansion in./100 ft/10°F	Coefficient mm/mm/°C	Expansion mm/10m/10°C
PVC	3.0×10^{-5}	0.36	5.4×10^{-5}	5.4
HDPE	12.0×10^{-5}	1.44	22.0×10^{-5}	21.6
ABS	5.5×10^{-5}	0.66	9.9×10^{-5}	9.9
Aluminum	1.3×10^{-5}	0.16	2.3×10^{-5}	2.3
Ductile iron	0.62×10^{-5}	0.07	1.1×10^{-5}	1.1
Steel	0.65×10^{-5}	0.08	1.2×10^{-5}	1.2
Clay	0.34×10^{-5}	0.04	0.61×10^{-5}	0.6
Concrete	0.55×10^{-5}	0.07	0.99×10^{-5}	1.0
Copper	0.98×10^{-5}	0.12	1.8×10^{-5}	1.8

Table 8.12 Length variation per 10ºF ΔT PVC pipe

Pipe length		Length change	
ft	m	in.	mm
20	6.1	0.072	1.83
14	4.3	0.050	1.27
13	4.0	0.047	1.19
10	3.0	0.036	0.91

Unrestrained gasketed-joint PVC pipe is designed to accommodate thermal expansion and contraction. If gasketed joints are used within the accepted range of operating temperatures for PVC pipe, thermal expansion and contraction is not a significant factor in system design.

8.5 Flotation

Pipe can be buoyant depending on field conditions. Flotation occurs when groundwater surrounding the pipe produces an upward buoyant force greater than the weight of the pipe and its contents combined with soil weight and friction. Although flotation is generally not a design concern for buried pipe when it is full or where the groundwater table is below the pipe invert, sufficient backfill placed over the pipe will prevent flotation and movement. The recommended depth of cover over PVC pipe to prevent flotation is 1.5 times the pipe diameter.

8.6 Sources

ASTM D2241, Standard Specification for Polyvinyl Chloride (PVC) Pressure-Rated Pipe (SDR Series). ASTM International, West Conshohocken, PA (2009).

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CHAPTER 9

Hydraulics

Introduction to Hydraulics
•
Flow in PVC Pressure Pipes
•
Flow in PVC Nonpressure Pipe

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9.1 Notation

A = cross-sectional area of flow, ft^2

A_c = cross-sectional area of circle, $in.^2$

A_s = cross-sectional area of ellipse, $in.^2$

a = deflected pipe long semi-axis, in.

b = deflected pipe short semi-axis, in.

C = Hazen–Williams flow coefficient, dimensionless

d_i = pipe inside diameter, in.

D = pipe inside diameter, ft

D_i = pipe inside diameter, in.

f = friction loss, ft of H_2O/100 ft

f_D = Darcy friction factor, dimensionless

g = acceleration of gravity, ft/s^2

h_f = head loss, ft of H_2O

H = head loss, ft of H_2O/1,000 ft

H_1 = upstream pipe elevation, ft

H_2 = downstream pipe elevation, ft

ID = inside pipe diameter, in.

L = pipe length, ft

n = coefficient of roughness (Manning's equation and Kutter's formula), dimensionless

P_w = wetted perimeter, ft

P_1 = maximum pressure, psi

P_2 = minimum pressure, psi

Q or MGD = flow rate, gpm or ft^3/s or gpd

R_e = Reynolds number, dimensionless

R_H = hydraulic radius, ft

r_i = pipe inside radius, in.

S = hydraulic slope, ft/ft (pressure pipe)

s = hydraulic slope, ft/ft (non-pressure pipe)

S_E = slope of energy grade line, ft/ft

t = pipe wall thickness, in.

V = mean flow velocity, ft/s

ε = equivalent roughness, in. or ft (to match units of pipe inside diameter)

ν = kinematic viscosity of a fluid, ft^2/s

ΔX = horizontal pipe deflection, in.

ΔY = vertical pipe deflection, in.

9.2 Introduction to Hydraulics

9.2.1 Flow Theories and Equations

Many empirical formulas have been developed for solving the variety of problems related to flow in pipes. Equations developed by hydraulic engineers are used daily in the solution of problems encountered by water and sewer engineers. Relatively few specific problems in pipe hydraulics, such as laminar flow, can be solved entirely theoretically by mathematical means; rather, solutions to a majority of flow problems depend to some degree on experimentally determined coefficients. Thus, commonly used flow formulas have been developed through research by (among others) Fanning, Darcy, Chezy, Kutter, Scobey, Manning, Weisbach, Hazen, and Williams.

9.2.2 Hydraulic Radius

The *hydraulic radius* is used for hydraulic calculations for both pressure and nonpressure pipe. The hydraulic radius is obtained by dividing the cross-sectional area of the flow by the wetted perimeter of the pipe (i.e., the perimeter along which the flow is in contact with the pipe walls). The value of the hydraulic radius varies with the level of flow.

For the pressure pipe portion of this chapter, pipes will be assumed to be flowing full. For the nonpressure portion, pipes will be assumed to be flowing either full or half-full.

Equation 9.1

$$R_H = \frac{A}{P_w}$$

where:

R_H = hydraulic radius, ft

A = cross-sectional area of flow, ft^2

P_w = wetted perimeter of flow area, ft

For pipe flowing full,

$$A = \pi D_i^2/4$$
$$P_w = \pi D_i$$

where:

D_i = pipe inside diameter, ft

The hydraulic radius

$$R_H = \frac{A}{P_w} = \frac{\frac{\pi D_i^2}{4}}{\pi D_i} = \frac{D_i}{4}.$$

For pipe flowing half-full, both A and P_w are thus divided by 2, so $A = {}^1\!/_2\,(\pi D_i^2/4)$ and $P_w = {}^1\!/_2\,(\pi D_i)$.

Thus, hydraulic radius is given by:

$$R_H = \frac{A}{P_w} = \frac{\frac{1}{2}\pi\frac{D_i^2}{4}}{\frac{1}{2}\pi D_i} = \frac{D_i}{4}.$$

Therefore, for the design of all pressure pipe and nonpressure pipe, the hydraulic radius = $D_i/4$.

9.3 Flow in PVC Pressure Pipe

Hydraulic flow research and analysis has established that flow conditions in PVC pressure piping systems can be designed conservatively using the *Hazen–Williams* equation. Flow conditions also can be designed with more detailed analysis through the *Darcy–Weisbach* equation. These two formulas are covered in the next sections.

9.3.1 Hazen–Williams Flow Formula

The Hazen–Williams flow formula is most widely used in the calculation of pressure pipe conditions. Various forms of Hazen–Williams are given in Equations 9.2 through

9.9. Equations 9.2 through 9.5 are generic, while Equations 9.6 through 9.9 are specific to PVC pipe.

Equation 9.2

$$V = 1.318 C R_H^{0.63} S^{0.54}$$

where:

V = mean flow velocity, ft/s
C = Hazen–Williams flow coefficient, dimensionless
S = hydraulic slope, ft/ft

Equation 9.3

$$Q = 0.442 C D_i^{2.63} \left(\frac{P_1 - P_2}{L} \right)^{0.54}$$

where:

Q = flow rate, gpm
L = pipe length, ft
P_1 = maximum pressure, psi
P_2 = minimum pressure, psi

Equation 9.4

$$Q = 0.006756 C D_i^{2.63} H^{0.54}$$

where:

H = head loss, ft of H_2O/1,000 ft

Friction loss (f) in hydraulic flow is derived through the following expression of the Hazen–Williams equation:

Equation 9.5

$$f = 0.2083 \left(\frac{100}{C} \right)^{1.85} \frac{Q^{1.85}}{D_i^{4.86}}$$

where:

f = friction loss, ft of H_2O/100 ft

PVC pipe flow coefficients were discovered through the research and analysis of various individuals, including Neale, Price, Jeppson, and Bishop. The Hazen–Williams flow coefficient (or “C Factor”) is commonly calculated as a range of values from 155 to 165 for both new and used PVC pipe. The coefficient has been established, conservatively, at C = 150 for gasketed PVC piping system design. Research has also established that the internal bead formed from the butt-fusion of PVC is adequately addressed with a C Factor of 150.

With C established at 150 for PVC pipe, Equations 9.2 through 9.5 can be simplified for PVC piping system design:

Equation 9.6

$$V = 197.7\,R_H^{0.63}\,S^{0.54}$$

Equation 9.7

$$Q = 66.3\,D_i^{2.63}\left(\frac{P_1 - P_2}{L}\right)^{0.54}$$

Equation 9.8

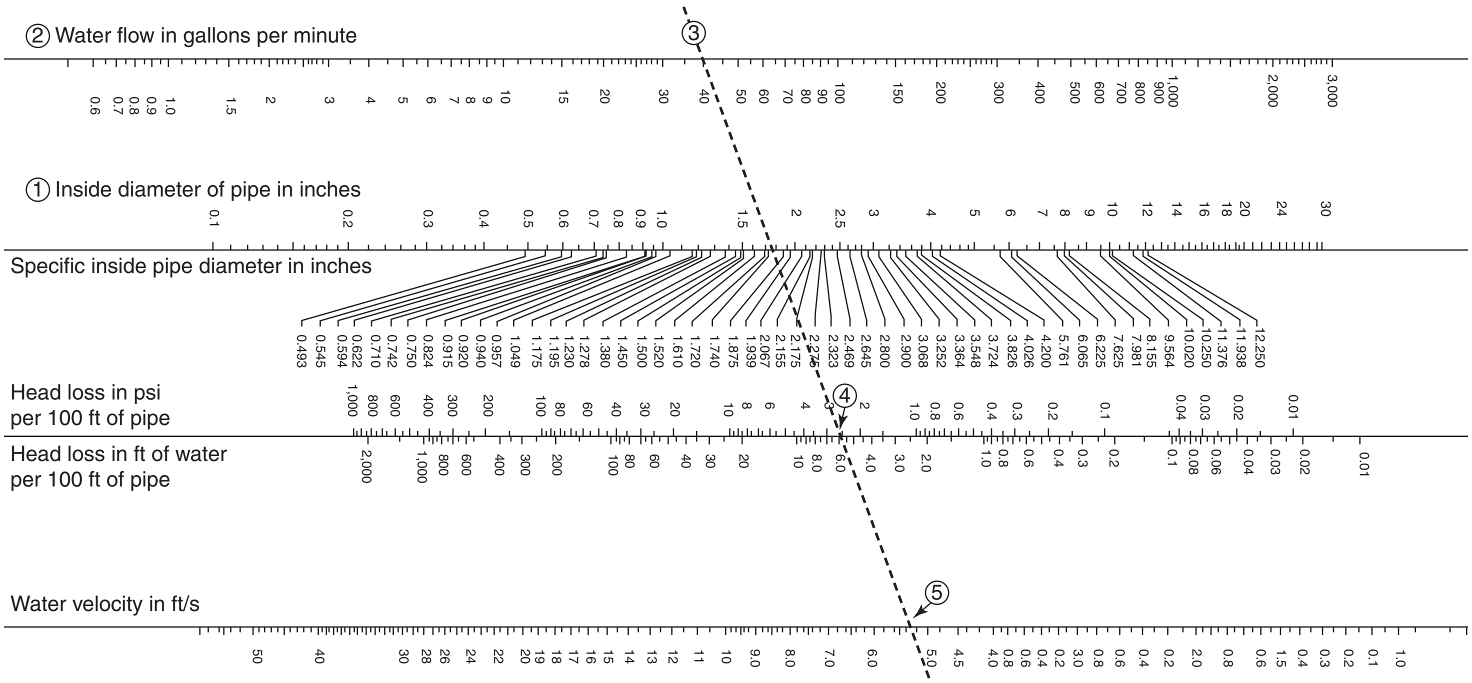
$$Q = 1.0134\,D_i^{2.63}\,H^{0.54}$$

Equation 9.9

$$f = 0.0984\,\frac{Q^{1.85}}{D_i^{4.86}}$$

Nomographs for solving flow characteristics are provided in Figs. 9.1 and 9.2; Table 9.1 shows some of these data in tabular form. Additionally, Tables 9.3, 9.4, and 9.5 were developed based on the Hazen–Williams formula with C Factor of 150 to provide flow capacity (gpm), friction loss (ft of H_2O/100 ft), and flow velocity (ft/s) for PVC pressure pipe products.

Friction Loss Characteristics of Water Flow Through PVC Pipe



How to use this graph:

1. Select the desired pipe size (inside diameter).
2. Determine the amount of water to flow through the pipe.
3. Place a straight-edge on these two points.
4. The point at which the straight-edge intersects the head-loss line and the velocity line gives these two values under the given conditions.
5. This graph should be used for approximate values only.

Example:
Given 1.5 in. schedule A pipe (ID = 1.740 in.) ① and 40 gal/min service ②, find the corresponding values as follows:

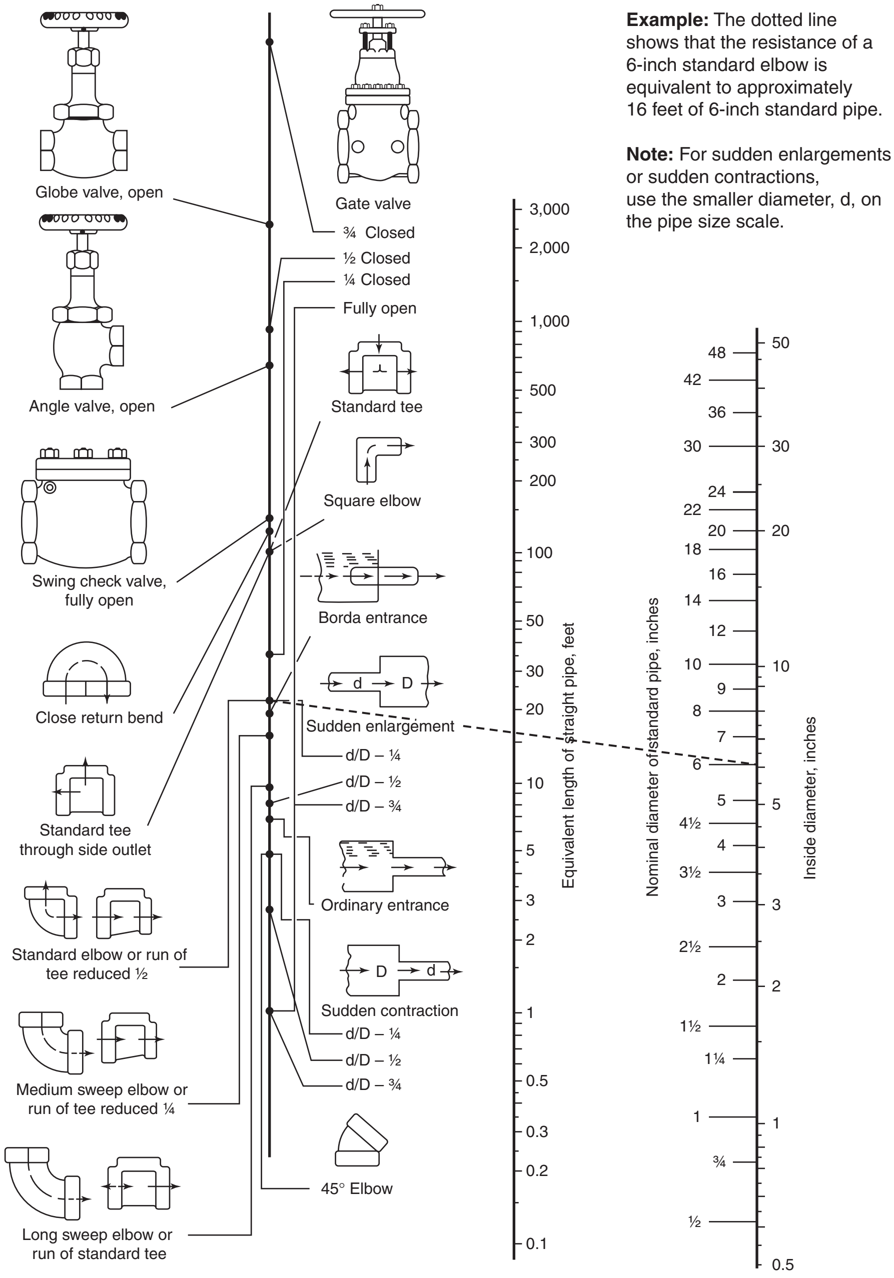
- Line up points ① and ② with a straight-edge ③
- Read 2.6 psi (or 6 ft) from the head loss line ④
- Read 5.38 ft/s from the velocity line ⑤

The values on this graph are based on the Hazen–Williams formula (Equation 9.4):

$$f = 0.2083 \left(\frac{100}{C}\right)^{1.85} \times \frac{Q^{1.85}}{D_i^{4.86}}$$

Where : f = friction head in feet of water per 100 feet of pipe
D_i = inside diameter of pipe in inches
Q = flow in gallons per minute
C = constant for inside roughness of pipe (150 for PVC)

Fig. 9.1 Friction loss characteristics of water flow through PVC pipe.



Example: The dotted line shows that the resistance of a 6-inch standard elbow is equivalent to approximately 16 feet of 6-inch standard pipe.

Note: For sudden enlargements or sudden contractions, use the smaller diameter, d, on the pipe size scale.

Notes:
1. Head loss through check valves varies with type manufactured; consult manufacturer for correct values.
2. Data in above chart are satisfactory for most applications; for more detailed information consult fittings manufacturer.

Fig. 9.2 Resistance of valves and fittings to flow of fluids.

Table 9.1 Friction loss of water in pipe fittings in terms of equivalent length (L), feet of straight pipe

Pipe size, in.	Approx inside diam, in.	Friction factor	Gate Valve --- full open	90° Elbow	Long radius 90° or 45° std elbow	Std tee --- thru flow	Std tee --- branch flow	Close return bend	Swing check valve --- Full open	Angle valve --- Full open	Globe valve --- Full open	Butterfly valve	90° welding elbow		Miter bend	
													r/d = 1	r/d = 2	45°	90°
0.5	0.622	0.027	0.41	1.55	0.83	1.04	3.11	2.59	5.18	7.78	17.6	–	–	–	–	–
0.75	0.824	0.025	0.55	2.06	1.10	1.37	4.12	3.43	6.86	10.3	23.3					
1	1.049	0.023	0.70	2.62	1.40	1.75	5.25	4.37	8.74	13.1	29.7					
1.25	1.380	0.022	0.92	3.45	1.84	2.30	6.90	5.75	11.5	17.3	39.1					
1.5	1.610	0.021	1.07	4.03	2.15	2.68	8.05	6.71	13.4	20.1	45.6					
2	2.067	0.019	1.38	5.17	2.76	3.45	10.3	8.61	17.2	25.8	58.6	7.75	3.45	2.07	2.58	10.3
2.5	2.469	0.018	1.65	6.17	3.29	4.12	12.3	10.3	20.6	30.9	70.0	9.26	4.12	2.47	3.08	12.3
3	3.068	0.018	2.04	7.67	4.09	5.11	15.3	12.8	25.5	38.4	86.9	11.5	5.11	3.07	3.84	15.3
4	4.026	0.017	2.68	10.1	5.37	6.71	20.1	16.8	33.6	50.3	114	15.1	6.71	4.03	5.03	20.1
5	5.047	0.016	3.36	12.6	6.73	8.41	25.2	21.0	42.1	63.1	143	18.9	8.41	5.05	6.31	25.2
6	6.065	0.015	4.04	15.2	8.09	10.1	30.3	25.3	50.5	75.8	172	22.7	10.1	6.07	7.58	30.3
8	7.981	0.014	5.32	20.0	10.6	13.3	39.9	33.3	33.3	99.8	226	29.9	13.3	7.98	9.98	39.9
10	10.02	0.014	6.68	25.1	13.4	16.7	50.1	41.8	41.8	125	284	29.2	16.7	10.0	12.5	50.1
12	11.938	0.013	7.96	29.8	15.9	19.9	59.7	49.7	49.7	149	338	34.8	19.9	11.9	14.9	59.7
14	13.124	0.013	8.75	32.8	17.5	21.8	65.6	54.7	54.7	164	372	38.3	21.8	13.1	16.4	65.6
16	15.00	0.013	10.0	37.5	20.0	25.0	75.0	62.5	62.5	188	425	31.3	25.0	15.0	18.8	75.0
18	16.876	0.012	16.9	42.2	22.5	28.1	84.4	70.3	70.3	210	478	35.2	28.1	16.9	21.1	84.4
20	18.814	0.012	12.5	47.0	25.1	31.4	94.1	78.4	78.4	235	533	39.2	31.4	18.8	23.5	94.1
24	22.628	0.012	15.1	56.6	30.2	37.7	113	94.3	94.3	283	641	47.1	37.7	22.6	28.3	113
30	28	0.011	18.7	70	37.3	46.7	140	117	–	–	–	–	46.7	28	35	140
36	34	0.011	22.7	85	45.3	56.7	170	142	–	–	–	–	56.7	34	43	170
42	40	0.010	26.7	100	53.3	66.7	200	167					66.7	40	50	200
48	46	0.010	30.7	115	61.3	76.7	230	192					76.7	46	58	230
L/D			8	30	16	20	60	50	0.5 to 6 = 100 28 to 48 = 50	150	340	–	20	12	15	60

Calculated from data in Crane Co. – Technical Paper 410. $K = f\frac{L}{D}$, $f = \frac{KD}{L}$, $L = \frac{KD}{f}$, where D is inside pipe diameter in feet.

9.3.2 Darcy–Weisbach Formula

In hydraulic design of PVC pressure water pipe, conditions are defined relative to pipe roughness ε/D_i, where ε is the equivalent roughness; and Reynolds number $R_e = VD/\nu$, where ν is the kinematic viscosity of the fluid. For water at 70 °F and at atmospheric pressure, kinematic viscosity is 1.052×10^{-5} ft^2/s. In this case, the Darcy–Weisbach formula provides a sound design basis. The most commonly used Darcy–Weisbach formula is given next:

Equation 9.10

$$h_f = f_D \frac{LV^2}{D\,2g}$$

where:
h_f = head loss, ft of H_2O
f_D = Darcy-Weisbach friction factor, dimensionless
L = pipe length, ft
D = pipe inside diameter, ft
V = mean flow velocity, ft/s
g = acceleration of gravity, 32.2 ft/s^2

Investigation and analysis by Neale and Jeppson established that the friction factor (f_D) for PVC pipe can be given as in the following equation for hydraulically smooth flow:

Equation 9.11

$$\frac{1}{\sqrt{f_D}} = 2\log\left(R_e\sqrt{f_D}\right) - 0.8$$

where:
R_e = Reynolds number, dimensionless

Calculations of friction factor f_D are obviously tedious. In common practice, the factor is found by referencing the Moody diagram (Fig. 9.4)), using equivalent roughness values from Table 9.2. Equation 9.12 gives the relationship between relative roughness ε/D_i and friction factor f_D:

Fig. 9.3 12-in. molded PVC fitting.

Equation 9.12

$$\frac{1}{\sqrt{f_D}} = 1.14 - 2\log\left(\frac{\varepsilon}{D_i} + \frac{9.35}{R_e\sqrt{f_D}}\right) \text{ for } R_e > 4{,}000$$

where:

ε = equivalent roughness, in.

At velocities above 5 ft/s (1.5 m/s), special consideration should be given to surge pressures that could damage system components. It should also be noted that high fluid velocity results in high head loss.

Table 9.2 Equivalent roughness (ε) for pipe products.

	ε	
Material	in.	cm
Concrete	0.01 to 0.1	0.02 to 0.2
Cast iron	0.0102	0.026
Galvanized iron	0.006	0.015
Asphalted cast iron	0.0048	0.012
Steel or wrought iron	0.0018	0.046
PVC	0.000084	0.00021

Note: The equivalent roughness values (ε) listed above must be divided by pipe inside diameter (D_i), expressed in the same units, to properly utilize the Moody diagram, Figure 9.4.

Source: *Analysis of Flow in Pipe Networks,* R.W. Jeppson, Ann Arbor Science, Ann Arbor, MI.

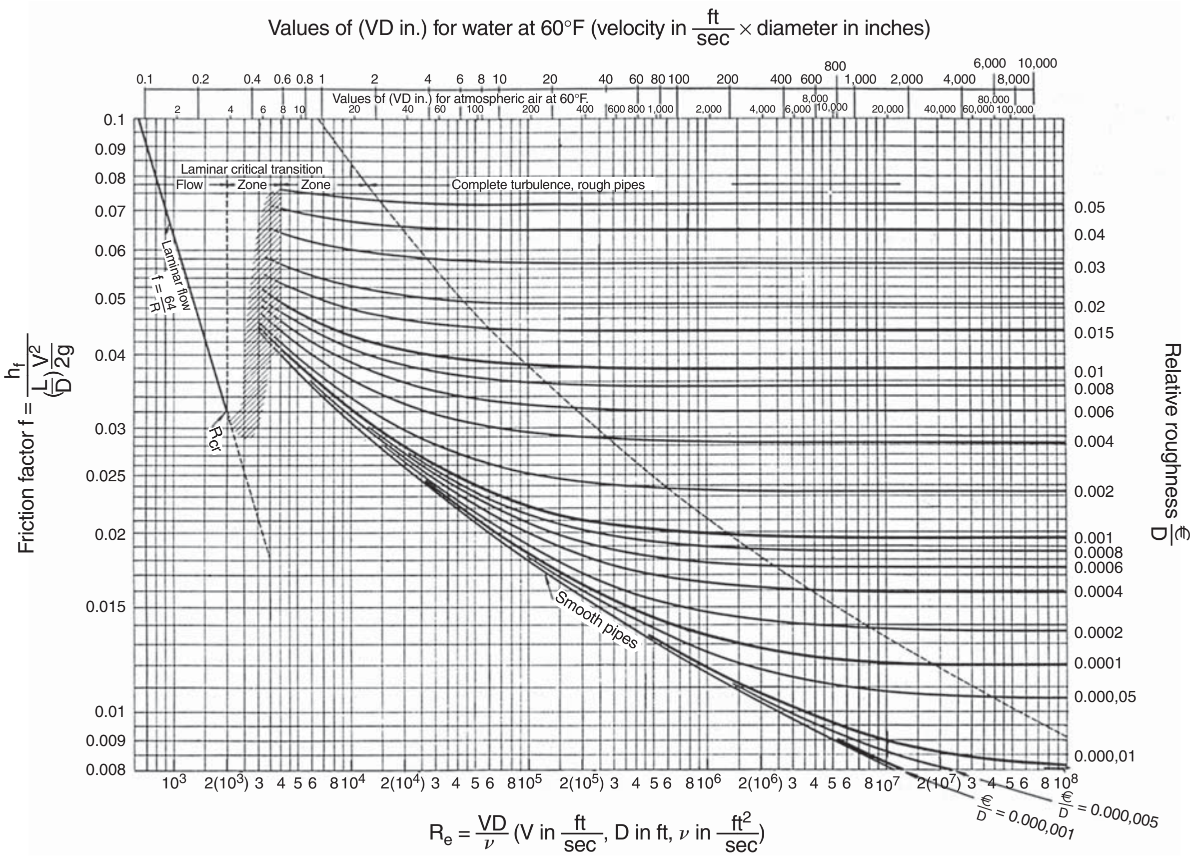


Fig. 9.4 Moody diagram: friction factor. Values of equivalent roughness (ε) for commercial pipes (new).

Source: American Society of Mechanical Engineers, New York, *Tansactions ASME,* Vol. 66 (1944) L. F. Moody.

Table 9.3 Flow friction loss, AWWA C900 and C905 CIOD PVC pipe

4 in. CIOD (AWWA C900)									
Flow, gpm	DR 25 Pressure class 165 psi			DR 18 Pressure class 235 psi			DR 14 Pressure class 305 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
25	0.530	0.0286	0.0124	0.571	0.0343	0.0148	0.617	0.0414	0.0179
40	0.849	0.0683	0.0296	0.914	0.0818	0.0354	0.987	0.0987	0.0427
55	1.17	0.123	0.0533	1.26	0.147	0.0638	1.36	0.178	0.0770
70	1.49	0.192	0.0833	1.60	0.230	0.0997	1.73	0.278	0.120
85	1.80	0.275	0.119	1.94	0.330	0.143	2.10	0.398	0.172
100	2.12	0.372	0.161	2.29	0.446	0.193	2.47	0.537	0.233
120	2.55	0.521	0.226	2.74	0.624	0.270	2.96	0.753	0.326
140	2.97	0.693	0.300	3.20	0.830	0.360	3.46	1.00	0.434
160	3.39	0.888	0.384	3.66	1.06	0.460	3.95	1.28	0.555
180	3.82	1.10	0.478	4.11	1.32	0.572	4.44	1.59	0.690
200	4.24	1.34	0.581	4.57	1.61	0.696	4.94	1.94	0.839
225	4.77	1.67	0.722	5.14	2.00	0.865	5.55	2.41	1.04
250	5.30	2.03	0.878	5.71	2.43	1.05	6.17	2.93	1.27
275	5.83	2.42	1.05	6.28	2.90	1.25	6.79	3.49	1.51
300	6.36	2.84	1.23	6.86	3.40	1.47	7.40	4.10	1.78
350	7.43	3.78	1.64	8.00	4.52	1.96	8.64	5.46	2.36
400	8.49	4.84	2.09	9.14	5.79	2.51	9.87	6.99	3.02
450	9.55	6.01	2.60	10.3	7.20	3.12	11.1	8.69	3.76

Notes:

1. Table is based on Equations 9.2 through 9.5, using C = 150.
2. Friction-loss values are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$, where:

D_i = pipe inside diameter, in.
D_o = pipe outside diameter, in.
t_{min} = minimum wall thickness, in.

Table 9.3 Flow friction loss, AWWA C900 and C905 CIOD PVC pipe (*continued*)

6 in. CIOD (AWWA C900)									
Flow, gpm	DR 25 Pressure class 165 psi			DR 18 Pressure class 235 psi			DR 14 Pressure class 305 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
50	0.513	0.0177	0.00766	0.551	0.0210	0.00911	0.595	0.0254	0.0110
75	0.770	0.0375	0.0162	0.827	0.0445	0.0193	0.893	0.0537	0.0232
100	1.03	0.0638	0.0276	1.10	0.0758	0.0328	1.19	0.0914	0.0396
125	1.28	0.0964	0.0417	1.38	0.115	0.0496	1.49	0.138	0.0598
150	1.54	0.135	0.0585	1.65	0.161	0.0695	1.79	0.194	0.0838
175	1.80	0.180	0.0778	1.93	0.213	0.0924	2.08	0.257	0.111
200	2.05	0.230	0.0996	2.20	0.273	0.118	2.38	0.330	0.143
250	2.57	0.348	0.150	2.76	0.413	0.179	2.98	0.498	0.216
300	3.08	0.487	0.211	3.31	0.579	0.251	3.57	0.698	0.302
350	3.59	0.648	0.280	3.86	0.770	0.333	4.17	0.928	0.402
400	4.11	0.829	0.359	4.41	0.985	0.427	4.76	1.19	0.514
450	4.62	1.03	0.446	4.96	1.23	0.531	5.36	1.48	0.640
500	5.13	1.25	0.543	5.51	1.49	0.645	5.95	1.80	0.777
600	6.16	1.76	0.760	6.61	2.09	0.903	7.14	2.52	1.09
700	7.19	2.33	1.01	7.72	2.77	1.20	8.33	3.35	1.45
800	8.22	2.99	1.29	8.82	3.55	1.54	9.53	4.28	1.85
900	9.24	3.72	1.61	9.92	4.42	1.91	10.7	5.33	2.31
1,000	10.3	4.52	1.96	11.0	5.37	2.32	11.9	6.47	2.80

Table 9.3 Flow friction loss, AWWA C900 and C905 CIOD PVC pipe (*continued*)

8 in. CIOD (AWWA C900)									
Flow, gpm	DR 25 Pressure class 165 psi			DR 18 Pressure class 235 psi			DR 14 Pressure class 305 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
100	0.596	0.0170	0.00738	0.642	0.0204	0.00883	0.693	0.0246	0.0106
125	0.745	0.0257	0.0111	0.803	0.0308	0.0133	0.866	0.0371	0.0161
150	0.895	0.0361	0.0156	0.963	0.0432	0.0187	1.04	0.0520	0.0225
200	1.19	0.0614	0.0266	1.28	0.0735	0.0318	1.39	0.0885	0.0383
250	1.49	0.0928	0.0402	1.61	0.111	0.0481	1.73	0.134	0.0579
300	1.79	0.130	0.0563	1.93	0.156	0.0674	2.08	0.187	0.0812
350	2.09	0.173	0.0749	2.25	0.207	0.0896	2.43	0.249	0.108
400	2.39	0.221	0.0959	2.57	0.265	0.115	2.77	0.319	0.138
450	2.68	0.275	0.119	2.89	0.329	0.143	3.12	0.397	0.172
500	2.98	0.335	0.145	3.21	0.400	0.173	3.47	0.482	0.209
600	3.58	0.469	0.203	3.85	0.561	0.243	4.16	0.676	0.293
700	4.17	0.623	0.270	4.49	0.746	0.323	4.85	0.899	0.389
800	4.77	0.798	0.346	5.14	0.955	0.413	5.55	1.15	0.498
1,000	5.96	1.21	0.522	6.42	1.44	0.625	6.93	1.74	0.753
1,200	7.16	1.69	0.732	7.70	2.02	0.875	8.32	2.44	1.05
1,400	8.35	2.25	0.973	8.99	2.69	1.16	9.70	3.24	1.40
1,600	9.54	2.88	1.25	10.3	3.44	1.49	11.1	4.15	1.80
1,800	10.7	3.58	1.55	11.6	4.28	1.85	12.5	5.16	2.23

Notes:

1. Table is based on Equations 9.2 through 9.5, using C = 150.
2. Friction-loss values are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$, where:

   D_i = pipe inside diameter, in.
   D_o = pipe outside diameter, in.
   t_{min} = minimum wall thickness, in.

Table 9.3 Flow friction loss, AWWA C900 and C905 CIOD PVC pipe (*continued*)

10 in. CIOD (AWWA C900)									
Flow, gpm	DR 25 Pressure class 165 psi			DR 18 Pressure class 235 psi			DR 14 Pressure class 305 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
150	0.594	0.0133	0.00578	0.640	0.0160	0.00692	0.691	0.0193	0.00834
200	0.792	0.0227	0.00984	0.853	0.0272	0.0118	0.922	0.0328	0.0142
250	0.990	0.0343	0.0149	1.07	0.0411	0.0178	1.15	0.0496	0.0215
300	1.19	0.0481	0.0208	1.28	0.0576	0.0249	1.38	0.0695	0.0301
350	1.39	0.0640	0.0277	1.49	0.0766	0.0332	1.61	0.0924	0.0400
400	1.58	0.0819	0.0355	1.71	0.0981	0.0425	1.84	0.118	0.0512
450	1.78	0.102	0.0441	1.92	0.122	0.0528	2.07	0.147	0.0637
500	1.98	0.124	0.0536	2.13	0.148	0.0642	2.30	0.179	0.0774
600	2.38	0.173	0.0751	2.56	0.208	0.0899	2.76	0.250	0.108
700	2.77	0.231	0.100	2.99	0.276	0.120	3.23	0.333	0.144
800	3.17	0.295	0.128	3.41	0.354	0.153	3.69	0.426	0.185
1,000	3.96	0.446	0.193	4.27	0.534	0.231	4.61	0.644	0.279
1,200	4.75	0.625	0.271	5.12	0.749	0.324	5.53	0.903	0.391
1,400	5.55	0.831	0.360	5.97	1.00	0.431	6.45	1.20	0.520
1,600	6.34	1.06	0.461	6.83	1.27	0.552	7.37	1.54	0.666
1,800	7.13	1.32	0.573	7.68	1.59	0.686	8.29	1.91	0.828
2,200	8.71	1.92	0.831	9.39	2.30	0.995	10.1	2.77	1.20
2,600	10.3	2.61	1.13	11.1	3.13	1.36	12.0	3.77	1.63

Table 9.3 Flow friction loss, AWWA C900 and C905 CIOD PVC pipe (*continued*)

12 in. CIOD (AWWA C900)									
Flow, gpm	DR 25 Pressure class 165 psi			DR 18 Pressure class 235 psi			DR 14 Pressure class 305 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
200	0.560	0.00980	0.00424	0.602	0.0117	0.00506	0.652	0.0141	0.00613
250	0.700	0.0148	0.00641	0.753	0.0177	0.00764	0.815	0.0214	0.00926
300	0.841	0.0207	0.00898	0.904	0.0247	0.0107	0.978	0.0300	0.0130
350	0.981	0.0276	0.0119	1.05	0.0329	0.0142	1.14	0.0398	0.0173
400	1.12	0.0353	0.0153	1.20	0.0421	0.0182	1.30	0.0510	0.0221
500	1.40	0.0534	0.0231	1.51	0.0636	0.0276	1.63	0.0771	0.0334
600	1.68	0.0748	0.0324	1.81	0.0892	0.0386	1.96	0.108	0.0468
700	1.96	0.0994	0.0431	2.11	0.119	0.0514	2.28	0.144	0.0622
800	2.24	0.127	0.0551	2.41	0.152	0.0657	2.61	0.184	0.0796
1,000	2.80	0.192	0.0833	3.01	0.229	0.0993	3.26	0.278	0.120
1,200	3.36	0.270	0.117	3.61	0.321	0.139	3.91	0.389	0.169
1,400	3.92	0.358	0.155	4.22	0.428	0.185	4.56	0.518	0.224
1,600	4.48	0.459	0.199	4.82	0.547	0.237	5.22	0.663	0.287
2,000	5.60	0.694	0.300	6.02	0.827	0.358	6.52	1.00	0.434
2,400	6.72	0.972	0.421	7.23	1.16	0.502	7.82	1.40	0.608
2,800	7.85	1.29	0.560	8.43	1.54	0.667	9.13	1.87	0.808
3,200	8.97	1.65	0.716	9.64	1.97	0.854	10.4	2.39	1.03
3,600	10.1	2.06	0.891	10.8	2.45	1.06	11.7	2.97	1.29

Notes:

1. Table is based on Equations 9.2 through 9.5, using C = 150.
2. Friction-loss values are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$, where:

    D_i = pipe inside diameter, in.
    D_o = pipe outside diameter, in.
    t_{min} = minimum wall thickness, in.

Table 9.3 Flow friction loss, AWWA C900 and C905 CIOD PVC pipe (*continued*)

14 in. CIOD (AWWA C905)									
Flow, gpm	DR 41 Pressure class 100 psi			DR 32.5 Pressure class 125 psi			DR 25 Pressure class 165 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
300	0.583	0.00851	0.00369	0.600	0.00914	0.00396	0.626	0.0101	0.00439
450	0.874	0.0180	0.00780	0.900	0.0193	0.00838	0.939	0.0214	0.00928
600	1.17	0.0307	0.0133	1.20	0.0329	0.0143	1.25	0.0365	0.0158
800	1.55	0.0522	0.0226	1.60	0.0561	0.0243	1.67	0.0622	0.0269
1,000	1.94	0.0789	0.0342	2.00	0.0847	0.0367	2.09	0.0939	0.0407
1,200	2.33	0.111	0.0479	2.40	0.119	0.0514	2.50	0.132	0.0570
1,400	2.72	0.147	0.0637	2.80	0.158	0.0684	2.92	0.175	0.0758
1,600	3.11	0.188	0.0815	3.20	0.202	0.0875	3.34	0.224	0.0970
1,800	3.50	0.234	0.101	3.60	0.251	0.109	3.75	0.279	0.121
2,000	3.88	0.285	0.123	4.00	0.305	0.132	4.17	0.339	0.147
2,200	4.27	0.339	0.147	4.40	0.364	0.158	4.59	0.404	0.175
2,600	5.05	0.462	0.200	5.20	0.496	0.215	5.42	0.550	0.238
3,000	5.83	0.603	0.261	6.00	0.647	0.280	6.26	0.717	0.310
3,400	6.60	0.759	0.329	6.80	0.815	0.353	7.09	0.904	0.391
3,800	7.38	0.933	0.404	7.60	1.00	0.434	7.93	1.11	0.481
4,200	8.16	1.12	0.486	8.40	1.21	0.522	8.76	1.34	0.579
4,600	8.93	1.33	0.575	9.20	1.43	0.618	9.60	1.58	0.685
5,000	9.71	1.55	0.671	10.0	1.66	0.721	10.4	1.84	0.799

Table 9.3 Flow friction loss, AWWA C900 and C905 CIOD PVC pipe (*continued*)

14 in. CIOD (AWWA C905)									
Flow, gpm	DR 21 Pressure class 200 psi			DR 18 Pressure class 235 psi			DR 14 Pressure class 305 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
300	0.648	0.0110	0.00477	0.673	0.0121	0.00523	0.728	0.0146	0.00633
450	0.972	0.0233	0.0101	1.01	0.0256	0.0111	1.09	0.0310	0.0134
600	1.30	0.0397	0.0172	1.35	0.0436	0.0189	1.46	0.0527	0.0228
800	1.73	0.0676	0.0293	1.79	0.0742	0.0321	1.94	0.0898	0.0389
1,000	2.16	0.102	0.0442	2.24	0.112	0.0485	2.43	0.136	0.0587
1,200	2.59	0.143	0.0620	2.69	0.157	0.0680	2.91	0.190	0.0823
1,400	3.02	0.190	0.0824	3.14	0.209	0.0904	3.40	0.253	0.109
1,600	3.46	0.244	0.106	3.59	0.267	0.116	3.88	0.324	0.140
1,800	3.89	0.303	0.131	4.04	0.333	0.144	4.37	0.402	0.174
2,000	4.32	0.368	0.159	4.49	0.404	0.175	4.85	0.489	0.212
2,200	4.75	0.439	0.190	4.94	0.482	0.209	5.34	0.583	0.253
2,600	5.61	0.598	0.259	5.83	0.657	0.284	6.31	0.795	0.344
3,000	6.48	0.780	0.338	6.73	0.856	0.370	7.28	1.04	0.448
3,400	7.34	0.983	0.426	7.63	1.08	0.467	8.25	1.31	0.565
3,800	8.21	1.21	0.523	8.52	1.32	0.574	9.22	1.60	0.694
4,200	9.07	1.45	0.629	9.42	1.59	0.690	10.2	1.93	0.836
4,600	9.93	1.72	0.745	10.3	1.89	0.817	11.2	2.28	0.989
5,000	10.8	2.01	0.869	11.2	2.20	0.953	12.1	2.66	1.15

Notes:

1. Table is based on Equations 9.2 through 9.5, using $C = 150$.
2. Friction-loss values are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$, where:

    D_i = pipe inside diameter, in.
    D_o = pipe outside diameter, in.
    t_{min} = minimum wall thickness, in.

Table 9.3 Flow friction loss, AWWA C900 and C905 CIOD PVC pipe (*continued*)

16 in. CIOD (AWWA C905)									
Flow, gpm	DR 41 Pressure class 100 psi			DR 32.5 Pressure class 125 psi			DR 25 Pressure class 165 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
350	0.526	0.00606	0.00262	0.541	0.00651	0.00282	0.565	0.00721	0.00312
500	0.751	0.0117	0.00508	0.773	0.0126	0.00545	0.807	0.0140	0.00604
650	0.976	0.0191	0.00825	1.01	0.0205	0.00886	1.05	0.0227	0.00982
800	1.20	0.0280	0.0121	1.24	0.0300	0.0130	1.29	0.0333	0.0144
1,000	1.50	0.0423	0.0183	1.55	0.0454	0.0197	1.61	0.0503	0.0218
1,200	1.80	0.0592	0.0256	1.86	0.0636	0.0275	1.94	0.0705	0.0305
1,400	2.10	0.0788	0.0341	2.17	0.0846	0.0366	2.26	0.0937	0.0406
1,800	2.70	0.125	0.0543	2.78	0.135	0.0583	2.90	0.149	0.0646
2,200	3.30	0.182	0.0787	3.40	0.195	0.0845	3.55	0.216	0.0937
2,600	3.90	0.248	0.107	4.02	0.266	0.115	4.19	0.295	0.128
3,000	4.51	0.323	0.140	4.64	0.346	0.150	4.84	0.384	0.166
3,500	5.26	0.429	0.186	5.41	0.461	0.200	5.65	0.511	0.221
4,000	6.01	0.549	0.238	6.19	0.590	0.255	6.45	0.654	0.283
4,500	6.76	0.683	0.296	6.96	0.733	0.318	7.26	0.813	0.352
5,000	7.51	0.830	0.359	7.73	0.891	0.386	8.07	0.988	0.428
5,500	8.26	0.990	0.429	8.51	1.06	0.460	8.87	1.18	0.510
6,000	9.01	1.16	0.504	9.28	1.25	0.541	9.68	1.38	0.599
6,500	9.76	1.35	0.584	10.1	1.45	0.627	10.5	1.60	0.695

Table 9.3 Flow friction loss, AWWA C900 and C905 CIOD PVC pipe (*continued*)

16 in. CIOD (AWWA C905)									
Flow, gpm	DR 21 Pressure class 200 psi			DR 18 Pressure class 235 psi			DR 14 Pressure class 305 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
350	0.585	0.00786	0.00340	0.607	0.00861	0.00373	0.656	0.0104	0.00450
500	0.836	0.0152	0.00659	0.868	0.0167	0.00721	0.937	0.0201	0.00870
650	1.09	0.0247	0.0107	1.13	0.0271	0.0117	1.22	0.0326	0.0141
800	1.34	0.0363	0.0157	1.39	0.0397	0.0172	1.50	0.0479	0.0207
1,000	1.67	0.0548	0.0237	1.74	0.0600	0.0260	1.87	0.0724	0.0314
1,200	2.01	0.0768	0.0333	2.08	0.0841	0.0364	2.25	0.101	0.0439
1,400	2.34	0.102	0.0442	2.43	0.112	0.0485	2.62	0.135	0.0584
1,800	3.01	0.163	0.0704	3.12	0.178	0.0771	3.37	0.215	0.0930
2,200	3.68	0.236	0.102	3.82	0.258	0.112	4.12	0.311	0.135
2,600	4.35	0.321	0.139	4.51	0.352	0.152	4.87	0.424	0.184
3,000	5.01	0.418	0.181	5.21	0.458	0.198	5.62	0.553	0.239
3,500	5.85	0.557	0.241	6.07	0.610	0.264	6.56	0.735	0.318
4,000	6.69	0.713	0.309	6.94	0.780	0.338	7.50	0.941	0.407
4,500	7.52	0.886	0.384	7.81	0.970	0.420	8.43	1.17	0.507
5,000	8.36	1.08	0.466	8.68	1.18	0.511	9.37	1.42	0.616
5,500	9.19	1.28	0.556	9.54	1.41	0.609	10.3	1.70	0.734
6,000	10.0	1.51	0.653	10.4	1.65	0.715	11.2	1.99	0.863
6,500	10.9	1.75	0.757	11.3	1.92	0.830	12.2	2.31	1.00

Notes:

1. Table is based on Equations 9.2 through 9.5, using C = 150.
2. Friction-loss values are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$, where:

   D_i = pipe inside diameter, in.
   D_o = pipe outside diameter, in.
   t_{min} = minimum wall thickness, in.

Table 9.3 Flow friction loss, AWWA C900 and C905 CIOD PVC pipe (*continued*)

18 in. CIOD (AWWA C905)									
Flow, gpm	DR 51 Pressure class 80 psi			DR 41 Pressure class 100 psi			DR 32.5 Pressure class 125 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
500	0.585	0.00640	0.00277	0.598	0.00674	0.00292	0.615	0.00722	0.00313
800	0.936	0.0153	0.00661	0.957	0.0161	0.00696	0.984	0.0172	0.00746
1,100	1.29	0.0275	0.0119	1.32	0.0290	0.0126	1.35	0.0311	0.0134
1,400	1.64	0.0430	0.0186	1.67	0.0453	0.0196	1.72	0.0485	0.0210
1,800	2.11	0.0684	0.0296	2.15	0.0721	0.0312	2.21	0.0772	0.0334
2,200	2.58	0.0992	0.0429	2.63	0.105	0.0453	2.71	0.112	0.0485
2,600	3.04	0.135	0.585	3.11	0.142	0.0616	3.20	0.153	0.0660
3,000	3.51	0.176	0.0762	3.59	0.186	0.0803	3.69	0.199	0.0860
3,500	4.10	0.234	0.101	4.19	0.247	0.107	4.31	0.264	0.114
4,000	4.68	0.300	0.130	4.78	0.316	0.137	4.92	0.338	0.147
4,500	5.27	0.373	0.161	5.38	0.393	0.170	5.54	0.421	0.182
5,000	5.85	0.453	0.196	5.98	0.477	0.207	6.15	0.511	0.221
5,500	6.44	0.540	0.234	6.58	0.569	0.247	6.77	0.610	0.264
6,000	6.44	0.635	0.275	7.18	0.669	0.290	7.38	0.716	0.310
6,500	7.61	0.736	0.319	7.77	0.775	0.336	8.00	0.831	0.360
7,000	8.19	0.844	0.366	8.37	0.889	0.385	8.61	0.953	0.413
7,500	8.78	0.959	0.415	8.97	1.01	0.438	9.23	1.08	0.469
8,000	9.36	1.08	0.468	9.57	1.14	0.493	9.84	1.22	0.528

Table 9.3 Flow friction loss, AWWA C900 and C905 CIOD PVC pipe (*continued*)

18 in. CIOD (AWWA C905)									
Flow, gpm	DR 25 Pressure class 165 psi			DR 21 Pressure class 200 psi			DR 18 Pressure class 235 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
500	0.642	0.00800	0.00346	0.665	0.00874	0.00378	0.691	0.00958	0.00415
800	1.03	0.0191	0.00826	1.06	0.0208	0.00902	1.11	0.0229	0.00990
1,100	1.41	0.0344	0.0149	1.46	0.0376	0.0163	1.52	0.0412	0.0178
1,400	1.80	0.0537	0.0233	1.86	0.0587	0.0254	1.93	0.0644	0.0279
1,800	2.31	0.0856	0.0370	2.39	0.0934	0.0405	2.49	0.102	0.0444
2,200	2.82	0.124	0.0537	2.93	0.135	0.0586	3.04	0.149	0.0643
2,600	3.34	0.169	0.0732	3.46	0.184	0.0799	3.59	0.202	0.0876
3,000	3.85	0.220	0.0953	3.99	0.240	0.104	4.15	0.264	0.114
3,500	4.49	0.293	0.127	4.66	0.320	0.138	4.84	0.351	0.152
4,000	5.13	0.375	0.162	5.32	0.409	0.177	5.53	0.449	0.194
4,500	5.77	0.466	0.202	5.99	0.509	0.220	6.22	0.558	0.242
5,000	6.42	0.566	0.245	6.65	0.618	0.268	6.91	0.678	0.294
5,500	7.06	0.676	0.293	7.32	0.738	0.319	7.60	0.809	0.350
6,000	7.70	0.794	0.344	7.98	0.867	0.375	8.29	0.950	0.412
6,500	8.34	0.920	0.398	8.65	1.00	0.435	8.98	1.10	0.477
7,000	8.98	1.06	0.457	9.31	1.15	0.499	9.67	1.26	0.547
7,500	9.62	1.20	0.519	9.98	1.31	0.567	10.4	1.44	0.622
8,000	10.3	1.35	0.585	10.6	1.48	0.639	11.1	1.62	0.701

Notes:

1. Table is based on Equations 9.2 through 9.5, using C = 150.
2. Friction-loss values are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$, where:

    D_i = pipe inside diameter, in.
    D_o = pipe outside diameter, in.
    t_{min} = minimum wall thickness, in.

Table 9.3 Flow friction loss, AWWA C900 and C905 CIOD PVC pipe (*continued*)

18 in. CIOD (AWWA C905)			
Flow, gpm	DR 14 Pressure class 305 psi		
	Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft
500	0.746	0.0116	0.00500
800	1.19	0.0276	0.0119
1,100	1.64	0.0497	0.0215
1,400	2.09	0.0776	0.0336
1,800	2.69	0.124	0.0535
2,200	3.28	0.179	0.0776
2,600	3.88	0.244	0.106
3,000	4.48	0.318	0.138
3,500	5.22	0.423	0.183
4,000	5.97	0.541	0.234
4,500	6.72	0.673	0.291
5,000	7.46	0.818	0.354
5,500	8.21	0.976	0.422
6,000	8.96	1.15	0.496
6,500	9.70	1.33	0.575
7,000	10.4	1.52	0.660
7,500	11.2	1.73	0.750
8,000	11.9	1.95	0.845

Table 9.3 Flow friction loss, AWWA C900 and C905 CIOD PVC pipe (*continued*)

20 in. CIOD (AWWA C905)									
Flow, gpm	DR 51 Pressure class 80 psi			DR 41 Pressure class 100 psi			DR 32.5 Pressure class 125 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
600	0.573	0.00546	0.00236	0.585	0.00575	0.00249	0.602	0.00616	0.00267
1,000	0.954	0.0140	0.00608	0.975	0.0148	0.00640	1.00	0.0159	0.00686
1,400	1.34	0.0262	0.0113	1.36	0.0276	0.0119	1.40	0.0295	0.0128
1,800	1.72	0.0417	0.0180	1.75	0.0439	0.0190	1.81	0.0470	0.0204
2,200	2.10	0.0604	0.0261	2.14	0.0636	0.0275	2.21	0.0682	0.0295
2,600	2.48	0.0822	0.0356	2.53	0.0866	0.0375	2.61	0.0928	0.0402
3,000	2.86	0.107	0.0464	2.92	0.113	0.0489	3.01	0.121	0.0524
3,500	3.34	0.143	0.0617	3.41	0.150	0.0650	3.51	0.161	0.0697
4,000	3.82	0.182	0.0790	3.90	0.192	0.0832	4.01	0.206	0.0892
4,500	4.29	0.227	0.0982	4.39	0.239	0.103	4.51	0.256	0.111
5,000	4.77	0.276	0.119	4.87	0.290	0.126	5.02	0.311	0.135
5,500	5.25	0.329	0.142	5.36	0.346	0.150	5.52	0.371	0.161
6,000	5.73	0.386	0.167	5.85	0.407	0.176	6.02	0.436	0.189
6,500	6.20	0.448	0.194	6.34	0.472	0.204	6.52	0.506	0.219
7,000	6.68	0.514	0.222	6.82	0.541	0.234	7.02	0.580	0.251
8,000	7.63	0.658	0.285	7.80	0.693	0.300	8.02	0.743	0.322
9,000	8.59	0.818	0.354	8.77	0.862	0.373	9.03	0.923	0.400
10,000	9.54	0.994	0.430	9.75	1.05	0.453	10.0	1.12	0.486

Notes:

1. Table is based on Equations 9.2 through 9.5, using $C = 150$.
2. Friction-loss values are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$,
   where:
   D_i = pipe inside diameter, in.
   D_o = pipe outside diameter, in.
   t_{min} = minimum wall thickness, in.

Table 9.3 Flow friction loss, AWWA C900 and C905 CIOD PVC pipe (*continued*)

20 in. CIOD (AWWA C905)									
Flow, gpm	DR 25 Pressure class 165 psi			DR 21 Pressure class 200 psi			DR 18 Pressure class 235 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
600	0.628	0.00682	0.00295	0.650	0.00744	0.00322	0.675	0.00815	0.00353
1,000	1.05	0.0176	0.00760	1.08	0.0191	0.00829	1.13	0.0210	0.00908
1,400	1.46	0.0327	0.0142	1.52	0.0357	0.0155	1.58	0.0391	0.0169
1,800	1.88	0.0521	0.0225	1.95	0.0568	0.0246	2.03	0.0622	0.0269
2,200	2.30	0.0755	0.0327	2.39	0.0823	0.0357	2.48	0.0902	0.0390
2,600	2.72	0.103	0.0445	2.82	0.112	0.0486	2.93	0.123	0.0532
3,000	3.14	0.134	0.0580	3.25	0.146	0.0633	3.38	0.160	0.0693
3,500	3.66	0.178	0.0772	3.79	0.194	0.0842	3.94	0.213	0.0922
4,000	4.18	0.228	0.0988	4.34	0.249	0.108	4.50	0.273	0.118
4,500	4.71	0.284	0.123	4.88	0.309	0.134	5.06	0.339	0.147
5,000	5.23	0.345	0.149	5.42	0.376	0.163	5.63	0.412	0.178
5,500	5.75	0.411	0.178	5.96	0.449	0.194	6.19	0.491	0.213
6,000	6.28	0.483	0.209	6.50	0.527	0.228	6.75	0.577	0.250
6,500	6.80	0.560	0.243	7.05	0.611	0.265	7.32	0.669	0.290
7,000	7.32	0.642	0.278	7.59	0.701	0.303	7.88	0.767	0.332
8,000	8.37	0.822	0.356	8.67	0.897	0.388	9.00	0.982	0.425
9,000	9.41	1.02	0.443	9.76	1.12	0.483	10.1	1.22	0.529
10,000	10.5	1.24	0.538	10.8	1.36	0.587	11.3	1.48	0.643

Table 9.3 Flow friction loss, AWWA C900 and C905 CIOD PVC pipe (*continued*)

24 in. CIOD (AWWA C905)									
Flow, gpm	DR 51 Pressure class 80 psi			DR 41 Pressure class 100 psi			DR 32.5 Pressure class 125 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
800	0.535	0.00391	0.00169	0.546	0.00412	0.00178	0.562	0.00442	0.00191
1,200	0.802	0.00829	0.00359	0.819	0.00872	0.00378	0.843	0.00936	0.00405
1,600	1.07	0.0141	0.00611	1.09	0.0149	0.00643	1.12	0.0159	0.00690
2,000	1.34	0.0213	0.00923	1.37	0.0224	0.00972	1.41	0.0241	0.0104
2,600	1.74	0.0346	0.0150	1.78	0.0365	0.0158	1.83	0.0391	0.0169
3,200	2.14	0.0509	0.0220	2.19	0.0536	0.0232	2.25	0.0574	0.0249
3,800	2.54	0.0699	0.0303	2.59	0.0736	0.0319	2.67	0.0789	0.0342
4,600	3.08	0.100	0.0431	3.14	0.105	0.0454	3.23	0.112	0.0487
5,400	3.61	0.134	0.0580	3.69	0.141	0.0610	3.80	0.151	0.0655
6,200	4.14	0.173	0.0749	4.23	0.182	0.0788	4.36	0.195	0.0845
7,000	4.68	0.216	0.0937	4.78	0.228	0.0987	4.92	0.244	0.106
8,000	5.35	0.277	0.120	5.46	0.292	0.126	5.62	0.313	0.135
9,000	6.02	0.345	0.149	6.15	0.363	0.157	6.33	0.389	0.168
10,000	6.69	0.419	0.181	6.83	0.441	0.191	7.03	0.473	0.205
11,000	7.35	0.499	0.216	7.51	0.526	0.228	7.73	0.564	0.244
12,000	8.02	0.587	0.254	8.19	0.618	0.267	8.43	0.662	0.287
13,500	9.03	0.730	0.316	9.22	0.768	0.333	9.49	0.824	0.357
15,000	10.0	0.887	0.384	10.2	0.933	0.404	10.5	1.00	0.433

Notes:

1. Table is based on Equations 9.2 through 9.5, using C = 150.
2. Friction-loss values are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$, where:

   D_i = pipe inside diameter, in.
   D_o = pipe outside diameter, in.
   t_{min} = minimum wall thickness, in.

Table 9.3 Flow friction loss, AWWA C900 and C905 CIOD PVC pipe (*continued*)

24 in. CIOD (AWWA C905)									
Flow, gpm	DR 25 Pressure class 165 psi			DR 21 Pressure class 200 psi			DR 18 Pressure class 235 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
800	0.587	0.00490	0.00212	0.608	0.00534	0.00231	0.631	0.00586	0.00254
1,200	0.880	0.0104	0.00449	0.912	0.0113	0.00489	0.947	0.0124	0.00537
1,600	1.17	0.0177	0.00765	1.22	0.0192	0.00833	1.26	0.0211	0.00915
2,000	1.47	0.0267	0.0116	1.52	0.0291	0.0126	1.58	0.0319	0.0138
2,600	1.91	0.0434	0.0188	1.98	0.0473	0.0205	2.05	0.0519	0.0225
3,200	2.35	0.0637	0.0276	2.43	0.0694	0.0300	2.53	0.0761	0.0330
3,800	2.79	0.0876	0.0379	2.89	0.0954	0.0413	3.00	0.105	0.0453
4,600	3.37	0.125	0.0540	3.49	0.136	0.0588	3.63	0.149	0.0645
5,400	3.96	0.168	0.0726	4.10	0.183	0.0791	4.26	0.200	0.0868
6,200	4.55	0.217	0.0938	4.71	0.236	0.102	4.89	0.259	0.112
7,000	5.13	0.271	0.117	5.32	0.295	0.128	5.52	0.324	0.140
8,000	5.87	0.347	0.150	6.08	0.378	0.164	6.31	0.415	0.180
9,000	6.60	0.432	0.187	6.84	0.470	0.203	7.10	0.516	0.223
10,000	7.33	0.525	0.227	7.60	0.571	0.247	7.89	0.627	0.271
11,000	8.07	0.626	0.271	8.36	0.681	0.295	8.68	0.748	0.324
12,000	8.80	0.735	0.318	9.12	0.800	0.346	9.47	0.878	0.380
13,500	9.90	0.914	0.396	10.3	1.00	0.431	10.7	1.09	0.473
15,000	11.0	1.11	0.481	11.4	1.21	0.524	11.8	1.33	0.575

Table 9.3 Flow friction loss, AWWA C900 and C905 CIOD PVC pipe (*continued*)

30 in. CIOD (AWWA C905)									
Flow, gpm	DR 51 Pressure class 80 psi			DR 41 Pressure class 100 psi			DR 32.5 Pressure class 125 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
1,200	0.522	0.00291	0.00126	0.533	0.00306	0.00133	0.548	0.00329	0.00142
1,800	0.782	0.00616	0.00267	0.799	0.00649	0.00281	0.823	0.00696	0.00301
2,400	1.04	0.0105	0.00454	1.07	0.0110	0.00478	1.10	0.0119	0.00513
3,200	1.39	0.0179	0.00774	1.42	0.0188	0.00814	1.46	0.0202	0.00874
4,000	1.74	0.0270	0.0117	1.78	0.0284	0.0123	1.83	0.0305	0.0132
5,000	2.17	0.0408	0.0177	2.22	0.0429	0.0186	2.29	0.0461	0.0200
6,000	2.61	0.0572	0.0248	2.66	0.0602	0.0260	2.74	0.0646	0.0280
7,000	3.04	0.0760	0.0329	3.11	0.0800	0.0346	3.20	0.0859	0.0372
8,000	3.48	0.0973	0.0421	3.55	0.102	0.0444	3.66	0.110	0.0476
9,000	3.91	0.121	0.0524	3.99	0.127	0.0551	4.11	0.137	0.0592
10,000	4.35	0.147	0.0637	4.44	0.155	0.0670	4.57	0.166	0.0719
12,000	5.22	0.206	0.0892	5.33	0.217	0.0939	5.48	0.233	0.101
14,000	6.09	0.274	0.119	6.21	0.288	0.125	6.40	0.310	0.134
16,000	6.95	0.351	0.152	7.10	0.369	0.160	7.31	0.396	0.172
18,000	7.82	0.436	0.189	7.99	0.459	0.199	8.23	0.493	0.213
20,000	8.69	0.530	0.230	8.88	0.558	0.242	9.14	0.599	0.259
22,000	9.56	0.632	0.274	9.77	0.666	0.288	10.1	0.715	0.309
24,000	10.4	0.743	0.322	10.7	0.782	0.339	11.0	0.839	0.363

Notes:

1. Table is based on Equations 9.2 through 9.5, using $C = 150$.
2. Friction-loss values are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$, where:

   D_i = pipe inside diameter, in.
   D_o = pipe outside diameter, in.
   t_{min} = minimum wall thickness, in.

Table 9.3 Flow friction loss, AWWA C900 and C905 CIOD PVC pipe (*continued*)

30 in. CIOD (AWWA C905)									
Flow, gpm	DR 25 Pressure class 165 psi			DR 21 Pressure class 200 psi			DR 18 Pressure class 235 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
1,200	0.572	0.00364	0.00158	0.593	0.00397	0.00172	0.616	0.00436	0.00189
1,800	0.858	0.00771	0.00334	0.889	0.00841	0.00364	0.923	0.00922	0.00399
2,400	1.14	0.0131	0.00568	1.19	0.0143	0.00620	1.23	0.0157	0.00680
3,200	1.53	0.0223	0.00968	1.58	0.0244	0.0106	1.64	0.0267	0.0116
4,000	1.91	0.0338	0.0146	1.98	0.0368	0.0160	2.05	0.0404	0.0175
5,000	2.38	0.0510	0.0221	2.47	0.0557	0.0241	2.57	0.0610	0.0264
6,000	2.86	0.0715	0.0310	2.96	0.0780	0.0338	3.08	0.0855	0.0370
7,000	3.34	0.0951	0.0412	3.46	0.104	0.0449	3.59	0.114	0.0493
8,000	3.81	0.122	0.0527	3.95	0.133	0.0575	4.10	0.146	0.0631
9,000	4.29	0.151	0.0656	4.45	0.165	0.0715	4.62	0.181	0.0784
10,000	4.77	0.184	0.0797	4.94	0.201	0.0869	5.13	0.220	0.0953
12,000	5.72	0.258	0.112	5.93	0.281	0.122	6.16	0.308	0.134
14,000	6.67	0.343	0.148	6.92	0.374	0.162	7.18	0.410	0.178
16,000	7.63	0.439	0.190	7.90	0.479	0.207	8.21	0.525	0.227
18,000	8.58	0.546	0.236	8.89	0.595	0.258	9.23	0.653	0.283
20,000	9.53	0.663	0.287	9.88	0.724	0.313	10.3	0.793	0.344
22,000	10.5	0.791	0.343	10.9	0.863	0.374	11.3	0.946	0.410
24,000	11.4	0.929	0.402	11.9	1.01	0.439	12.3	1.11	0.481

Table 9.3 Flow friction loss, AWWA C900 and C905 CIOD PVC pipe (*continued*)

36 in. CIOD (AWWA C905)									
Flow, gpm	DR 51 Pressure class 80 psi			DR 41 Pressure class 100 psi			DR 32.5 Pressure class 125 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
2,000	0.607	0.00313	0.00135	0.620	0.00329	0.00143	0.638	0.00353	0.00153
3,500	1.06	0.00880	0.00381	1.08	0.00927	0.00402	1.12	0.00995	0.00431
5,000	1.52	0.0170	0.00737	1.55	0.0179	0.00777	1.60	0.0192	0.00833
7,000	2.12	0.0317	0.0137	2.17	0.0334	0.0145	2.23	0.0359	0.0155
9,000	2.73	0.0505	0.0219	2.79	0.0532	0.0230	2.87	0.0571	0.0247
11,000	3.34	0.0732	0.0317	3.41	0.0771	0.0334	3.51	0.0827	0.0358
13,000	3.94	0.0998	0.0432	4.03	0.105	0.0455	4.15	0.113	0.0488
15,000	4.55	0.130	0.0563	4.65	0.137	0.0593	4.79	0.147	0.0636
17,000	5.16	0.164	0.0710	5.27	0.173	0.0747	5.42	0.185	0.0802
19,000	5.76	0.201	0.0872	5.89	0.212	0.0918	6.06	0.227	0.0985
21,000	6.37	0.242	0.105	6.51	0.255	0.110	6.70	0.274	0.118
23,000	6.98	0.287	0.124	7.13	0.302	0.131	7.34	0.324	0.140
25,000	7.58	0.334	0.145	7.75	0.352	0.153	7.98	0.378	0.164
27,000	8.19	0.386	0.167	8.37	0.406	0.176	8.61	0.436	0.189
29,000	8.80	0.440	0.191	8.99	0.464	0.201	9.25	0.497	0.215
31,000	9.41	0.498	0.216	9.61	0.524	0.227	9.89	0.563	0.244
33,000	10.0	0.559	0.242	10.2	0.589	0.255	10.5	0.632	0.273
35,000	10.6	0.623	0.270	10.8	0.656	0.284	11.2	0.704	0.305

Notes:

1. Table is based on Equations 9.2 through 9.5, using C = 150.
2. Friction-loss values are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$, where:

   D_i = pipe inside diameter, in.
   D_o = pipe outside diameter, in.
   t_{min} = minimum wall thickness, in.

Table 9.3 Flow friction loss, AWWA C900 and C905 CIOD PVC pipe (*continued*)

36 in. CIOD (AWWA C905)									
Flow, gpm	DR 25 Pressure class 165 psi			DR 21 Pressure class 200 psi			DR 18 Pressure class 235 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
2,000	0.666	0.00391	0.00170	0.690	0.00427	0.00185	0.716	0.00468	0.00203
3,500	1.16	0.0110	0.00477	1.21	0.0120	0.00521	1.25	0.0132	0.00570
5,000	1.66	0.0213	0.00923	1.72	0.0233	0.0101	1.79	0.0255	0.011
7,000	2.33	0.0397	0.0172	2.41	0.0433	0.0188	2.51	0.0475	0.021
9,000	3.00	0.0633	0.0274	3.10	0.0690	0.0299	3.22	0.0756	0.033
11,000	3.66	0.0917	0.0397	3.79	0.100	0.0433	3.94	0.110	0.047
13,000	4.33	0.125	0.0541	4.48	0.136	0.0590	4.66	0.149	0.065
15,000	4.99	0.163	0.0705	5.17	0.178	0.0769	5.37	0.194	0.084
17,000	5.66	0.205	0.0888	5.86	0.224	0.0969	6.09	0.245	0.106
19,000	6.32	0.252	0.109	6.55	0.275	0.119	6.80	0.301	0.130
21,000	6.99	0.303	0.131	7.24	0.331	0.143	7.52	0.362	0.157
23,000	7.65	0.359	0.155	7.93	0.391	0.169	8.24	0.429	0.186
25,000	8.32	0.419	0.181	8.62	0.457	0.198	8.95	0.500	0.217
27,000	8.99	0.483	0.209	9.31	0.527	0.228	9.67	0.577	0.250
29,000	9.65	0.551	0.239	10.0	0.601	0.260	10.4	0.658	0.285
31,000	10.3	0.623	0.270	10.7	0.680	0.294	11.1	0.745	0.323
33,000	11.0	0.700	0.303	11.4	0.763	0.331	11.8	0.836	0.362
35,000	11.6	0.780	0.338	12.1	0.851	0.369	12.5	0.932	0.404

Table 9.3 Flow friction loss, AWWA C900 and C905 CIOD PVC pipe (*continued*)

42 in. CIOD (AWWA C905)									
Flow, gpm	DR 51 Pressure class 80 psi			DR 41 Pressure class 100 psi			DR 32.5 Pressure class 125 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
2,500	0.562	0.00228	0.000987	0.574	0.00240	0.00104	0.591	0.00257	0.00111
4,000	0.899	0.00544	0.00235	0.918	0.00573	0.00248	0.945	0.00614	0.00266
5,500	1.24	0.00980	0.00424	1.26	0.0103	0.00447	1.30	0.0111	0.00479
7,000	1.57	0.0153	0.00663	1.61	0.0161	0.00698	1.65	0.0173	0.00748
9,500	2.14	0.0269	0.0117	2.18	0.0284	0.0123	2.24	0.0304	0.0132
12,000	2.70	0.0415	0.0180	2.76	0.0437	0.0189	2.84	0.0468	0.0203
14,500	3.26	0.0589	0.0255	3.33	0.0620	0.0269	3.43	0.0665	0.0288
17,000	3.82	0.0791	0.0342	3.90	0.0832	0.0360	4.02	0.0892	0.0386
20,000	4.50	0.107	0.0462	4.59	0.112	0.0487	4.73	0.121	0.0522
23,000	5.17	0.138	0.0599	5.28	0.146	0.0630	5.43	0.156	0.0676
26,000	5.84	0.173	0.0751	5.97	0.183	0.0791	6.14	0.196	0.0848
29,000	6.52	0.212	0.0919	6.66	0.224	0.0968	6.85	0.240	0.104
32,000	7.19	0.255	0.110	7.35	0.268	0.116	7.56	0.288	0.125
35,000	7.87	0.301	0.130	8.04	0.317	0.137	8.27	0.339	0.147
38,000	8.54	0.350	0.152	8.72	0.369	0.160	8.98	0.395	0.171
42,000	9.44	0.421	0.182	9.64	0.444	0.192	9.92	0.476	0.206
46,000	10.3	0.499	0.216	10.6	0.525	0.227	10.9	0.563	0.244
50,000	11.2	0.582	0.252	11.5	0.612	0.265	11.8	0.657	0.284

Notes:

1. Table is based on Equations 9.2 through 9.5, using $C = 150$.
2. Friction-loss values are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$,
   where:
   - D_i = pipe inside diameter, in.
   - D_o = pipe outside diameter, in.
   - t_{min} = minimum wall thickness, in.

Table 9.3 Flow friction loss, AWWA C900 and C905 CIOD PVC pipe (*continued*)

42 in. CIOD (AWWA C905)			
Flow, gpm	DR 25 Pressure class 165 psi		
	Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft
2,500	0.616	0.00285	0.00123
4,000	0.986	0.00680	0.00295
5,500	1.36	0.0123	0.00531
7,000	1.73	0.0192	0.00829
9,500	2.34	0.0337	0.0146
12,000	2.96	0.0519	0.0225
14,500	3.57	0.0737	0.0319
17,000	4.19	0.0989	0.0428
20,000	4.93	0.134	0.0578
23,000	5.67	0.173	0.0749
26,000	6.41	0.217	0.0940
29,000	7.15	0.266	0.115
32,000	7.89	0.319	0.138
35,000	8.63	0.376	0.163
38,000	9.37	0.438	0.190
42,000	10.4	0.527	0.228
46,000	11.3	0.624	0.270
50,000	12.3	0.728	0.315

Table 9.3 Flow friction loss, AWWA C900 and C905 CIOD PVC pipe (*continued*)

48 in. CIOD (AWWA C905)

Flow, gpm	DR 51 Pressure class 80 psi			DR 41 Pressure class 100 psi			DR 32.5 Pressure class 125 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
3,000	0.517	0.00168	0.000726	0.529	0.00177	0.000765	0.544	0.00189	0.000820
5,000	0.862	0.00432	0.00187	0.881	0.00455	0.00197	0.906	0.00487	0.00211
8,000	1.38	0.0103	0.00446	1.41	0.0108	0.00470	1.45	0.0116	0.00503
11,000	1.90	0.0186	0.00804	1.94	0.0196	0.00847	1.99	0.0210	0.00907
14,000	2.41	0.0290	0.0126	2.47	0.0306	0.0132	2.54	0.0327	0.0142
17,000	2.93	0.0415	0.0180	3.00	0.0438	0.0189	3.08	0.0469	0.0203
20,000	3.45	0.0561	0.0243	3.52	0.0591	0.0256	3.63	0.0633	0.0274
23,000	3.97	0.0726	0.0315	4.05	0.0765	0.0331	4.17	0.0820	0.0355
26,000	4.48	0.0911	0.0395	4.58	0.0960	0.0416	4.71	0.103	0.0446
29,000	5.00	0.112	0.0483	5.11	0.118	0.0509	5.26	0.126	0.0545
32,000	5.52	0.134	0.0579	5.64	0.141	0.0611	5.80	0.151	0.0654
36,000	6.21	0.166	0.0721	6.34	0.175	0.0759	6.53	0.188	0.0813
40,000	6.90	0.202	0.0876	7.05	0.213	0.0923	7.25	0.228	0.0989
44,000	7.59	0.241	0.104	7.75	0.254	0.110	7.98	0.272	0.118
48,000	8.28	0.283	0.123	8.46	0.299	0.129	8.70	0.320	0.139
52,000	8.97	0.329	0.142	9.16	0.346	0.150	9.43	0.371	0.161
56,000	9.66	0.377	0.163	9.87	0.397	0.172	10.2	0.425	0.184
60,000	10.3	0.428	0.185	10.6	0.451	0.195	10.9	0.483	0.209

Notes:

1. Table is based on Equations 9.2 through 9.5, using C = 150.
2. Friction-loss values are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$, where:

   D_i = pipe inside diameter, in.
   D_o = pipe outside diameter, in.
   t_{min} = minimum wall thickness, in.

Table 9.3 Flow friction loss, AWWA C900 and C905 CIOD PVC pipe (*continued*)

48 in. CIOD (AWWA C905)			
Flow, gpm	DR 25 Pressure class 165 psi		
	Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft
3,000	0.568	0.00210	0.000909
5,000	0.946	0.00540	0.00234
8,000	1.51	0.0129	0.00558
11,000	2.08	0.0232	0.0101
14,000	2.65	0.0363	0.0157
17,000	3.22	0.0520	0.0225
20,000	3.78	0.0702	0.0304
23,000	4.35	0.0910	0.0394
26,000	4.92	0.114	0.0494
29,000	5.49	0.140	0.0605
32,000	6.05	0.168	0.0726
36,000	6.81	0.208	0.0902
40,000	7.57	0.253	0.110
44,000	8.32	0.302	0.131
48,000	9.08	0.355	0.154
52,000	9.84	0.411	0.178
56,000	10.6	0.472	0.204
60,000	11.4	0.536	0.232

Table 9.4 Flow friction loss, ASTM D2241 and AWWA C905 IPS OD PVC pipe

3 in. IPS (ASTM D2241)									
Flow, gpm	DR 41 Pressure rated 100 psi			DR 32.5 Pressure rated 125 psi			DR 26 Pressure rated 160 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
15	0.557	0.0433	0.0188	0.573	0.0464	0.0201	0.593	0.0506	0.0219
20	0.742	0.0738	0.0319	0.764	0.0791	0.0342	0.791	0.0861	0.0373
25	0.928	0.111	0.0483	0.955	0.120	0.0517	0.989	0.130	0.0564
30	1.11	0.156	0.0676	1.15	0.167	0.0725	1.19	0.182	0.0790
40	1.48	0.266	0.115	1.53	0.285	0.123	1.58	0.311	0.134
50	1.86	0.402	0.174	1.91	0.431	0.187	1.98	0.469	0.203
60	2.23	0.563	0.244	2.29	0.604	0.261	2.37	0.658	0.285
70	2.60	0.749	0.324	2.67	0.803	0.348	2.77	0.875	0.379
80	2.97	0.959	0.415	3.06	1.03	0.445	3.17	1.12	0.485
90	3.34	1.19	0.516	3.44	1.28	0.553	3.56	1.39	0.603
100	3.71	1.45	0.627	3.82	1.55	0.672	3.96	1.69	0.733
120	4.45	2.03	0.879	4.58	2.18	0.942	4.75	2.37	1.03
140	5.20	2.70	1.17	5.35	2.89	1.25	5.54	3.15	1.37
160	5.94	3.46	1.50	6.11	3.71	1.60	6.33	4.04	1.75
180	6.68	4.30	1.86	6.88	4.61	2.00	7.12	5.02	2.17
200	7.42	5.22	2.26	7.64	5.60	2.42	7.91	6.10	2.64
220	8.17	6.23	2.70	8.40	6.68	2.89	8.70	7.27	3.15
240	8.91	7.32	3.17	9.17	7.84	3.40	9.50	8.55	3.70

Notes:

1. Table is based on Equations 9.2 through 9.5, using C = 150.
2. Friction-loss values are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$, where:

D_i = pipe inside diameter, in.
D_o = pipe outside diameter, in.
t_{min} = minimum wall thickness, in.

Table 9.4 Flow friction loss, ASTM D2241 and AWWA C905 IPS OD PVC pipe (*continued*)

3 in. IPS (ASTM D2241)									
Flow, gpm	DR 21 Pressure rated 200 psi			DR 17 Pressure rated 250 psi			DR 13.5 Pressure rated 315 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
15	0.619	0.0561	0.0243	0.653	0.0639	0.0277	0.705	0.0768	0.0332
20	0.826	0.0956	0.0414	0.871	0.109	0.0471	0.939	0.131	0.0566
25	1.03	0.144	0.0625	1.09	0.164	0.0712	1.17	0.198	0.0855
30	1.24	0.202	0.0876	1.31	0.230	0.100	1.41	0.277	0.120
40	1.65	0.345	0.149	1.74	0.392	0.170	1.88	0.471	0.204
50	2.06	0.521	0.225	2.18	0.593	0.257	2.35	0.712	0.308
60	2.48	0.729	0.316	2.61	0.831	0.360	2.82	1.00	0.432
70	2.89	0.970	0.420	3.05	1.11	0.478	3.29	1.33	0.575
80	3.30	1.24	0.538	3.49	1.41	0.613	3.76	1.70	0.736
90	3.72	1.54	0.669	3.92	1.76	0.762	4.23	2.11	0.915
100	4.13	1.88	0.813	4.36	2.14	0.926	4.70	2.57	1.11
120	4.96	2.63	1.14	5.23	3.00	1.30	5.64	3.60	1.56
140	5.78	3.50	1.51	6.10	3.98	1.72	6.58	4.78	2.07
160	6.61	4.48	1.94	6.97	5.10	2.21	7.52	6.12	2.65
180	7.43	5.57	2.41	7.84	6.34	2.75	8.45	7.61	3.30
200	8.26	6.77	2.93	8.71	7.71	3.34	9.39	9.25	4.01
220	9.08	8.07	3.49	9.58	9.19	3.98	10.3	11.0	4.78
240	9.91	9.48	4.11	10.5	10.8	4.68	11.3	13.0	5.61

Table 9.4 Flow friction loss, ASTM D2241 and AWWA C905 IPS OD PVC pipe (*continued*)

4 in. IPS (ASTM D2241)									
Flow, gpm	DR 41 Pressure rated 100 psi			DR 32.5 Pressure rated 125 psi			DR 26 Pressure rated 160 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
25	0.561	0.0329	0.0142	0.578	0.0352	0.0153	0.598	0.0384	0.0166
40	0.898	0.0784	0.0339	0.924	0.0841	0.0364	0.957	0.0916	0.0396
55	1.23	0.141	0.0612	1.27	0.152	0.0656	1.32	0.165	0.0715
70	1.57	0.221	0.0956	1.62	0.237	0.102	1.68	0.258	0.112
85	1.91	0.316	0.137	1.96	0.339	0.147	2.03	0.369	0.160
100	2.25	0.427	0.185	2.31	0.458	0.198	2.39	0.499	0.216
125	2.81	0.645	0.279	2.89	0.692	0.300	2.99	0.754	0.326
150	3.37	0.904	0.391	3.47	0.969	0.420	3.59	1.06	0.457
175	3.93	1.20	0.521	4.04	1.29	0.558	4.19	1.40	0.608
200	4.49	1.54	0.667	4.62	1.65	0.715	4.79	1.80	0.779
225	5.05	1.91	0.829	5.20	2.05	0.889	5.39	2.24	0.968
250	5.61	2.33	1.01	5.78	2.49	1.08	5.98	2.72	1.18
275	6.17	2.77	1.20	6.35	2.98	1.29	6.58	3.24	1.40
300	6.74	3.26	1.41	6.93	3.49	1.51	7.18	3.81	1.65
325	7.30	3.78	1.64	7.51	4.05	1.75	7.78	4.41	1.91
350	7.86	4.33	1.88	8.09	4.65	2.01	8.38	5.06	2.19
375	8.42	4.92	2.13	8.67	5.28	2.29	8.98	5.75	2.49
400	8.98	5.55	2.40	9.24	5.95	2.58	9.57	6.48	2.81

Notes:

1. Table is based on Equations 9.2 through 9.5, using C = 150.
2. Friction-loss values are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$, where:

    D_i = pipe inside diameter, in.
    D_o = pipe outside diameter, in.
    t_{min} = minimum wall thickness, in.

Table 9.4 Flow friction loss, ASTM D2241 and AWWA C905 IPS OD PVC pipe (*continued*)

4 in. IPS (ASTM D2241)									
Flow, gpm	DR 21 Pressure rated 200 psi			DR 17 Pressure rated 250 psi			DR 13.5 Pressure rated 315 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
25	0.624	0.0426	0.0184	0.659	0.0485	0.0210	0.710	0.0582	0.0252
40	1.00	0.102	0.0440	1.05	0.116	0.0501	1.14	0.139	0.0602
55	1.37	0.183	0.0793	1.45	0.209	0.0903	1.56	0.250	0.108
70	1.75	0.286	0.124	1.84	0.326	0.141	1.99	0.391	0.169
85	2.12	0.410	0.177	2.24	0.467	0.202	2.42	0.560	0.243
100	2.50	0.553	0.240	2.64	0.630	0.273	2.84	0.757	0.328
125	3.12	0.836	0.362	3.29	0.952	0.412	3.55	1.14	0.495
150	3.75	1.17	0.507	3.95	1.33	0.578	4.26	1.60	0.694
175	4.37	1.56	0.675	4.61	1.77	0.768	4.97	2.13	0.923
200	5.00	1.99	0.864	5.27	2.27	0.984	5.68	2.73	1.18
225	5.62	2.48	1.07	5.93	2.83	1.22	6.39	3.39	1.47
250	6.24	3.01	1.31	6.59	3.43	1.49	7.10	4.12	1.78
275	6.87	3.60	1.56	7.25	4.10	1.77	7.81	4.92	2.13
300	7.49	4.22	1.83	7.91	4.81	2.08	8.52	5.78	2.50
325	8.12	4.90	2.12	8.57	5.58	2.42	9.23	6.70	2.90
350	8.74	5.62	2.43	9.22	6.40	2.77	9.94	7.68	3.33
375	9.37	6.38	2.76	9.88	7.27	3.15	10.7	8.73	3.78
400	10.0	7.19	3.11	10.5	8.19	3.55	11.4	9.83	4.26

Table 9.4 Flow friction loss, ASTM D2241 and AWWA C905 IPS OD PVC pipe (*continued*)

5 in. IPS (ASTM D2241)									
Flow, gpm	DR 41 Pressure rated 100 psi			DR 32.5 Pressure rated 125 psi			DR 26 Pressure rated 160 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
40	0.588	0.0280	0.0121	0.605	0.0300	0.0130	0.626	0.0327	0.0141
55	0.808	0.0504	0.0218	0.832	0.0541	0.0234	0.861	0.0589	0.0255
70	1.03	0.0788	0.0341	1.06	0.0845	0.0366	1.10	0.0920	0.0398
85	1.25	0.113	0.0488	1.29	0.121	0.0524	1.33	0.132	0.0570
100	1.47	0.152	0.0660	1.51	0.163	0.0707	1.57	0.178	0.0771
125	1.84	0.230	0.100	1.89	0.247	0.107	1.96	0.269	0.116
150	2.20	0.323	0.140	2.27	0.346	0.150	2.35	0.377	0.163
175	2.57	0.429	0.186	2.65	0.460	0.199	2.74	0.501	0.217
200	2.94	0.549	0.238	3.02	0.589	0.255	3.13	0.642	0.278
225	3.31	0.683	0.296	3.40	0.732	0.317	3.52	0.798	0.345
250	3.67	0.830	0.359	3.78	0.890	0.385	3.92	0.969	0.420
300	4.41	1.16	0.504	4.54	1.25	0.540	4.70	1.36	0.588
350	5.14	1.55	0.670	5.29	1.66	0.718	5.48	1.81	0.782
400	5.88	1.98	0.857	6.05	2.12	0.919	6.26	2.31	1.00
450	6.61	2.46	1.07	6.80	2.64	1.14	7.05	2.88	1.25
500	7.35	2.99	1.30	7.56	3.21	1.39	7.83	3.49	1.51
550	8.08	3.57	1.55	8.32	3.83	1.66	8.61	4.17	1.80
600	8.82	4.19	1.82	9.07	4.50	1.95	9.40	4.90	2.12

Notes:

1. Table is based on Equations 9.2 through 9.5, using $C = 150$.
2. Friction-loss values are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$, where:

   D_i = pipe inside diameter, in.
   D_o = pipe outside diameter, in.
   t_{min} = minimum wall thickness, in.

Table 9.4 Flow friction loss, ASTM D2241 and AWWA C905 IPS OD PVC pipe (*continued*)

5 in. IPS (ASTM D2241)									
Flow, gpm	DR 21 Pressure rated 200 psi			DR 17 Pressure rated 250 psi			DR 13.5 Pressure rated 315 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
40	0.654	0.0362	0.0157	0.690	0.0413	0.0179	0.744	0.0496	0.0215
55	0.899	0.0653	0.0283	0.948	0.0744	0.0322	1.02	0.0893	0.0387
70	1.14	0.102	0.0442	1.21	0.116	0.0503	1.30	0.140	0.0604
85	1.39	0.146	0.0633	1.47	0.166	0.0721	1.58	0.200	0.0866
100	1.63	0.197	0.0855	1.72	0.225	0.0974	1.86	0.270	0.117
125	2.04	0.298	0.129	2.16	0.340	0.147	2.32	0.408	0.177
150	2.45	0.418	0.181	2.59	0.476	0.206	2.79	0.572	0.248
175	2.86	0.556	0.241	3.02	0.633	0.274	3.25	0.760	0.329
200	3.27	0.712	0.308	3.45	0.811	0.351	3.72	0.973	0.421
225	3.68	0.885	0.383	3.88	1.01	0.436	4.18	1.21	0.524
250	4.09	1.08	0.466	4.31	1.22	0.530	4.65	1.47	0.637
300	4.90	1.51	0.652	5.17	1.72	0.743	5.58	2.06	0.892
350	5.72	2.00	0.868	6.04	2.28	0.988	6.51	2.74	1.19
400	6.54	2.57	1.11	6.90	2.92	1.27	7.44	3.51	1.52
450	7.36	3.19	1.38	7.76	3.63	1.57	8.37	4.36	1.89
500	8.17	3.88	1.68	8.62	4.42	1.91	9.30	5.30	2.30
550	8.99	4.62	2.00	9.48	5.27	2.28	10.2	6.32	2.74
600	9.81	5.43	2.35	10.3	6.19	2.68	11.2	7.43	3.22

Table 9.4 Flow friction loss, ASTM D2241 and AWWA C905 IPS OD PVC pipe (*continued*)

6 in. IPS (ASTM D2241)									
Flow, gpm	DR 41 Pressure rated 100 psi			DR 32.5 Pressure rated 125 psi			DR 26 Pressure rated 160 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
50	0.518	0.0181	0.00783	0.533	0.0194	0.00839	0.552	0.0211	0.00914
75	0.777	0.0383	0.0166	0.800	0.0410	0.0178	0.828	0.0447	0.0194
100	1.04	0.0652	0.0282	1.07	0.0699	0.0303	1.10	0.0761	0.0330
125	1.29	0.0985	0.0426	1.33	0.106	0.0457	1.38	0.115	0.0498
150	1.55	0.138	0.0598	1.60	0.148	0.0641	1.66	0.161	0.0698
175	1.81	0.184	0.0795	1.87	0.197	0.0852	1.93	0.214	0.0928
200	2.07	0.235	0.102	2.13	0.252	0.109	2.21	0.274	0.119
225	2.33	0.292	0.127	2.40	0.313	0.136	2.48	0.341	0.148
250	2.59	0.355	0.154	2.67	0.381	0.165	2.76	0.415	0.180
300	3.11	0.497	0.215	3.20	0.533	0.231	3.31	0.581	0.252
350	3.63	0.662	0.286	3.73	0.709	0.307	3.87	0.773	0.335
400	4.14	0.847	0.367	4.26	0.908	0.393	4.42	0.989	0.428
450	4.66	1.05	0.456	4.80	1.13	0.489	4.97	1.23	0.533
500	5.18	1.28	0.554	5.33	1.37	0.594	5.52	1.50	0.647
600	6.22	1.79	0.777	6.40	1.92	0.833	6.63	2.09	0.907
700	7.25	2.39	1.03	7.46	2.56	1.11	7.73	2.79	1.21
800	8.29	3.05	1.32	8.53	3.27	1.42	8.83	3.57	1.54
900	9.32	3.80	1.64	9.59	4.07	1.76	9.94	4.44	1.92

Notes:

1. Table is based on Equations 9.2 through 9.5, using C = 150.
2. Friction-loss values are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$, where:

D_i = pipe inside diameter, in.
D_o = pipe outside diameter, in.
t_{min} = minimum wall thickness, in.

Table 9.4 Flow friction loss, ASTM D2241 and AWWA C905 IPS OD PVC pipe (*continued*)

6 in. IPS (ASTM D2241)									
Flow, gpm	DR 21 Pressure rated 200 psi			DR 17 Pressure rated 250 psi			DR 13.5 Pressure rated 315 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
50	0.576	0.0234	0.0101	0.608	0.0267	0.0116	0.655	0.0320	0.0139
75	0.864	0.0496	0.0215	0.912	0.0565	0.0245	0.983	0.0678	0.0294
100	1.15	0.0845	0.0366	1.22	0.0962	0.0417	1.31	0.116	0.0500
125	1.44	0.128	0.0553	1.52	0.145	0.0629	1.64	0.175	0.0756
150	1.73	0.179	0.0774	1.82	0.204	0.0882	1.97	0.245	0.106
175	2.02	0.238	0.103	2.13	0.271	0.117	2.29	0.325	0.141
200	2.30	0.304	0.132	2.43	0.347	0.150	2.62	0.416	0.180
225	2.59	0.379	0.164	2.74	0.431	0.187	2.95	0.518	0.224
250	2.88	0.460	0.199	3.04	0.524	0.227	3.28	0.629	0.272
300	3.46	0.645	0.279	3.65	0.734	0.318	3.93	0.882	0.382
350	4.03	0.857	0.371	4.26	0.977	0.423	4.59	1.17	0.508
400	4.61	1.10	0.475	4.86	1.25	0.541	5.24	1.50	0.650
450	5.19	1.36	0.591	5.47	1.55	0.673	5.90	1.87	0.808
500	5.76	1.66	0.718	6.08	1.89	0.818	6.55	2.27	0.982
600	6.91	2.32	1.01	7.30	2.65	1.15	7.87	3.18	1.38
700	8.07	3.09	1.34	8.51	3.52	1.52	9.18	4.23	1.83
800	9.22	3.96	1.71	9.73	4.51	1.95	10.5	5.41	2.34
900	10.4	4.92	2.13	10.9	5.60	2.43	11.8	6.73	2.91

Table 9.4 Flow friction loss, ASTM D2241 and AWWA C905 IPS OD PVC pipe (*continued*)

8 in. IPS (ASTM D2241)									
Flow, gpm	DR 41 Pressure rated 100 psi			DR 32.5 Pressure rated 125 psi			DR 26 Pressure rated 160 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
90	0.550	0.0149	0.00644	0.566	0.0160	0.00691	0.586	0.0174	0.00753
120	0.733	0.0253	0.0110	0.755	0.0272	0.0118	0.782	0.0296	0.0128
150	0.917	0.0383	0.0166	0.943	0.0411	0.0178	0.977	0.0447	0.0194
200	1.22	0.0652	0.0282	1.26	0.0699	0.0303	1.30	0.0761	0.0330
250	1.53	0.0985	0.0427	1.57	0.106	0.0457	1.63	0.115	0.0498
300	1.83	0.138	0.0598	1.89	0.148	0.0641	1.95	0.161	0.0698
350	2.14	0.184	0.0795	2.20	0.197	0.0852	2.28	0.214	0.0928
400	2.44	0.235	0.102	2.52	0.252	0.109	2.61	0.274	0.119
500	3.06	0.355	0.154	3.14	0.381	0.165	3.26	0.415	0.180
600	3.67	0.498	0.215	3.77	0.534	0.231	3.91	0.581	0.252
700	4.28	0.662	0.287	4.40	0.710	0.307	4.56	0.773	0.335
800	4.89	0.847	0.367	5.03	0.908	0.393	5.21	0.990	0.428
900	5.50	1.05	0.456	5.66	1.13	0.489	5.86	1.23	0.533
1,000	6.11	1.28	0.554	6.29	1.37	0.594	6.52	1.50	0.647
1,100	6.72	1.53	0.661	6.92	1.64	0.709	7.17	1.78	0.772
1,200	7.33	1.79	0.777	7.55	1.92	0.833	7.82	2.10	0.907
1,400	8.56	2.39	1.03	8.81	2.56	1.11	9.12	2.79	1.21
1,600	9.78	3.05	1.32	10.1	3.27	1.42	10.4	3.57	1.54

Notes:

1. Table is based on Equations 9.2 through 9.5, using C = 150.
2. Friction-loss values are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$,
   where:
   D_i = pipe inside diameter, in.
   D_o = pipe outside diameter, in.
   t_{min} = minimum wall thickness, in.

Table 9.4 Flow friction loss, ASTM D2241 and AWWA C905 IPS OD PVC pipe (*continued*)

8 in. IPS (ASTM D2241)						
Flow, gpm	DR 21 Pressure rated 200 psi			DR 17 Pressure rated 250 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
90	0.612	0.0193	0.00834	0.646	0.0220	0.00952
120	0.816	0.0328	0.0142	0.861	0.0374	0.0162
150	1.02	0.0496	0.0215	1.08	0.0566	0.0245
200	1.36	0.0844	0.0365	1.44	0.0963	0.0417
250	1.70	0.128	0.0552	1.79	0.146	0.0630
300	2.04	0.179	0.0774	2.15	0.204	0.0883
350	2.38	0.238	0.103	2.51	0.271	0.117
400	2.72	0.304	0.132	2.87	0.347	0.150
500	3.40	0.460	0.199	3.59	0.525	0.227
600	4.08	0.644	0.279	4.31	0.735	0.318
700	4.76	0.857	0.371	5.02	0.978	0.423
800	5.44	1.10	0.475	5.74	1.25	0.542
900	6.12	1.36	0.591	6.46	1.56	0.674
1,000	6.80	1.66	0.718	7.18	1.89	0.819
1,100	7.48	1.98	0.856	7.89	2.26	0.977
1,200	8.16	2.32	1.01	8.61	2.65	1.15
1,400	9.52	3.09	1.34	10.0	3.52	1.53
1,600	10.9	3.95	1.71	11.5	4.51	1.95

Table 9.4 Flow friction loss, ASTM D2241 and AWWA C905 IPS OD PVC pipe (*continued*)

10 in. IPS (ASTM D2241)									
Flow, gpm	DR 41 Pressure rated 100 psi			DR 32.5 Pressure rated 125 psi			DR 26 Pressure rated 160 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
150	0.590	0.0131	0.00568	0.607	0.0141	0.00610	0.629	0.0153	0.00664
200	0.787	0.0224	0.00968	0.810	0.0240	0.0104	0.839	0.0261	0.0113
250	0.984	0.0338	0.0146	1.01	0.0362	0.0157	1.05	0.0395	0.0171
300	1.18	0.0473	0.0205	1.21	0.0507	0.0220	1.26	0.0553	0.0239
400	1.57	0.0806	0.0349	1.62	0.0864	0.0374	1.68	0.0941	0.0408
500	1.97	0.122	0.0527	2.02	0.131	0.0565	2.10	0.142	0.0616
600	2.36	0.171	0.0739	2.43	0.183	0.0792	2.52	0.199	0.0863
700	2.75	0.227	0.0982	2.83	0.243	0.105	2.94	0.265	0.115
800	3.15	0.290	0.126	3.24	0.311	0.135	3.36	0.339	0.147
900	3.54	0.361	0.156	3.64	0.387	0.168	3.77	0.422	0.183
1,000	3.93	0.439	0.190	4.05	0.471	0.204	4.19	0.513	0.222
1,200	4.72	0.615	0.266	4.86	0.659	0.286	5.03	0.718	0.311
1,400	5.51	0.818	0.354	5.67	0.877	0.380	5.87	0.955	0.414
1,600	6.29	1.05	0.453	6.48	1.12	0.486	6.71	1.22	0.530
1,800	7.08	1.30	0.564	7.29	1.40	0.605	7.55	1.52	0.659
2,000	7.87	1.58	0.685	8.10	1.70	0.735	8.39	1.85	0.800
2,200	8.66	1.89	0.817	8.91	2.02	0.876	9.23	2.20	0.955
2,500	9.84	2.39	1.04	10.1	2.56	1.11	10.5	2.79	1.21

Notes:

1. Table is based on Equations 9.2 through 9.5, using C = 150.
2. Friction-loss values are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$, where:

   D_i = pipe inside diameter, in.
   D_o = pipe outside diameter, in.
   t_{min} = minimum wall thickness, in.

Table 9.4 Flow friction loss, ASTM D2241 and AWWA C905 IPS OD PVC pipe (*continued*)

10 in. IPS (ASTM D2241)						
Flow, gpm	DR 21 Pressure rated 200 psi			DR 17 Pressure rated 250 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
150	0.656	0.0170	0.00736	0.693	0.0194	0.00839
200	0.875	0.0289	0.0125	0.924	0.0330	0.0143
250	1.09	0.0437	0.0189	1.15	0.0499	0.0216
300	1.31	0.0613	0.0265	1.39	0.0698	0.0302
400	1.75	0.104	0.0452	1.85	0.119	0.0515
500	2.19	0.158	0.0683	2.31	0.180	0.0778
600	2.63	0.221	0.0956	2.77	0.252	0.109
700	3.06	0.294	0.127	3.23	0.335	0.145
800	3.50	0.376	0.163	3.69	0.429	0.186
900	3.94	0.468	0.202	4.16	0.533	0.231
1,000	4.38	0.568	0.246	4.62	0.648	0.281
1,200	5.25	0.796	0.345	5.54	0.908	0.393
1,400	6.13	1.06	0.459	6.47	1.21	0.523
1,600	7.00	1.36	0.587	7.39	1.55	0.669
1,800	7.88	1.69	0.730	8.31	1.92	0.832
2,000	8.75	2.05	0.887	9.24	2.34	1.01
2,200	9.63	2.44	1.06	10.2	2.79	1.21
2,500	10.9	3.10	1.34	11.5	3.53	1.53

Table 9.4 Flow friction loss, ASTM D2241 and AWWA C905 IPS OD PVC pipe (*continued*)

12 in. IPS (ASTM D2241)									
Flow, gpm	DR 41 Pressure rated 100 psi			DR 32.5 Pressure rated 125 psi			DR 26 Pressure rated 160 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
200	0.559	0.00975	0.00422	0.576	0.0105	0.00453	0.596	0.0114	0.00493
300	0.839	0.0207	0.00894	0.864	0.0221	0.00959	0.894	0.0241	0.0104
400	1.12	0.0352	0.0152	1.15	0.0377	0.0163	1.19	0.0411	0.0178
500	1.40	0.0531	0.0230	1.44	0.0570	0.0247	1.49	0.0621	0.0269
600	1.68	0.0744	0.0322	1.73	0.0798	0.0346	1.79	0.0870	0.0377
700	1.96	0.0990	0.0429	2.01	0.106	0.0460	2.09	0.116	0.0501
800	2.24	0.127	0.0549	2.30	0.136	0.0589	2.39	0.148	0.0641
900	2.52	0.158	0.0683	2.59	0.169	0.0732	2.68	0.184	0.0797
1,000	2.80	0.192	0.0829	2.88	0.205	0.0889	2.98	0.224	0.0969
1,200	3.36	0.268	0.116	3.45	0.288	0.125	3.58	0.313	0.136
1,400	3.92	0.357	0.155	4.03	0.383	0.166	4.17	0.417	0.181
1,600	4.47	0.457	0.198	4.61	0.490	0.212	4.77	0.534	0.231
1,800	5.03	0.568	0.246	5.18	0.609	0.264	5.37	0.664	0.287
2,000	5.59	0.691	0.299	5.76	0.740	0.321	5.96	0.807	0.349
2,400	6.71	0.968	0.419	6.91	1.04	0.449	7.16	1.13	0.489
2,800	7.83	1.29	0.557	8.06	1.38	0.597	8.35	1.50	0.651
3,200	8.95	1.65	0.713	9.21	1.77	0.765	9.54	1.92	0.833
3,600	10.1	2.05	0.887	10.4	2.20	0.951	10.7	2.39	1.04

Notes:

1. Table is based on Equations 9.2 through 9.5, using C = 150.
2. Friction-loss values are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$, where:

    D_i = pipe inside diameter, in.
    D_o = pipe outside diameter, in.
    t_{min} = minimum wall thickness, in.

Table 9.4 Flow friction loss, ASTM D2241 and AWWA C905 IPS OD PVC pipe (*continued*)

12 in. IPS (ASTM D2241)						
Flow, gpm	DR 21 Pressure rated 200 psi			DR 17 Pressure rated 250 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
200	0.622	0.0126	0.00547	0.657	0.0144	0.00623
300	0.933	0.0267	0.0116	0.985	0.0305	0.0132
400	1.24	0.0455	0.0197	1.31	0.0519	0.0225
500	1.56	0.0688	0.0298	1.64	0.0784	0.0340
600	1.87	0.0964	0.0417	1.97	0.110	0.0476
700	2.18	0.128	0.0555	2.30	0.146	0.0633
800	2.49	0.164	0.0711	2.63	0.187	0.0810
900	2.80	0.204	0.0884	2.95	0.233	0.101
1,000	3.11	0.248	0.107	3.28	0.283	0.122
1,200	3.73	0.347	0.150	3.94	0.396	0.172
1,400	4.35	0.462	0.200	4.60	0.527	0.228
1,600	4.98	0.592	0.256	5.25	0.674	0.292
1,800	5.60	0.736	0.319	5.91	0.839	0.363
2,000	6.22	0.894	0.387	6.57	1.02	0.441
2,400	7.46	1.25	0.542	7.88	1.43	0.618
2,800	8.71	1.67	0.721	9.19	1.90	0.822
3,200	10.0	2.13	0.923	10.5	2.43	1.05
3,600	11.2	2.65	1.15	11.8	3.02	1.31

Table 9.4 Flow friction loss, ASTM D2241 and AWWA C905 IPS OD PVC pipe (*continued*)

14 in. IPS (ASTM D2241 and AWWA C905)									
Flow, gpm	DR 41 Pressure rated 100 psi			DR 32.5 Pressure rated 125 psi			DR 26 Pressure rated 160 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
250	0.580	0.00936	0.00405	0.597	0.0100	0.00434	0.618	0.0109	0.00473
300	0.696	0.0131	0.00568	0.716	0.0140	0.00608	0.742	0.0153	0.00663
350	0.812	0.0174	0.00755	0.835	0.0187	0.00809	0.866	0.0204	0.00882
400	0.928	0.0223	0.00966	0.955	0.0239	0.0104	0.989	0.0261	0.0113
500	1.16	0.0337	0.0146	1.19	0.0361	0.0156	1.24	0.0394	0.0171
600	1.39	0.0473	0.0205	1.43	0.0506	0.0219	1.48	0.0552	0.0239
700	1.62	0.0628	0.0272	1.67	0.0674	0.0292	1.73	0.0734	0.0318
800	1.86	0.0805	0.0348	1.91	0.0862	0.0373	1.98	0.0940	0.0407
1,000	2.32	0.122	0.0526	2.39	0.130	0.0564	2.47	0.142	0.0615
1,200	2.78	0.170	0.0738	2.86	0.183	0.0790	2.97	0.199	0.0862
1,400	3.25	0.227	0.0981	3.34	0.243	0.105	3.46	0.265	0.115
1,600	3.71	0.290	0.126	3.82	0.311	0.135	3.96	0.339	0.147
2,000	4.64	0.438	0.190	4.77	0.470	0.203	4.95	0.512	0.222
2,400	5.57	0.614	0.266	5.73	0.658	0.285	5.93	0.717	0.311
2,800	6.50	0.817	0.354	6.68	0.875	0.379	6.92	0.954	0.413
3,200	7.42	1.05	0.453	7.64	1.12	0.485	7.91	1.22	0.529
3,700	8.58	1.37	0.592	8.83	1.47	0.635	9.15	1.60	0.692
4,200	9.74	1.73	0.749	10.0	1.85	0.802	10.4	2.02	0.875

Notes:

1. Table is based on Equations 9.2 through 9.5, using C = 150.
2. Friction-loss values are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$, where:

    D_i = pipe inside diameter, in.
    D_o = pipe outside diameter, in.
    t_{min} = minimum wall thickness, in.

Table 9.4 Flow friction loss, ASTM D2241 and AWWA C905 IPS OD PVC pipe (*continued*)

14 in. IPS (ASTM D2241 and AWWA C905)						
Flow, gpm	DR 21 Pressure rated 200 psi			DR 17 Pressure rated 250 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
250	0.645	0.0121	0.00525	0.681	0.0138	0.00598
300	0.774	0.0170	0.00735	0.817	0.0193	0.00837
350	0.903	0.0226	0.00978	0.953	0.0257	0.0111
400	1.03	0.0289	0.0125	1.09	0.0329	0.0143
500	1.29	0.0437	0.0189	1.36	0.0498	0.0215
600	1.55	0.0612	0.0265	1.63	0.0697	0.0302
700	1.81	0.0814	0.0352	1.91	0.0927	0.0401
800	2.06	0.104	0.0451	2.18	0.119	0.0514
1,000	2.58	0.157	0.0682	2.72	0.179	0.0777
1,200	3.10	0.221	0.0955	3.27	0.251	0.109
1,400	3.61	0.293	0.127	3.81	0.334	0.145
1,600	4.13	0.376	0.163	4.36	0.428	0.185
2,000	5.16	0.568	0.246	5.44	0.647	0.280
2,400	6.19	0.795	0.344	6.53	0.906	0.392
2,800	7.22	1.06	0.458	7.62	1.21	0.522
3,200	8.26	1.35	0.586	8.71	1.54	0.668
3,700	9.55	1.77	0.767	10.1	2.02	0.874
4,200	10.8	2.24	0.970	11.4	2.55	1.10

Table 9.4 Flow friction loss, ASTM D2241 and AWWA C905 IPS OD PVC pipe (*continued*)

16 in. IPS (ASTM D2241 and AWWA C905)

Flow, gpm	DR 41 Pressure rated 100 psi			DR 32.5 Pressure rated 125 psi			DR 26 Pressure rated 160 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
300	0.533	0.00685	0.00297	0.548	0.00735	0.00318	0.568	0.00800	0.00346
400	0.710	0.0117	0.00505	0.731	0.0125	0.00542	0.757	0.0136	0.00590
500	0.888	0.0176	0.00763	0.914	0.0189	0.00818	0.947	0.0206	0.00891
600	1.07	0.0247	0.0107	1.10	0.0265	0.0115	1.14	0.0288	0.0125
700	1.24	0.0328	0.0142	1.28	0.0352	0.0152	1.33	0.0384	0.0166
800	1.42	0.0420	0.0182	1.46	0.0451	0.0195	1.51	0.0491	0.0213
1,000	1.78	0.0635	0.0275	1.83	0.0681	0.0295	1.89	0.0742	0.0321
1,300	2.31	0.103	0.0447	2.38	0.111	0.0479	2.46	0.121	0.0522
1,600	2.84	0.152	0.0656	2.92	0.163	0.0704	3.03	0.177	0.0767
1,900	3.37	0.208	0.0902	3.47	0.223	0.0967	3.60	0.243	0.105
2,200	3.91	0.273	0.118	4.02	0.293	0.127	4.17	0.319	0.138
2,500	4.44	0.346	0.150	4.57	0.371	0.161	4.73	0.404	0.175
3,000	5.33	0.485	0.210	5.48	0.520	0.225	5.68	0.566	0.245
3,500	6.22	0.645	0.279	6.40	0.692	0.299	6.63	0.753	0.326
4,000	7.10	0.826	0.358	7.31	0.885	0.383	7.57	0.965	0.418
4,500	7.99	1.03	0.445	8.23	1.10	0.477	8.52	1.20	0.519
5,000	8.88	1.25	0.540	9.14	1.34	0.579	9.47	1.46	0.631
5,500	9.77	1.49	0.644	10.1	1.60	0.691	10.4	1.74	0.753

Notes:

1. Table is based on Equations 9.2 through 9.5, using C = 150.
2. Friction-loss values are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$,
   where:

   D_i = pipe inside diameter, in.
   D_o = pipe outside diameter, in.
   t_{min} = minimum wall thickness, in.

Table 9.4 Flow friction loss, ASTM D2241 and AWWA C905 IPS OD PVC pipe (*continued*)

16 in. IPS (ASTM D2241 and AWWA C905)						
Flow, gpm	DR 21 Pressure rated 200 psi			DR 17 Pressure rated 250 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
300	0.593	0.00888	0.00384	0.625	0.0101	0.00438
400	0.790	0.0151	0.00654	0.834	0.0172	0.00745
500	0.988	0.0228	0.00989	1.04	0.0260	0.0113
600	1.19	0.0320	0.0139	1.25	0.0364	0.0158
700	1.38	0.0426	0.0184	1.46	0.0485	0.0210
800	1.58	0.0545	0.0236	1.67	0.0621	0.0269
1,000	1.98	0.0823	0.0357	2.08	0.0938	0.0406
1,300	2.57	0.134	0.0579	2.71	0.152	0.0660
1,600	3.16	0.196	0.0851	3.34	0.224	0.0969
1,900	3.75	0.270	0.117	3.96	0.307	0.133
2,200	4.35	0.354	0.153	4.59	0.403	0.175
2,500	4.94	0.449	0.194	5.21	0.511	0.221
3,000	5.93	0.628	0.272	6.25	0.716	0.310
3,500	6.92	0.836	0.362	7.30	0.952	0.412
4,000	7.90	1.07	0.463	8.34	1.22	0.528
4,500	8.89	1.33	0.576	9.38	1.52	0.656
5,000	9.88	1.62	0.700	10.4	1.84	0.797
5,500	10.9	1.93	0.835	11.5	2.20	0.951

Table 9.4 Flow friction loss, ASTM D2241 and AWWA C905 IPS OD PVC pipe (*continued*)

18 in. IPS (ASTM D2241 and AWWA C905)									
Flow, gpm	DR 41 Pressure rated 100 psi			DR 32.5 Pressure rated 125 psi			DR 26 Pressure rated 160 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
400	0.561	0.00658	0.00285	0.578	0.00706	0.00306	0.598	0.00769	0.00333
600	0.842	0.0139	0.00603	0.867	0.0149	0.00647	0.898	0.0163	0.00705
800	1.12	0.0237	0.0103	1.16	0.0254	0.0110	1.20	0.0277	0.0120
1,000	1.40	0.0358	0.0155	1.44	0.0384	0.0166	1.50	0.0419	0.0181
1,200	1.68	0.0502	0.0217	1.73	0.0539	0.0233	1.80	0.0587	0.0254
1,400	1.96	0.0668	0.0289	2.02	0.0716	0.0310	2.09	0.0780	0.0338
1,800	2.53	0.106	0.0460	2.60	0.114	0.0494	2.69	0.124	0.0538
2,200	3.09	0.154	0.0667	3.18	0.165	0.0716	3.29	0.180	0.0780
2,600	3.65	0.210	0.0909	3.75	0.225	0.0975	3.89	0.245	0.106
3,000	4.21	0.274	0.118	4.33	0.293	0.127	4.49	0.320	0.138
3,500	4.91	0.364	0.158	5.05	0.390	0.169	5.24	0.425	0.184
4,000	5.61	0.466	0.202	5.78	0.500	0.216	5.98	0.544	0.236
4,500	6.31	0.579	0.251	6.50	0.621	0.269	6.73	0.677	0.293
5,000	7.02	0.704	0.305	7.22	0.755	0.327	7.48	0.822	0.356
5,500	7.72	0.840	0.364	7.94	0.900	0.390	8.23	0.981	0.425
6,000	8.42	0.986	0.427	8.67	1.06	0.458	8.98	1.15	0.499
6,500	9.12	1.14	0.495	9.39	1.23	0.531	9.72	1.34	0.578
7,000	9.82	1.31	0.568	10.1	1.41	0.609	10.5	1.53	0.663

Notes:

1. Table is based on Equations 9.2 through 9.5, using $C = 150$.
2. Friction-loss values are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$, where:

   D_i = pipe inside diameter, in.
   D_o = pipe outside diameter, in.
   t_{min} = minimum wall thickness, in.

Table 9.4 Flow friction loss, ASTM D2241 and AWWA C905 IPS OD PVC pipe (*continued*)

18 in. IPS (ASTM D2241 and AWWA C905)						
Flow, gpm	DR 21 Pressure rated 200 psi			DR 17 Pressure rated 250 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
400	0.624	0.00853	0.00369	0.659	0.00971	0.00421
600	0.937	0.0181	0.00782	0.988	0.0206	0.00890
800	1.25	0.0307	0.0133	1.32	0.0350	0.0152
1,000	1.56	0.0465	0.0201	1.65	0.0529	0.0229
1,200	1.87	0.0651	0.0282	1.98	0.0741	0.0321
1,400	2.19	0.0866	0.0375	2.31	0.0986	0.0427
1,800	2.81	0.138	0.0597	2.96	0.157	0.0680
2,200	3.43	0.200	0.0865	3.62	0.228	0.0985
2,600	4.06	0.272	0.118	4.28	0.310	0.134
3,000	4.68	0.355	0.154	4.94	0.404	0.175
3,500	5.46	0.472	0.204	5.76	0.537	0.233
4,000	6.24	0.604	0.261	6.59	0.688	0.298
4,500	7.03	0.751	0.325	7.41	0.855	0.370
5,000	7.81	0.912	0.395	8.24	1.04	0.450
5,500	8.59	1.09	0.471	9.06	1.24	0.537
6,000	9.37	1.28	0.553	9.88	1.46	0.630
6,500	10.1	1.48	0.642	10.7	1.69	0.731
7,000	10.9	1.70	0.736	11.5	1.94	0.838

Table 9.4 Flow friction loss, ASTM D2241 and AWWA C905 IPS OD PVC pipe (*continued*)

20 in. IPS (ASTM D2241 and AWWA C905)									
Flow, gpm	DR 41 Pressure rated 100 psi			DR 32.5 Pressure rated 125 psi			DR 26 Pressure rated 160 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
500	0.568	0.00596	0.00258	0.585	0.00639	0.00277	0.606	0.00696	0.00301
800	0.909	0.0142	0.00616	0.936	0.0152	0.00660	0.969	0.0166	0.00719
1,100	1.25	0.0256	0.0111	1.29	0.0275	0.0119	1.33	0.0299	0.0130
1,400	1.59	0.0400	0.0173	1.64	0.0429	0.0186	1.70	0.0468	0.0202
1,700	1.93	0.0573	0.0248	1.99	0.0615	0.0266	2.06	0.0670	0.0290
2,000	2.27	0.0774	0.0335	2.34	0.0830	0.0360	2.42	0.0905	0.0392
2,500	2.84	0.117	0.0507	2.92	0.125	0.0543	3.03	0.137	0.0592
3,000	3.41	0.164	0.0710	3.51	0.176	0.0761	3.64	0.192	0.0829
3,500	3.98	0.218	0.0944	4.09	0.234	0.101	4.24	0.255	0.110
4,000	4.55	0.279	0.121	4.68	0.299	0.130	4.85	0.326	0.141
4,500	5.11	0.347	0.150	5.26	0.372	0.161	5.45	0.405	0.176
5,000	5.68	0.422	0.183	5.85	0.452	0.196	6.06	0.493	0.213
5,500	6.25	0.503	0.218	6.43	0.540	0.234	6.66	0.588	0.254
6,000	6.82	0.591	0.256	7.02	0.634	0.274	7.27	0.690	0.299
6,500	7.39	0.685	0.297	7.60	0.735	0.318	7.88	0.801	0.347
7,000	7.96	0.786	0.340	8.19	0.843	0.365	8.48	0.918	0.398
7,500	8.52	0.893	0.387	8.77	0.958	0.415	9.09	1.04	0.452
8,000	9.09	1.01	0.436	9.36	1.08	0.467	9.69	1.18	0.509

Notes:

1. Table is based on Equations 9.2 through 9.5, using C = 150.
2. Friction-loss values are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$, where:

    D_i = pipe inside diameter, in.
    D_o = pipe outside diameter, in.
    t_{min} = minimum wall thickness, in.

Table 9.4 Flow friction loss, ASTM D2241 and AWWA C905 IPS OD PVC pipe (*continued*)

20 in. IPS (ASTM D2241 and AWWA C905)						
Flow, gpm	DR 21 Pressure rated 200 psi			DR 17 Pressure rated 250 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
500	0.632	0.00772	0.00334	0.667	0.00879	0.00381
800	1.01	0.0184	0.00798	1.07	0.0210	0.00909
1,100	1.39	0.0332	0.0144	1.47	0.0378	0.0164
1,400	1.77	0.0519	0.0225	1.87	0.0591	0.0256
1,700	2.15	0.0743	0.0322	2.27	0.0846	0.0366
2,000	2.53	0.100	0.0435	2.67	0.114	0.0495
2,500	3.16	0.152	0.0657	3.34	0.173	0.0748
3,000	3.79	0.212	0.0920	4.00	0.242	0.105
3,500	4.43	0.283	0.122	4.67	0.322	0.139
4,000	5.06	0.362	0.157	5.34	0.412	0.178
4,500	5.69	0.450	0.195	6.00	0.512	0.222
5,000	6.32	0.547	0.237	6.67	0.623	0.270
5,500	6.96	0.652	0.282	7.34	0.743	0.322
6,000	7.59	0.766	0.332	8.00	0.872	0.378
6,500	8.22	0.888	0.385	8.67	1.01	0.438
7,000	8.85	1.02	0.441	9.34	1.16	0.502
7,500	9.48	1.16	0.501	10.0	1.32	0.571
8,000	10.1	1.30	0.565	10.7	1.49	0.643

Table 9.4 Flow friction loss, ASTM D2241 and AWWA C905 IPS OD PVC pipe (*continued*)

24 in. IPS (ASTM D2241 and AWWA C905)									
Flow, gpm	DR 41 Pressure rated 100 psi			DR 32.5 Pressure rated 125 psi			DR 26 Pressure rated 160 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
700	0.553	0.00458	0.00198	0.569	0.00491	0.00213	0.589	0.00535	0.00232
1,100	0.868	0.0106	0.00457	0.894	0.0113	0.00490	0.926	0.0123	0.00534
1,500	1.18	0.0187	0.00812	1.22	0.0201	0.00871	1.26	0.0219	0.00948
2,000	1.58	0.0319	0.0138	1.62	0.0342	0.0148	1.68	0.0373	0.0161
2,500	1.97	0.0482	0.0209	2.03	0.0517	0.0224	2.10	0.0563	0.0244
3,000	2.37	0.0676	0.0293	2.44	0.0725	0.0314	2.52	0.0790	0.0342
3,500	2.76	0.0899	0.0389	2.84	0.0964	0.0417	2.95	0.105	0.0455
4,000	3.16	0.115	0.0498	3.25	0.123	0.0534	3.37	0.134	0.0582
4,500	3.55	0.143	0.0620	3.66	0.153	0.0664	3.79	0.167	0.0724
5,000	3.95	0.174	0.0753	4.06	0.186	0.0807	4.21	0.203	0.0880
5,500	4.34	0.207	0.0898	4.47	0.222	0.0963	4.63	0.242	0.105
6,000	4.74	0.244	0.106	4.87	0.261	0.113	5.05	0.285	0.123
7,000	5.53	0.324	0.140	5.69	0.348	0.150	5.89	0.379	0.164
8,000	6.31	0.415	0.180	6.50	0.445	0.193	6.73	0.485	0.210
9,000	7.10	0.516	0.223	7.31	0.553	0.240	7.57	0.603	0.261
10,000	7.89	0.627	0.271	8.12	0.672	0.291	8.41	0.732	0.317
11,000	8.68	0.748	0.324	8.94	0.802	0.347	9.26	0.874	0.378
12,000	9.47	0.878	0.380	9.75	0.942	0.408	10.1	1.03	0.444

Notes:

1. Table is based on Equations 9.2 through 9.5, using C = 150.
2. Friction-loss values are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$, where:

   D_i = pipe inside diameter, in.
   D_o = pipe outside diameter, in.
   t_{min} = minimum wall thickness, in.

Table 9.4 Flow friction loss, ASTM D2241 and AWWA C905 IPS OD PVC pipe (*continued*)

24 in. IPS (ASTM D2241 and AWWA C905)						
Flow, gpm	DR 21 Pressure rated 200 psi			DR 17 Pressure rated 250 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
700	0.615	0.00593	0.00257	0.649	0.00676	0.00293
1,100	0.966	0.0137	0.00593	1.02	0.0156	0.00675
1,500	1.32	0.0243	0.0105	1.39	0.0277	0.0120
2,000	1.76	0.0414	0.0179	1.85	0.0471	0.0204
2,500	2.20	0.0625	0.0271	2.32	0.0712	0.0308
3,000	2.63	0.0876	0.0379	2.78	0.100	0.0432
3,500	3.07	0.116	0.0504	3.24	0.133	0.0575
4,000	3.51	0.149	0.0646	3.71	0.170	0.0736
4,500	3.95	0.185	0.0803	4.17	0.211	0.0915
5,000	4.39	0.225	0.0976	4.63	0.257	0.111
5,500	4.83	0.269	0.116	5.10	0.306	0.133
6,000	5.27	0.316	0.137	5.56	0.360	0.156
7,000	6.15	0.420	0.182	6.49	0.478	0.207
8,000	7.03	0.538	0.233	7.41	0.612	0.265
9,000	7.90	0.669	0.289	8.34	0.761	0.330
10,000	8.78	0.812	0.352	9.27	0.925	0.401
11,000	9.66	0.969	0.420	10.2	1.10	0.478
12,000	10.5	1.14	0.493	11.1	1.30	0.561

Table 9.4 Flow friction loss, ASTM D2241 and AWWA C905 IPS OD PVC pipe (*continued*)

30 in. IPS (ASTM D2241 and AWWA C905)									
Flow, gpm	DR 41 Pressure rated 100 psi			DR 32.5 Pressure rated 125 psi			DR 26 Pressure rated 160 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
1,000	0.505	0.00299	0.00130	0.520	0.00321	0.00139	0.539	0.00350	0.00151
1,500	0.758	0.00634	0.00274	0.780	0.00680	0.00294	0.808	0.00740	0.00321
2,000	1.01	0.0108	0.00467	1.04	0.0116	0.00501	1.08	0.0126	0.00546
2,500	1.26	0.0163	0.00706	1.30	0.0175	0.00757	1.35	0.0191	0.00825
3,000	1.52	0.0229	0.00989	1.56	0.0245	0.0106	1.62	0.0267	0.0116
3,800	1.92	0.0354	0.0153	1.98	0.0379	0.0164	2.05	0.0413	0.0179
4,600	2.32	0.0504	0.0218	2.39	0.0540	0.0234	2.48	0.0589	0.0255
5,400	2.73	0.0678	0.0294	2.81	0.0727	0.0315	2.91	0.0792	0.0343
6,200	3.13	0.0875	0.0379	3.22	0.0939	0.0406	3.34	0.102	0.0443
7,000	3.54	0.110	0.0474	3.64	0.117	0.0509	3.77	0.128	0.0554
8,500	4.29	0.157	0.0679	4.42	0.168	0.0729	4.58	0.183	0.0794
10,000	5.05	0.212	0.0918	5.20	0.227	0.0984	5.39	0.248	0.107
11,500	5.81	0.274	0.119	5.98	0.294	0.127	6.19	0.321	0.139
13,000	6.57	0.344	0.149	6.76	0.369	0.160	7.00	0.402	0.174
14,500	7.33	0.421	0.183	7.54	0.452	0.196	7.81	0.492	0.213
16,000	8.08	0.506	0.219	8.32	0.542	0.235	8.62	0.591	0.256
18,000	9.09	0.629	0.272	9.36	0.674	0.292	9.69	0.734	0.318
20,000	10.1	0.764	0.331	10.4	0.819	0.355	10.8	0.893	0.386

Notes:

1. Table is based on Equations 9.2 through 9.5, using C = 150.
2. Friction-loss values are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$,
   where:
   D_i = pipe inside diameter, in.
   D_o = pipe outside diameter, in.
   t_{min} = minimum wall thickness, in.

Table 9.4 Flow friction loss, ASTM D2241 and AWWA C905 IPS OD PVC pipe (*continued*)

30 in. IPS (ASTM D2241 and AWWA C905)						
Flow, gpm	DR 21 Pressure rated 200 psi			DR 17 Pressure rated 250 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
1,000	0.562	0.00388	0.00168	0.593	0.00442	0.00191
1,500	0.843	0.00821	0.00356	0.889	0.00936	0.00405
2,000	1.12	0.0140	0.00605	1.19	0.0159	0.00690
2,500	1.40	0.0211	0.00915	1.48	0.0241	0.0104
3,000	1.69	0.0296	0.0128	1.78	0.0337	0.0146
3,800	2.14	0.0458	0.0199	2.25	0.0522	0.0226
4,600	2.59	0.0653	0.0283	2.73	0.0744	0.0322
5,400	3.03	0.0878	0.0380	3.20	0.100	0.0433
6,200	3.48	0.113	0.0491	3.68	0.129	0.0559
7,000	3.93	0.142	0.0615	4.15	0.162	0.0700
8,500	4.78	0.203	0.0880	5.04	0.232	0.100
10,000	5.62	0.275	0.119	5.93	0.313	0.135
11,500	6.46	0.356	0.154	6.82	0.405	0.175
13,000	7.31	0.446	0.193	7.71	0.508	0.220
14,500	8.15	0.546	0.236	8.60	0.622	0.269
16,000	8.99	0.655	0.284	9.49	0.746	0.323
18,000	10.1	0.815	0.353	10.7	0.928	0.402
20,000	11.2	0.990	0.429	11.9	1.13	0.488

Table 9.4 Flow friction loss, ASTM D2241 and AWWA C905 IPS OD PVC pipe (*continued*)

36 in. IPS (ASTM D2241 and AWWA C905)									
Flow, gpm	DR 41 Pressure rated 100 psi			DR 32.5 Pressure rated 125 psi			DR 26 Pressure rated 160 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
1,500	0.526	0.00261	0.00113	0.542	0.00280	0.00121	0.561	0.00305	0.00132
2,000	0.702	0.00445	0.00193	0.722	0.00477	0.00207	0.748	0.00520	0.00225
2,500	0.877	0.00672	0.00291	0.903	0.00721	0.00312	0.935	0.00785	0.00340
3,000	1.05	0.00942	0.00408	1.08	0.0101	0.00437	1.12	0.0110	0.00476
4,000	1.40	0.0160	0.00695	1.44	0.0172	0.00745	1.50	0.0187	0.00811
5,000	1.75	0.0242	0.0105	1.81	0.0260	0.0113	1.87	0.0283	0.0123
6,000	2.10	0.0340	0.0147	2.17	0.0364	0.0158	2.24	0.0397	0.0172
7,000	2.46	0.0452	0.0196	2.53	0.0484	0.0210	2.62	0.0528	0.0228
8,000	2.81	0.0578	0.0250	2.89	0.0620	0.0269	2.99	0.0675	0.0292
9,000	3.16	0.0719	0.0311	3.25	0.0771	0.0334	3.37	0.0840	0.0364
10,000	3.51	0.0874	0.0378	3.61	0.0937	0.0406	3.74	0.102	0.0442
12,000	4.21	0.122	0.0530	4.33	0.131	0.0568	4.49	0.143	0.0619
14,000	4.91	0.163	0.0705	5.05	0.175	0.0756	5.24	0.190	0.0824
16,000	5.61	0.208	0.0903	5.78	0.224	0.0968	5.98	0.244	0.105
18,000	6.31	0.259	0.112	6.50	0.278	0.120	6.73	0.303	0.131
20,000	7.02	0.315	0.136	7.22	0.338	0.146	7.48	0.368	0.159
24,000	8.42	0.441	0.191	8.67	0.473	0.205	8.98	0.516	0.223
28,000	9.82	0.587	0.254	10.1	0.629	0.273	10.5	0.686	0.297

Notes:

1. Table is based on Equations 9.2 through 9.5, using C = 150.
2. Friction-loss values are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$, where:

   D_i = pipe inside diameter, in.
   D_o = pipe outside diameter, in.
   t_{min} = minimum wall thickness, in.

Table 9.4 Flow friction loss, ASTM D2241 and AWWA C905 IPS OD PVC pipe (*continued*)

36 in. IPS (ASTM D2241 and AWWA C905)						
Flow, gpm	DR 21 Pressure rated 200 psi			DR 17 Pressure rated 250 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
1,500	0.585	0.00339	0.00147	0.618	0.00386	0.00167
2,000	0.781	0.00577	0.00250	0.824	0.00657	0.00284
2,500	0.976	0.00871	0.00377	1.03	0.00992	0.00430
3,000	1.17	0.0122	0.00529	1.24	0.0139	0.00602
4,000	1.56	0.0208	0.00900	1.65	0.0237	0.0103
5,000	1.95	0.0314	0.0136	2.06	0.0358	0.0155
6,000	2.34	0.0440	0.0191	2.47	0.0501	0.0217
7,000	2.73	0.0585	0.0253	2.88	0.0667	0.0289
8,000	3.12	0.0749	0.0324	3.29	0.0854	0.0370
9,000	3.51	0.0932	0.0403	3.71	0.106	0.0460
10,000	3.90	0.113	0.0490	4.12	0.129	0.0558
12,000	4.68	0.159	0.0687	4.94	0.181	0.0782
14,000	5.46	0.211	0.0914	5.76	0.240	0.104
16,000	6.24	0.270	0.117	6.59	0.308	0.133
18,000	7.03	0.336	0.145	7.41	0.383	0.166
20,000	7.81	0.408	0.177	8.24	0.465	0.201
24,000	9.37	0.572	0.248	9.88	0.651	0.282
28,000	10.9	0.761	0.329	11.5	0.866	0.375

Table 9.5 Flow friction loss, ASTM D2241 PIP PVC pipe

6 in. PIP (ASTM D2241)									
Flow, gpm	DR 51 Pressure rated 80 psi			DR 41 Pressure rated 100 psi			DR 32.5 Pressure rated 125 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
50	0.590	0.0248	0.0108	0.603	0.0262	0.0113	0.621	0.0281	0.0121
75	0.885	0.0526	0.0228	0.905	0.0554	0.0240	0.931	0.0594	0.0257
100	1.18	0.0896	0.0388	1.21	0.0943	0.0408	1.24	0.101	0.0438
125	1.48	0.135	0.0586	1.51	0.143	0.0617	1.55	0.153	0.0662
150	1.77	0.190	0.0821	1.81	0.200	0.0865	1.86	0.214	0.0927
175	2.07	0.252	0.109	2.11	0.266	0.115	2.17	0.285	0.123
200	2.36	0.323	0.140	2.41	0.340	0.147	2.48	0.365	0.158
225	2.66	0.401	0.174	2.71	0.423	0.183	2.79	0.453	0.196
250	2.95	0.488	0.211	3.02	0.514	0.222	3.10	0.551	0.239
300	3.54	0.684	0.296	3.62	0.720	0.312	3.72	0.772	0.334
350	4.13	0.909	0.394	4.22	0.957	0.415	4.34	1.03	0.445
400	4.72	1.16	0.504	4.82	1.23	0.531	4.96	1.31	0.569
450	5.31	1.45	0.627	5.43	1.52	0.660	5.59	1.63	0.708
500	5.90	1.76	0.762	6.03	1.85	0.802	6.21	1.99	0.860
600	7.08	2.46	1.07	7.24	2.59	1.12	7.45	2.78	1.20
700	8.26	3.28	1.42	8.44	3.45	1.49	8.69	3.70	1.60
800	9.45	4.20	1.82	9.65	4.42	1.91	9.93	4.74	2.05
900	10.6	5.22	2.26	10.9	5.49	2.38	11.2	5.89	2.55

Notes:

1. Table is based on Equations 9.2 through 9.5, using C = 150.
2. Friction-loss values are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$,
   where:
   D_i = pipe inside diameter, in.
   D_o = pipe outside diameter, in.
   t_{min} = minimum wall thickness, in.

Table 9.5 Flow friction loss, ASTM D2241 PIP PVC pipe (*continued*)

8 in. PIP (ASTM D2241)									
Flow, gpm	DR 51 Pressure rated 80 psi			DR 41 Pressure rated 100 psi			DR 32.5 Pressure rated 125 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
75	0.501	0.0132	0.00572	0.512	0.0139	0.00602	0.527	0.0149	0.00646
100	0.668	0.0225	0.00973	0.683	0.0237	0.0103	0.703	0.0254	0.0110
125	0.836	0.0340	0.0147	0.854	0.0358	0.0155	0.878	0.0384	0.0166
150	1.00	0.0476	0.0206	1.02	0.0501	0.0217	1.05	0.0537	0.0233
200	1.34	0.0810	0.0351	1.37	0.0853	0.0370	1.41	0.0915	0.0396
250	1.67	0.122	0.0530	1.71	0.129	0.0558	1.76	0.138	0.0599
300	2.01	0.172	0.0743	2.05	0.181	0.0782	2.11	0.194	0.0839
350	2.34	0.228	0.0988	2.39	0.240	0.104	2.46	0.258	0.112
400	2.67	0.292	0.127	2.73	0.308	0.133	2.81	0.330	0.143
500	3.34	0.441	0.191	3.41	0.465	0.201	3.51	0.498	0.216
600	4.01	0.619	0.268	4.10	0.651	0.282	4.22	0.698	0.302
700	4.68	0.823	0.356	4.78	0.866	0.375	4.92	0.929	0.402
800	5.35	1.05	0.456	5.46	1.11	0.480	5.62	1.19	0.515
900	6.02	1.31	0.567	6.15	1.38	0.597	6.32	1.48	0.640
1,000	6.68	1.59	0.689	6.83	1.68	0.726	7.03	1.80	0.778
1,200	8.02	2.23	0.966	8.19	2.35	1.02	8.43	2.52	1.09
1,400	9.36	2.97	1.28	9.56	3.12	1.35	9.84	3.35	1.45
1,600	10.7	3.80	1.64	10.9	4.00	1.73	11.2	4.29	1.86

Table 9.5 Flow friction loss, ASTM D2241 PIP PVC pipe (*continued*)

10 in. PIP (ASTM D2241)									
Flow, gpm	DR 51 Pressure rated 80 psi			DR 41 Pressure rated 100 psi			DR 32.5 Pressure rated 125 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
125	0.535	0.0115	0.00497	0.546	0.0121	0.00524	0.562	0.0130	0.00561
150	0.642	0.0161	0.00697	0.656	0.0169	0.00734	0.675	0.0182	0.00787
175	0.749	0.0214	0.00927	0.765	0.0225	0.00976	0.787	0.0242	0.0105
200	0.856	0.0274	0.0119	0.874	0.0289	0.0125	0.899	0.0309	0.0134
250	1.07	0.0414	0.0179	1.09	0.0436	0.0189	1.12	0.0467	0.0202
300	1.28	0.0580	0.0251	1.31	0.0611	0.0264	1.35	0.0655	0.0284
350	1.50	0.0772	0.0334	1.53	0.0812	0.0352	1.57	0.0871	0.0377
400	1.71	0.0988	0.0428	1.75	0.104	0.0450	1.80	0.112	0.0483
500	2.14	0.149	0.0646	2.19	0.157	0.0681	2.25	0.169	0.0730
600	2.57	0.209	0.0905	2.62	0.220	0.0954	2.70	0.236	0.102
700	2.99	0.278	0.120	3.06	0.293	0.127	3.15	0.314	0.136
800	3.42	0.356	0.154	3.50	0.375	0.162	3.60	0.402	0.174
1,100	4.71	0.642	0.278	4.81	0.676	0.293	4.95	0.725	0.314
1,400	5.99	1.00	0.434	6.12	1.06	0.457	6.30	1.13	0.490
1,700	7.27	1.44	0.622	7.43	1.51	0.655	7.65	1.62	0.702
2,000	8.56	1.94	0.840	8.74	2.04	0.884	8.99	2.19	0.948
2,300	9.84	2.51	1.09	10.1	2.65	1.15	10.3	2.84	1.23
2,600	11.1	3.15	1.36	11.4	3.32	1.44	11.7	3.56	1.54

Notes:

1. Table is based on Equations 9.2 through 9.5, using C = 150.
2. Friction-loss values are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$, where:

D_i = pipe inside diameter, in.
D_o = pipe outside diameter, in.
t_{min} = minimum wall thickness, in.

Table 9.5 Flow friction loss, ASTM D2241 PIP PVC pipe (*continued*)

12 in. PIP (ASTM D2241)									
Flow, gpm	DR 51 Pressure rated 80 psi			DR 41 Pressure rated 100 psi			DR 32.5 Pressure rated 125 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
200	0.594	0.0113	0.00489	0.607	0.0119	0.00515	0.625	0.0128	0.00552
300	0.891	0.0239	0.0104	0.910	0.0252	0.0109	0.937	0.0270	0.0117
400	1.19	0.0407	0.0176	1.21	0.0429	0.0186	1.25	0.0460	0.0199
500	1.49	0.0615	0.0266	1.52	0.0648	0.0281	1.56	0.0695	0.0301
600	1.78	0.0862	0.0373	1.82	0.0908	0.0393	1.87	0.0973	0.0422
700	2.08	0.115	0.0496	2.12	0.121	0.0523	2.19	0.129	0.0561
800	2.38	0.147	0.0636	2.43	0.155	0.0669	2.50	0.166	0.0718
1,000	2.97	0.222	0.0960	3.03	0.234	0.101	3.12	0.250	0.108
1,200	3.57	0.311	0.135	3.64	0.327	0.142	3.75	0.351	0.152
1,400	4.16	0.413	0.179	4.25	0.435	0.188	4.37	0.467	0.202
1,700	5.05	0.592	0.256	5.16	0.623	0.270	5.31	0.668	0.289
2,000	5.94	0.800	0.346	6.07	0.842	0.365	6.25	0.903	0.391
2,300	6.83	1.04	0.448	6.98	1.09	0.472	7.18	1.17	0.506
2,600	7.72	1.30	0.563	7.89	1.37	0.592	8.12	1.47	0.635
2,900	8.62	1.59	0.689	8.80	1.67	0.725	9.06	1.80	0.777
3,200	9.51	1.91	0.826	9.71	2.01	0.870	10.0	2.15	0.933
3,500	10.4	2.25	0.975	10.6	2.37	1.03	10.9	2.54	1.10
3,800	11.3	2.62	1.14	11.5	2.76	1.20	11.9	2.96	1.28

Table 9.5 Flow friction loss, ASTM D2241 PIP PVC pipe (*continued*)

15 in. PIP (ASTM D2241)									
Flow, gpm	DR 51 Pressure rated 80 psi			DR 41 Pressure rated 100 psi			DR 32.5 Pressure rated 125 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
300	0.570	0.00809	0.00350	0.583	0.00851	0.00369	0.600	0.00913	0.00395
450	0.856	0.0171	0.00741	0.874	0.0180	0.00781	0.899	0.0193	0.00837
600	1.14	0.0291	0.0126	1.17	0.0307	0.0133	1.20	0.0329	0.0143
800	1.52	0.0496	0.0215	1.55	0.0523	0.0226	1.60	0.0560	0.0243
1,000	1.90	0.0750	0.0325	1.94	0.0790	0.0342	2.00	0.0847	0.0367
1,200	2.28	0.105	0.0455	2.33	0.111	0.0479	2.40	0.119	0.0514
1,500	2.85	0.159	0.0687	2.91	0.167	0.0724	3.00	0.179	0.0776
1,800	3.42	0.222	0.0963	3.50	0.234	0.101	3.60	0.251	0.109
2,100	3.99	0.296	0.128	4.08	0.312	0.135	4.20	0.334	0.145
2,400	4.56	0.379	0.164	4.66	0.399	0.173	4.80	0.428	0.185
2,800	5.32	0.504	0.218	5.44	0.531	0.230	5.60	0.569	0.246
3,200	6.08	0.645	0.279	6.22	0.679	0.294	6.40	0.728	0.315
3,600	6.85	0.802	0.347	6.99	0.845	0.366	7.20	0.906	0.392
4,000	7.61	0.975	0.422	7.77	1.03	0.444	8.00	1.10	0.477
4,400	8.37	1.16	0.503	8.55	1.22	0.530	8.80	1.31	0.568
4,800	9.13	1.37	0.591	9.32	1.44	0.623	9.59	1.54	0.668
5,200	9.89	1.58	0.686	10.1	1.67	0.722	10.4	1.79	0.774
5,600	10.6	1.82	0.786	10.9	1.91	0.828	11.2	2.05	0.888

Notes:

1. Table is based on Equations 9.2 through 9.5, using C = 150.
2. Friction-loss values are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$, where:

   D_i = pipe inside diameter, in.
   D_o = pipe outside diameter, in.
   t_{min} = minimum wall thickness, in.

Table 9.5 Flow friction loss, ASTM D2241 PIP PVC pipe (*continued*)

15 in. PIP (ASTM D2241)						
Flow, gpm	DR 26 Pressure rated 160 psi			DR 21 Pressure rated 200 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
300	0.621	0.00994	0.00431	0.648	0.0110	0.00478
450	0.932	0.0211	0.00912	0.972	0.0234	0.0101
600	1.24	0.0359	0.0155	1.30	0.0398	0.0172
800	1.66	0.0610	0.0264	1.73	0.0677	0.0293
1,000	2.07	0.0922	0.0399	2.16	0.102	0.0443
1,200	2.48	0.129	0.0560	2.59	0.143	0.0621
1,500	3.11	0.195	0.0846	3.24	0.217	0.0938
1,800	3.73	0.274	0.118	3.89	0.304	0.131
2,000	4.14	0.333	0.144	4.32	0.369	0.160
2,400	4.97	0.466	0.202	5.19	0.517	0.224
2,800	5.80	0.620	0.268	6.05	0.687	0.298
3,200	6.63	0.793	0.344	6.91	0.880	0.381
3,600	7.45	0.986	0.427	7.78	1.09	0.474
4,000	8.28	1.20	0.519	8.64	1.33	0.576
4,400	9.11	1.43	0.619	9.51	1.59	0.687
4,800	9.94	1.68	0.727	10.4	1.86	0.807
5,200	10.8	1.95	0.843	11.2	2.16	0.936
5,600	11.6	2.23	0.967	12.1	2.48	1.07

Table 9.5 Flow friction loss, ASTM D2241 PIP PVC pipe (*continued*)

18 in. PIP (ASTM D2241)									
Flow, gpm	DR 51 Pressure rated 80 psi			DR 41 Pressure rated 100 psi			DR 32.5 Pressure rated 125 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
400	0.509	0.00519	0.00225	0.520	0.00547	0.00237	0.535	0.00586	0.00254
700	0.891	0.0146	0.00633	0.910	0.0154	0.00666	0.937	0.0165	0.00715
1,000	1.27	0.0283	0.0122	1.30	0.0298	0.0129	1.34	0.0319	0.0138
1,300	1.65	0.0459	0.0199	1.69	0.0484	0.0209	1.74	0.0519	0.0225
1,700	2.16	0.0755	0.0327	2.21	0.0795	0.0344	2.27	0.0852	0.0369
2,100	2.67	0.112	0.0483	2.73	0.117	0.0509	2.81	0.126	0.0545
2,500	3.18	0.154	0.0667	3.25	0.162	0.0702	3.34	0.174	0.0753
3,000	3.82	0.216	0.0934	3.90	0.227	0.0984	4.01	0.244	0.106
3,500	4.45	0.287	0.124	4.55	0.302	0.131	4.68	0.324	0.140
4,000	5.09	0.367	0.159	5.20	0.387	0.168	5.35	0.415	0.180
4,500	5.73	0.457	0.198	5.85	0.481	0.208	6.02	0.516	0.223
5,000	6.36	0.555	0.240	6.50	0.585	0.253	6.69	0.627	0.271
5,500	7.00	0.662	0.287	7.15	0.697	0.302	7.36	0.748	0.324
6,000	7.64	0.778	0.337	7.80	0.819	0.355	8.03	0.878	0.380
6,600	8.40	0.928	0.402	8.58	0.977	0.423	8.83	1.05	0.454
7,200	9.16	1.09	0.472	9.36	1.15	0.497	9.63	1.23	0.533
7,800	9.93	1.26	0.547	10.1	1.33	0.576	10.4	1.43	0.618
8,400	10.7	1.45	0.628	10.9	1.53	0.661	11.2	1.64	0.709

Notes:

1. Table is based on Equations 9.2 through 9.5, using C = 150.
2. Friction-loss values are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$,
   where:
   D_i = pipe inside diameter, in.
   D_o = pipe outside diameter, in.
   t_{min} = minimum wall thickness, in.

Table 9.5 Flow friction loss, ASTM D2241 PIP PVC pipe (*continued*)

18 in. PIP (ASTM D2241)			
Flow, gpm	DR 26 Pressure rated 160 psi		
	Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft
400	0.554	0.00638	0.00276
700	0.970	0.0180	0.00778
1,000	1.39	0.0348	0.0151
1,300	1.80	0.0565	0.0245
1,700	2.36	0.0928	0.0402
2,100	2.91	0.137	0.0594
2,500	3.46	0.189	0.0820
3,000	4.16	0.265	0.115
3,500	4.85	0.353	0.153
4,000	5.54	0.452	0.196
4,500	6.24	0.562	0.243
5,000	6.93	0.683	0.296
5,500	7.62	0.815	0.353
6,000	8.32	0.957	0.414
6,600	9.15	1.14	0.494
7,200	9.98	1.34	0.581
7,800	10.8	1.55	0.673
8,400	11.6	1.78	0.772

Table 9.5 Flow friction loss, ASTM D2241 PIP PVC pipe (*continued*)

21 in. PIP (ASTM D2241)									
Flow, gpm	DR 51 Pressure rated 80 psi			DR 41 Pressure rated 100 psi			DR 32.5 Pressure rated 125 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
600	0.549	0.00494	0.00214	0.561	0.00520	0.00225	0.578	0.00558	0.00241
1,000	0.916	0.0127	0.00550	0.935	0.0134	0.00579	0.963	0.0143	0.00621
1,500	1.37	0.0269	0.0116	1.40	0.0283	0.0123	1.44	0.0304	0.0132
2,000	1.83	0.0458	0.0198	1.87	0.0482	0.0209	1.93	0.0517	0.0224
2,500	2.29	0.0692	0.0300	2.34	0.0729	0.0316	2.41	0.0781	0.0338
3,000	2.75	0.0970	0.0420	2.81	0.102	0.0442	2.89	0.109	0.0474
3,500	3.20	0.129	0.0558	3.27	0.136	0.0588	3.37	0.146	0.0631
4,000	3.66	0.165	0.0715	3.74	0.174	0.0753	3.85	0.186	0.0807
4,500	4.12	0.205	0.0889	4.21	0.216	0.0936	4.33	0.232	0.100
5,000	4.58	0.249	0.108	4.68	0.263	0.114	4.81	0.282	0.122
5,800	5.31	0.328	0.142	5.43	0.346	0.150	5.58	0.371	0.161
6,600	6.04	0.417	0.181	6.17	0.439	0.190	6.35	0.471	0.204
7,400	6.78	0.515	0.223	6.92	0.543	0.235	7.12	0.582	0.252
8,200	7.51	0.623	0.270	7.67	0.656	0.284	7.89	0.703	0.305
9,000	8.24	0.740	0.320	8.42	0.779	0.337	8.66	0.836	0.362
10,000	9.16	0.899	0.389	9.35	0.947	0.410	9.63	1.02	0.440
11,000	10.1	1.07	0.465	10.3	1.13	0.489	10.6	1.21	0.525
12,000	11.0	1.26	0.546	11.2	1.33	0.575	11.6	1.42	0.616

Notes:

1. Table is based on Equations 9.2 through 9.5, using $C = 150$.
2. Friction-loss values are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$, where:

    D_i = pipe inside diameter, in.
    D_o = pipe outside diameter, in.
    t_{min} = minimum wall thickness, in.

Table 9.5 Flow friction loss, ASTM D2241 PIP PVC pipe (*continued*)

21 in. PIP (ASTM D2241)			
Flow, gpm	DR 26 Pressure rated 160 psi		
	Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft
600	0.598	0.00607	0.00263
1,000	1.00	0.0156	0.00677
1,500	1.50	0.0331	0.0143
2,000	1.99	0.0563	0.0244
2,500	2.49	0.0851	0.0369
3,000	2.99	0.119	0.0516
3,500	3.49	0.159	0.0687
4,000	3.99	0.203	0.0879
4,500	4.49	0.253	0.109
5,000	4.99	0.307	0.133
5,800	5.78	0.404	0.175
6,600	6.58	0.513	0.222
7,400	7.38	0.634	0.274
8,200	8.18	0.766	0.332
9,000	8.97	0.910	0.394
10,000	10.0	1.11	0.479
11,000	11.0	1.32	0.571
12,000	12.0	1.55	0.671

Table 9.5 Flow friction loss, ASTM D2241 PIP PVC pipe (*continued*)

24 in. PIP (ASTM D2241)									
Flow, gpm	DR 51 Pressure rated 80 psi			DR 41 Pressure rated 100 psi			DR 32.5 Pressure rated 125 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
800	0.579	0.00474	0.00205	0.591	0.00499	0.00216	0.608	0.00536	0.00232
1,200	0.868	0.0100	0.00435	0.887	0.0106	0.00458	0.913	0.0113	0.00491
1,600	1.16	0.0171	0.00740	1.18	0.0180	0.00780	1.22	0.0193	0.00836
2,000	1.45	0.0258	0.0112	1.48	0.0272	0.0118	1.52	0.0292	0.0126
2,500	1.81	0.0390	0.0169	1.85	0.0411	0.0178	1.90	0.0441	0.0191
3,000	2.17	0.0547	0.0237	2.22	0.0576	0.0249	2.28	0.0618	0.0267
4,000	2.89	0.0931	0.0403	2.96	0.0981	0.0425	3.04	0.105	0.0455
5,000	3.62	0.141	0.0609	3.70	0.148	0.0642	3.80	0.159	0.0688
6,000	4.34	0.197	0.0854	4.43	0.208	0.0899	4.56	0.223	0.0964
7,000	5.06	0.262	0.114	5.17	0.276	0.120	5.32	0.296	0.128
8,000	5.79	0.336	0.145	5.91	0.354	0.153	6.08	0.379	0.164
9,000	6.51	0.418	0.181	6.65	0.440	0.190	6.85	0.471	0.204
10,000	7.24	0.507	0.220	7.39	0.534	0.231	7.61	0.573	0.248
11,000	7.96	0.605	0.262	8.13	0.637	0.276	8.37	0.683	0.296
12,000	8.68	0.711	0.308	8.87	0.749	0.324	9.13	0.803	0.348
13,000	9.41	0.824	0.357	9.61	0.868	0.376	9.89	0.931	0.403
14,000	10.1	0.945	0.409	10.3	1.00	0.431	10.6	1.07	0.462
15,000	10.9	1.07	0.465	11.1	1.13	0.490	11.4	1.21	0.525

Notes:

1. Table is based on Equations 9.2 through 9.5, using C = 150.
2. Friction-loss values are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$, where:

D_i = pipe inside diameter, in.
D_o = pipe outside diameter, in.
t_{min} = minimum wall thickness, in.

Table 9.5 Flow friction loss, ASTM D2241 PIP PVC pipe (*continued*)

24 in. PIP (ASTM D2241)			
Flow, gpm	DR 26 Pressure rated 160 psi		
	Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft
800	0.630	0.00583	0.00253
1,200	0.945	0.0124	0.00535
16,000	12.61	1.4888	0.64467
16,400	12.92	1.5584	0.6748
16,900	13.31	1.6475	0.7134
17,400	13.71	1.7388	0.7529
18,400	14.50	1.928	0.8349
19,400	15.28	2.126	0.9208
20,400	16.07	2.334	1.010
21,400	16.86	2.550	1.104
22,400	17.65	2.775	1.201
23,400	18.44	3.008	1.302
24,400	19.22	3.250	1.407
25,400	20.01	3.501	1.516
26,400	20.80	3.760	1.628
27,400	21.6	4.03	1.744
28,400	22.4	4.30	1.864
29,400	23.2	4.59	1.987

Table 9.5 Flow friction loss, ASTM D2241 PIP PVC pipe (*continued*)

27 in. PIP (ASTM D2241)									
Flow, gpm	DR 51 Pressure rated 80 psi			DR 41 Pressure rated 100 psi			DR 32.5 Pressure rated 125 psi		
	Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop		Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft		ft H_2O/100 ft	psi/100 ft
1,000	0.570	0.00401	0.00174	0.582	0.00422	0.00183	0.599	0.00453	0.00196
1,500	0.854	0.00849	0.00367	0.873	0.00894	0.00387	0.898	0.00958	0.00415
2,000	1.14	0.0145	0.00626	1.16	0.0152	0.00659	1.20	0.0163	0.00707
2,500	1.42	0.0218	0.00945	1.45	0.0230	0.0100	1.50	0.0247	0.0107
3,000	1.71	0.0306	0.0132	1.75	0.0322	0.0140	1.80	0.0345	0.0150
3,500	1.99	0.0407	0.0176	2.04	0.0428	0.0186	2.10	0.0459	0.0199
4,000	2.28	0.0521	0.0226	2.33	0.0549	0.0238	2.40	0.0588	0.0255
5,000	2.85	0.0787	0.0341	2.91	0.0829	0.0359	2.99	0.0889	0.0385
6,000	3.42	0.110	0.0478	3.49	0.116	0.0503	3.59	0.125	0.0539
7,000	3.99	0.147	0.0635	4.07	0.154	0.0669	4.19	0.166	0.0717
8,000	4.56	0.188	0.0813	4.66	0.198	0.0856	4.79	0.212	0.0918
9,000	5.13	0.234	0.101	5.24	0.246	0.106	5.39	0.264	0.114
10,000	5.70	0.284	0.123	5.82	0.299	0.129	5.99	0.320	0.139
11,000	6.27	0.338	0.147	6.40	0.356	0.154	6.59	0.382	0.165
12,000	6.84	0.398	0.172	6.98	0.419	0.181	7.19	0.449	0.194
14,000	7.97	0.529	0.229	8.15	0.557	0.241	8.38	0.597	0.259
16,000	9.11	0.677	0.293	9.31	0.713	0.309	9.58	0.764	0.331
18,000	10.3	0.842	0.365	10.5	0.886	0.384	10.8	0.951	0.412

Notes:

1. Table is based on Equations 9.2 through 9.5, using C = 150.
2. Friction-loss values are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$, where:

    D_i = pipe inside diameter, in.
    D_o = pipe outside diameter, in.
    t_{min} = minimum wall thickness, in.

Table 9.5 Flow friction loss, ASTM D2241 PIP PVC pipe (*continued*)

27 in. PIP (ASTM D2241)

Flow, gpm	DR 26 Pressure rated 160 psi		
	Velocity, ft/s	Pressure drop	
		ft H_2O/100 ft	psi/100 ft
1,000	0.620	0.00493	0.00213
1,500	0.930	0.0104	0.00452
2,000	1.24	0.0178	0.00770
2,500	1.55	0.0269	0.0116
3,000	1.86	0.0376	0.0163
3,500	2.17	0.0500	0.0217
4,000	2.48	0.0641	0.0277
5,000	3.10	0.0968	0.0419
6,000	3.72	0.136	0.0587
7,000	4.34	0.180	0.0781
8,000	4.96	0.231	0.100
9,000	5.58	0.287	0.124
10,000	6.20	0.349	0.151
11,000	6.82	0.416	0.180
12,000	7.44	0.489	0.212
14,000	8.68	0.650	0.282
16,000	9.92	0.833	0.361
18,000	11.2	1.04	0.448

9.4 Flow in PVC Nonpressure Pipe

Hydraulic flow research has shown that flow conditions in PVC gravity sewer pipes can be designed conservatively using *Manning's formula*. Although *Kutter's formula* had been used since the early 1900s for open-channel flow, the equation was unwieldy and difficult to use. Due to its relative simplicity, Manning's formula has become the preferred design method.

Equation 9.13

Kutter's formula

$$V = \left[\frac{\frac{1.81}{n} + 41.67 + \frac{0.0028}{S_E}}{1 + \frac{n}{\sqrt{R_H}}\left(41.67 + \frac{0.0028}{S_E}\right)} \right] \sqrt{R_H S_E}$$

where:

V = mean flow velocity, ft/s
R_H = hydraulic radius, ft (see section 9.2.2) = $D_i/4$
n = coefficient of roughness, dimensionless
S_E = slope of energy grade line, ft/ft

Like water, sewage will seek its own level when introduced into a pipe with a sloping invert, which induces movement of the sewage (this movement is known as "gravity flow"). For simplification in solving the problem of sewer design, it is necessary to assume "steady" flow conditions even though most sewers operate with constantly fluctuating flow rate. Also, as long as the surface of the sewage is permitted to expand or contract, it is considered "open channel" flow. If open channel flow is not the condition, then a sewer is said to be "flowing full under head" or "flowing full under internal pressure."

Manning's equation is based on the above assumptions of steady flow and open channel flow for computing discharge of a sewer line. In this equation, the coefficient of roughness (n) is determined by research and analysis; it represents the interior surface characteristics of the pipe. The coefficient of roughness (often called "Manning's n factor") helps determine frictional losses in Manning's equation: the greater the losses, the higher the value of "n".

Equation 9.14

Manning's equation

$$V = \frac{1.486}{n} R_H{}^{2/3} s^{1/2}$$

where:

V = mean flow velocity, ft/s
n = coefficient of roughness, dimensionless
R_H = hydraulic radius, ft
s = hydraulic slope, ft/ft = $(H_1 - H_2)/L$
L = pipe length, ft
H_1 = upstream pipe elevation, ft
H_2 = downstream pipe elevation, ft

Slope (s) is equal in most cases to slope of the invert and slope of the flowing surface.

The value for "n" has been experimentally determined for all common sewer piping materials. The value can be as low as 0.007 under laboratory conditions, in which clean water is used, or higher than 0.015 under less favorable conditions and with rough-surfaced pipe. Historically, most engineers have selected roughness coefficient "n" to be 0.013 for all sewer products that were available before the advent of PVC sewer pipe.

There is no basis for using a single-value approach for "n." Such an approach fails to recognize the sizeable variation in "n" values for different pipe materials in sewers operating at or near a flow velocity of 2 ft/s. Both laboratory research and field studies support the variability of "n" values as a function of pipe material, number of joints, and close tolerance quality of each joint.

The most prevalent error made with respect to minimum slope criteria occurs as a result of using an average flow velocity calculated from a wide range of velocity measurements. Use of an average value is not recommended because "n" values vary with flow conditions:

- High flow velocities—As velocities increase, the associated "n" value will decrease because high velocities will keep solids suspended and will minimize slime growth.
- Low flow velocities—As velocities decrease, solids will settle and slime will become thicker and more irregular.

This means that the parameters used for determining minimum slopes for sewers should be based on data obtained under similar velocity conditions, i.e., flow velocities no greater than 2.5 ft/s.

No published technical study has ever reported an "n" value as high as 0.013 for a PVC sewer pipeline operating at the recommended minimum velocities, either in-service or in the laboratory. Studies in the laboratory, and more importantly, in actual use, have found the value of "n" for PVC to range from 0.007 to 0.011. These relatively low values can be attributed to:

- the nonporous, smooth surface of PVC pipe;
- the low profile gap at the joints;
- the longer laying lengths available in PVC pipe, resulting in fewer joints;
- the chemical and abrasion resistance of PVC.

PVC pipe's long lengths result in fewer joints than are necessary for competitive products. This causes reduced friction losses for PVC pipe and a lower value for the coefficient of roughness "n". The Uni-Bell PVC Pipe Association recommends the use of Manning's "n" = 0.009 for hydraulic design of PVC sewer pipe.

The following example demonstrates how Manning's equation is used in the design of a PVC gravity sewer system.

Example 9.1

Calculate the velocity and quantity of flow for 8-in. PVC sewer pipe (ASTM D3034 DR 35) flowing half-full with an invert slope of 4 ft per 1,000 ft.

Solution:

Data from the given information and the product dimensions found in ASTM D3034 SDR 35:

$$D_o = 8.400 \text{ in.}, \qquad t = 0.240 \text{ in.}$$

$$D_i = D_o - 2t(1.06) = 7.891 \text{ in.}$$

$$D_i = \frac{7.891 \text{ in.}}{12} = 0.658 \text{ ft}$$

Solving both ways:

$$\text{Full pipe cross-sectional area} = \frac{\pi D_i^2}{4}$$

$$\text{Half-full pipe cross-sectional area} = \frac{1}{2}\left(\frac{\pi D_i^2}{4}\right)$$

Wetted perimeter = πD_i for full flow, ½ πD_i for half-full flow.

$$R_H = \frac{D_i}{4} = \frac{0.658\,\text{ft}}{4} = 0.165\,\text{ft}, \qquad s = \frac{4\text{ ft}}{1{,}000\text{ ft}} = 0.004, \qquad n = 0.009 \text{ for PVC pipe,}$$

$$V = \frac{1.486}{0.009}(0.165^{2/3})(0.004^{1/2}) = 165.1(0.301)(0.063) = 3.1 \text{ ft/s velocity.}$$

Next, the calculation of volume flow rate:

Equation 9.15

$$Q = VA$$

where:

Q = volume flow rate, ft^3/s
V = mean flow velocity, ft/s
A = cross sectional area of flow, ft^2

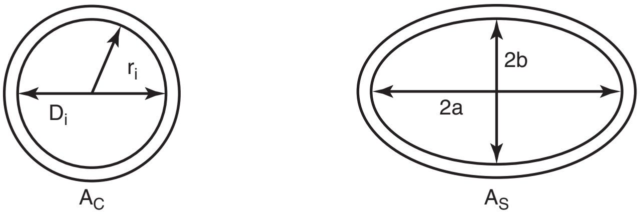


Fig. 9.5 Pipe cross-sectional area.

$$A = \frac{1}{2}\frac{\pi D_i^2}{4} = \pi\frac{0.658^2}{8} = 0.170\ \text{ft}^2$$

$$Q = 3.1\ \text{ft/s} \times 0.170\ \text{ft}^2 = 0.53\ \text{ft}^3/\text{s} = 343{,}000\ \text{gal/day}$$

It is recommended that flow velocity in sanitary sewer lines not be less than 2 ft/s (0.6 m/s) for self-cleansing action in the lines. Some authorities may require 2.5 ft/s (0.8 m/s) minimum velocity, particularly for storm sewers. At velocities above 10 ft/s (3 m/s) special consideration should be given to energy dissipation and erosion prevention. Where slopes exceed 40%, pipe anchorage should be considered. To allow for future growth or unanticipated flows, it is customary to size sanitary collection sewers to flow one-half full at maximum design inflow.

As flexible pipe is deflected, its cross-sectional area is slightly reduced. The elliptical cross-sectional area (A_s) after pipe ovalization will be only slightly less than the undeflected circular cross-sectional area (A_c) (Fig. 9.5).

Equation 9.16

$$A_c = \frac{\pi D_i^2}{4} = \pi r_i^2$$

Equation 9.17

$$A_s = \pi ab$$

where:

A_c = circle cross-sectional area, in.^{2}
A_s = ellipse cross-sectional area, in.^{2}
D_i = pipe inside diameter, in.
r_i = pipe inside radius, in.
a = deflected pipe long semi-axis, in.
b = deflected pipe short semi-axis, in.

For deflections less than 10%, the dimensions of the deflected elliptical shape are calculated using Spangler's relationship from Chapter 7:

Equation 9.18

$$\Delta X = 0.913\ \Delta Y$$

The vertical dimension of the ellipse is given by:

Equation 9.19

$$b = r_i\ (1 - \Delta Y/D_i)$$

And the horizontal dimension is:

Equation 9.20

$$a = r_i(1 + 0.913\Delta Y/D_i)$$

where:

ΔX = horizontal pipe deflection, in.
ΔY = vertical pipe deflection, in.

The resulting reductions in flow area for 5.0% and 7.5% vertical deflection are given in Table 9.6.

Reduction in flow volume is a function not only of reduced flow area, but also of reduced hydraulic radius. Calculations are simplified by assuming that the wetted circumference is not changed (i.e., the inside circumference of the ellipse is the same as the inside circumference of the circle). This means that the percent reduction in the hydraulic radius is the same as the percent reduction in flow area above. The reductions in flow volumes for 5.0% and 7.5% vertical deflection are also given in Table 9.6.

Table 9.6 Reduction in circular cross-sectional area and flow of deflected PVC pipe

Deflection (%)	% Reduction in internal cross-sectional area from circular to elliptical shape	% Reduction in flow
5.0	0.66%	1.10%
7.5	1.17%	1.94%

All sewers should be designed and constructed to give mean velocities of no less than 2.0 ft/s (0.61 m/s) when flowing full, based on Manning's equation using an appropriate "n" value. Table 9.7 lists the minimum slope values needed to maintain a 2.0-ft/s full flow velocity and corresponding flow capacities for PVC sewer pipe.

Table 9.8 provides velocities and flow rates for 4-in. through 60-in. PVC sewer pipe for the following conditions:

- Pipe products with pipe stiffness = 46 psi
- Slopes from 0.1% to 1.0% (at increments of 0.1%)
- Depth of flow = 100%
- Manning's "n" = 0.009

Table 9.7 Minimum slopes needed to maintain 2.0-ft/s full flow velocity, PVC sewer pipe

Pipe size, in.	n = 0.009	
	s, ft/100 ft	Q, 1,000 gpd
4	0.41	111
6	0.24	247
8	0.16	442
10	0.12	691
12	0.10	978
15	0.07	1,470
18	0.056	2,190
21	0.045	3,050
24	0.038	3,850
27	0.033	4,900
30	0.028	6,100
33	0.025	7,400
36	0.022	8,830
39	0.020	10,400
42	0.018	12,100
45	0.016	13,900
48	0.015	15,800

Table 9.8 PVC Sewer pipe—flow rates

Manning's n = 0.009			**Pipe stiffness = 46 psi**			**Depth of flow = 100%**		
Pipe size = 4 in.								
Pipe deflection = 0%					Pipe deflection = 7.5%			
Slope, ft/100 ft	Velocity, ft/s	Flow rate,			Slope, ft/100 ft	Velocity, ft/s	Flow rate,	
		ft^3/s	1000 gal/day				ft^3/s	1000 gal/day
0.1	0.988	0.0845	54.5		0.1	0.975	0.0818	52.8
0.2	1.40	0.119	77.1		0.2	1.38	0.116	74.6
0.3	1.71	0.146	94.4		0.3	1.69	0.142	91.4
0.4	1.98	0.169	109		0.4	1.95	0.164	106
0.5	2.21	0.189	122		0.5	2.18	0.183	118
0.6	2.42	0.207	134		0.6	2.39	0.200	129
0.7	2.61	0.224	144		0.7	2.58	0.216	140
0.8	2.79	0.239	154		0.8	2.76	0.231	149
0.9	2.96	0.253	164		0.9	2.93	0.245	158
1.0	3.12	0.267	172		1.0	3.08	0.259	167
Pipe size = 6 in.								
Pipe deflection = 0%					Pipe deflection = 7.5%			
Slope, ft/100 ft	Velocity, ft/s	Flow rate,			Slope, ft/100 ft	Velocity, ft/s	Flow rate,	
		ft^3/s	1000 gal/day				ft^3/s	1000 gal/day
0.1	1.29	0.244	157		0.1	1.27	0.236	152
0.2	1.82	0.345	223		0.2	1.80	0.334	215
0.3	2.23	0.423	273		0.3	2.20	0.409	264
0.4	2.58	0.488	315		0.4	2.54	0.472	305
0.5	2.88	0.546	352		0.5	2.84	0.528	341
0.6	3.16	0.598	386		0.6	3.11	0.578	373
0.7	3.41	0.646	416		0.7	3.36	0.625	403
0.8	3.64	0.690	445		0.8	3.60	0.668	431
0.9	3.86	0.732	472		0.9	3.81	0.708	457
1.0	4.07	0.772	498		1.0	4.02	0.747	482

Table 9.8 PVC Sewer pipe—flow rates (*continued*)

Manning's n = 0.009 Pipe stiffness = 46 psi Depth of flow = 100%

Pipe size = 8 in.

Pipe deflection = 0%				Pipe deflection = 7.5%			
Slope, ft/100 ft	Velocity, ft/s	Flow rate,		Slope, ft/100 ft	Velocity, ft/s	Flow rate,	
		ft^3/s	1000 gal/day			ft^3/s	1000 gal/day
0.1	1.56	0.532	343	0.1	1.54	0.514	332
0.2	2.21	0.752	485	0.2	2.18	0.728	469
0.3	2.71	0.921	594	0.3	2.68	0.891	575
0.4	3.13	1.06	686	0.4	3.09	1.03	664
0.5	3.50	1.19	767	0.5	3.45	1.15	742
0.6	3.83	1.30	840	0.6	3.78	1.26	813
0.7	4.14	1.41	907	0.7	4.09	1.36	878
0.8	4.43	1.50	970	0.8	4.37	1.46	939
0.9	4.69	1.59	1030	0.9	4.63	1.54	1000
1.0	4.95	1.68	1080	1.0	4.88	1.63	1050

Pipe size = 10 in.

Pipe deflection = 0%				Pipe deflection = 7.5%			
Slope, ft/100 ft	Velocity, ft/s	Flow rate,		Slope, ft/100 ft	Velocity, ft/s	Flow rate,	
		ft^3/s	1000 gal/day			ft^3/s	1000 gal/day
0.1	1.82	0.964	622	0.1	1.79	0.933	602
0.2	2.57	1.36	879	0.2	2.53	1.32	851
0.3	3.15	1.67	1080	0.3	3.10	1.62	1040
0.4	3.63	1.93	1240	0.4	3.58	1.87	1200
0.5	4.06	2.16	1390	0.5	4.01	2.09	1350
0.6	4.45	2.36	1520	0.6	4.39	2.28	1470
0.7	4.80	2.55	1640	0.7	4.74	2.47	1590
0.8	5.14	2.73	1760	0.8	5.07	2.64	1700
0.9	5.45	2.89	1870	0.9	5.38	2.80	1810
1.0	5.74	3.05	1970	1.0	5.67	2.95	1900

Table 9.8 PVC Sewer pipe—flow rates (*continued*)

Manning's n = 0.009 **Pipe stiffness = 46 psi** **Depth of flow = 100%**

Pipe size = 12 in.

Pipe deflection = 0%				Pipe deflection = 7.5%			
Slope, ft/100 ft	Velocity, ft/s	Flow rate,		Slope, ft/100 ft	Velocity, ft/s	Flow rate,	
		ft^3/s	1000 gal/day			ft^3/s	1000 gal/day
0.1	2.04	1.53	988	0.1	2.01	1.48	957
0.2	2.88	2.17	1400	0.2	2.85	2.10	1350
0.3	3.53	2.65	1710	0.3	3.49	2.57	1660
0.4	4.08	3.06	1980	0.4	4.03	2.97	1910
0.5	4.56	3.43	2210	0.5	4.50	3.32	2140
0.6	5.00	3.75	2420	0.6	4.93	3.63	2340
0.7	5.40	4.05	2620	0.7	5.33	3.92	2530
0.8	5.77	4.33	2800	0.8	5.69	4.19	2710
0.9	6.12	4.60	2970	0.9	6.04	4.45	2870
1.0	6.45	4.85	3130	1.0	6.37	4.69	3030

Pipe size = 15 in.

Pipe deflection = 0%				Pipe deflection = 7.5%			
Slope, ft/100 ft	Velocity, ft/s	Flow rate,		Slope, ft/100 ft	Velocity, ft/s	Flow rate,	
		ft^3/s	1000 gal/day			ft^3/s	1000 gal/day
0.1	2.33	2.63	1700	0.1	2.30	2.55	1640
0.2	3.30	3.72	2400	0.2	3.26	3.60	2320
0.3	4.04	4.56	2940	0.3	3.99	4.41	2840
0.4	4.67	5.26	3390	0.4	4.61	5.09	3280
0.5	5.22	5.88	3790	0.5	5.15	5.69	3670
0.6	5.72	6.44	4160	0.6	5.64	6.24	4020
0.7	6.18	6.96	4490	0.7	6.10	6.74	4350
0.8	6.60	7.44	4800	0.8	6.52	7.20	4650
0.9	7.00	7.89	5090	0.9	6.91	7.64	4930
1.0	7.38	8.32	5370	1.0	7.29	8.05	5190

Table 9.8 PVC Sewer pipe—flow rates (*continued*)

Manning's n = 0.009				**Pipe stiffness = 46 psi**			**Depth of flow = 100%**	
Pipe size = 18 in.								
Pipe deflection = 0%					Pipe deflection = 7.5%			
Slope, ft/100 ft	Velocity, ft/s	Flow rate,			Slope, ft/100 ft	Velocity, ft/s	Flow rate,	
		ft^3/s	1000 gal/day				ft^3/s	1000 gal/day
0.1	2.68	4.54	2930		0.1	2.64	4.40	2840
0.2	3.79	6.43	4150		0.2	3.74	6.22	4010
0.3	4.64	7.87	5080		0.3	4.58	7.62	4910
0.4	5.35	9.09	5860		0.4	5.28	8.80	5670
0.5	5.98	10.2	6550		0.5	5.91	9.83	6340
0.6	6.56	11.1	7180		0.6	6.47	10.8	6950
0.7	7.08	12.0	7760		0.7	6.99	11.6	7510
0.8	7.57	12.9	8290		0.8	7.47	12.4	8020
0.9	8.03	13.6	8790		0.9	7.93	13.2	8510
1.0	8.46	14.4	9270		1.0	8.35	13.9	8970
Pipe size = 21 in.								
Pipe deflection = 0%					Pipe deflection = 7.5%			
Slope, ft/100 ft	Velocity, ft/s	Flow rate,			Slope, ft/100 ft	Velocity, ft/s	Flow rate,	
		ft^3/s	1000 gal/day				ft^3/s	1000 gal/day
0.1	2.99	7.05	4550		0.1	2.95	6.82	4400
0.2	4.22	9.97	6430		0.2	4.17	9.65	6220
0.3	5.17	12.2	7880		0.3	5.11	11.8	7620
0.4	5.97	14.1	9090		0.4	5.90	13.6	8800
0.5	6.68	15.8	10200		0.5	6.59	15.3	9840
0.6	7.32	17.3	11100		0.6	7.22	16.7	10800
0.7	7.90	18.6	12000		0.7	7.80	18.1	11600
0.8	8.45	19.9	12900		0.8	8.34	19.3	12400
0.9	8.96	21.1	13600		0.9	8.84	20.5	13200
1.0	9.45	22.3	14400		1.0	9.32	21.6	13900

Table 9.8 PVC Sewer pipe—flow rates (*continued*)

Manning's n = 0.009				**Pipe stiffness = 46 psi**			**Depth of flow = 100%**	
Pipe size = 24 in.								
Pipe deflection = 0%					Pipe deflection = 7.5%			
Slope, ft/100 ft	Velocity, ft/s	Flow rate,			Slope, ft/100 ft	Velocity, ft/s	Flow rate,	
		ft^3/s	1000 gal/day				ft^3/s	1000 gal/day
0.1	3.23	9.65	6230		0.1	3.19	9.34	6030
0.2	4.57	13.6	8810		0.2	4.51	13.2	8520
0.3	5.60	16.7	10800		0.3	5.52	16.2	10400
0.4	6.46	19.3	12500		0.4	6.38	18.7	12100
0.5	7.23	21.6	13900		0.5	7.13	20.9	13500
0.6	7.92	23.6	15300		0.6	7.81	22.9	14800
0.7	8.55	25.5	16500		0.7	8.44	24.7	15900
0.8	9.14	27.3	17600		0.8	9.02	26.4	17000
0.9	9.69	29.0	18700		0.9	9.57	28.0	18100
1.0	10.2	30.5	19700		1.0	10.1	29.5	19100
Pipe size = 27 in.								
Pipe deflection = 0%					Pipe deflection = 7.5%			
Slope, ft/100 ft	Velocity, ft/s	Flow rate,			Slope, ft/100 ft	Velocity, ft/s	Flow rate,	
		ft^3/s	1000 gal/day				ft^3/s	1000 gal/day
0.1	3.50	13.3	8560		0.1	3.45	12.8	8290
0.2	4.95	18.8	12100		0.2	4.88	18.2	11700
0.3	6.06	23.0	14800		0.3	5.98	22.3	14400
0.4	7.00	26.6	17100		0.4	6.91	25.7	16600
0.5	7.83	29.7	19200		0.5	7.72	28.7	18500
0.6	8.57	32.5	21000		0.6	8.46	31.5	20300
0.7	9.26	35.1	22700		0.7	9.14	34.0	21900
0.8	9.90	37.6	24200		0.8	9.77	36.3	23400
0.9	10.5	39.8	25700		0.9	10.4	38.5	24900
1.0	11.1	42.0	27100		1.0	10.9	40.6	26200

Table 9.8 PVC Sewer pipe—flow rates (*continued*)

Manning's n = 0.009				**Pipe stiffness = 46 psi**				**Depth of flow = 100%**
Pipe size = 30 in.								
Pipe deflection = 0%					Pipe deflection = 7.5%			
Slope, ft/100 ft	Velocity, ft/s	Flow rate, ft^3/s	Flow rate, 1000 gal/day		Slope, ft/100 ft	Velocity, ft/s	Flow rate, ft^3/s	Flow rate, 1000 gal/day
0.1	3.83	19.0	12300		0.1	3.78	18.4	11900
0.2	5.42	26.9	17400		0.2	5.35	26.1	16800
0.3	6.63	33.0	21300		0.3	6.55	31.9	20600
0.4	7.66	38.1	24600		0.4	7.56	36.9	23800
0.5	8.56	42.6	27500		0.5	8.45	41.2	26600
0.6	9.38	46.6	30100		0.6	9.26	45.1	29100
0.7	10.1	50.4	32500		0.7	10.0	48.8	31500
0.8	10.8	53.9	34700		0.8	10.7	52.1	33600
0.9	11.5	57.1	36900		0.9	11.3	55.3	35700
1.0	12.1	60.2	38800		1.0	12.0	58.3	37600
Pipe size = 33 in.								
Pipe deflection = 0%					Pipe deflection = 7.5%			
Slope, ft/100 ft	Velocity, ft/s	Flow rate, ft^3/s	Flow rate, 1000 gal/day		Slope, ft/100 ft	Velocity, ft/s	Flow rate, ft^3/s	Flow rate, 1000 gal/day
0.1	4.02	23.2	15000		0.1	3.97	19.4	12500
0.2	5.69	32.8	21100		0.2	5.62	27.4	17700
0.3	6.97	40.1	25900		0.3	6.88	33.5	21600
0.4	8.05	46.3	29900		0.4	7.94	38.7	25000
0.5	9.00	51.8	33400		0.5	8.88	43.3	27900
0.6	9.85	56.8	36600		0.6	9.73	47.4	30600
0.7	10.6	61.3	39600		0.7	10.5	51.2	33000
0.8	11.4	65.5	42300		0.8	11.2	54.8	35300
0.9	12.1	69.5	44900		0.9	11.9	58.1	37500
1.0	12.7	73.3	47300		1.0	12.6	61.2	39500

Table 9.8 PVC Sewer pipe—flow rates (*continued*)

Manning's n = 0.009				**Pipe stiffness = 46 psi**				**Depth of flow = 100%**
Pipe size = 36 in.								
Pipe deflection = 0%					Pipe deflection = 7.5%			
Slope, ft/100 ft	Velocity, ft/s	Flow rate,			Slope, ft/100 ft	Velocity, ft/s	Flow rate,	
		ft^3/s	1000 gal/day				ft^3/s	1000 gal/day
0.1	4.32	30.7	19800		0.1	4.26	29.8	19200
0.2	6.11	43.5	28100		0.2	6.03	42.1	27200
0.3	7.48	53.3	34400		0.3	7.38	51.5	33300
0.4	8.64	61.5	39700		0.4	8.52	59.5	38400
0.5	9.65	68.8	44400		0.5	9.53	66.5	42900
0.6	10.6	75.3	48600		0.6	10.4	72.9	47000
0.7	11.4	81.4	52500		0.7	11.3	78.7	50800
0.8	12.2	87.0	56100		0.8	12.1	84.2	54300
0.9	13.0	92.2	59500		0.9	12.8	89.3	57600
1.0	13.7	97.2	62700		1.0	13.5	94.1	60700
Pipe size = 39 in.								
Pipe deflection = 0%					Pipe deflection = 7.5%			
Slope, ft/100 ft	Velocity, ft/s	Flow rate,			Slope, ft/100 ft	Velocity, ft/s	Flow rate,	
		ft^3/s	1000 gal/day				ft^3/s	1000 gal/day
0.1	4.50	36.4	23500		0.1	4.45	35.2	22700
0.2	6.37	51.5	33200		0.2	6.29	49.8	32200
0.3	7.80	63.1	40700		0.3	7.70	61.0	39400
0.4	9.01	72.8	47000		0.4	8.89	70.5	45500
0.5	10.1	81.4	52500		0.5	9.94	78.8	50800
0.6	11.0	89.2	57500		0.6	10.9	86.3	55700
0.7	11.9	96.3	62100		0.7	11.8	93.2	60200
0.8	12.7	103	66400		0.8	12.6	99.7	64300
0.9	13.5	109	70500		0.9	13.3	106	68200
1.0	14.2	115	74300		1.0	14.1	111	71900

Table 9.8 PVC Sewer pipe—flow rates (*continued*)

Manning's n = 0.009 **Pipe stiffness = 46 psi** **Depth of flow = 100%**

Pipe size = 42 in.

Pipe deflection = 0%				Pipe deflection = 7.5%			
Slope, ft/100 ft	Velocity, ft/s	Flow rate,		Slope, ft/100 ft	Velocity, ft/s	Flow rate,	
		ft^3/s	1000 gal/day			ft^3/s	1000 gal/day
0.1	4.77	45.9	29600	0.1	4.71	44.4	28600
0.2	6.75	64.9	41900	0.2	6.66	62.8	40500
0.3	8.27	79.5	51300	0.3	8.16	76.9	49600
0.4	9.54	91.7	59200	0.4	9.42	88.8	57300
0.5	10.7	103	66200	0.5	10.5	99.3	64000
0.6	11.7	112	72500	0.6	11.5	109	70200
0.7	12.6	121	78300	0.7	12.5	117	75800
0.8	13.5	130	83700	0.8	13.3	126	81000
0.9	14.3	138	88800	0.9	14.1	133	85900
1.0	15.1	145	93600	1.0	14.9	140	90600

Pipe size = 45 in.

Pipe deflection = 0%				Pipe deflection = 7.5%			
Slope, ft/100 ft	Velocity, ft/s	Flow rate,		Slope, ft/100 ft	Velocity, ft/s	Flow rate,	
		ft^3/s	1000 gal/day			ft^3/s	1000 gal/day
0.1	4.96	53.6	34600	0.1	4.90	51.9	33500
0.2	7.02	75.8	48900	0.2	6.92	73.3	47300
0.3	8.59	92.8	59900	0.3	8.48	89.8	57900
0.4	9.92	107	69100	0.4	9.79	104	66900
0.5	11.1	120	77300	0.5	10.9	116	74800
0.6	12.2	131	84700	0.6	12.0	127	81900
0.7	13.1	142	91500	0.7	13.0	137	88500
0.8	14.0	152	97800	0.8	13.8	147	94600
0.9	14.9	161	104000	0.9	14.7	156	100000
1.0	15.7	169	109000	1.0	15.5	164	106000

Table 9.8 PVC Sewer pipe—flow rates (*continued*)

Manning's n = 0.009 **Pipe stiffness = 46 psi** **Depth of flow = 100%**

Pipe size = 48 in.

Pipe deflection = 0%				Pipe deflection = 7.5%			
Slope, ft/100 ft	Velocity, ft/s	Flow rate,		Slope, ft/100 ft	Velocity, ft/s	Flow rate,	
		ft^3/s	1000 gal/day			ft^3/s	1000 gal/day
0.1	5.21	65.3	42100	0.1	5.14	63.2	40800
0.2	7.37	92.4	59600	0.2	7.28	89.4	57700
0.3	9.03	113	73000	0.3	8.91	109	70600
0.4	10.4	131	84300	0.4	10.3	126	81600
0.5	11.7	146	94200	0.5	11.5	141	91200
0.6	12.8	160	103000	0.6	12.6	155	100000
0.7	13.8	173	111000	0.7	13.6	167	108000
0.8	14.7	185	119000	0.8	14.6	179	115000
0.9	15.6	196	126000	0.9	15.4	190	122000
1.0	16.5	207	133000	1.0	16.3	200	129000

Pipe size = 54 in.

Pipe deflection = 0%				Pipe deflection = 7.5%			
Slope, ft/100 ft	Velocity, ft/s	Flow rate,		Slope, ft/100 ft	Velocity, ft/s	Flow rate,	
		ft^3/s	1000 gal/day			ft^3/s	1000 gal/day
0.1	5.61	87.6	56500	0.1	5.54	84.8	54700
0.2	7.93	124	79900	0.2	7.83	120	77300
0.3	9.72	152	97800	0.3	9.59	147	94700
0.4	11.2	175	113000	0.4	11.07	170	109000
0.5	12.5	196	126000	0.5	12.38	190	122000
0.6	13.7	214	138000	0.6	13.56	208	134000
0.7	14.8	232	149000	0.7	14.65	224	145000
0.8	15.9	248	160000	0.8	15.66	240	155000
0.9	16.8	263	169000	0.9	16.61	254	164000
1.0	17.7	277	179000	1.0	17.51	268	173000

Table 9.8 PVC Sewer pipe—flow rates (*continued*)

Manning's n = 0.009			**Pipe stiffness = 46 psi**				**Depth of flow = 100%**	
Pipe size = 60 in.								
Pipe deflection = 0%					Pipe deflection = 7.5%			
Slope, ft/100 ft	Velocity, ft/s	Flow rate,			Slope, ft/100 ft	Velocity, ft/s	Flow rate,	
		ft^3/s	1000 gal/day				ft^3/s	1000 gal/day
0.1	6.02	116	75000		0.1	5.94	113	72600
0.2	8.52	164	106000		0.2	8.41	159	103000
0.3	10.4	201	130000		0.3	10.3	195	126000
0.4	12.0	233	150000		0.4	11.9	225	145000
0.5	13.5	260	168000		0.5	13.3	252	162000
0.6	14.7	285	184000		0.6	14.6	276	178000
0.7	15.9	308	198000		0.7	15.7	298	192000
0.8	17.0	329	212000		0.8	16.8	318	205000
0.9	18.1	349	225000		0.9	17.8	338	218000
1.0	19.0	368	237000		1.0	18.8	356	230000

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CHAPTER 10

General Construction

Receiving, Storage, and Handling
•
Joint Assembly
•
Field-Cutting and Chamfering
•
Curvature of the Pipeline
•
Butt-Fused PVC Pipe

Table of Contents

10.1 Introduction

The importance of proper construction practices for any piping system cannot be overstated. Construction procedures fall under the following categories:

- receiving, storage, and handling
- joint assembly
- field cutting and chamfering
- curvature of pipeline.

Chapters 11, 12, and 13 discuss specific installation techniques for PVC pressure pipe, PVC nonpressure pipe, and trenchless pipe, respectively. Chapter 10 discusses construction that applies to all PVC pipe installation.

10.2 Receiving, Storage, and Handling

10.2.1 Receiving

The following procedures should be followed by a contractor or purchaser upon receipt of a PVC pipe shipment.

10.2.1.1 Inspection

PVC pipes are inspected and loaded at the factory using methods acceptable to the manufacturer. The carrier's responsibility is to deliver a shipment in good condition. Each pipe shipment should be inventoried and inspected upon arrival, and the receiver must ensure there has been no loss or damage.

A complete list of items should accompany each shipment. The physical pieces are checked against this record. Any errors should immediately be reported to the carrier, and proper notation should be made on the delivery receipt.

It is recommended that the person accepting delivery perform the following actions:

- Conduct an overall examination of the load. If the load is intact, ordinary inspection while unloading should be sufficient to ensure the pipe arrived in good condition.
- Verify that correct size and type of pipe was shipped.
- If a load has shifted, has broken packaging, or exhibits signs of receiving rough treatment, carefully inspect each piece for damage.
- Check total quantities of each item (pipe gaskets, fittings, lubricant, etc.) against shipping records.

- Note any damaged or missing items on the delivery receipt, notify carrier immediately, and make a claim in accordance with the manufacturer's instructions.
- Do not dispose of any damaged material. The carrier gives a procedure to follow in this case.
- Request reshipment in case of shortages or damaged materials, since reshipment will not be made otherwise. If replacement material is needed, reorder directly from the manufacturer, the manufacturer's representative, or the distributor.

10.2.1.2 Unloading

The means by which PVC pipe is unloaded in the field is the decision and responsibility of the receiver. Preferred unloading is done in packaged units with mechanical equipment (Fig. 10.1).

The following instructions should be carefully followed during the unloading of packaged units:

- Remove restraints from the top unit loads. These restraints may be fabric or they may be steel straps or ropes.
- Remove any boards across the top and down the sides of the load that are not part of the packaging.
- Use a forklift with thin chisel forks (or a front-end loader equipped with forks); extend forks to remove each top unit (one at a time) from the truck. Remove back units first. Do not run forks too far under units: fork ends striking adjacent units may cause damage. Ensure forks are fully engaged on the pipe before lifting.

Fig. 10.1 Unloading PVC pipe with a fork truck.

Fig. 10.2 PVC pipe stored on level ground.

- If a forklift is not available, a spreader bar with fabric straps that is capable of handling the load (with straps spaced approximately 8 ft apart and looped under the load) may be used. Cables may also be used if cushioned with rubber hose sleeves or other material to prevent abrasion of the pipe. Ensure that units do not strike anything during removal and handling. Severe impact could cause damage.
- As with any pipe, do not handle units by use of individual chains or single cables. Do not attach cables to unit frames or banding for lifting.
- Store and place pipe package units on level ground (Fig. 10.2).
- Do not stack package units more than 8 ft high. Units should be protected by dunnage in the same way they were protected when loaded on the truck.
- To unload lower units, repeat the above process.

10.2.2 Storage

Figure 10.2 shows storage of pipe at a job site. The following practices are recommended to prevent damage to stored PVC pipe:

- Pipe should be stored, if possible, at a job site in the unit packages provided by the manufacturer. Caution should be exercised to avoid compression, damage, or deformation of the pipe's bell ends.
- When unit packages of PVC pipe are stacked, ensure that the weight of upper units does not cause deformation to the pipe in the lower units. Also, ensure that stack

height does not result in instability, which could result in collapse of the stack, damage to the pipe, or personal injury.

- PVC pipe unit packages should be supported by racks or dunnage to prevent damage to the bottom during storage. Supports should be spaced to prevent pipe bending.
- When prolonged exposure to direct sunlight is anticipated, PVC pipe should be covered with an opaque material while still permitting adequate air circulation above and around the pipe. This practice is required to prevent excessive heat accumulation (see Chapter 3).
- PVC pipe should not be stored close to heat sources or hot objects such as heaters, boilers, steam lines, and engine exhaust.
- When unit packages of PVC pipe are stacked, the pipe interior as well as all its sealing surfaces, fittings, and other accessories should be kept free from dirt and foreign matter.
- Gaskets should be protected from exposure to excessive heat, prolonged direct sunlight, and oil and grease. Do not store near electrical motors or transformers or other sources of ozone.

10.2.3 Handling

In order to prevent damage to PVC pipe during handling, the following procedures are recommended (see Section 10.2.1.2 on unloading).

- Avoid severe impact blows, abrasion damage, and gouging or cutting by metal surfaces or rocks. Avoid stressing bell joints and damage to bevel ends.
- Pipe should be lowered, not dropped, from trucks and into trenches.
- In preparation for pipe installation, placement (stringing) of pipe should be as close to the trench as practical and on the side opposite excavated earth. Bell ends should point in the direction of the work progress.
- In subfreezing temperatures, additional care is advised to prevent impact damage.

10.2.4 Lowering Pipe and Fittings into the Trench

Placement of pipe and fittings into a trench should be done with ropes and skids, slings on a backhoe bucket, or by hand (Fig. 10.3). Pipe or fittings should not be thrown into the trench and no part of the pipe should be allowed to take an unrestrained fall onto the trench bottom.

After they are lowered, pipe and other accessories are in a good position for a final inspection. Ensure there are no damaged materials before assembly begins.

Fig. 10.3 PVC pipe is light enough for manual handling of some sizes.

10.3 Joint Assembly

Assembly of pipes may be performed by various methods. The technique used most often employs a gasketed joint, which may be either of integral bell design (formed as a continuous, homogeneous entity with the pipe, as in Fig. 10.4), or it may consist of a separate sleeve-type coupling. Gasketed joint pipe provides the following advantages:

- allowance for expansion and contraction
- reliable assembly in poor weather conditions
- flexibility and resiliency
- ease of installation
- watertightness.

Fig. 10.4 Assembling a pipe joint.

10.3.1 Assembly of Pipe with Gasketed Joints

Gasketed joint assembly should be performed as recommended by the pipe manufacturer (Fig. 10.5). Elastomeric gaskets are usually prepositioned in the bell joint (or coupling).

The manufacturer should be consulted prior to any attempts to remove gaskets from bells. Some profile wall pipes have gaskets installed on the outside of the pipe spigot at the factory. Consult the pipe manufacturer or product literature for the significance of any color-coded gaskets. In all cases, clean the gasket, bell or coupling interior, groove area, and spigot area to remove dirt or foreign material before assembling. Inspect the gasket, pipe spigot bevel, gasket groove, and sealing surfaces for damage or deformation. In cases when gaskets are supplied separately from pipe, ensure that the gaskets supplied are designed for the pipe in use.

It is essential that only the lubricant supplied or recommended by the pipe manufacturer be used and applied as specified. Bacterial growth and/or damage to gaskets or pipe might result if nonapproved lubricants are used or if they are excessively applied.

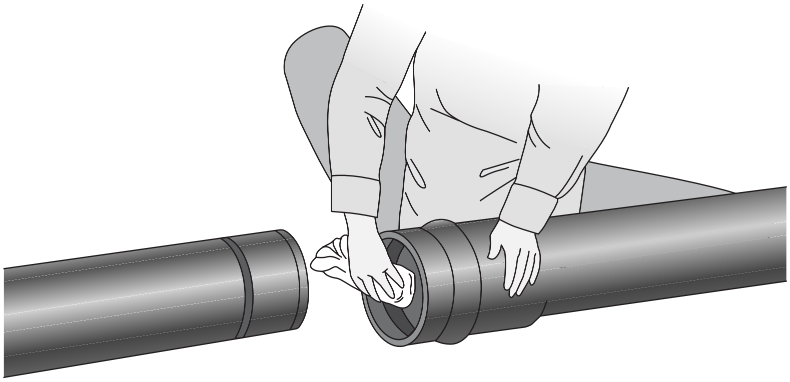
After lubrication in accordance with manufacturer recommendations, the pipe lengths are ready to be joined. Care should be taken to ensure lubricated spigot ends do not come in contact with soil or backfill material. Straight alignment of pipe is essential for ease of joint assembly; the spigot is aligned to the bell then inserted into the bell until it contacts the gasket uniformly.

Typically, smaller diameter pipes can be assembled using manual force (bar and block per Fig. 10.6). The bar and block method is recommended whenever possible because an installer is able to feel the amount of force being used and determine if the spigot is going into the bell smoothly.

Larger diameter pipes require mechanical assistance such as hydraulic pipe pullers (Fig. 10.7), jacks, pulleys, come-alongs, or a backhoe bucket. If mechanical equipment is used for installation, it is difficult for the installer to feel the resistance to the spigot entering the bell. Observation by a spotter is recommended to prevent overinsertion. Overinsertion may compromise the joint and may also cause overinsertion of previously assembled joints.

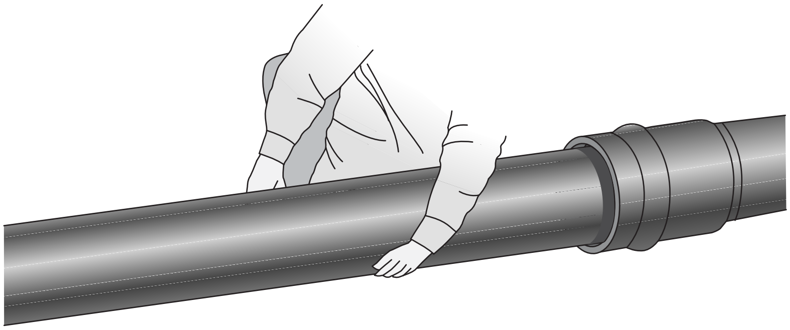
The spigot end of a pipe is marked with a “reference mark” by the manufacturer to indicate proper insertion depth. In a properly assembled pipe-to-pipe joint, the reference mark on the spigot is visible and flush with the lip of the adjoining bell.

Other names for the reference mark are “insertion line,” “stop mark,” or “assembly stripe.” The spigot must not be overinserted and previously assembled pipe joints must be left undisturbed. Note: The reference mark is intended for pipe-to-pipe joints. Few fittings and appurtenances allow as much spigot insertion length as pipe bells and couplings.



Clean bell. Make certain the beveled spigot end and the gasket groove are free from dirt.

Lubricate. Apply lubricant per the pipe manufacturer's instructions



Assemble. Push lubricated end past the gasket into the bell until reference mark is even with bell entrance.

Fig. 10.5 Joint assembly procedure.

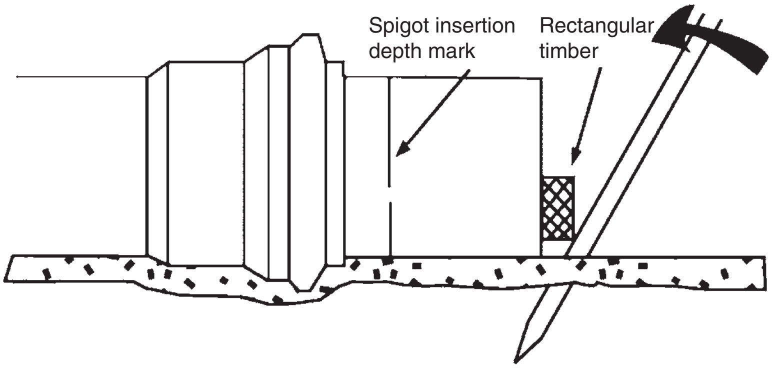


Fig. 10.6 Bar and block assembly method.

Fig. 10.7 Hydraulic pipe puller.

The temperature of the bell and gasket may affect insertion force; most gasket materials become harder with decreasing temperature, which may result in a larger force being required for spigot insertion.

If undue resistance to insertion of the spigot is encountered or the reference mark does not position properly, the joint should be disassembled and the position of the gasket checked. If it is twisted or pushed out (“fish-mouthed”), the components should be checked, damaged items repaired or replaced, components cleaned, and assembly steps repeated. Be sure both pipe lengths are in straight alignment.

If the gasket was not out of position, verify proper location of the reference mark and relocate if necessary. As mentioned previously, few fittings allow as much spigot insertion length as do pipe bells and couplings.

10.3.2 Assembly of PVC Fittings with Gasketed Joints

The recommended procedure to assemble PVC fittings with gasketed joints is:

1. Make sure both bell and spigot are clean.
2. When field cutting the pipe (Fig. 10.8), cut it square to the required length and bevel the pipe to match the factory bevel (Fig. 10.9).
3. Measure the insertion depth of the fitting bell.

Fig. 10.8 Field cutting.

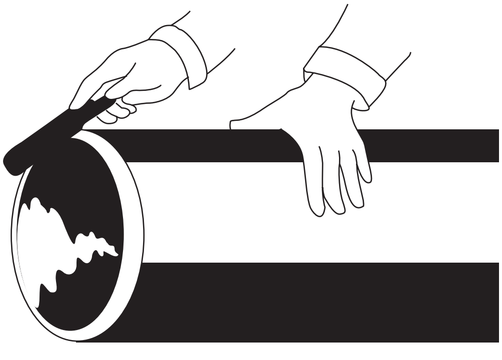


Fig. 10.9 Chamfering of field cut pipe.

4. Mark the spigot with a 360° line around the pipe according to the fitting manufacturer's recommendation.
5. Apply lubricant per fitting manufacturer recommendations.
6. Check again that the bell and spigot remain free of debris.
7. Place the spigot at the bell lip, positioning the pipe in straight alignment. Push the spigot into the bell until the assembly line on the spigot is even with the lip of the bell. Joints with spigots inserted past the assembly mark are overinserted and may result in excessive stresses or leakage.
8. PVC fittings are not recommended for use with iron pipe, due to OD inconsistencies of the iron pipe.

10.3.3 Assembly of Iron Fittings

The bells of both mechanical joint and push-fit iron fittings are much shallower than the bells of PVC pipe or fittings. For this reason, the assembly line on the pipe spigot is of no value as an indicator of proper assembly to cast iron fittings. In order to fully engage the gasket of the iron push-fit bell, the PVC pipe spigot should have only a slight chamfer (Fig. 10.11). When assembling to mechanical joints, remove the spigot chamfer, debur, and remove the sharp edge. For mechanical joints, use the torque requirements specified for PVC.

Notes:

1. Debur and remove the sharp edge of the spigot when assembling it to iron fittings. Bottom the pipe in the bell.

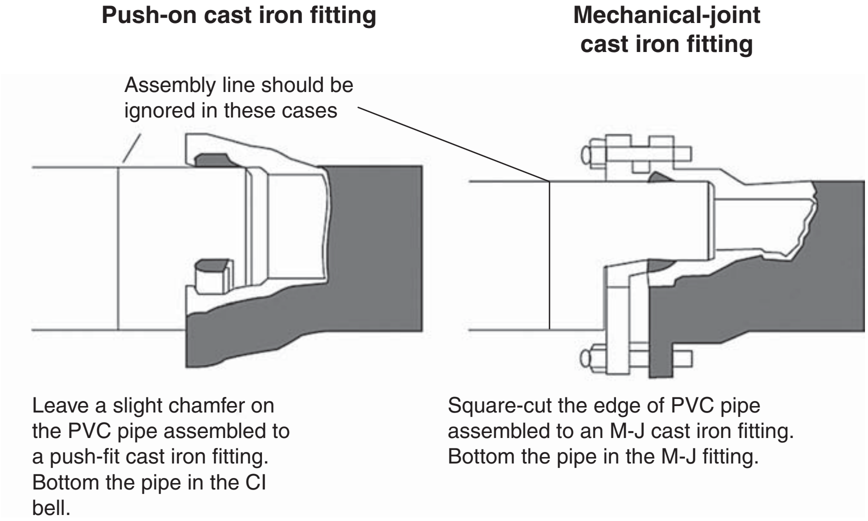


Fig. 10.10 Iron-fitting assembly.

2. Corrosion protection should be provided for iron fittings.
3. For axial deflection, consult the fitting manufacturer.

10.4 Field-Cutting and Chamfering

Conventional PVC pipe can be field-cut to any length; because of its consistent outside diameter, no special lengths are required. To join field-cut pipe, it is necessary to first prepare the pipe end. A square cut is essential for proper assembly. The pipe can be easily cut with an abrasive disc or steel blade power saw, a hacksaw, or a handsaw, depending on the size of the pipe. It is recommended that the pipe be marked around its entire circumference prior to cutting to ensure a square cut. Use a factory-finished beveled end as a guide for proper bevel angle and depth. Measure the distance to the insertion reference mark and redraw to ensure proper assembly of a cut segment and pipe bell. Round off any sharp edge on the leading edge of the spigot, as sharp edges can result in gasket damage or gasket fishmouthing. Cutting of profile pipe products may require different techniques. Consult the pipe manufacturer if making a field cut to profile pipe.

10.5 Curvature of the Pipeline

There are three common methods for achieving changes in direction with PVC pipe:

1. PVC fittings
2. angular deflection of the joint
3. bending of the pipe barrel.

10.5.1 PVC Fittings

PVC fittings can be utilized to accommodate changes in direction. Standard fittings are available in a variety of configurations, such as 5 (Fig. 10.11), 11¼, 22½, 45, and 90 degrees.

5° sweep

5° high deflection coupling

Fig. 10.11 Fittings, 5°.

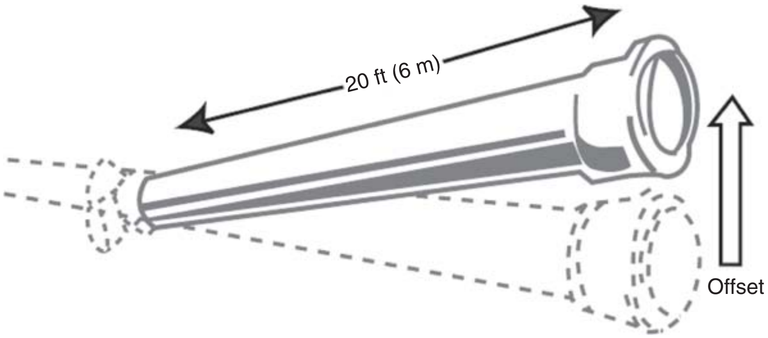


Fig. 10.12 Deflecting the joint.

10.5.2 Angular Joint Deflection

The procedure for offsetting a gasketed joint is illustrated in Fig. 10.12 and described here:

1. Assemble the joint in accordance with the manufacturer's recommendation.
2. Shift the loose bell end of the assembled length by no more than the manufacturer's recommended maximum deflection. Use only manual effort.
3. For example, with 20-ft lengths of pipe 1^{o} of angular joint deflection equals a 4 in. offset.

10.5.3 Bending the Pipe Barrel

Gasketed PVC pipes can be laid to the line of a curved trench by bending the pipe barrel into a curved shape (see Chapter 8 for longitudinal bending allowances). The procedure is as follows:

1. Keep the spigot in straight alignment with the bell (Fig. 10.13).
2. Place compacted backfill around the assembled joint. This backfill restricts movement while the curvature is being made.
3. Place compacted backfill at the inside of the curve at the mid-point of the pipe length to form a fulcrum.
4. Using only manual effort, move the leading bell of the pipe length to be curved. Bending radius tables can be found in Chapter 8 (Tables 8.2 through 8.4).

10.6 Butt-Fused PVC Pipe

Recommended construction practices for butt-fused PVC are discussed in Chapter 13 with trenchless applications. Butt-fused PVC can be field-chamfered and connected to a bell end of a PVC pipe.

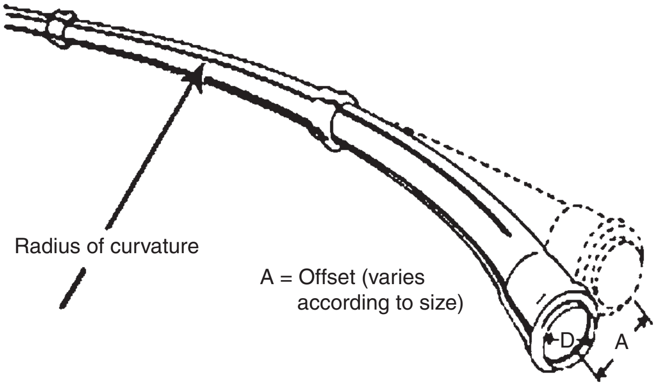


Fig. 10.13 Bending the pipe barrel.

Butt-fused PVC pipe handling differs from bell-end-spigot pipe in the following ways:

- Butt-fused PVC is normally provided in 40-ft lengths. This requires handling the PVC with properly sized equipment for the weight.
- Straps should be positioned at the one-third points along the length of the pipe segment.

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CHAPTER 11

PVC Pressure Pipe Installation

PVC Pressure Pipe Installation – Overview
•
Trench Construction
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Appurtenances
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Direct Tapping
•
Procedures for Locating, Leak Detection, Grounding, and Thawing
•
Inspection and Testing of the Pipe System

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11.1 Notation

D = nominal pipe diameter, in.

L = make-up water allowance, gal/h

N = number of joints in the tested pipeline (pipe and fittings), dimensionless

P = test pressure, psi

11.2 Introduction

As noted in Chapter 10, the importance of proper construction practice for any piping system cannot be overstated. In this chapter, recommended practices for PVC pressure pipe installation are presented in the following categories:

- trench construction
- appurtenances
- service connections
- inspection and testing of the pipe system
- locating, leak detection, and thawing procedures.

11.3 PVC Pressure Pipe Installation—Overview

As is true for all types of pipe, PVC pipe performance depends on proper installation. High strength-to-weight ratio, ease of handling, and ease of installation (Fig. 11.1) all contribute to safer and more cost efficient construction. Implementation of installation practices recommended in this chapter will ensure the long, trouble-free performance of buried PVC pressure piping systems.

11.4 Trench Construction

11.4.1 Stockpiling Excavated Material

All excavated material should be stockpiled in a manner that does not endanger work or workers; nor should it obstruct sidewalks and driveways. Hydrants, valve pit covers, valve boxes, curb stop boxes, and any other utility control should be left unobstructed. If the excavated material is to be used for backfill, it should be easily accessible.

Fig. 11.1 PVC fittings can be easily handled and installed.

11.4.2 Trench Width

Trench width at ground surface may vary with depth, type of soil, and position of surface structures. The minimum clear width of the trench, sheeted or unsheeted, is measured at the *springline* of the pipe (see Fig. 11.2). Width should be kept to a practical minimum, generally specified to be at least 12 in. (300 mm) greater than the pipe's outside diameter (OD). The general rule is that the maximum width at the top of the pipe should not be greater than OD plus 24 in. (600 mm). This lateral spacing facilitates easy placement and shovel-slicing of bedding material in the *haunch zone* of the trench. *Haunching* refers to the section of the embedment extending from the bottom of the pipe to the springline. The minimum trench width is determined by the minimum space workers need to safely place and compact haunching material with appropriate compaction equipment.

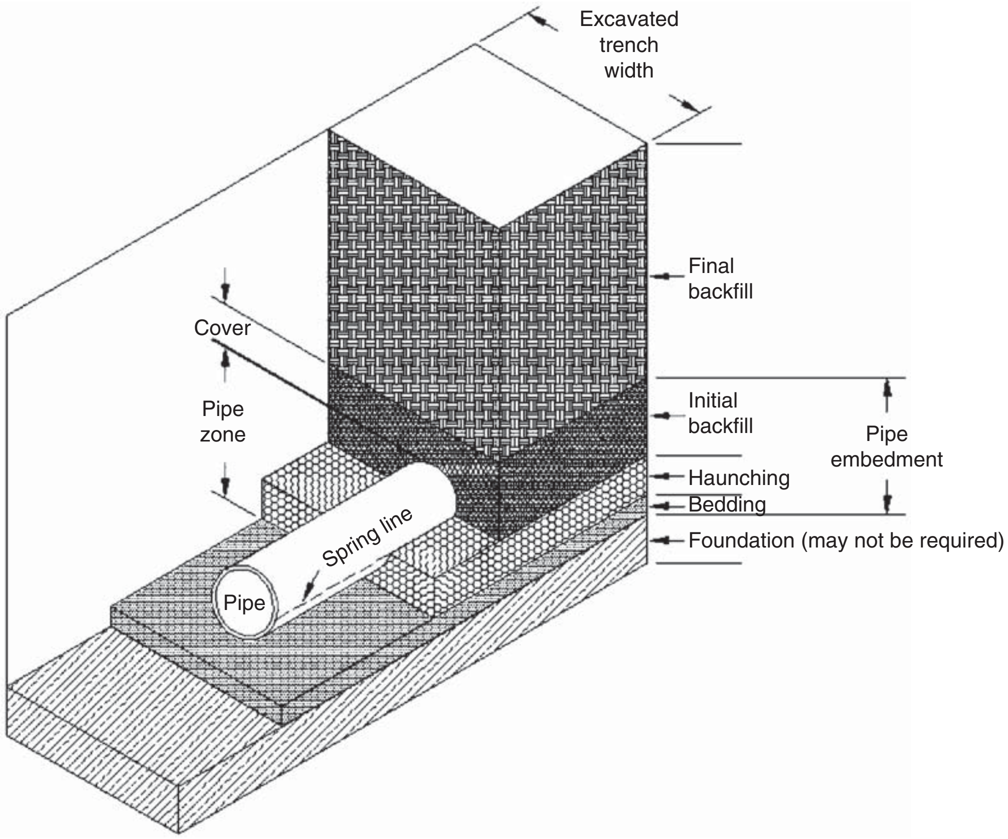


Fig. 11.2 Trench cross-section with terminology.

11.4.3 Dewatering

When a trench bottom contains running or standing water or the soil in the trench bottom displays a "quick" tendency, the water should be removed by pumps or other suitable means such as well points or pervious underdrain bedding. This is done until the pipe has been installed and the backfill placed to a sufficient height of at least $1\frac{1}{2}$ pipe diameters above the top of the pipe to prevent pipe flotation. Care should be taken that any underdrain is of proper gradation and thickness to prevent migration of material between the underdrain, pipe embedment, and native soils in the trench below and at the sides of the pipe.

11.4.4 Preparation of the Trench Bottom

The trench bottom should be constructed to provide a firm, stable, and uniform support for the full length of the pipe. Any part of the trench bottom excavated below grade should be backfilled and compacted as required to provide a firm foundation. When unstable subgrade conditions exist that would result in inadequate pipe support, additional trench depth should be excavated and refilled with suitable foundation material. Ledge rock, boulders, and large stones should be removed to allow for at least 4 in. (100 mm) of soil cushion all around the pipe and accessories.

A cushion of acceptable bedding material should always be provided between any hard foundation and the pipe. Bedding material should be loosely placed and bell holes should be provided at each joint to facilitate proper joint assembly and pipe support.

11.4.5 Laying of Pipe

Proper placement of pipe in a trench requires the right tools and equipment. Pipes and appurtenances should be lowered carefully into the trench. All foreign matter and dirt should be removed from the pipe interior. Pipe joints should be assembled as recommended (see Chapter 10 for more on proper handling). When pipe laying is not in progress, open ends of installed pipe should be closed to prevent trench water, dirt, and foreign matter from entering the line.

11.4.6 Thrust Restraints and Thrust Blocking

Concrete thrust blocking or mechanical thrust restraint devices should be provided at each hydrant, valve, dead end, reducer, and fitting—wherever changes occur in pipe diameter or direction. (See Section 11.5.3.5 for more information.)

11.4.7 Pipe Embedment

There are three components to pipe embedment:

1. Bedding—bedding material provides uniform support under the pipe.
2. Haunching—the purpose of haunching is to provide sufficient side support without causing displacement from proper alignment. Material should be placed and consolidated under the pipe haunches and up to the pipe springline.
3. Initial backfill—the function of initial backfill is to provide protection over the top of the pipe when final backfill is placed.

Where coarse materials are used for bedding, the same coarse material should be used for haunching to prevent soil migration. Embedment material should not contain debris, frozen lumps, or rock of diameter greater than $1\frac{1}{2}$ in. (38 mm).

Often, local labor codes require the use of a trench box or sheeting to support the walls of an open trench during construction. Removal of these supports after pipe installation may leave gaps in the pipe zone of the trench. These voids should be filled with additional embedment material after sheeting removal. In some cases, it may be desirable to leave the sheeting in place as part of the pipe embedment or to use a "notched" trench box.

11.4.8 Final Backfill

After placement and compaction of initial backfill, the balance of backfill materials may be machine-placed and should contain no large stones, rocks, frozen material, or debris. Compaction, when required, should provide specified soil densities. Prior to compaction, sufficient cover should be in place to provide adequate protection to the pipe.

11.5 Appurtenances

11.5.1 Overview

Piping systems include not only pipe but also various appurtenances for control, operation, and maintenance of systems. These include control valves, relief valves, fire hydrants, and fittings. Proper design, installation, and operation of PVC piping systems must take into account appurtenances as well as pipe. Valves, air vents, and hydrants should be installed with their valves and hydrant stems plumb.

11.5.2 System Parts and Requirements

11.5.2.1 Control Valves

Control valves (e.g., gate or butterfly) are needed in a system to permit isolation of pipes. Secondary lines are valved from main feeder lines.

11.5.2.2 Relief Valves

Common relief valve types and their applications are as follows:

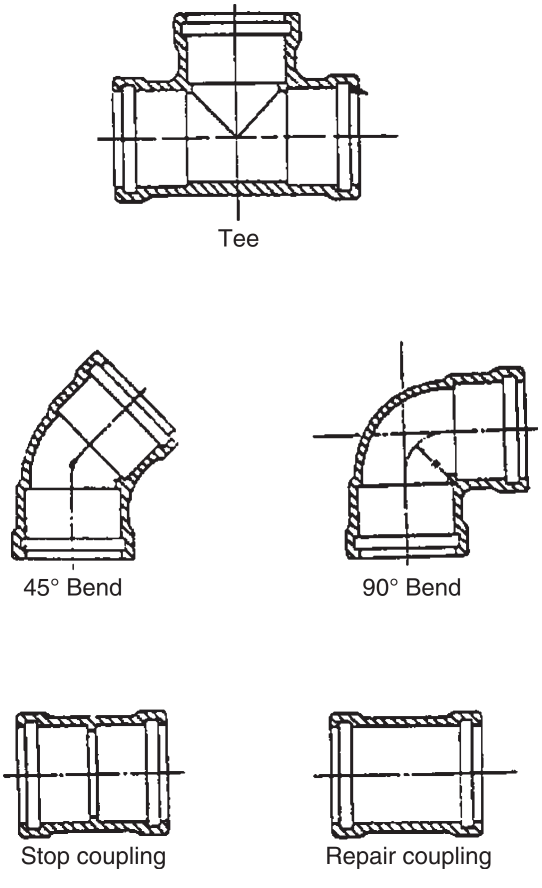
- Pressure-relief valves are important in long pipelines for surge control.
- Air-relief valves are recommended at high points and should be sized according to manufacturer recommendations.
- Vacuum-relief valves prevent a vacuum from developing.
- Blow-off and drain valves are used at low system elevations and dead ends to permit line flushing and to relieve pressure.

11.5.2.3 Fire Hydrants

Fire hydrants are normally spaced to provide fire protection as required by the authority having jurisdiction. Lines that service fire hydrants are normally 6 in. (150 mm) in diameter or larger. Hydrant connections from main lines should be valved.

11.5.2.4 Fittings

Fittings are required to provide for changes in line direction or size and branch connections (e.g., tee and cross fittings). They are available in a variety of sizes and configurations. Injection molded PVC fittings are frequently used in small-diameter IPS (steel pipe size equivalent) and CIOD (cast iron outside diameter) pipe systems (see Chapter 5 for more on fittings). Fabricated PVC fittings are available for any size PVC pipe. Figure 11.3 shows typical PVC fittings.


Tee

45° Bend

90° Bend

Stop coupling

Repair coupling

Fig. 11.3 Typical PVC pipe fittings.

11.5.3 Appurtenance Installation

11.5.3.1 Control Valves

The weight of control valves should not be borne by the pipe; rather, valves should have individual supports such as crushed stone, concrete pads, or a well-compacted trench bottom. Control valves in pressurized systems require anchorage or thrust restraint to prevent movement from pressure thrust, which occurs in cases where the valve is closed or when torque is experienced from a power actuator. Butterfly valves may not function properly on certain sizes of PVC pipe because wall thickness may interfere with disc movement. Special adapters may be required.

11.5.3.2 Relief Valves

As is the case for control valves, relief valve weight must not be carried by the pipe. Again, valves should be provided with individual support.

11.5.3.3 Fire Hydrants

Fire hydrant weight should not be carried by the connected pipe. Hydrants, hydrant lead valves, fittings, and branch tee connectors should be supported by crushed stone, concrete pads, or a well-compacted trench bottom. Hydrants should be set plumb at designed burial depth and firmly braced during installation. Utilizing a concrete foundation (Fig. 11.4) for fire hydrant installation provides thrust restraint and anchorage.

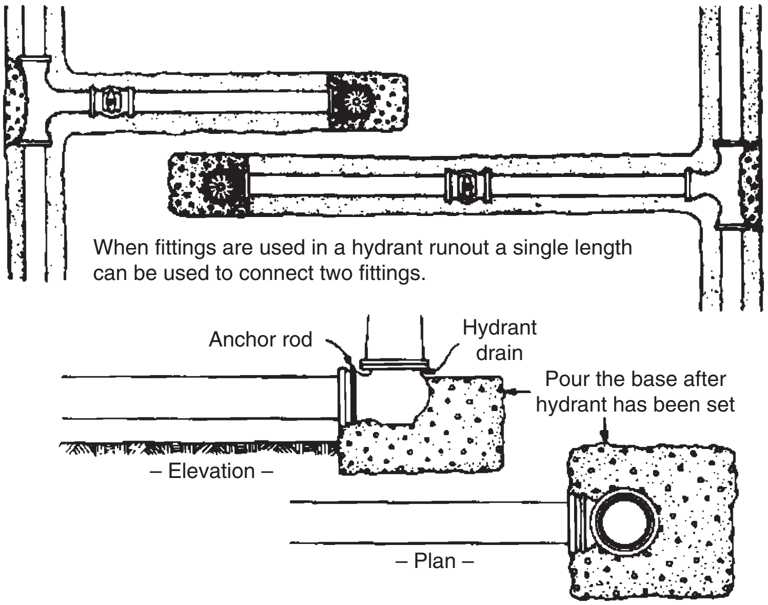
11.5.3.4 Fittings

Iron fitting weight should be supported by properly compacted embedment. Fittings need thrust restraint so that movement which would otherwise be caused by longitudinal line thrust is prevented.

11.5.3.5 Thrust Restraint

Thrust blocking or joint restraint should be provided, as needed, to prevent movement of pipe or appurtenances in response to thrust forces. Thrust blocking or joint-restraint devices may be needed when the pipeline:

- changes direction at a fitting (tees, bends, elbows, and crosses)
- changes size (reducers)



When fittings are used in a hydrant runout a single length can be used to connect two fittings.

This type of hydrant foundation acts as a thrust-block, as an anchorage against frost heave and eliminates washouts from waste-water drain.

Fig. 11.4 Fire hydrant foundation.

- stops (dead ends)
- develops thrusts when valves and hydrants are closed.

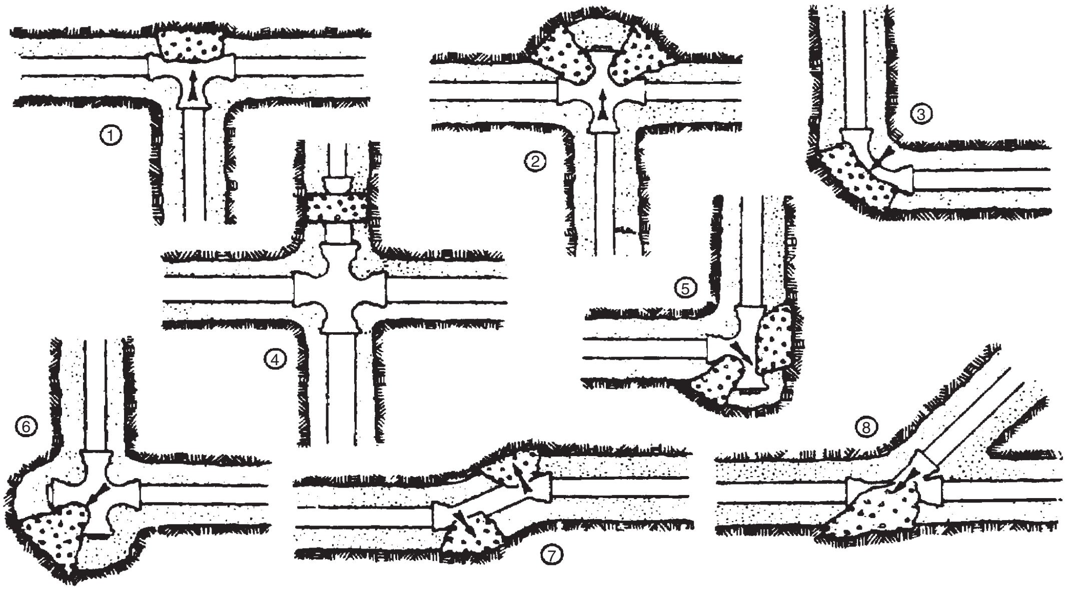
Size and type of thrust blocking or joint-restraint devices depend on:

- maximum system pressure (including field testing pressures)
- pipe size
- type of fitting or appurtenance
- line profile (horizontal or vertical bends)
- soil type
- depth of cover.

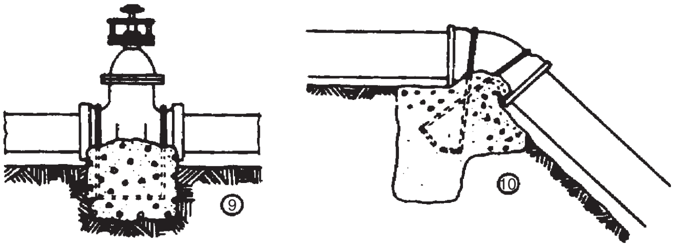
Figures 11.5, 11.6, and 11.7 display common configurations of thrust blocking and joint restraint used in pressurized water systems.

Table 11.1 shows the approximate thrust developed at fittings and appurtenances for each 100 psi of either test or operating pressure. Thrusts from greater or lesser pressures may be proportioned accordingly.

Design methods available for sizing thrust blocks use assumed soil-bearing values. Table 11.2 has approximate allowable load-bearing capacities for various types of soils. These bearing loads pertain to horizontal thrusts when depth of soil cover exceeds 2 ft. When doubt exists, soil-bearing tests should be conducted.



If thrusts due to high pressure are expected, anchor valves as shown below. At vertical bends, anchor to resist outward thrusts.



1. *Through line connection, tee*
2. *Through line connection, cross used as tee*
3. *Direction change, elbow*
4. *Change line size, reducer*
5. *Direction change, tee used as elbow*
6. *Direction change, cross used as elbow*
7. *Direction change*
8. *Through line connection, wye*
9. *Valve anchor*
10. *Direction change vertical, bend anchor*

Fig. 11.5 Types of thrust blocking.

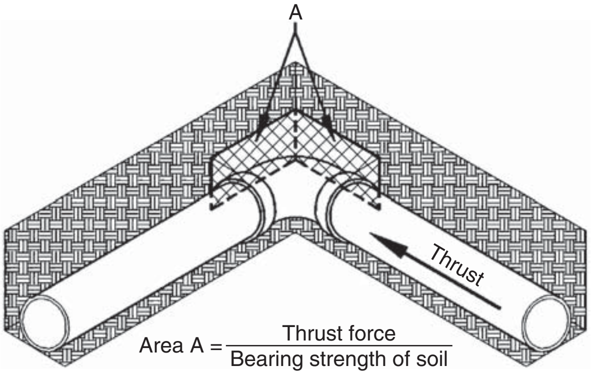
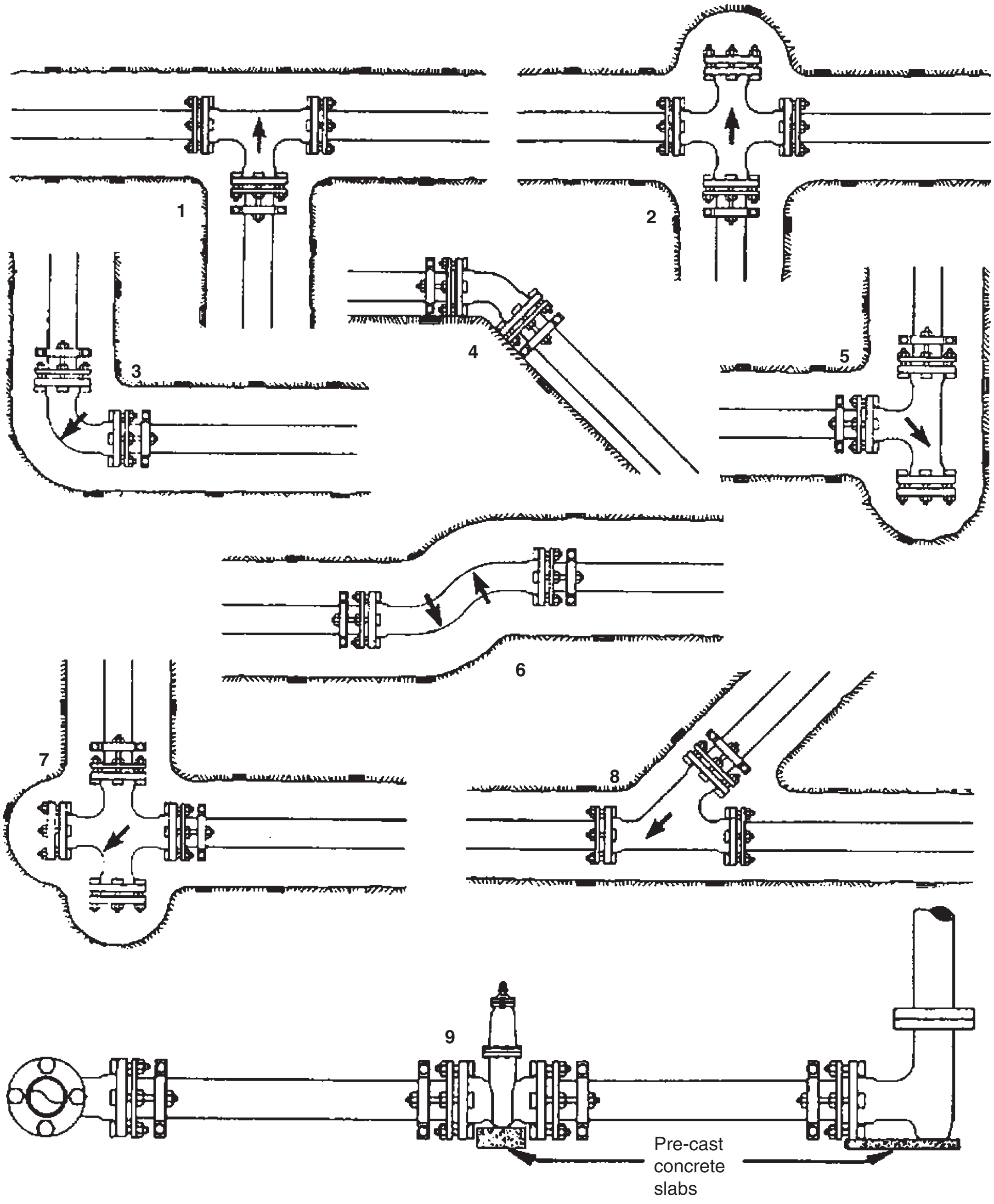


Fig. 11.6 Thrust block area.



1. *Through line connection, tee*
2. *Through line connection, cross used as tee*
3. *Direction change, elbow*
4. *Direction change vertical, bend*
5. *Direction change, tee used as elbow*
6. *Offset*
7. *Direction change, cross used as elbow*
8. *Through line connection, wye*
9. *Hydrant run-out*

Fig. 11.7 Types of joint restraint.

Note: Adjacent pipe joints may also need to be restrained.

Table 11.1 Thrust developed (lb force) per 100 psi pressure for AWWA PVC pressure pipe (CIOD)

Pipe size	Fitting 90° elbow	Fitting 45° elbow	Valves, tees, dead ends
4	2,560	1,390	1,810
6	5,290	2,860	3,740
8	9,100	4,920	6,430
10	13,700	7,410	9,680
12	19,400	10,500	13,700
14	26,000	14,100	18,400
16	33,600	18,200	23,800
18	42,200	22,900	29,900
20	51,800	28,100	36,600
24	73,900	40,000	52,300
30	114,000	61,600	80,400
36	163,000	88,000	115,000
42	220,000	119,000	156,000
48	287,000	155,000	203,000

Table 11.2 Estimated bearing strength

Soil type	psi
Muck, peat, etc.	0
Soft clay	500
Sand	1,000
Sand and gravel	1,500
Sand and gravel with clay	2,000
Sand and gravel cemented with clay	4,000
Hard pan	5,000

Design methods for mechanical thrust restraint devices are available from several device manufacturers. Restraint-design computer programs calculate required restrained lengths and guide the user to suggested configurations.

Design of thrust blocking can be calculated as shown in the following example:

Example 11.1 Calculate thrust and thrust block size for the following project:

Thrust block design conditions:

- pipe size = 24 in.
- configuration = 90° elbow
- maximum test pressure = 200 psi
- soil type = sand

Solution

Step 1: Calculate thrust

From Table 11.1:

Thrust on 24-in. 90° elbow = 73,900 lb per 100 psi operating pressure

Total thrust for 200 psi = $2 \times 73{,}900 \approx 148{,}000$ lb

Step 2: Calculate thrust block size

From Table 11.2:

Safe bearing load for sand = 1,000 lb/ft^2

$$\text{Total thrust support area} = \frac{148{,}000}{1{,}000} = 148 \text{ ft}^2$$

Additional information on thrust block design can be found in American Water Works Association (AWWA) Manual M23, PVC Pipe — Design and Installation. For mechanical joint restraint calculations, consult the joint restraint device manufacturer for recommendations regarding design.

11.5.3.6 Service Connections

Service connections vary in size from small (which supply individual homes) to large outlets (for industrial users). Service connections to PVC water mains are accomplished in the field via:

- tapping through service saddles;
- tapping with large service connections through tapping sleeves;

- using injection-molded couplings with threaded outlets;
- direct tapping.

During the drilling or tapping of any pressurized pipe, essential, basic safety precautions assure personal safety of workers in the event of a sudden and unexpected pipe failure. Although such failures are extremely infrequent, the following safety precautions are recommended:

- When a worker is drilling or tapping pipe under pressure, a second worker or supervisor should be in the immediate vicinity.
- In addition to normal protective clothing, goggles or face shields should be worn.
- Ladders should be provided in the work area for quick exit.
- A protective blanket with a hole at its center to permit installation and operation of the tapping and drilling machine should be provided to cover the exposed area of the pipe.
- The tapping crew should be familiar with the location of valves and their proper operation in case depressurization of the line is needed.

The literature listed below provides additional information and recommendations; tapping crews should be familiar with:

- UNI-PUB-8, Tapping Guide for AWWA C900 PVC Pressure Pipe
- Uni-Bell tapping video, Tapping of PVC Pressure Pipe
- AWWA C605, Underground Installation of Polyvinyl Chloride (PVC) Pressure Pipe and Fittings for Water
- AWWA M23, PVC Pipe – Design and Installation.

11.5.3.7 Service Saddles

Service connections may be made using a service saddle (Fig. 11.8). The maximum outlet size recommended with service saddles is 2 in. (50 mm). The service saddle manufacturer should be consulted for recommended pressure capacity. When this type of connection is made, equipment is used that attaches to the corporation stop, permitting a cutting tool to be fed through the corporation stop to cut a hole in the pipe. No threading of the pipe wall is required since the corporation stop is threaded into the service saddle. Service saddles used for attaching service connections to PVC water pipe should:

- provide full support around the circumference of the pipe;
- be properly sized and designed for use with PVC pipe;
- provide a bearing area of sufficient width along the axis of the pipe, ensuring that the pipe is not distorted when the saddle is properly tightened;
- be installed according to manufacturer recommendations.

(a) Service saddle (b) Saddle tapping

Fig. 11.8 Examples of (a) service saddle and (b) saddle tapping.

Service saddles should not:

- have a U-bolt type of strap;
- have a clamping arrangement that is not fully contoured to the outside diameter of the pipe.

A number of tapping machines are available that can drill through a corporation stop. The cutting tool should be a shell-type design, have a minimum of two slots, retain the cut coupon after penetrating the PVC pipe wall, and be designed to accommodate AWWA pipe wall thicknesses. Some shell cutters are designed only for PVC pressure-rated pipe (ASTM D2241). Consequently, they do not have sufficient throat depth to handle heavier walled pipe. It is recommended that the tapping machine have an operator-controlled feed rate. In no case should a handheld electric drill be used.

11.5.3.8 Tapping Sleeves

Tapping sleeves (Fig. 11.9) are used when service connections larger than 2 in. (50 mm) in diameter are to be installed in a PVC water main. Tapping sleeves may be used for making large taps under pressure. Lightweight iron or fabricated steel tapping sleeves are available.

When tapping sleeves are ordered from a manufacturer, specifications should be made concerning the outside diameter of the pipe being tapped, the size of the outlet desired, and the working pressure. This ensures that the sleeve furnished is satisfactory in all regards, including outside diameter tolerance and minimum sleeve length.

Tapping sleeves should be assembled in accordance with manufacturer recommendations. Drilling equipment can be purchased or rented from sleeve manufacturers, who also furnish instructions and/or instructors trained in making such taps. Other possible sources of information are contractors who specialize in this type of work.

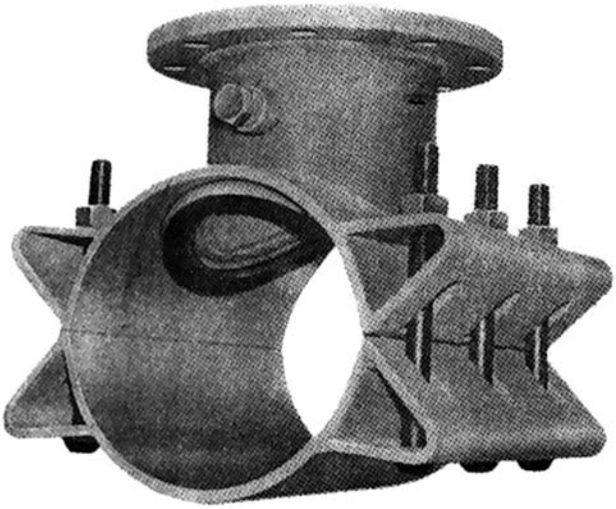


Fig. 11.9 Tapping sleeve.

Tapping sleeves should be supported independently from the pipe. Sleeves made of fabricated steel are lighter in weight than those of other available materials. Any support used during installation should be left in place after tapping. Thrust blocks or joint restraint should be used with tapping sleeves, the same as with any other fitting or appurtenance.

11.5.3.9 Tapped Couplings

Service connections can be made with an injection-molded or fabricated coupling, which has one or two center outlets that provide tapping threads into the coupling wall. Tapped couplings are available to accommodate various mainline sizes with several tap configurations. Couplings should conform to applicable AWWA and/or CSA standards and provide threads per AWWA C800 requirements.

11.6 Direct Tapping

Service connections can be made by direct tapping of AWWA PVC pipe and insertion of a corporation stop. This method is suitable for Class 235 (DR 18) and Class 305 (DR 14) PVC pipe of 6-in. (150-mm) through 16-in. (400-mm) diameter. Sizes 14-in. (350-mm) and 16-in. (400-mm) DR 25 pipe may also be direct tapped. This method is not suitable for 4-in. (100-mm) diameter and smaller pipe or for 18-in. (450-mm) diameter and larger. In some jurisdictions the above size restrictions may be modified.

Fig. 11.10 Typical slotted core cutter.

The recommended direct tapping equipment and corporation stops should be used. Corporation stops should be AWWA tapered, with thread complying with AWWA C800. Tapping crews unfamiliar with direct tapping of PVC pipe should practice a few dry taps on pieces of scrap pipe to learn the appropriate machine adjustments (such as tapping depth).

Proper procedure ensures a successful and safe tapping operation. Direct tapping under pressure begins with a preoperative inspection consisting of examining the PVC pipe and its corporation stop to ensure that materials are appropriate for direct tapping. The tapping machine itself should also be inspected for wear, sharpness, and overall condition of the cutting/tapping tool (Fig. 11.10).

Placement of the tapping machine on the pipe is done in accordance with manufacturer recommendations. The cutting operation itself is done with a sharp shell-cutter tool, lubricated with manufacturer-recommended lubricant.

The threading operation should begin immediately after cutting. Post-operation inspection is necessary to ensure there is no leakage at the threads. Direct tapping of butt-fused PVC is not recommended.

11.6.1 Connecting Service Lines

It is recommended that all service connections (service saddles and direct taps) be installed so that the outlet is angled between 45° above the horizontal (Fig. 11.11) and at the horizontal (Fig. 11.12). A bend, or “gooseneck,” in the service line should always be provided to ensure flexibility and to accommodate the effects of load due to settlement

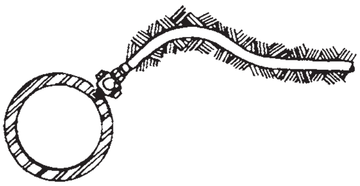


Fig. 11.11 Vertical gooseneck.

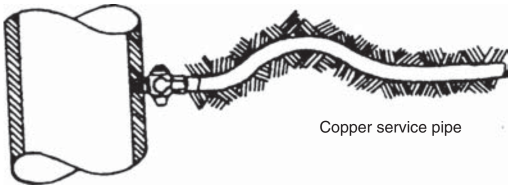


Fig. 11.12 Horizontal gooseneck.

or expansion/contraction. The bend of the gooseneck must be kept below the frost penetration level. Proper soil consolidation should be provided in the area of the service connection.

11.7 Procedures for Locating, Leak Detection, Grounding, and Thawing

11.7.1 Locating Buried Pipelines

The best method for locating pipelines is the use of accurate "as-built" drawings. Although municipalities retain up-to-date records of installations, problems may occur if they do not accurately reflect field work, if landmarks (curbs, hydrants, light standards) have been moved, or if road grades have been altered. In case of these circumstances, alternate methods of locating nonconductive buried pipelines may be required.

Electronic scopes employ a conductor that is buried with the pipe, which can be easily connected to a valve box or hydrant.

Metallic wire can be used as a tracer or conductor. An inexpensive metallic tracer wire can be buried with the pipe. Plastic-coated metal strips designed specifically for this purpose are also available. These brightly colored strips double as warning markers. Different colored tracer tapes may be used to identify various underground utilities.

The American Gas Association (AGA) polled its Plastic Materials Committee to survey plastic facility location methods. Of the respondents, 98% reported using insulated tracer wire, with size #12 or #14 being predominant. The tracer wire was generally accessible at the riser but not electrically connected to it. AGA also reported, in Plastic Pipe Manual for Gas Service, that most companies had greater success with conductive systems (i.e., the transmitter is physically connected to the tracer wire) than with inductive systems (i.e., the transmitter induces a signal onto the tracer wire).

Acoustical methods of locating plastic pressure pipe use an acoustical device composed of a transmitter and a receiver. Transmitters introduce a sound wave into the system, which can propagate along plastic pipes. The receiver is used in its traditional mode to locate the source of the sound and thus locate the line. Transmitters can be attached to service lines, fire hydrants, and water meters to facilitate the location of a wide range of pipe diameters.

Electronic pipe detection devices called "ground-penetrating radar" produce pulses of energy (similar to seismographs) which when directed downward send back echoes. Trained operators can identify the depth and location of buried water pipes using such devices.

11.7.2 Leak Detection

The equipment used for acoustic location of plastic pressure pipe also has been adapted to effectively detect leaks in these same pipes. A study performed by the National Research Council in Canada and funded by the American Water Works Association Research Foundation (AWWARF) concluded that acoustical leak detection and computer correlation can successfully pinpoint leaks in plastic water mains.

11.7.3 Grounding Electrical Services

The AWWA policy statement maintains that water utilities have no obligation to provide a means of grounding any electric circuit and that a water utility reserves the right to use nonmetallic pipes.

Many municipalities have adopted regulations that prohibit grounding to water distribution pipes and typically require installation of grounding rods specifically for electrical systems.

11.7.4 Frozen Pipes

The possibility of frozen mains and service connections should always be considered in the design and installation of water distribution systems (see Chapter 3 for more on weathering and temperature extremes). In extreme cases, such as in the permafrost areas of the far north, pipe may be installed with one or a combination of several heating and insulation systems.

Frozen mains are not easily thawed and therefore usually need redesign before the subsequent cold season. Service connections are generally much easier to thaw and may be handled on an as-needed basis.

Proper management of water distribution systems in relation to freezing should consider:

- prevention
- traditional thawing methods
- alternative thawing methods.

The remainder of this section will address these three important considerations.

11.7.4.1 Prevention

As a general rule, pipes should be buried to at least 12 in. below the normal frost depth line to prevent freezing (Fig. 11.13). When these minimum depths of cover are observed, there are rarely any piping problems resulting from freezing systems.

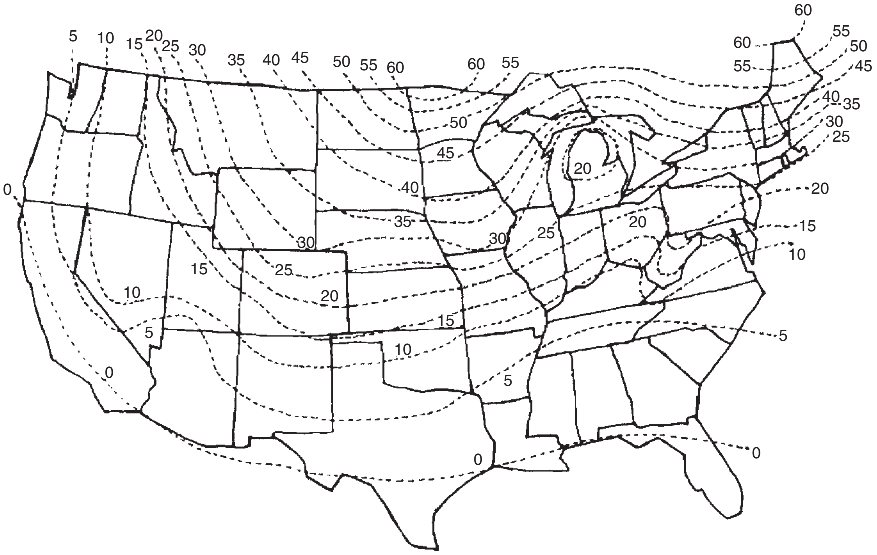


Fig. 11.13 Annual frost penetration, in.

Heavy clay soils are typically more resistant to frost penetration (particularly when they are covered with a layer of undisturbed snow) than soils consisting of sand or loose gravel. Therefore, even greater burial depths may be necessary in areas where sand and gravel will be the primary backfill material. Alternatively, compacted clays may be required for backfilling such pipes.

In Canada, stating the minimum cover for buried pipelines due to frost penetration is a distinct step in the design process. Because of the wide variation of pertinent variables such as annual number of freezing days, soil type, and groundwater elevation, burial depth is selected on a project-by-project basis. A study was conducted in Alberta, Canada, on PVC pipe in various backfill materials to evaluate cold weather performance. This study concluded that PVC pipe performed very well after repeated seasons of subzero weather.

One area of design that is often a cause of frozen services is the vertical gooseneck. Traditionally, a service stop is placed in a main between the 45-degree and horizontal position; the service tubing is curved gently around and then put on grade to the house (Fig. 11.11). However, goosenecks are rarely applied to 2-in. diameter or larger service connections. As can be seen in Fig. 11.11, a vertical gooseneck may bring the service pipe considerably closer to the surface than the water main, thus inviting freezing. The solution is to use a horizontal gooseneck (Fig. 11.12). This should eliminate any chances of freezing.

11.7.4.2 Thawing Frozen Pipes

Designing pipe burial depth to prevent freezing is the best course. If freezing occurs, thawing of water mains is different from thawing of service lines, as shown below.

11.7.4.2.1 Thawing Water Mains

There are no reliable methods for thawing frozen water mains, regardless of pipe material used. There are problems with all of the traditional methods used for thawing mains.

Electrical thawing can be quite dangerous. Problems may occur if there is poor conductivity between pipe main joints or between joints in the service pipe, electrical grounds to the service or main, and/or direct contact with other metal pipes such as in a natural gas system. Elastomeric joining materials in metal pipes often become overheated, a situation that can cause leakage. In addition, any circuits grounded to the water system may be damaged or destroyed. Plastic pipe cannot be thawed electrically.

11.7.4.2.2 Thawing Service Lines

A nonelectrical thawing technique has been developed to thaw frozen service pipes. Hot water is introduced into the frozen area by a small tube fed into the service pipe. The small tube technique involves gaining access to the service in the house, connecting a fitting that allows drainage, and feeding a small ($^3/_{16}$- or $^1/_4$-in.) tube into the service. If the curb stop is fully open, the feed tube will pass through many irregularities with some manipulation. The tube is fed to the point of blockage and then hot water is pumped through the tube. The tube is advanced until the entire blockage has melted.

Drainage from the service increases rapidly as soon as the blockage is eliminated. The tube is then withdrawn. Figures 11.14 and 11.15 show a schematic layout for this alternative thawing method.

When water services are to be thawed by the method described, several precautions should be taken. Since this procedure forms a cross-connection with the potable water system, all equipment should be thoroughly cleaned and every effort taken to maintain cleanliness. The hot water used should be of potable quality; if it is not, the line should be disinfected in accordance with AWWA Standard C651, Disinfecting Water Mains, before the connection to the plumbing system is made. The line may be flushed into a basement drain or suitable container.

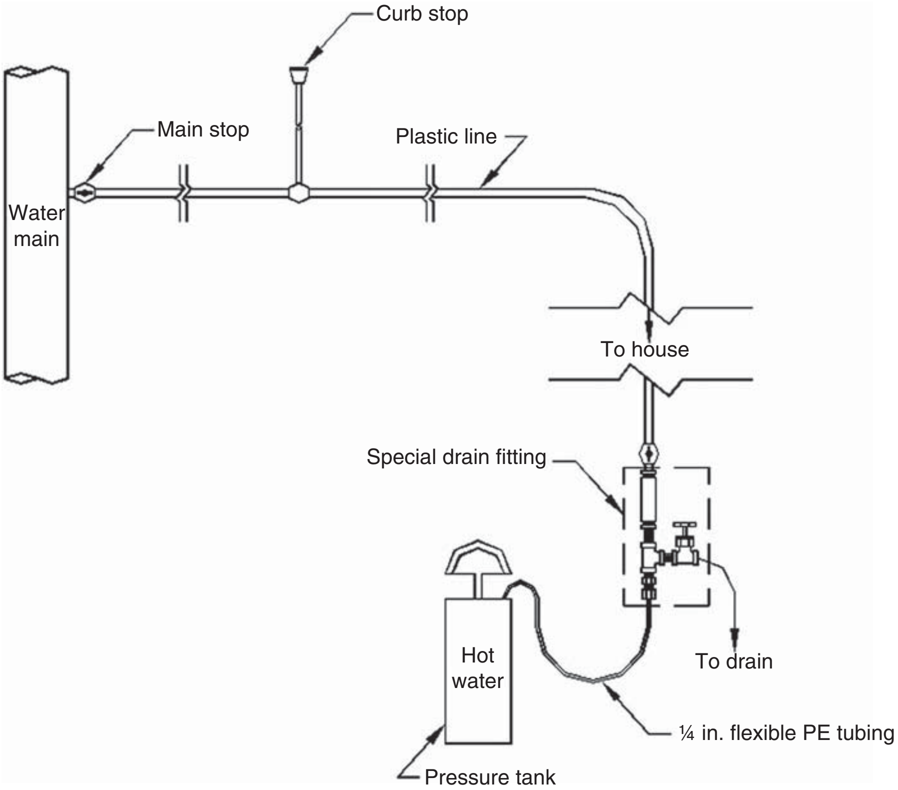


Fig. 11.14 Schematic layout.

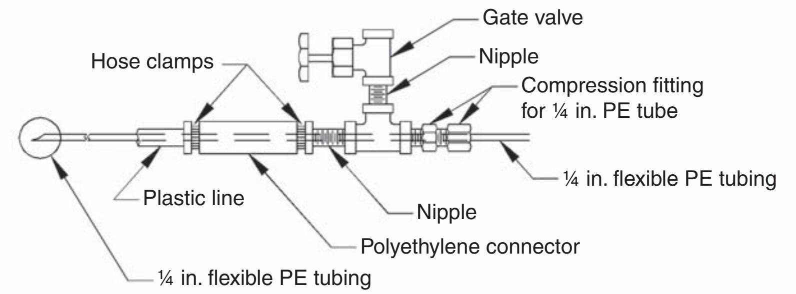


Fig. 11.15 Close up of schematic layout.

Thawing by warm water through a tube has many advantages: it is inexpensive; it is effective in the hands of the average worker; no special crews are required to ensure that electrical connections are continuous; a crew of one can easily thaw a frozen service; and this method can be used for all service/main material combinations.

11.8 Testing of the Pipe System

The usual way to test a pipe system is to pressure-test portions of a line as they are completed, in advance of the entire system completion. Three parameters should be considered when testing:

1. The pipe to be tested must be sufficiently backfilled and braced to prevent movement while under test pressure.
2. Joint restraint at fittings should be permanent and constructed to withstand test pressure. If concrete thrust blocks are used, sufficient time must be allowed before testing to permit the concrete to cure. A cure time of 7 days is recommended when Type I Portland cement is used; 3 days is recommended when Type III high-early-strength Portland cement is used. (Note that fast-setting cements generate much higher temperatures, which can be damaging to PVC pipe; these should be avoided, if possible.)
3. Test ends should be restrained to withstand the appreciable thrusts that are developed under test pressure.

11.8.1 Filling the Line

The line should be filled slowly from any available source of potable water. When any portion of line to be tested is not in range of an existing water system, another source will have to be provided. The water may be introduced from lines in service through valved connections, by temporary connections to hydrants, to taps made in the new line, or at the connection in the line cap. All such connections, however, should be made at the lowest possible point in the line. Flow velocity during line filling should not exceed 1 ft/s (0.3 m/s). Table 11.3 shows the quantity of water required to fill lines.

11.8.2 Expelling Air from the Pipeline

All air should be expelled from a pipeline during filling and again before acceptance tests are conducted. Automatic air release valves are recommended. Compressed entrapped air can create surges that exceed the test pressure prescribed and may cause system failure. Furthermore, entrapped air may cause imprecise pressure test results.

11.8.3 Acceptance Testing

The purpose of acceptance testing is to locate defects in materials or workmanship, thereby permitting proper repair. A test pressure of 50% above the normal operating

Table 11.3 Approximate volume of water required to fill a line

Pipe size, in.	U.S. gal/100 ft	L/10 m	m^3/10 m
4	70	90	0.09
6	153	190	0.19
8	259	320	0.32
10	405	500	0.50
12	573	710	0.71
14	810	1,010	1.01
16	1,050	1,300	1.30
18	1,320	1,630	1.63
20	1,620	2,000	2.01
24	2,310	2,860	2.86
30	3,550	4,400	4.40
36	5,080	6,310	6.31
42	7,200	8,940	8.94
48	9,400	11,700	11.70

pressure is generally sufficient. Test pressure should not exceed design pressure for pipe, appurtenances, or thrust restraints.

Pressures greater than what a design specifies should not be permitted to build up for a given test. This can happen if pressure is read from a gauge located at a high point in the line. In such cases, the actual pressure at low points will be greater. Pressures greater than those specified may cause damage to equipment and/or move thrust blocks. Specified test pressure should be maintained for the specified test time while monitoring for pressure loss is done. **Air pressure testing of installed PVC pressure pipe is expressly prohibited for reasons of safety.**

A properly installed line normally requires little or no make-up water. The acceptance test establishes that the section of line tested, including all its joints, fittings, and other appurtenances, will not leak. In addition, testing provides insight regarding the adequacy of the pipe assembly.

For acceptance tests, pressure should be maintained at a constant level throughout the testing period. If the amount of additional water introduced into the line during the test exceeds the testing allowance, the section fails the acceptance test. If the

Table 11.4 Testing allowance for PVC pipe, U.S. gal/h (L/h)

Pipe size, in.	Average test pressure in line, psi				
	50	100	150	200	250
	Testing allowance/1,000 ft (50 joints)				
4	0.19 (0.72)	0.27 (1.02)	0.33 (1.25)	0.38 (1.44)	0.43 (1.63)
6	0.29 (1.10)	0.41 (1.55)	0.50 (1.89)	0.57 (2.16)	0.64 (2.42)
8	0.38 (1.44)	0.54 (2.04)	0.66 (2.50)	0.76 (2.88)	0.85 (3.22)
10	0.48 (1.82)	0.68 (2.57)	0.83 (3.14)	0.96 (3.63)	1.07 (4.05)
12	0.57 (2.16)	0.81 (3.07)	0.99 (3.75)	1.15 (4.35)	1.28 (4.84)
14	0.67 (2.54)	0.95 (3.60)	1.16 (4.39)	1.34 (5.07)	1.50 (5.68)
16	0.76 (2.88)	1.08 (4.09)	1.32 (5.0)	1.53 (5.79)	1.71 (6.47)
18	0.86 (3.26)	1.22 (4.62)	1.49 (5.64)	1.72 (6.51)	1.92 (7.27)
20	0.96 (3.63)	1.35 (5.11)	1.66 (6.28)	1.91 (7.23)	2.1 (8.10)
24	1.15 (4.35)	1.62 (6.13)	1.99 (7.53)	2.29 (8.67)	2.56 (9.69)
30	1.43 (5.41)	2.03 (7.68)	2.48 (9.39)	2.87 (10.86)	3.20 (12.11)
36	1.72 (6.51)	2.43 (9.20)	2.98 (11.28)	3.44 (13.02)	3.85 (14.57)
42	2.01 (7.61)	2.84 (10.75)	3.48 (13.17)	4.01 (15.18)	4.49 (17.00)
48	2.29 (8.67)	3.24 (12.26)	3.97 (15.03)	4.59 (17.38)	5.18 (19.42)

Note: PVC pipe with elastomeric joints, when properly installed, complies with requirements for private fire service mains as specified by the National Fire Protection Association.

amount of water added is less than the amount allowed, the section passes the test. A testing allowance is provided to give a contractor some provision for entrapped air, engagement of joint restraints, seating of gaskets, slight swelling of the pipe diameter, temperature variations, and the like. The testing allowance is not intended to permit a pressure piping system to actually leak. The American Water Works Association installation standard AWWA C605 requires all visible leaks be repaired, regardless of extent.

Entrapped air in a line during testing affects test results. Generally, the project engineer will establish a testing allowance and indicate methods and a procedure for testing. If this is not done, Table 11.4 may be used to determine maximum make-up water allowable.

Acceptance testing is also discussed in standard AWWA C605, Underground Installation of Polyvinyl Chloride (PVC) Pressure Pipe and Fittings for Water.

The following procedure is recommended for determining if air is entrapped in a pipe line:

1. Pressurize with water to desired test pressure.
2. Allow pressure to drop to predetermined level.
3. Measure make-up water required to establish test pressure.
4. Repeat second and third steps.

If the make-up water required to fill a line the second time is significantly less than what was required for the first filling, then air is present in the line. If no significant difference is measured, a leak is probable.

The testing allowances given in Table 11.4 were calculated using Equation 11.1.

Equation 11.1

$$L = \frac{ND\sqrt{P}}{7{,}400}$$

where:

L = testing allowance, gal/h

N = number of joints in the tested line (pipe and fittings), dimensionless

D = nominal pipe diameter, in.

P = average test pressure, psi

Note: Equation 11.1 for gasketed joint pipe in 20-ft lengths is used to account for a testing allowance of 10.5 gal/in. of pipe diameter/mi/day when evaluated at a pressure of 150 psi.

11.9 Disinfection of Potable Water Lines

Before being placed in service, all new and exposed portions of existing systems should be flushed and disinfected. Flushing should be done at flow rates sufficient to provide a velocity in the lines of at least 2.5 ft/s (0.8 m/s). Disinfection should comply with AWWA Standard C651, Disinfecting Water Mains.

The most common forms of chlorine used for disinfection are liquid, granules, and tablets. Liquid chlorine and calcium hypochlorite granules are mixed with water and fed into the completed line. Calcium hypochlorite tablets, on the other hand, are fastened to the pipeline with adhesive as each section is completed and water is introduced into the line, where it sits for at least 24 hours.

Improper disinfection with concentrated chlorine products can cause explosive conditions and health/safety hazards for crews. Large amounts of concentrated powdered chlorine, if thrown into the pipeline, may have deleterious effects on the interior wall or rubber gasket if allowed to remain for several months and if exposed to moisture. Such practices do not comply with AWWA C651 and should never be permitted.

After flushing the line and prior to connection for final service, samples of pipeline water should be collected and tested for bacteriological quality. If satisfactory test results are not obtained, disinfection must be repeated until tests meet the applicable specification. PVC pipe is not affected when proper disinfection practices are followed.

11.10 Sources

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CHAPTER 12

PVC Nonpressure Pipe Installation

Trench Construction
•
Pipe Laying
•
System Components
•
Inspection and Testing of the Pipe System

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12.1 Notation

A = OD tolerance (ASTM D3034 or F679), in.
B = excess wall thickness tolerance = 0.06t, in.
C = out-of-roundness tolerance (ASTM D3034 or F679), in.
DR = dimension ratio, dimensionless
ID_{avg} = pipe average inside diameter, in.
ID_{base} = pipe base inside diameter, in.
OD_{avg} = pipe average outside diameter, in.
t = minimum wall thickness (ASTM D3034 or F679), in.

12.2 Introduction

The importance of proper construction practices for any piping system cannot be overstated. A functional PVC *nonpressure* piping system depends on its raw materials, the research and development behind the technology, product specifications, manufacturing, quality control, design, and proper installation.

Recommended practices for nonpressure sewer pipe installation are presented in the following categories:

- trench construction
- pipe laying
- appurtenances
- inspection and testing of the pipe system.

12.3 Trench Construction

Excavation for pipe installation is minimal, being just enough to allow the trench to be safely maintained by available equipment and so trench sides will be stable under all working conditions. Furthermore, trench walls should be sloped or supported in conformance with all safety codes. Trenches should be backfilled as soon as is practical (but no later than the end of each workday). Other trench construction best practices are as follows:

- Trenches should be excavated to the alignment and elevations indicated on drawings; any deviations should be approved by the piping system design engineer.
- Appurtenances should be located and installed in accordance with design requirements.
- Excavated material should be stockpiled in a manner that will not endanger the workers.
- Hydrants, water and gas valves, manhole covers, and other utilities should be left unobstructed and accessible until work is completed.
- Gutters should be kept open or other satisfactory provisions made for street drainage.
- Unless otherwise approved, stockpiles should not obstruct adjacent streets, walks, or driveways.
- If excavated material is to be used for backfill, it should be easily accessible.

12.3.1 Minimum Trench Width

Where trench walls are stable (i.e., do not need supports) trench width should be sufficient for the safe placement and compaction of haunching. The space between pipe and trench wall must be wider than the compaction equipment used in the pipe zone. Minimum width recommendations are:

- 18 in. (450 mm) for 4- and 6-in. (100- and 150-mm) pipe sizes
- No less than 12 to 18 in. (300 to 450 mm) greater than the pipe OD for 8-in. (200-mm) and larger sizes
- Resulting minimum trench widths are given in Table 12.1.

Table 12.1 Narrow trench width, minimum

Pipe diam.		No. of pipe diams. of trench	Trench width	
in.	mm		in.	mm
4	100	4.3	18	460
6	150	2.9	18	460
8	200	2.9	24	610
10	250	2.5	26	660
12	300	2.4	30	760
15	375	2.0	30	760
18	450	1.8	32	810
21	525	1.6	34	860
24	600	1.5	36	920
27	675	1.5	40	1,020
30	750	1.4	42	1,070
33	825	1.4	45	1,140
36	900	1.4	48	1,220
42	1,050	1.4	54	1,370
48	1,200	1.3	60	1,530
54	1,350	1.2	66	1,680
60	1,500	1.2	72	1,830

Note: Minimum trench widths are intended to provide adequate spacing between pipe and trench wall for proper placing and compaction of haunching material; minimum widths may vary somewhat, depending on construction procedures used.

The minimum trench widths shown in Table 12.1 are based on the use of free-flowing granular materials (Classes I and II in Table 12.2). These materials can often be adequately compacted by nothing more than shovel-slicing and modest effort.

In places where trench walls must be supported:

- minimum widths are measured to the inside of the support structure;
- compaction of the foundation and embedment materials should extend to the trench walls, or sheeting should be left in place.

In addition to safety considerations, minimum trench widths in unsupported, unstable soils will depend on size and stiffness of pipe, stiffness of embedment and in-situ soil, and depth of cover. In some cases, where in-situ lateral soil resistance is negligible such as in very poor native soils (for example, peat, muck, or highly expansive soils), wide trenches may be more economical than a trench-support system. Under these conditions, a minimum width of embedment material is required to ensure that adequate embedment stiffness is developed to support the pipe without assistance from the sidewalls. Per ASTM D2321, if the native soil cannot sustain a vertical cut or if it is an embankment situation, the recommended minimum embedment width should be one pipe diameter on both sides of the pipe. Embedment materials should be Class II granular material or Class I crushed rock. Installation of embedment materials around the pipe should follow ASTM D2321 guidelines.

In either stable or unstable soil conditions, where wide trench construction is required a variation of vertical minimum trench width is to lay the pipe in a subditch and backcut or slope the sides of the excavation above the pipe, as shown in Figs. 12.1 and 12.2. This type of construction may be permitted where no inconvenience to the public or damage to property, buildings, subsurface structures, or pavement will result. In such a case, the width of the subditch below the top of the pipe should coincide with the values in Table 12.1.

12.3.2 Movable Sheeting, Trench Boxes, or Shields

When movable trench support is used, care should be taken to prevent disturbing the pipe location, jointing and embedment. Removal of any trench protection below the top of the pipe and within the dimensions outlined in Table 12.1 for wide trench installations should be prohibited after pipe embedment has been compacted. For this reason, movable trench supports should be used only in wide trench construction, where supports extend below the top of the pipe, or on a shelf above the pipe (with the pipe installed in a narrow, vertical-wall subditch). Any voids left in the embedment material as a result of trench protection removal should be carefully filled with granular material that is adequately compacted. Removal of bracing between sheeting should be done only where backfilling proceeds and where bracing can be removed in a manner that does not relax trench support. When trench boxes or shields are advanced, care should be taken to prevent longitudinal pipe movement or disjointing.

In instances where a trench support must extend to the bottom of a ditch, where a subditch is impractical, or where native soils are unstable, a simple alteration to the commonly used trench box may be the best alternative. A section one-half the length of the box, with a depth of approximately 2 ft cut from the bottom of the box (see Fig. 12.3) will allow the trench shield to ride on the bottom of a narrow trench, while allowing undisturbed pipe embedment to sit in the back half. As the trench box is moved forward, embedment may be compacted all the way to the trench wall.

Trench safety is especially important in deep installations.

Fig. 12.1 Deep installation.

12.3.3 Dewatering

Where running or standing water occurs in the trench bottom, or the soil in the trench bottom displays a "quick" tendency, the water should be removed by pumps and other suitable means such as well points or pervious underdrain bedding to prevent pipe flotation, until the pipe has been installed and the backfill has been placed to a sufficient height.

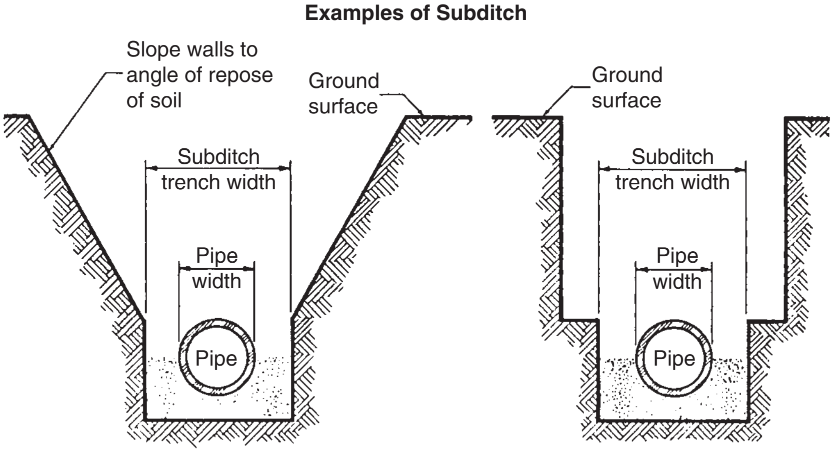


Fig. 12.2 Subditch examples.

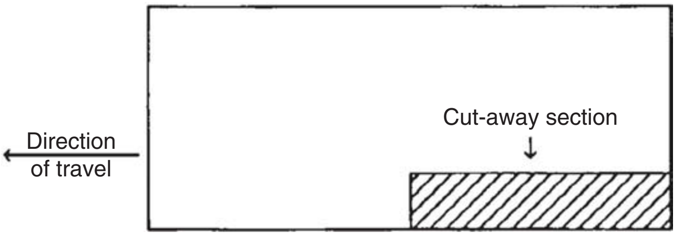


Fig. 12.3 Trench box schematic.

Care should be taken that any underdrain is of proper gradation and thickness to prevent migration of material between the underdrain, pipe embedment, and native soils in the trench below and at the sides of the pipe.

12.3.4 Preparation of Trench Bottom

The trench bottom should be constructed to provide a firm, stable, and uniform support for the full length of the pipe. Bell holes should be provided at each joint to permit proper joint assembly and alignment. Any part of the trench bottom excavated below grade should be backfilled to grade and compacted as required to provide firm foundation. When unstable subgrade conditions that will not provide adequate pipe support are encountered, additional trench depth should be excavated and the space refilled with suitable foundation material as specified by the design engineer. In severe conditions, special foundations may be required to maintain grade, as specified by the design engineer. A cushion of acceptable bedding material should always be provided between any hard foundation and the pipe. Ledge rock, boulders, and large stones should be removed to provide at least 4 in. (100 mm) of soil cushion on all sides of a pipe and accessories.

12.4 Pipe Laying

To prevent pipe damage, proper implements, tools, and equipment should be used for placement of the pipe in the trench; pipe and/or accessories should never be dropped into the trench. Pipe laying should generally commence at the lowest elevation and terminate at manholes, service branches, or clean-outs. Pipe bells can be laid either upstream or downstream. However, common practice is to lay them in the direction of work progress. Insertion of the spigot into the bell (rather than pushing of the bell over spigot) reduces the risk of soil or rubble being scooped under the gasket. Whenever pipe laying is interrupted, the open ends of installed pipe should be closed to prevent entrance of trench water, mud, and foreign matter.

Figure 12.4 shows the embedment zones described in Sections 12.4.1 through 12.4.4.

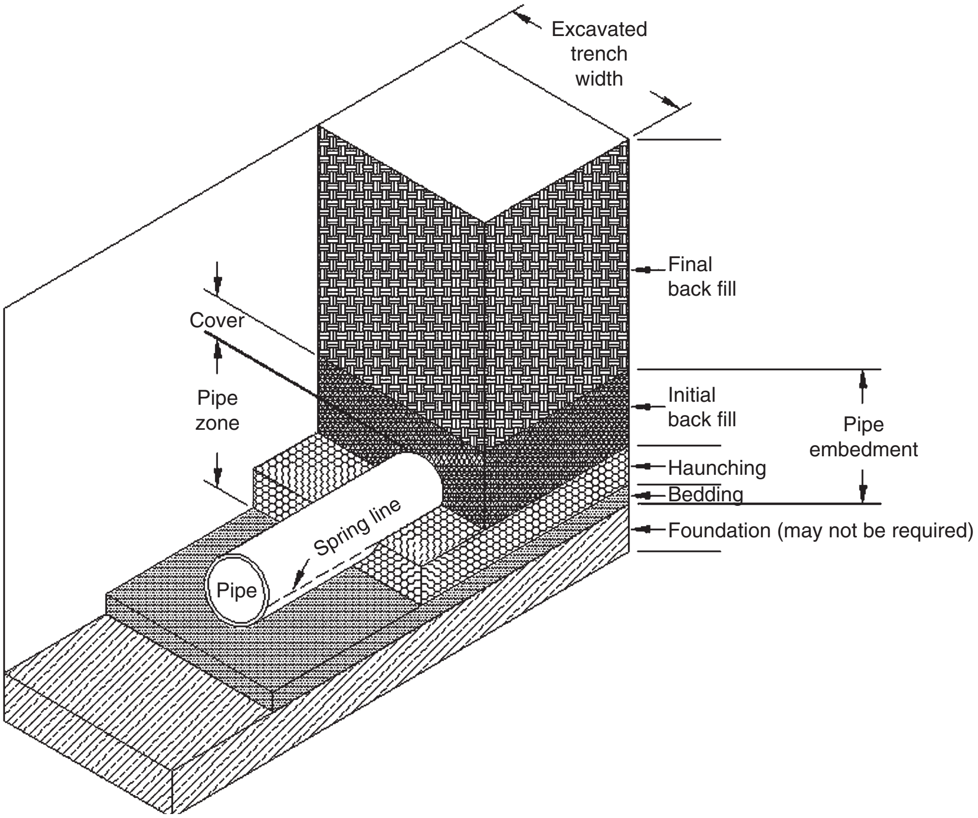


Fig. 12.4 Embedment zones of trench ditch.

12.4.1 Bedding

Bedding is primarily required to bring the trench bottom up to grade; it should be placed so as to provide uniform and adequate support under the pipe (Fig. 12.4). (Blocking should not be used.) Bell holes at each joint provide for proper assembly of the pipe while uniform pipe support is maintained. A depth of 4 to 6 in. (100 to 150 mm) is generally sufficient for bedding thickness. In trenches with natural materials of fine grains and in conditions where migration of trench wall material into bedding material can be anticipated, either wide trench construction or well-graded bedding material without voids should be used.

12.4.2 Haunching

The factor that most affects pipe performance and deflection is haunching material and density. Material should be placed and consolidated under the pipe haunch (Fig. 12.4) so adequate side support is provided to the pipe without causing displacement from its proper alignment (either vertical or horizontal). Where coarse materials with voids have been used for bedding, the same coarse material should also be used for haunching; consideration should be given to native soil migration. Haunching is placed up to the pipe's springline.

12.4.3 Initial Backfill

Initial backfill is the portion of pipe embedment that extends from the springline to some distance over the top of the pipe (Fig. 12.4). Since little or no additional side support is gained above the springline by initial backfilling, native soils may be used without employment of special compaction efforts. The sole purpose of the somewhat careful placement of these native trench materials is to protect the pipe from impact loads that might occur during final backfill.

At shallow depths of cover (3 ft and less), flexible conduits can deflect and rebound under dynamic loading conditions if the soil along the trench width is not highly compacted. Unless this compaction is achieved, road surfaces may be damaged. For pipe installed under flexible road surfaces at depths of 3 ft or less, it is recommended that a minimum of 95% Proctor density be achieved from the trench bottom up to the road surface using Class I or Class II materials, as described in Table 12.2. A minimum cover of 1 ft from the top of rigid road surfaces or 1 ft from the bottom of flexible road surfaces is recommended.

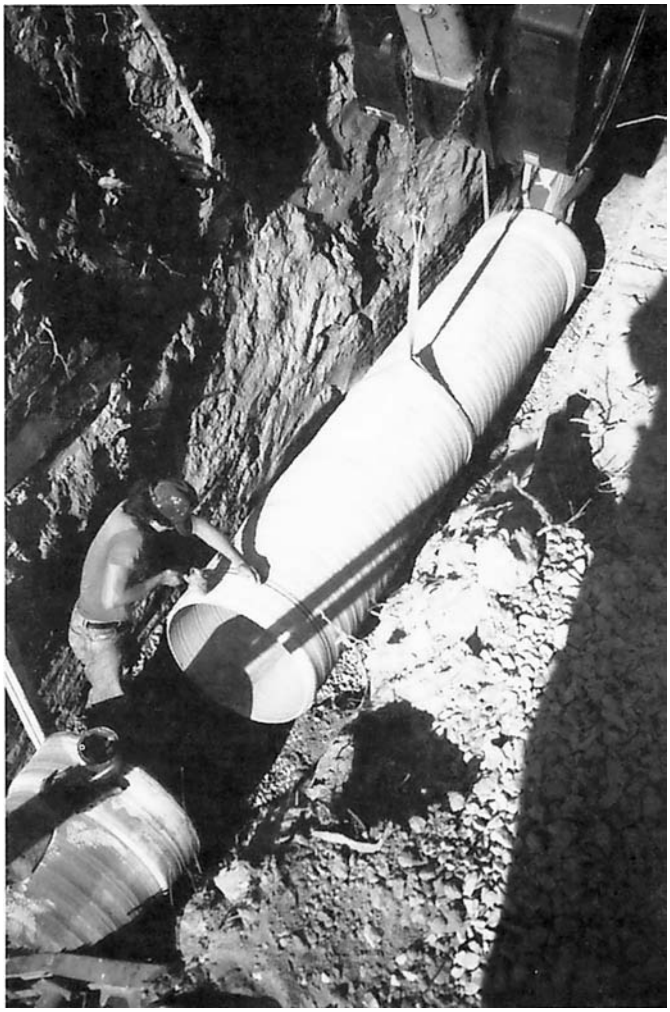


Fig. 12.5 Profile wall pipe installation.

12.4.4 Final Backfill

The material used in the final backfilling operation does not need to be as carefully selected as the bedding, haunching, and initial backfill materials. Final backfill material (Fig. 12.4) should have no boulders, frozen clumps of dirt, or rubble that could damage the pipe.

Under improved surfaces and shoulders of streets, roads, aprons, curbs, and walks, the final backfill should be placed using special compaction, as defined by the design engineer. Under open fields, lawns, wide shoulders, unimproved rights-of-way, or neutral grounds which are free of traffic, final backfill should be placed using *natural compaction*.

Table 12.2 Soil classes*

Soil group[A,B]	Soil class	American Association of State Highway and Transportation Officials (AASHTO) Soil Groups[C]
Crushed rock, angular[D]: 100% passing $1\frac{1}{2}$ in. sieve, ≤15% passing #4 sieve, ≤25% passing $\frac{3}{8}$ in. sieve and ≤12% passing #200 sieve	Class I	—
Clean, coarse-grained soils: SW, SP, GW, GP or any soil beginning with one of these symbols, with ≤12% passing #200 sieve[E,F]	Class II	A1, A3
Coarse-grained soils with fines: GM, GC, SM, SC, or any soil beginning with one of these symbols, containing >12% passing #200 sieve; sandy or gravelly fine-grained soils: CL, ML, or any soil beginning with one of these symbols, with ≥30% retained on #200 sieve	Class III	A-2-4, A-2-5, A-2-6, or A-4 or A-6 soils with more than 30% retained on #200 sieve
Fine-grained soils: CL, ML, or any soil beginning with these symbols, with <30% retained on #200 sieve	Class IV	A-2-7, A-2-6, A-2-4 with 30% or less retained on #200 sieve
MH, CH, OL, OH, PT	Class V Not for use as embedment	A5, A7

*Reprinted from ASTM D2321 ASTM International, 100 Barr Harbor Dr., West Conshohocken, PA.

[A] See Classification D2487, Standard of Soils for Engineering Purposes (Unified Soil Classification System).

[B] Limits may be imposed on the soil group to meet project or local requirements if the specified soil remains within the group. For example, some project applications require a Class I material with minimal fines to address specific structural or hydraulic conditions and the specification may read "Use Class I soil with a maximum of 5% passing the #200 sieve."

[C] AASHTO M145, Classification of Soils and Soil Aggregate Mixtures.

[D] All particle faces shall be fractured.

[E] Materials such as broken coral, shells, and recycled concrete, with ≤12% passing a No. 200 sieve, are considered to be Class II materials. These materials should only be used when evaluated and approved by the engineer.

[F] Uniform fine sands (SP) with more than 50% passing a No. 100 sieve (0.006 in., 0.15 mm) are very sensitive to moisture and should not be used as backfill unless specifically allowed in the contract documents. If use of these materials is allowed, compaction and handling procedures should follow the guidelines for Class III materials.

Natural compaction is attained by the loose placement of material (usually pushed or bladed) into the trench, rolling the surface layer with placement equipment, mounding the surface, and filling and maintaining all sunken trenches until final acceptance of the work. In natural compaction, the main consolidation results from rainfall and groundwater fluctuations.

12.4.5 Embedment Materials

Materials suitable for foundation and embedment are classified in Table 12.2. They include a number of processed materials plus soil types defined in accordance with the Unified Soil Classification System (USCS) in ASTM D2487, Standard Method for Classification of Soils for Engineering Purposes. Table 12.3 provides recommendations on installation and use based on class of soil or aggregates and location of pipe in the trench.

12.4.5.1 Class I Materials

Class I materials provide maximum stability and pipe support for a given density as a result of angular interlock of their particles (Fig. 12.6). With minimum effort these materials can be installed at relatively high densities over a wide range of moisture content. In addition, the good drainage characteristics of Class I materials may aid in the control of water, making these materials desirable for embedment in rock cuts where water is frequently encountered. However, when groundwater flow is anticipated, consideration should be given to the potential for migration of fines (see Section 12.4.6) from adjacent materials into open-graded Class I materials.

12.4.5.2 Class II Materials

Class II materials, when compacted, provide a relatively high level of pipe support. In most respects, they have all the desirable characteristics of Class I materials when widely graded. However, open-graded groups may allow material migration, and the sizes should be checked for compatibility with adjacent material. Typically, Class II materials consist of rounded particles and are less stable than angular materials, unless they are confined and compacted.

12.4.5.3 Class III Materials

Class III materials provide less support for a given density than Class I or II materials. High levels of compactive effort may be required, unless moisture content is controlled. These materials provide reasonable levels of pipe support once proper density is achieved.

Table 12.3 Recommendations for installation and use of soils and aggregates for foundation and pipe-zone embedment*

Soil class[A]	Class I[B]	Class II	Class III	Class IV
General recommendations and restrictions	Acceptable and common where no migration is probable or when combined with a geotextile filter media. Suitable for use as a drainage blanket and underdrain where adjacent material is suitably graded or when used with a geotextile filter fabric.	Where hydraulic gradient exists, check gradation to minimize migration. Clean groups are suitable for use as drainage blanket and underdrain (see Table 12.2). Uniform fine sands (SP) with >50% passing a #100 sieve (0.06 in., 0.15 mm) behave like silts and should be treated as Class IV soils.	Do not use where water conditions in trench prevent proper placement and compaction. Not recommended for use with pipes with stiffness of 9 psi or less.	Difficult to achieve high soil stiffness. Do not use where water conditions in trench prevent proper placement and compation. Not recommended for use with pipe stiffness of 9 psi or less.
Foundation	Suitable as foundation and for replacing overexcavated and unstable trench bottom as restricted above.	Suitable as foundation and for replacing overexcavated and unstable trench bottom as restricted above. Install and compact in 12 in. (300 mm) maximum layers.	Suitable for replacing overexcavated trench bottom as restricted above. Install and compact in 6 in. (150 mm) maximum layers.	Suitable for replacing overexcavated trench bottom as restricted above. Install and compact in 6 in. (150 mm) maximum layers.

Table 12.3 Recommendations for installation and use of soils and aggregates for foundation and pipe-zone embedment* (*continued*)

Soil class[A]	Class I[B]	Class II	Class III	Class IV
Pipe embedment	Suitable as retricted above. Work material under pipe to provide uniform haunch support.	Suitable as restricted above. Work material under pipe to provide uniform haunch support.	Suitable as restricted above. Difficult to place and compact in the haunch zone.	Suitable as restricted above. Difficult to place and compact in the haunch zone.
Embedment compaction: min recommended % compaction, SPD[D]	See Note[C]	85% (SW and SP soils). For GW and GP soils see Note[E]	90%	95%
Relative compactive effort required to achieve minimum % compaction	Low	Moderate	High	Very high
Compaction methods	Vibration or impact	Vibration or impact	Impact	Impact
Required moisture control	None	None	Maintain near optimum to minimize compactive effort.	Maintain near optimum to minimize compactive effort.

*Reprinted from ASTM D2321 ASTM International, 100 Barr Harbor Dr., West Conshohocken, PA.

[A] Class V materials are unsuitable as embedment. They may be used as final backfill as permitted by the engineer.

[B] Class I materials have higher stiffness than Class II materials, but data on specific soil stiffness of placed, compacted Class I materials can be taken equivalent to Class II materials compacted to 95% of maximum standard Proctor density (SPD95), and the soil stiffness of compacted Class I materials can be taken equivalent to Class II materials compacted to 100% of maximum standard Proctor density (SPD100). Even if placed uncompacted (that is, dumped), Class I materials should always be worked into the haunch zone to assure complete placement.

[C] Suitable compaction typically achieved by dumped placement (that is, uncompacted, but worked into haunch zone to ensure complete placement).

[D] SPD is standard Proctor density as determined by Test Method D698.

[E] Place and compact GW and GP soils with at least two passes of compaction equipment.

Fig. 12.6 Backfilling with Class I material.

12.4.5.4 Class IV Materials

Class IV materials should be carefully evaluated prior to use. Moisture content must be near optimum to minimize compactive effort and achieve the required density. Properly placed and compacted Class IV materials can provide reasonable levels of pipe support; however, these materials may not be suitable under high fills, under surface-applied wheel loads, or under heavy vibratory compactors and tampers. Class IV materials should not be used where water conditions in the trench may cause instability and result in uncontrolled water content.

12.4.6 Migration

When coarse or open-graded material is placed adjacent to a finer material, fines may migrate into the coarser material under the action of a hydraulic gradient from groundwater flow. Significant hydraulic gradients may arise in the pipeline trench during construction, when water levels are being controlled by various pumping or well-pointing methods; or after construction, when permeable underdrain or embedment material acts as a trench drain under high groundwater levels.

During construction, downward percolation of surface water can carry fine granular haunching materials down into more coarse, open-graded bedding materials if the trench is not properly designed and constructed. The gradation and relative size of the embedment and adjacent materials must be compatible in order to minimize migration. In general, where significant groundwater flow is anticipated, placement of coarse, open-graded materials (such as Class I) above, below, or adjacent to finer materials should be avoided, unless methods are employed to impede migration, such as the use of an appropriate stone filter or filter fabric along the boundary of the incompatible materials.

12.4.7 Embedment Compaction

The moisture content of embedment materials should be maintained within suitable limits that permit placement and compaction to required levels with reasonable efforts. For non-free-draining soils, such as Class III and IV, moisture content should be held close to optimum. In applications where water exists in the trench, free-draining embedment materials are generally more suitable because they are more readily densified while saturated. Maximum particle size for embedment is limited to material passing a 1½-inch (38-mm) sieve.

Contact with pipe is to be avoided when mechanical compactors are used; when a small mechanical compactor for compacting over the pipe crown is used, a minimum of 6 in. (150 mm) of cover must be maintained, and for larger compactors, minimum clearances as the engineer requires are to be maintained. Decisions are to be based on the depth of influence of the specific compaction equipment being used. For compaction by heavy wheel loading or hydro hammer methods, a minimum distance of 30 in. over the pipe crown (top) may be required. Heavy wheel loading and hydrohammer methods of compaction should not be used for compacting in shallow bury applications, where total cover is less than the influence zone of the compaction device. In shallow cover applications, materials requiring little to no mechanical compaction should be used for embedment.

The methods chosen to deliver compactive energy determine whether desired densities for specific types of materials are achieved. Coarse-grained, clean materials such as crushed stone, gravels, and sand are free-flowing and may not require mechanical compaction in some installations. These materials are more readily compacted using vibratory equipment, whereas fine materials with high plasticity require kneading and impact force along with controlled water content to achieve acceptable densities. In pipe trenches, small handheld or walk-behind compactors work well not only to prevent damage to the pipe, but to ensure thorough compaction in confined areas around the pipe and along the trench wall. As examples, vibratory plate tampers work well for coarse-grained materials of Class I and Class II, whereas hand tampers or air-driven handheld impact rammers are suitable for the fine-grained plastic groups of Classes III and IV. Gas- or diesel-powered jumping jacks or small, walk-behind vibratory rollers impart both vibratory and kneading forces and are therefore suitable for most classes of embedment and backfill material.

Table 12.4 provides an approximate guide of obtainable densities of various soils by a variety of compaction methods. The minimum embedment density required is typically determined by the project engineer during design and will depend upon depth of cover,

Table 12.4 Estimated range of compaction* by embedment class and method of placement

Class of embedment	**I**	**II**	**III**	**IV**
Material description	Manufactured granular materials	Sand and gravel soils, clean	Mixed-grain soils	Fine-grain soils
Optimum moisture content range limit, % of dry wgt	—	9–12	9–18	6–30
Soil consolidation method	**% of Proctor (or relative) density range**			
Compact by power tamper or rammer	95–100 (75–100)	95–100 (60–80)	95–100	90–100
Densify by portable vibrators	80–95 (60–75)	80–95 (60–80)	—	—
Hand place	60–80 (40–60)	—	—	—
Hand tamp	—	60–80 (50–60)	60–80	60–75
Dump	60–80 (40–60)	60–80 (50–60)	60–80	60–75

*Compaction given in standard Proctor densities, relative density is noted in parentheses.

Note: This table serves as an approximate guide defining average Proctor densities attained through various methods of soil consolidation in different classes of soil. The table is intended to provide guidance and is not recommended for design use. Actual design values should be developed by the engineer for specific soils at specific moisture contents.

pipe stiffness, and type of soil used. For additional information on required densities, see Chapter 7, Design of Buried PVC Pipe.

12.4.8 Common Trenches

PVC pipe may be used in a common trench with either another flexible pipe or rigid pipe. In either case, the installer need only obtain sufficient soil stiffness around the pipe to maintain structural integrity. Spacing between pipes in a common trench should be at least 12 in. to permit adequate space for tamping or mechanical compaction. Consideration should also be given to whether Class I or Class II embedment materials should be used, which require minimal compaction effort.

Fig. 12.7 PVC pipe may be anchored on steep slopes.

If water and sewer pipes are installed in common trenches, the water pipe is laid higher in the trench to minimize any possibility of contamination. Gasketed PVC water and sewer pipe with joints conforming to ASTM D3139 and ASTM D3212 do not require external protective wrap applied at the joints when installed in a common trench. Joint tightness specified in the ASTM standards is sufficient to prevent any infiltration or exfiltration.

12.4.9 Sewers on Steep Slopes

It is recommended that sewers on steep slopes (greater than 20^o)—where shallow-bury and/or poorly consolidated soil conditions exist—be anchored securely with concrete collars or other appropriate abutments immediately downhill from bells to prevent downhill movement of pipe (Fig. 12.7).

12.4.10 Recommended Embedment Densities

Table 12.5 provides a quick reference of recommended embedment material class and density combinations for burial depths up to 50 ft (15.2 m). Burial depths in excess of 50 ft are permissible.

Table 12.5 Recommended pipe zone conditions for pipe stiffness of 46 psi

Pipe zone conditions		Height of cover	
Embedment class	% Proctor density range	ft	m
I	95–100	≤50	≤15.2
II	90–100	≤50	≤15.2
	85	≤40	≤12.2
	80	≤24	≤7.3
III	90–100	≤50	≤15.2
	85	≤36	≤11.0
	80	≤14	≤4.3
IV	85–100	≤32	≤9.8
	80	≤12	≤3.7
V	Soil class not recommended		

Notes:
1. Table is applicable only when minimum pipe stiffness is 46 psi.
2. At heights of cover shown, deflections will not exceed 7.5% when proper installation procedures are used. This provides a safety factor ratio of 4 to 1 against structural failure.
3. Actual installations in excess of 50 ft are possible and have been successfully completed. For recommended pipe zone conditions for PVC pipe of other stiffness conforming to ASTM F794 or AASHTO M304, the pipe manufacturer should be contacted.

12.5 System Components

PVC pipes are used in various nonpressure piping applications such as drainage, venting, and sewage systems. The recommendations that follow (Sections 12.5.1 through 12.5.5) are made for PVC piping used in gravity sewer systems. Sewer systems can convey storm drainage, sanitary sewage, or both. The great majority of sewage collection systems in North America are nonpressure systems using open-channel gravity flow. Sewer systems are carefully designed and constructed and depend upon proper use of pipe and appurtenances.

12.5.1 Fittings

Fittings for service branches in new construction should be molded or fabricated PVC fittings. Connections into existing lines are commonly done using:

- gasketed tee leg inserted into a hole cut into the main line
- gasketed saddle wye
- gasketed saddle tee.

Saddles may be gasketed or solvent-cemented and should be secured to the sewer main by corrosion-proof banding.

Saddles should be installed in accordance with manufacturer recommendations. Holes for saddle connections should be made by mechanical hole-cutters designed for this purpose. Holes for wye saddles should be laid out with a template and deburred and carefully beveled where necessary to provide a smooth hole that is shaped to conform to the fitting. Installed fittings should not compromise the system integrity by allowing infiltration or exfiltration.

Fittings are required for lateral connections, clean-out access, and changes in line direction and/or size (not occurring in manholes). Tees, wyes, or tee-wyes are provided for service connections, risers, and clean-outs. Increasers are used for changes in line size. Caps or plugs are used at dead ends. Commonly used fittings are shown in Figs. 12.8 and 12.9. Elbows and bends are used where line direction changes, particularly at service connections into sewer main lines (see Fig. 12.10).

12.5.2 Service Lines

Normally, service lines that extend from property line to collection sewer should lie at a minimum depth of 3 ft (1 m) at property line; they should be laid to a straight alignment and uniform slope no less than $\frac{1}{4}$ in./ft (20 mm/m) for 4-in. (100-mm) pipe and not less than $\frac{1}{8}$ in./ft (10 mm/m) for 6-in. (150-mm) pipe. A vertical standpipe or stack is commonly permitted where collection sewers are deeper than 7 ft (2 m). Standpipes and stacks do not require concrete encasement; however, they should be uniformly supported by compacted backfill.

Sanitary sewer service connections vary in size, depending on local codes, regulations, and system requirements. Service connections for large industrial, municipal, or commercial installations may be quite large, whereas most service connections for private residences are usually 4-in. or 6-in. pipe. Service connections may be made with fittings

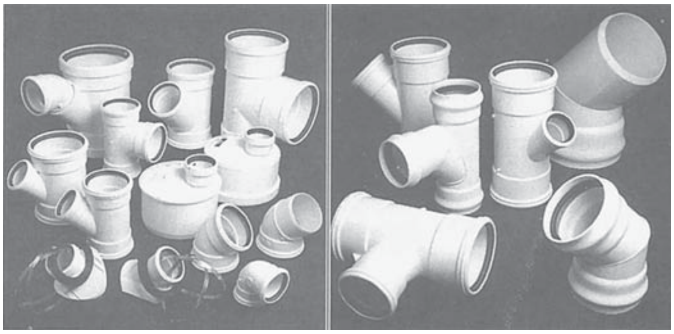


Fig. 12.8 Solid-wall PVC sewer fittings.

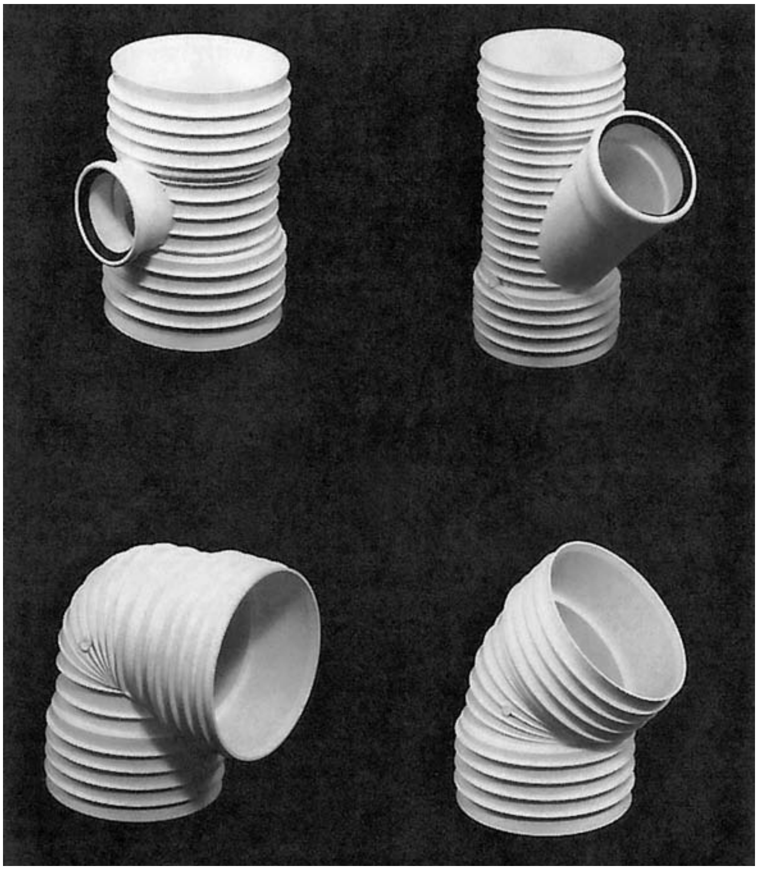


Fig. 12.9 Profile wall PVC sewer fittings.

installed in the sanitary sewer main line (tee, wye, or tee-wye) with field-installed service saddles (gasketed and clamped or solvent-cemented) or with tee legs inserted into the main line with the use of rubber gaskets.

The following are precautions to be taken when a field cut-in service connection is required:

- Foreign material should be prevented from entering cut-in pipe opening.
- Proper fittings and procedures should be used when field-connection saddles are installed.

The pipe manufacturer should be contacted for specific recommendations.

12.5.3 Pipe Caps and Plugs

All caps and plugs should be braced, staked, anchored, wired-on, or otherwise secured to the pipe to prevent leakage under the maximum anticipated thrust that results from abnormal internal operating conditions or test pressures from water or air.

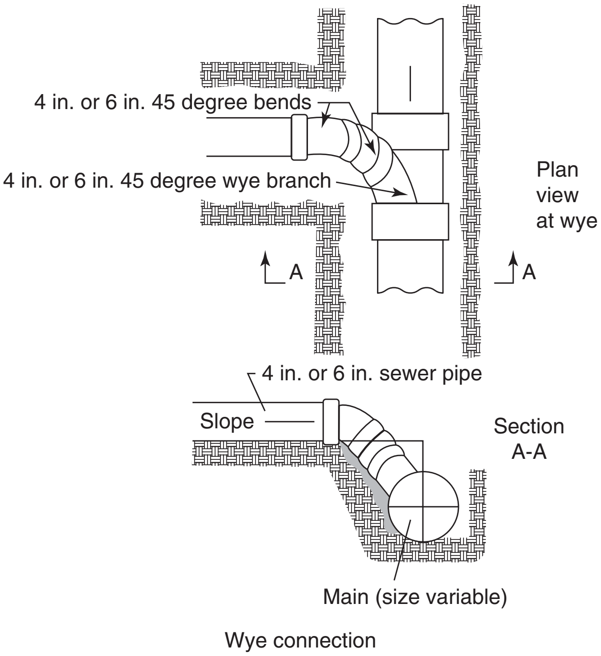


Fig. 12.10 Typical service connection.

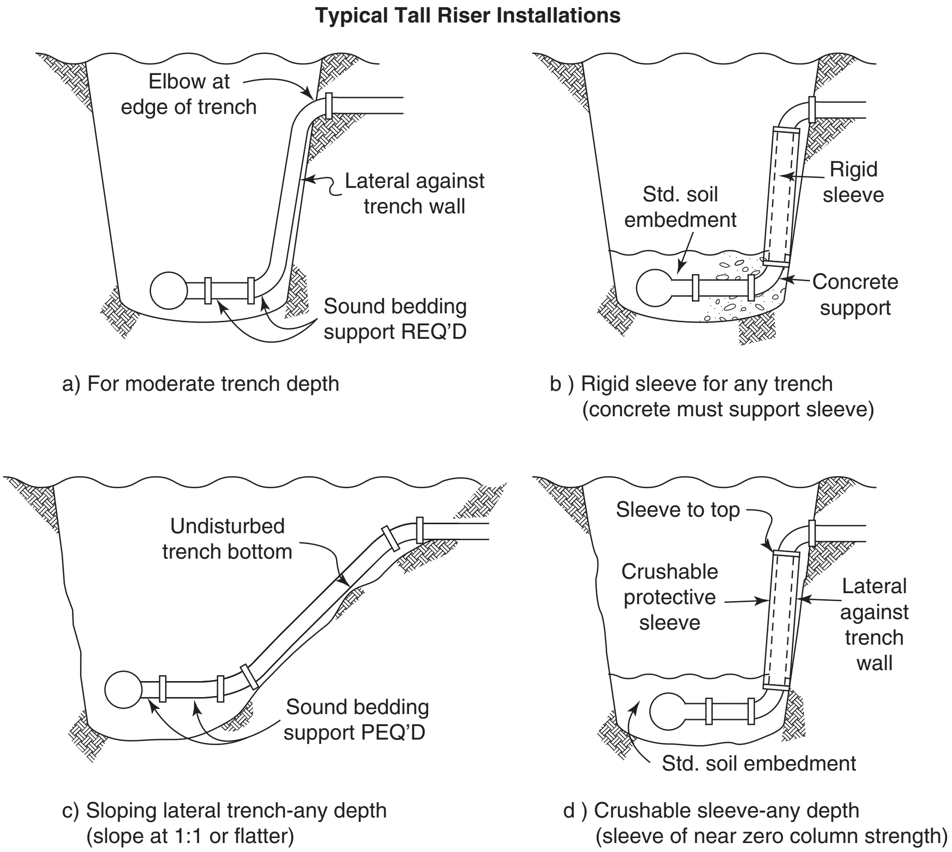
12.5.4 Risers

Sewer risers or vertical stacks may be required in deep sanitary sewers to minimize the need to excavate for service lines. Risers are generally permitted where the collection line is deeper than 7 ft (2 m).

For installation of PVC riser pipes on a PVC sewer line, the following practices are recommended:

- Use of a tee or tee-wye fitting and 45º elbow, or wye fitting and elbows to connect PVC riser pipe to the sewer line.
- Uniform support at the riser pipe connection by uniform bedding with good compaction all around and up the pipe.
- Use of a single length of pipe for the riser section whenever possible (up to 13 ft).
- Alignment of the lateral exit from the main at an angle no greater than 45º from the horizontal.
- Good compaction in the haunching from the base to the springline of the fitting and sewer line; this can be achieved with select material, if necessary.

Designers of very tall risers, in the case of deep main line sewers, must examine vertical loads that will be exerted on main line sewer fittings. These loads should be mitigated or



a) For moderate trench depth

b) Rigid sleeve for any trench (concrete must support sleeve)

c) Sloping lateral trench-any depth (slope at 1:1 or flatter)

d) Crushable sleeve-any depth (sleeve of near zero column strength)

Fig. 12.11 Typical tall-riser installations.

transferred harmlessly off the stack so that possible overinsertion, fracture of the fitting, or misalignment is prevented. Figure 12.11 shows typical tall-riser installations that help to minimize the vertical forces applied to the main line sewer due to soil settlement around the riser stack. The use of blunt tapers in these installations also can aid in prevention of stack settlement into the main line sewer.

12.5.5 Manholes and Junctions

Manholes and junctions are essential to the operation and maintenance of gravity sewer systems. Manholes are required to:

- provide workers access to the sewer line for inspection and maintenance;
- provide control of hydraulic flow for a change of direction, a change of grade, and for consolidation of converging flow channels (Fig. 12.12).

Fig. 12.12 Sewer pipe laid through and beyond manhole location prior to construction of manhole.

Manholes are commonly located at street intersections. Typically, intervals between sanitary sewer manholes vary from 300 (90 m) to 500 ft (150 m). Intervals between manholes may be greater for pipe products like PVC sewer pipe, which significantly minimizes cleaning and maintenance problems as compared to piping products that exhibit poor flow characteristics and are prone to root penetration and damage.

Manhole connections need to be watertight; a leak-free connection of sewer pipe to manholes has become more important. Emphasis is on system design, sizing, and operating

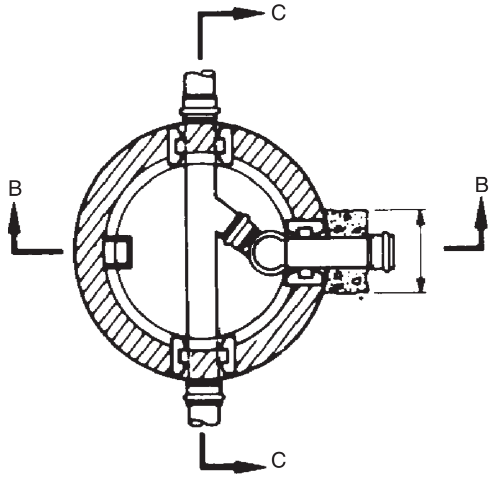
Fig. 12.13 An example of a watertight manhole connection.

cost incurred due to groundwater infiltration. Unlike some other sewer piping materials, PVC pipe does not bond with concrete. So, a PVC pipe/manhole connection must be accomplished using some form of watertight seal or waterstop (Fig. 12.13). Manhole connections can be made as follows:

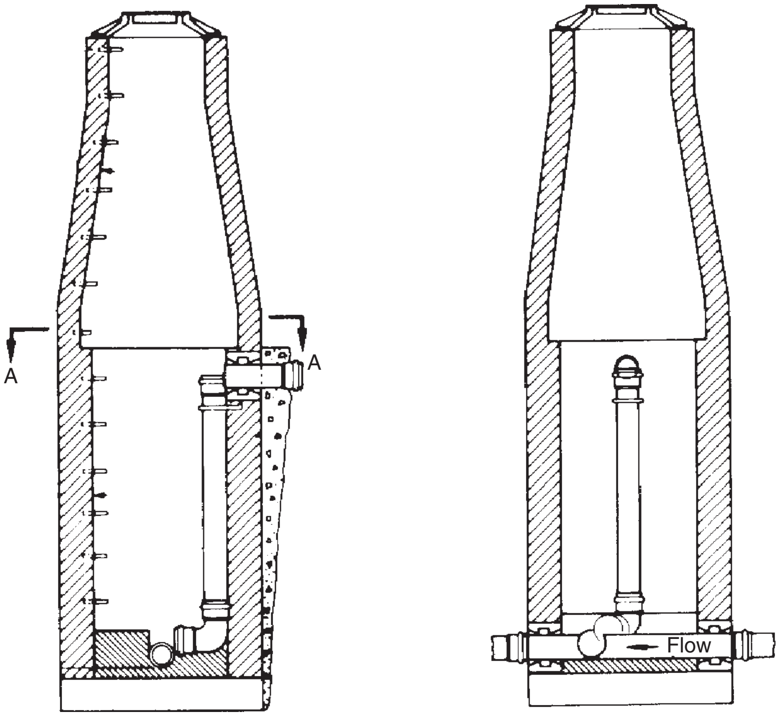
- Manhole couplings, providing an elastomeric gasket seal, can be grouted into the manhole wall.
- Waterstop in various forms (i.e., flexible boot or sleeve, O-ring, or gasket), produced from elastomeric compound, can be grouted or locked into manhole wall.
- Connection ports with elastomeric seals can be precast into manhole wall.
- Grouted connections directly to PVC pipe are effective if the pipe at the connection is coated with sand.

ASTM C923, Standard Specification for Resilient Connectors between Reinforced Concrete Manhole Structures, Pipes, and Laterals, contains additional discussion on manhole connections. Connections covered by ASTM C923 withstand hydrostatic pressures up to 10 psi (70 kPa).

Customarily, drop manholes are required when the difference in incoming and outgoing invert elevations is 2 ft (0.6 m) or more. Drop manhole connections must adhere to guidelines described above, and fittings should be installed to provide the requisite line profile. PVC pipe drop manholes may be designed in either inside-drop or outside-drop manhole configurations. Recommendations for making a proper connection in each case are detailed in Figs. 12.14 and 12.15.



Section A-A



Section B-B

Section C-C

Fig. 12.14 Inside-drop manhole connection.

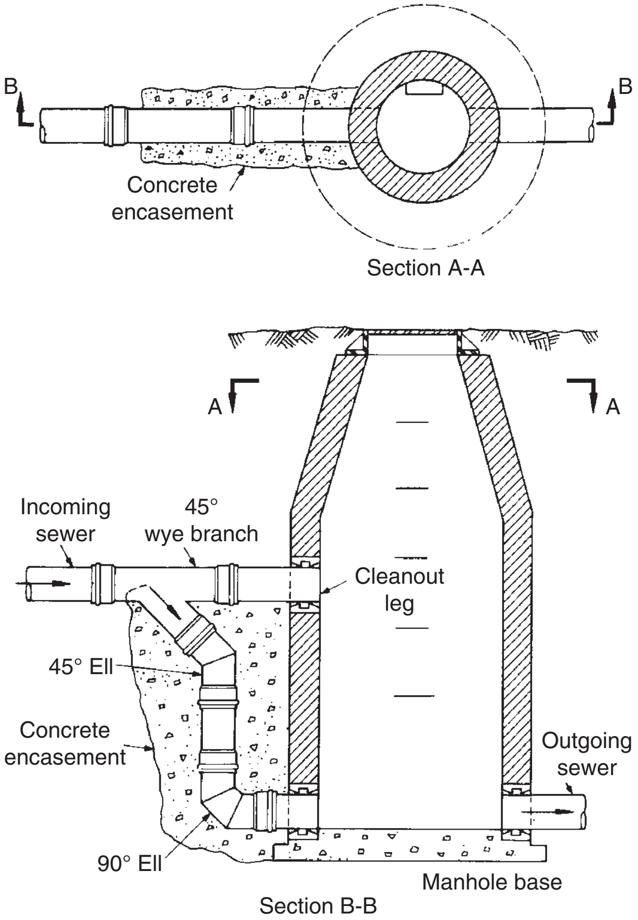


Fig. 12.15 Outside-drop manhole connection.

Connections must be done in a way that ensures proper compaction in pipe bedding and haunching. Rigid structures have to be properly bedded and installed. Settlement or shifting of rigid structures will normally not cause shear breakage, as is common with rigid piping products. However, excessive shifting or settlement could cause excessive deflection or distortion. Consequently, it is good practice for PVC pipes to have a gasketed pipe joint within 3 ft (1 m) of each side of the manhole to accommodate possible manhole settling (Fig. 12.16). In the case of outside-drop manholes, the concrete around the outside pipe provides support and eliminates drag-down loads.

Where flow velocities are greater than 15 ft/s, it is customary for baffles, cushioning, or energy dissipation within manholes to be provided. However, this practice is unrelated to PVC pipe performance (i.e., flow velocity does not limit design for PVC pipes).

Fig. 12.16 Placing a gasketed pipe joint within 3 ft of each side of the manhole helps to accommodate possible manhole settlement.

12.6 Inspection and Testing of the Pipe System

Good practice calls for all piping system projects to be tested upon completion of installation. The engineer should designate:

- locations of tests
- extent of the system to be tested
- optional methods of testing leakage
- alignment and deflection
- requirements for recording test results.

Sections of sewer that fail the tests should have defects located and then repaired or replaced. Any such sections should be retested until results are within specified allowances.

12.6.1 Precleaning

Prior to testing, sewer lines should be cleaned by flushing with an appropriately sized sewer cleaning ball. Precleaning by high velocity jet or other method may be necessary.

12.6.2 Visual Inspection

Sewer lines can be inspected visually to verify accuracy of alignment and freedom from debris and obstruction. The testing method can be photography, closed circuit television, or visual lamping with mirrors and lights.

12.6.3 Leakage Testing

Suitable leak testing methods are low-pressure air exfiltration, water infiltration, or water exfiltration. The preferred method is usually the low-pressure air exfiltration test. Plugs or caps on branch connections must be secured against blow-off during leakage tests.

12.6.3.1 Air Testing

The minimum time duration permitted for the prescribed low-pressure exfiltration pressure drop between two consecutive manholes should not be less than what is listed in Tables 12.6 or 12.7. Test duration values are listed for pressure drops of 1.0 psi (Table 12.6) and 0.5 psi (Table 12.7), respectively, in excess of groundwater pressure above the top of the sewer pipe. The values given accommodate both an allowable average loss per unit of surface area and an allowable maximum total leakage rate. This approach is based on the most recent work of Ramseier and eliminates the possibility of the acceptance of one or two significant leaks in an otherwise good section of pipe (see ASTM F1417 Standard Test Method for Installation Acceptance of Plastic Gravity Sewer Lines Using Low-Pressure Air; and Uni-Bell, UNI-B-6 Recommended Practice for Low-Pressure Air Testing of Installed Sewer Pipe).

12.6.3.2 Infiltration/Exfiltration Testing

Infiltration testing is an acceptable method of leakage test only when the ground level water is above the top (crown) of the pipe throughout the length being tested. The allowable infiltration for any portion of sewer system should be measured by a weir or current meter placed in the appropriate manhole and should not exceed 25 gal/in. of internal pipe diameter/mi/day (2.3 L/mm/km/day), including manholes.

Exfiltration testing is an acceptable testing method only in dry areas or where a line is sufficiently deep and groundwater level above the pipe is suitably low, so test pressures can exceed the external pressure generated by groundwater. The allowable water exfiltration for any length of sewer pipe between manholes should not exceed 25 gal/in. of internal pipe diameter/mi/day. During exfiltration testing the maximum internal pipe pressure at the lowest end should not exceed 25 ft (7.6 m) of water or 10.8 psi (75 kPa), and the water level inside the manhole should be 2 ft (0.6 m) higher than the top of the pipe or 2 ft (0.6 m) higher than groundwater level (whichever is greater).

12.6.4 Deflection Testing

Deflection tests of pipe may be required. They are performed before final acceptance. Locations with excessive deflection should be repaired by rebedding or replacing pipe.

Table 12.6 Specification time required for a 1.0 psig pressure drop for size and length of pipe indicated for Q = 0.0015*

1 Pipe diam, in.	2 Minimum time, min:s	3 Length for minimum time, ft	4 Time for longer length, s	Specified minimum time for length (L) shown (min:s)							
				100 ft	150 ft	200 ft	250 ft	300 ft	350 ft	400 ft	450 ft
4	3:46	597	0.380 L	3:46	3:46	3:46	3:46	3:46	3:46	3:46	3:46
6	5:40	398	0.854 L	5:40	5:40	5:40	5:40	5:40	5:40	5:42	6:24
8	7:34	298	1.520 L	7:34	7:34	7:34	7:34	7:36	8:52	10:08	11:24
10	9:26	239	2.374 L	9:26	9:26	9:26	9:53	11:52	13:51	15:49	17:48
12	11:20	199	3.418 L	11:20	11:20	11:24	14:15	17:05	19;56	22:47	25:38
15	14:10	159	5.342 L	14:10	14:10	17:48	22:15	26:42	31:09	35:36	40:04
18	17:00	133	7.692 L	17:00	19:13	25:38	32:03	38:27	44:52	51:16	57:41
21	19:50	114	10.470 L	19:50	26:10	34:54	43:37	52:21	61:00	69:48	78:31
24	22:40	99	13.674 L	22:47	34:11	45:34	56:58	68:22	79:46	91:10	102:33
27	25:30	88	17.306 L	28:51	43:16	57:41	72:07	86:32	100:57	115:22	129:48
30	28:20	80	21.366 L	35:37	53:25	71:13	89:02	106:50	124:38	142:26	160:15
33	31:10	72	25.852 L	43:05	64:38	86:10	107:43	129:16	150:43	172:21	193:53
36	34:00	66	30.768 L	51:17	76:55	102:34	128:12	153:50	179:29	205:07	230:46
42	39:48	57	41.883 L	69:48	104:42	139:37	174:30	209:24	244:19	279:13	314:07
48	45:34	50	54.705 L	91:10	136:45	182:21	227:55	273:31	319:06	364:42	410:17
54	51:02	44	69:236 L	115:24	173:05	230:47	288:29	346:11	403:53	461:34	519:16
60	65:40	40	85:476 L	142:28	213:41	284:55	356:09	427:23	498:37	569:50	641:04

*Q is the allowable leakage rate in ft^3/min/ft^2 of inside surface area of pipe.

Note: If no leakage (0 psig drop) is seen after 1 h of testing, the test section shall be accepted.

Table 12.7 Specification time required for a 0.5 psig pressure drop for size and length of pipe indicated for Q = 0.0015*

1 Pipe diameter (in.)	2 Minimum time (min:s)	3 Length for minimum time (ft)	4 Time for longer length (s)	Specified minimum time for length (L) shown (min:s)							
				100 ft	150 ft	200 ft	250 ft	300 ft	350 ft	400 ft	450 ft
4	1:53	597	0.190 L	1:53	1:53	1:53	1:53	1:53	1:53	1:53	1:53
6	2:50	398	0.427 L	2:50	2:50	2:50	2:50	2:50	2:50	2:51	3:12
8	3:47	298	0.760 L	3:47	3:47	3:47	3:47	3:48	4:26	5:04	5:42
10	4:43	239	1.187 L	4:43	4:43	4:43	4:57	5:56	6:55	7:54	8:54
12	5:40	199	1.709 L	5:40	5:40	5:42	7:08	8:33	9:58	11:24	12:50
15	7:05	159	2.671 L	7:05	7:05	8:54	11:08	13:21	15:35	17:48	20:02
18	8:30	133	3.846 L	8:30	9:37	12:49	16:01	19:14	22:26	25:38	28:51
21	9:55	114	5.235 L	9:55	13:05	17:27	21:49	26:11	30:32	34:54	39:16
24	11:20	99	6.837 L	11:24	17:57	22:48	28:30	34:11	39:53	45:35	51:17
27	12:45	88	8.653 L	14:25	21:38	28:51	36:04	43:16	50:30	57:42	64:54
30	14:10	80	10.683 L	17:48	26:43	35:37	44:31	53:25	62:19	71:13	80:07
33	15:35	72	12.926 L	21:33	32:19	43:56	53:52	64:38	75:24	86:10	96:57
36	17:00	66	15.384 L	25:39	38:28	51:17	64:06	76:55	89:44	102:34	115:23
42	19:74	57	20.942 L	34:54	52:21	69:49	87:15	104:42	122:10	139:37	157:04
48	22:47	50	27.352 L	45:35	68:23	91:11	113:58	136:46	159:33	182:21	205:09
54	25:31	44	34.618 L	57:42	86:33	115:24	144:15	173:05	201:56	230:47	259:38
60	28:20	40	42.738 L	71:14	106:51	142:28	178:05	213:41	249:18	284:55	320:32

*Q is the allowable leakage rate in $ft^3/min/ft^2$ of inside surface area of pipe.

Note: If no leakage (0 psig drop) is seen after 1 h of testing, the test section shall be accepted.

Table 12.8 Base inside diameters and deflection mandrel dimensions for ASTM D3034 DR 35 pipe

Pipe size, in.	Base inside diameter, in.	7.5% mandrel deflection, in.
6	5.742	5.31
8	7.665	7.09
10	9.563	8.84
12	11.361	10.51
15	13.898	12.86

Table 12.9 Base inside diameters and deflection mandrel dimensions for ASTM F679 PS 46 pipe

Pipe size, in.	Base inside diameter, in.	7.5% mandrel deflection, in.
18	17.054	15.77
21	20.098	18.59
24	22.586	20.89
27	25.446	23.53
30	29.151	26.96
36	34.869	32.25
42	40.491	37.45
48	46.209	42.74

Deflection testing is usually performed with a properly sized “go/no-go” mandrel or sewer ball. For the purpose of deflection measurements, base inside pipe diameters are provided in Tables 12.8 and 12.9. The maximum allowable deflection should be subtracted from base inside diameter to determine the maximum diameter of the “go/no-go” test mandrel or ball. It must be emphasized that accurate testing is possible only when the lines are thoroughly cleaned. This test is recommended for all pipe materials.

ASTM standards address deflection testing of PVC sewer pipe. If deflection testing is performed on installed pipe, it is recommended that a deflection limit of 7.5% of base inside diameter be used. To allow for stabilization of the pipe/soil system, deflection testing should be performed a minimum of 30 days after installation. Tests have shown that when PVC pipe is held under constant strain below the ultimate limit that would cause breakage, pipe failure will not occur. Additionally, PVC pipe does not experience reversal of curvature until deflection exceeds 30%. Decades of experience and testing have shown that a deflection limit of 7.5%, offering a safety factor of 4, provides for PVC pipelines that will meet or exceed the design life of the system.

Base ID depends on pipe average ID and a statistical tolerance package. The formulas are as follows:

Equation 12.1

$$\mathrm{ID}_{\mathrm{avg}} = \mathrm{OD}_{\mathrm{avg}} - 2(1.06)\,\mathrm{t}$$

Equation 12.2

$$\text{tolerance package} = \sqrt{\mathrm{A}^2 + 2\mathrm{B}^2 + \mathrm{C}^2}$$

Equation 12.3

$$\mathrm{ID}_{\mathrm{base}} = \mathrm{ID}_{\mathrm{avg}} - \text{tolerance package}$$

where:

$\mathrm{ID}_{\mathrm{avg}}$ = pipe average inside diameter, in.
$\mathrm{OD}_{\mathrm{avg}}$ = pipe average outside diameter, in.
t = minimum wall thickness (ASTM D3034 or F679), in.
A = OD tolerance (ASTM D3034 or F679), in.
B = excess wall thickness tolerance, in. = 0.06 t
C = out-of-roundness tolerance (ASTM D3034 or F679), in.
$\mathrm{ID}_{\mathrm{base}}$ = pipe base inside diameter, in.

Using a similar methodology, base inside diameters have also been developed for profile wall pipe manufactured in accordance with UNI-B-9, Recommended Performance Specification for Polyvinyl Chloride (PVC) Profile Wall Gravity Sewer Pipe and Fittings Based on Controlled Inside Diameter (Nominal Pipe Sizes 4–48 Inch). These are listed in Table 12.10, along with the suggested mandrel dimensions. Open, closed, and dual-wall corrugated profiles are specified in the UNI-B-9 standard, in which base inside diameters were calculated using out-of-roundness tolerances for similar-sized pipe from ASTM specifications D3034 and F679. Where no similar sizes existed, tolerances were extrapolated to the desired size.

Table 12.10 Base inside diameters and deflection mandrel dimensions for profile-wall PVC pipe*

Pipe size, in.	Base inside diameter, in.	7.5% mandrel deflection, in.
4	3.864	3.57
6	5.725	5.29
8	7.637	7.06
10	9.525	8.81
12	11.312	10.46
15	13.828	12.79
18	16.923	15.65
21	19.956	18.46
24	22.600	20.90
27	25.446	23.54
30	28.350	26.22
33	31.249	28.91
36	34.106	31.55
39	37.003	34.23
42	39.880	36.89
45	42.762	39.56
48	45.639	42.22

*Recommended for use with ASTM F794, F949, and F1803 products.

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CHAPTER 13

Trenchless Installation of PVC Pipe

Joining Methods

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Trenchless Construction—Casings

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Trenchless Construction—Horizontal Directional Drilling (HDD)

•

Trenchless Rehabilitation—Sliplining

•

Trenchless Rehabilitation—Pipe Bursting

•

Trenchless Rehabilitation—Tight Fit Structural Liners

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13.1 Notation

DR = dimension ratio, dimensionless

E = modulus of elasticity of pipe material, psi

D_o = pipe outside diameter, in.

$P_{critical}$ = critical grouting pressure, psi

t = pipe wall thickness, in.

13.2 Introduction

As infrastructure ages there is constant need to repair and replace it; as cities grow there is a continual need for additional underground services in already densely populated, complex environments. There are also situations that make traditional excavation costly and difficult (such as that presented by rivers, streams, and swamps that must be crossed). In all these applications, trenchless (or “no-dig”) pipe installation methods are being used effectively.

Construction in densely populated urban settings significantly increases both real construction costs and indirect social costs, including costs associated with interruptions to flow of traffic and obstacles to both businesses and the public. Construction of new underground infrastructure or rehabilitation of old infrastructure presents the utility engineer and contractor with the challenge of minimizing the impact of these disruptions on the surface while making needed improvements underground.

While open-cut installation procedures continue to be the standard method of construction for municipal piping projects, trenchless technology may be more appealing and economically viable in some situations. Trenchless, or no-dig, installation is distinguished from open-cut installation in both the construction techniques and the materials it employs. Construction methods for trenchless installation progressed from the first contractor—who pushed a single length of PVC pipe with a backhoe under a sidewalk—to computer-operated directional drilling rigs, capable of pulling in thousands of feet of assembled PVC pipe in one pull. Meanwhile, PVC materials and pipes have evolved to accommodate various trenchless installation methods. Through extensive research and development, specialized PVC compounds, uniquely manufactured pipe profiles, and specialized pipe joints have been developed to allow pipe to be folded, fused, and joined together. Because unique loads are placed on trenchless pipe during installation, special attention must be given to the axial compressive and/or tensile forces imparted on the pipe. These forces arise from pulling and pushing during installation and from the external loads on the pipeline once it is fixed in place.

Trenchless installation of PVC pipe is continually improving and expanding to include a variety of techniques, which can be classified into two groups:

- *Trenchless construction*: The installation of an entirely new pipeline with minimal open-cut excavation.
- *Trenchless rehabilitation*: The repair of an existing deteriorated pipeline, improving its performance and longevity with minimal open-cut excavation.

Trenchless installation methods highlighted in this chapter are proven to be cost effective and reliable for the building, renewal, replacement, or installation of new pipelines; these methods are minimally disruptive to property and/or traffic. It is the responsibility of owners, designers, and contractors to familiarize themselves with the variety of assembly and installation methods and be trained accordingly by the manufacturer or technology provider.

13.3 Joining Methods

Currently, there are several types of PVC pipe products designed to withstand trenchless installation forces:

- internally restrained gasketed joint
- pin-and-groove gasketed joint
- spline-lock gasketed joint
- butt-fused joint.

13.3.1 Internally Restrained Gasketed Joint

Restraint internal to the bell (Fig. 13.1) is available in 4-in. through 24-in. sizes for bell-and-spigot pipe and fabricated PVC fittings. Assembly of an internally restrained joint entails the following steps:

1. Cleaning of spigot, bell, and internal restraint hardware.
2. Lubrication of joint components per manufacturer instructions.
3. Insertion of the spigot into the bell to the insertion line while ensuring the pipe is kept in straight alignment.
4. Activation of the restraint when the system is pressurized or when the pipe string is pulled.

13.3.2 Pin-and-Groove Gasketed Joint

Pin-and-groove gasketed joints (Fig. 13.2) are available in 4-in. through 12-in. sizes. Assembly of a pin-and-groove joint follows these steps:

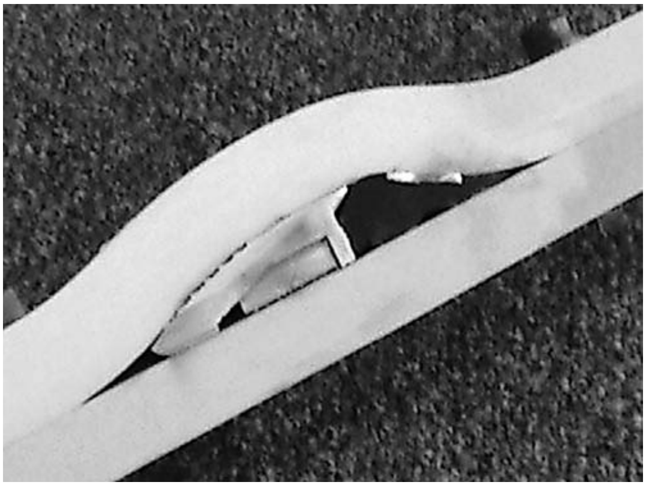

Fig. 13.1 Internally restrained gasketed joint.

1. Lubrication of spigot as in typical gasketed joint assembly.
2. Insertion of spigot into bell to the insertion line, which aligns bell holes with the spigot groove.
3. Placement of external ring over bell holes, with holes aligning.
4. Insertion of pins into holes until pins bottom out in grooves.

Fig. 13.2 Pin-and groove gasketed joint.

13.3.3 Spline-Lock Gasketed Joint

Spline-lock joints (Fig. 13.3) are available in both coupling and integral-bell versions in sizes 2-in. through 16-in. Joints are assembled as pullback progresses through these steps:

1. Insertion of pipe into coupling (or bell) using conventional lubricants and assembly techniques; spline grooves will automatically align.
2. Insertion of a nylon locking spline into mating grooves in pipe and coupling/bell. This provides continuous restraint with evenly distributed load.

Fig. 13.3 Spline-lock gasketed joint.

13.3.4 Butt-Fused Joint

Butt-fusible PVC pipe products (Fig. 13.4) are available in diameters ranging from 4-in. to 36-in. and provide monolithic, fully restrained joints with little or no exterior joint profile. The butt-fusion joining process consists of the following steps:

1. Accurate and secure aligning of pipe ends.
2. Precise facing and squaring of both ends of pipe simultaneously through a rotating dual cutting head.

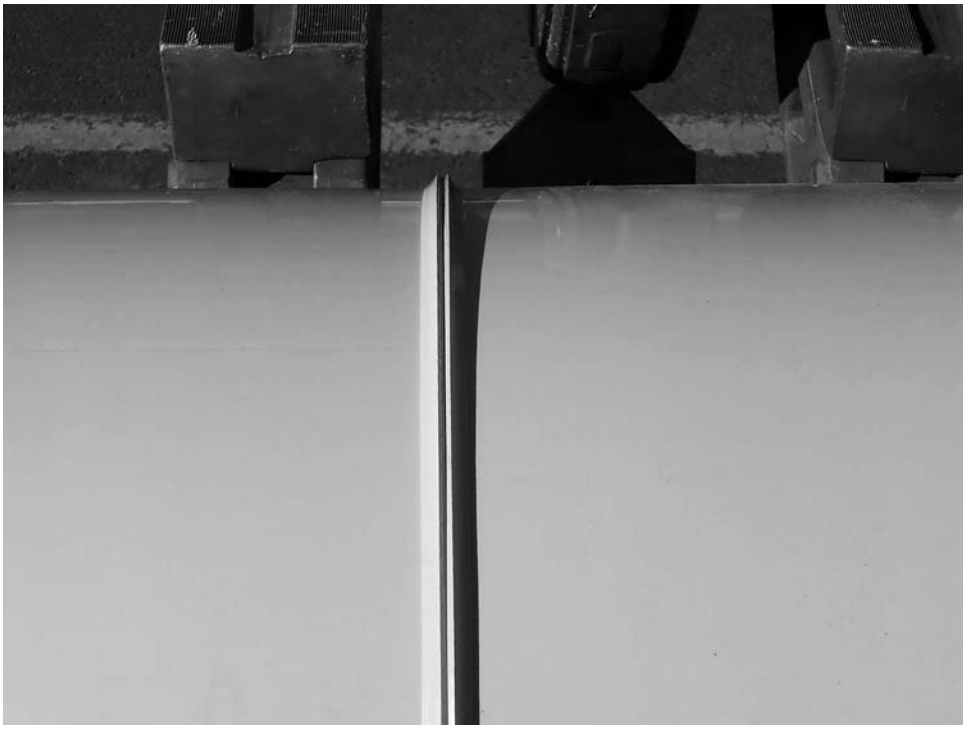

Fig. 13.4 Butt-fused joint.

3. Heating of pipe ends with an electronically controlled plate until prescribed bead configuration is achieved.
4. Quick removal of the heater plate and bringing the pipe ends together, holding under pressure until the newly formed joint cools.

13.4 Trenchless Construction—Casings

When PVC water or sewer pipe is installed under highways, runways, or railways, *casings* may be needed for the following reasons:

- To prevent damage to structures due to soil erosion or settlement in the pipe zone caused by line failure or leakage.
- To permit economical pipe removal and replacement in the future.
- To accommodate regulations or requirements imposed by public or private owners of property where pipe is installed.

13.4.1 Casing Spacers

When PVC pipe is installed in casings, *casing spacers* (Fig. 13.5) must be used to prevent damage to the pipe during installation and to provide proper long-term line support. PVC pipe in casings should not rest on bells. For butt-fused PVC, casing spacers are not needed.

Casing spacers must be securely attached at the insertion line of the pipe on the spigot end to ensure that overinsertion does not occur. Caution should be used when attempting longer installations using this method, as the frictional forces of the installation may build to a greater force than the casing spacer at the insertion line can resist. Restrained joints suitable for compressive loads may also be used (or required) if installation forces exceed slippage resistance of casing spacers.

Care must be exercised to avoid damage to pipe or bell joints. Non-petroleum-based lubricants applied to casing interior or spacer exterior makes sliding easier.

Casing spacers must provide sufficient height to permit clearance between the pipe bell and the casing wall.

Table 8.10, in Chapter 8, gives maximum support spacing values for casing spacers. Casings are normally sized to provide an inside diameter at least 2 in. (50 mm) greater than the maximum outside diameter (OD) of pipe bell, casing spacer, or joint restraint device. Approximate maximum ODs of the pipe bell for various PVC products are provided in the tables of the Handbook's Appendix.

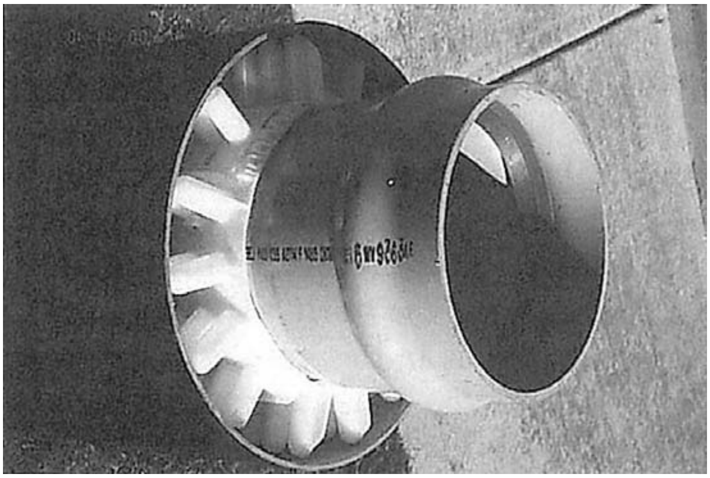

Fig. 13.5 Casing spacer.

13.4.2 Pulling Pipe through Casings

Restrained-joint PVC pipe can be pulled through casings. Pipes that are restrained by external mechanical joint-restraint devices (Chapter 11, Fig. 11.7) can also be pulled through casings, since the trenchless pull force is in the same direction as the thrust force caused by internal water pressure. The pull should be slow and steady to prevent any jerking movement. Placement of a protective wrap or pullhead on the spigot end of the pipe's first length minimizes any possibility of abrasion against the casing.

13.4.3 Pushing Pipe through Casings (Jacking)

Jacking pipe (pushing pipe through casing) should also be done at a slow and steady pace. It is critical that the end of the pipe that is pushed be protected from damage (e.g., by use of a wood cross-piece).

Placing a protective wrap around the spigot end of the first length will minimize any possible abrasion against the casing.

13.4.4 Filling or Grouting the Annular Space

The OD of the liner pipe is less than the inside diameter of host pipe, which leaves an *annular space* between the two. In many cases, this annulus is filled with a grout after installation, particularly if the host pipe is highly deteriorated. Grouting of the annular space provides additional support for the liner pipe, helps protect the liner pipe if the host pipe is in structural distress, and stops water infiltration through the host pipe annular space.

During the filling or grouting of the annular space, care must be exercised to keep the PVC pipe from floating out of its proper position. Wedges should not to be used to lock pipe into position during filling or grouting operations. If the annular space between the casing and PVC carrier pipe is filled, either by pressure grouting or blowing sand, caution should be exercised to ensure that excess grout pressure does not cause the pipe to distort or collapse. Table 13.1 lists *critical grouting pressure* ($P_{critical}$) and *allowable grouting pressure* ($P_{allowable}$) as a function of the pipe dimension ratio (DR). The allowable grouting pressure for profile wall PVC pipe is the same as that for solid wall pipe of the same stiffness. For example, profile wall PVC pipe with 46 psi pipe stiffness has the same allowable grout pressure as DR 35 pipe.

In addition to controlling grout pressures, it is important to control grout placement and temperature. The values in Table 13.1 assume uniform grout pressures in the annulus. Distortion may result if the level of the grout becomes too great on one side of the pipe compared to the other. Using a higher stiffness (lower DR) pipe can be advantageous in this case, as it offers greater resistance against distortion or collapse. If large amounts of grout—or grouts with a high heat of hydration temperature—are used, the heat of hydration must be taken into consideration, as excess heat will lower pipe stiffness. In this case, completely filling the pipe with water is a means of controlling distortion or buckling. Water also works as a heat dissipater for heat of hydration during grout curing. When water is used, end caps must be designed to withstand the hydrostatic pressures involved.

Equation 13.1

$$P_{critical} = \frac{2E}{(DR - 1)^3}$$

where:

$P_{critical}$ = critical buckling pressure, psi
E = modulus of elasticity of pipe material, psi
DR = dimension ratio, dimensionless = D_o/t
D_o = pipe outside diameter, in.
t = pipe wall thickness, in.

Table 13.1 Maximum recommended grouting pressures

DR	$P_{critical}$, psi	$P_{allowable}$, psi
51	7.5	3.7
41	14.6	7.3
35	23.8	12
32.5	29.9	15
28	47.5	24
26	59.8	30
25	67.6	34
23.5	82.1	41
21	117	58
18	190	95
17	228	110
14	426	210
13.5	479	240

$P_{allowable}$ is based on a SF against buckling of 2.0 (equal to DF = 0.5) at temperature of 73°F, using E = 400,000 psi.

Grouting pressures must be reduced for increased wall temperatures per Table 13.2.

Table 13.2 Temperature corrections for modulus of elasticity

Pipe wall temperature		Correction factor for modulus of elasticity
°F	°C	
90	32	0.93
100	38	0.88
110	43	0.84
120	49	0.79
130	54	0.75
140	60	0.70

Notes:
Interpolate between the temperatures listed to calculate other correction factors.
The maximum recommended wall temperature for PVC pipe and fitting is 140°F (60°C).

13.5 Trenchless Construction—Horizontal Directional Drilling (HDD)

Horizontal directional drilling (HDD) is the most commonly used trenchless process for installing new pipelines. This installation method has been extensively used for roadway and river crossings. Today, HDD is employed for numerous other applications where the benefits of trenchless installation can be realized. In recent years, developments in the precision of HDD machinery, specifically the ability to monitor and steer the pilot bore to high levels of accuracy to maintain line and grade, has enabled the trenchless installation of gravity sewer pipes. A typical drilling rig is shown in Fig. 13.6.

13.5.1 Preliminary Investigation

13.5.1.1 Utility Location Survey

The first critical component of all HDD projects is the establisment by the contractor of the location of all utilities close to the proposed path. All utilities in the vicinity of the drill path should be identified and clearly marked.

13.5.1.2 Geotechnical Survey

The contractor should review all geotechnical data provided and/or perform an on-site investigation of factors such as soil type, water table, and environmental hazards to ensure safe and effective installation. The contractor should also verify that selection criteria for reamer

Fig. 13.6 HDD drilling rig.

size and drilling fluids are correct. All applicable guidelines, regulations, and standards must be followed.

13.5.2 Installation Overview

HDD is performed with a drilling rig and involves three steps. Steps 2 and 3 are sometimes performed simultaneously:

1. The hole is bored.
2. The hole is reamed.
3. The pipe is pulled in.

13.5.3 Installation Details

13.5.3.1 Roller Stands or Timbers

Throughout installation, the pipe should be adequately protected to prevent deep scratches or gouges that could impair performance. Moving long lengths of pipe on roller stands or timbers or dragging pipe on grass or soft soil will help prevent potential damage to the pipeline.

Fig. 13.7 PVC pipe supported on rollers.

Supporting the pipeline on rollers also reduces the frictional drag coefficient and the pull force required to complete an installation. Figure 13.7 shows PVC pipe on a roller stand as it is being pulled into a horizontal directional drilling installation. PVC's hardness provides exceptional abrasion and gouge resistance. According to AWWA PVC pipe standards, nicks and scratches of less than 10% of the pipe wall thickness do not significantly reduce the strength of the pipe.

Rollers and other friction-reducing implements must be properly sized, spaced, and positioned for the pipe size and weight and for the environment. Proper pipe support design and location should also take into account horizontal alignment considerations and reactive forces to counteract the "straightening" of the pipe string (Fig. 13.8) as it is being pulled through a curve or deflection.

13.5.3.2 Pilot Holes

The HDD process uses sections of steel drilling rods connected to a steerable drill head. Guidance systems enable the rod to be steered and its direction of travel to be monitored.

Fig. 13.8 Preassembled PVC pipes.

Initially, a pilot hole is drilled with entry angle, α, and exit angle, β (Fig. 13.9). The entry and exit angles are dependent on the maximum radius of curvature allowed within the right of way provided. The radius of curvature must also meet or exceed the allowable bend radius of the PVC pipe system used. A larger radius of curvature reduces the stress transmitted to the pipe during the pullback operation. A trained operator relays guidance information to the drill rig operator and records the specific details of the drilling head using gyroscopic probe and interface, magnetic guidance systems, or electromagnetic systems. The team of operators can control inclination (depth) and azimuth (horizontal direction) to ensure a smooth and gradual radius of curvature.

13.5.3.3 Reaming the Pilot Hole

In horizontal directional drilling, special cutters called *reamers* are successively pulled through the pilot hole to produce a bore large enough for installation of a pipe of the required diameter. Simultaneously, drilling fluid is pumped into the hole to remove soil cuttings and to prevent soil collapse. The reamed hole allows drilling fluid to fill the annular space and to flow around the pipe. Soil type and water table may affect the borehole size. Generally, a finished borehole has the following characteristics:

- For pipe sizes up to 24 in., the borehole is 50% larger than the largest outside dimension of the pipe.
- For pipe sizes larger than 24 in., the borehole is 12 in. larger than the largest outside dimension of the pipe.

The largest outside diameter can be that of the coupling, the bell, or the fusion joint, depending on the type of joint used for the installation.

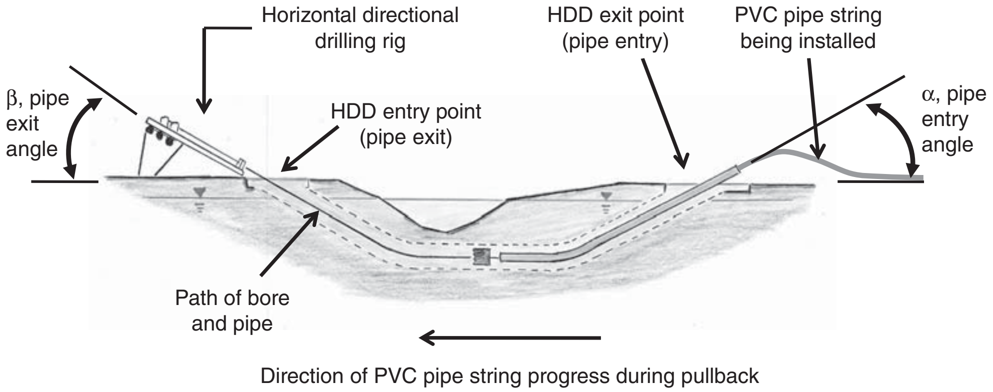

Fig. 13.9 Schematic of product pipe string being pulled back toward HDD rig.

13.5.3.4 Drilling Fluids

Drilling fluids are thixotropic materials comprising a base fluid, weighting agents, bentonite clay (to help remove cuttings from the borehole and to form a filter cake on the walls of the hole), and various other additives. Drilling fluids lubricate the drill rod, drill head, reamer, and pipe; they must be engineered to maintain an open reamed hole prior to pipe installation. Maintaining the density of the drilling fluid is part of a successful HDD installation. Ends of PVC pipe should be covered, capped, or plugged to prevent drilling fluid from entering the pipeline during installation.

13.5.3.5 Pullback

The installation step called *pullback* involves the connection of the pipe to the drill rod, followed by pulling the pipe back through the reamed hole. Figures 13.9 and 13.10 demonstrate the pipe being pulled into place.

In HDD, the direction of PVC pipe pullback is opposite the direction at which the pilot hole was drilled. A pulling head with a swivel eye to prevent torsional stresses connects the drilling rod or reamer to the leading end of the PVC pipe string. Pulling heads must comply with recommendations of the pipe manufacturer or the technology provider.

The pullback operation should happen as soon as a reamed hole is completed so stresses from thickening drilling fluids may be reduced and to minimize the possibility of borehole collapse. Pullback forces should be monitored to ensure they remain within

Fig. 13.10 Pipe string during pullback operation.

allowable limits. Safe pull forces vary with diameter and DR of the pipe provided and with the type of joint used.

Pullback with butt-fused PVC pipe is usually performed in continuous lengths. If necessary, intermediate fusions are performed during the pullback process. Segmented PVC pipe (internally restrained, pin-and-grooved bells, or spline-lock couplings) can be strung out in long lengths or installed one joint at a time as the drill rig pullback operation is in progress.

13.5.4 Design Considerations

13.5.4.1 Bending

HDD bore alignments are curvilinear in nature and require some amount of bending of pipe and joints. Each PVC pipe manufacturer or technology provider provides guidance on allowable minimum bend radii for their particular system. This guidance must be followed in the design of bore alignment, as well as during pipe layout and installation.

13.5.4.2 Pullback Force

Pullback force has four components:

1. Friction force between pipe and borehole.
2. Drag force—The friction force as pipe is pulled along the ground surface prior to entering the borehole. The force can be reduced by friction-reducing methods (such as pipe rollers).
3. Hydrokinetic friction force—The friction force between pipe and drilling fluid as the fluid is displaced during pipe insertion. The magnitude of this force is a function of the OD of the pipe versus the size of the borehole.
4. Capstan force at pipe bends—The increase in friction force when pipe is pulled around a curve. The force is due to the component of the pull force that acts normal to the curve.

Additional factors that may affect the required pullback force include variances in:

- drilling equipment
- drilling procedures
- borehole quality
- drilling-fluid density.

The heavier the drilling fluid is in the borehole, the greater the buoyant force lifting the pipe string. Buoyancy can be counteracted by filling the pipe with fluid to ballast the line. Monitoring and controlling the density of the drilling fluid is critical for minimizing the required pull force.

The combined effects of all of these frictional and resistive forces on the pipe create the pullback force required for successful pipe installation. The resultant pullback force required should not exceed the tensile capabilities of the pipe and/or joint with an appropriate safety factor.

Unlike some other thermoplastics, with PVC the magnitude and duration of pulls do not result in significant pipe elongation. Therefore, connections to PVC pipe can be made immediately following pullback. However, it is good practice to release tension in pulled-in pipe by pushing the pipe back after the pull-in is completed.

Information on how to calculate estimated pullback forces and safe allowable tensile stresses may be obtained by contacting the manufacturer or technology provider of the particular PVC pipe and restrained joining methodology selected for use.

13.6 Trenchless Rehabilitation—Sliplining

13.6.1 Overview

Sliplining is accomplished through insertion of a lining pipe into a host pipe that has leaks or is otherwise unsound. Unlike casings, sliplining installations allow PVC pipe to carry loads once the sliplining is installed inside an existing host pipe. Because it is limited by the size of the host pipe, PVC reline pipe is usually pushed or pulled directly into place (most times without the use of spacers). Prior to installation, the host pipe is cleaned of debris and service build-up (sediments and/or tuberculation) and surveyed for internal clearance, alignment, and obstructions. If the host pipe is a segmented pipe with bell-and-spigot joints, the deflection of the joints and the lay length of the host pipe must be considered when it is determined which pipe should be used in a slipline.

Joint spacing and deflection are used to determine the bend radius of the new pipe that will be inserted. In some cases, spot repairs are required on the host pipe in areas that the replacement pipe cannot pass. The largest PVC sliplining pipe that will fit is selected and inserted (dimensional information to aid in pipe size selection is provided in the Handbook Appendix). For long insertion lengths, approximately 2 in. of clearance between the host pipe inside diameter and the new pipe outside diameter is recommended. Hydraulic capacity can often be maintained despite the diameter reduction due to the lower Manning's sewer pipe flow coefficient (n) and the higher Hazen–Williams pressure pipe flow coefficient values (C) offered by PVC. Some PVC piping systems now offer zero-infringement joints, which lower the clearance dimensions required between the host pipe and the lining pipe. Sliplining pipes are usually grouted in place. Grouting recommendations are discussed in Section 13.4.4.

13.6.2 Design Considerations

13.6.2.1 Loading

Variations in loads in the trenched and trenchless portions of the slipliner must be considered and accommodated in the design of the system. Loading conditions are not identical since there are differences in the two regions' ring deformation and longitudinal pipe deflection.

13.6.2.2 Annular Space

As mentioned previously, annular space between outer and inner pipes may be grouted (see Section 13.4.4 for details). This adds strength to the annular cavity, enhancing resistance to collapse. Installation of load-bearing material such as fly ash, low density grout, flowable fill, cementitious grout, or polyurethane foam in this space significantly improves the structural integrity of the composite pipe. If the annular space is not grouted, hydrostatic loads may be exerted on the slipliner as the water table rises above the crown of the liner.

13.6.3 Installation

There are two general methods used for sliplining installations:

1. *Segmental sliplining*—Liner is installed one pipe length at a time.
2. *Continuous sliplining*—Liner pipe lengths are assembled, then installed in one long string.

13.6.3.1 Segmental Sliplining

Segmental sliplining is the least disruptive type of rehabilitation for gravity and storm sewers. With this method, bell-and-spigot and profile wall PVC pipe may be assembled in segments at entry points along the length of the deteriorated host pipe. Pipe is inserted directly into the host pipe by either pulling or pushing. Fused PVC is installed segmentally by fusing lengths together in the access pit and then inserting the fused string of pipe into the host pipe after each fusion is completed. Open-cut trenches are required to access the host pipe at strategic installation points when sliplining is done in a segmental application.

A section of the top half of the host pipe is often cut off to provide lead-in access. Often the access pit can be used for installing new PVC pipe in both directions. This is done by reversing the setup of the installation equipment. Where two segments of sliplining pipe meet at a point, the host pipe must be open-cut excavated there in order to expose the section of liner pipe that is to be connected. Laterals will need to be excavated, disconnected, and reconnected to the new PVC sliplining. Making connections to different materials also involves exposing both the lining pipe and the pipe to be connected with open cut excavation

13.6.3.2 Continuous Sliplining

In continuous sliplining, PVC liner pipe is preassembled in long lengths before it is pulled into the deteriorated host pipe. The pull-in can be done in one unsegmented length or in sections that require an intermediate joint or butt-fusion (Fig. 13.11). This method is more common with potable water pipelines, transmission mains, and forcemains. As is the case with gravity systems, the annulus that results in continuous sliplining may be grouted. When required, taps are made after the new pipe is pulled into the host pipe.

13.6.3.3 Pulling Heads

The pulling heads used in continuous sliplining applications do not increase the outside diameter of the new pipe, thus allowing the largest size pipe possible to be installed. The pull head must be designed to accommodate the recommended safe pulling force

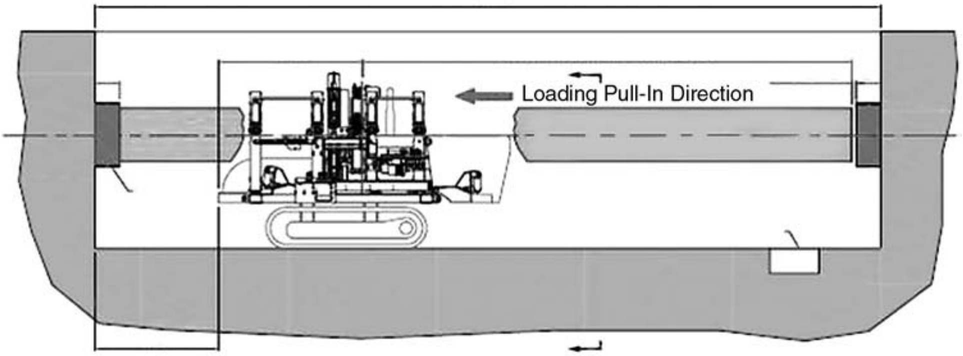

Fig. 13.11 Sliplining installation of butt-fused PVC segmental approach.

of the pipe being installed. The two primary components for the pull force required for sliplining are:

1. friction caused by the length of pipe being pulled above grade;
2. friction between the new pipe and the host pipe.

13.6.3.4 Installation Pits

Installation pits need to be excavated to a depth great enough for PVC pipe installation to proceed, without the pipe being bent tighter than the minimum bending radius of the liner pipe. In many cases, a significant amount of the alignment change for insertion can be accomplished above grade by supporting the pipe with rollers or equipment. This practice minimizes the length of pit needed. Pit length also dictates how much host pipe needs to be removed to allow for insertion (Fig. 13.12).

13.7 Trenchless Rehabilitation—Pipe Bursting

13.7.1 Overview

Pipe bursting is a method for replacing existing pressure or gravity pipelines. Much as is done in sliplining, an existing utility corridor is used in this procedure and the end result is replacement of old pipe with completely new pipe. However, pipe bursting has an advantage over sliplining: Sliplining requires the new pipe to be smaller in diameter than the existing pipe. In contrast, pipe bursting involves splitting or fracturing an existing

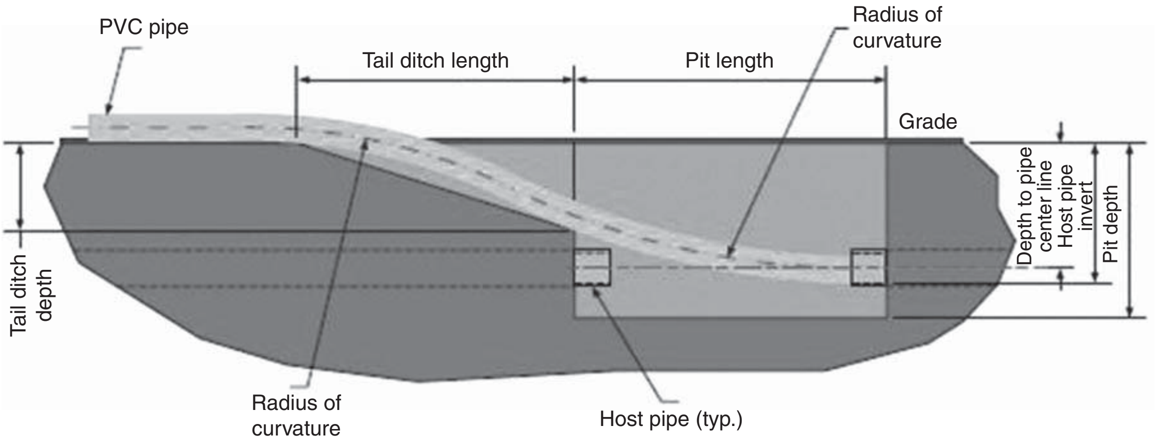

Fig. 13.12 Typical installation pit for continuous sliplined PVC pipe.

pipeline, pushing that pipeline out into the surrounding soil, thus creating an area large enough for a new pipeline of the same or larger diameter to be pulled in.

There are several methods by which existing pipe is split or fractured; these vary, depending on the kind of pipe being replaced and the equipment available to perform the operation. Figure 13.13 shows a pipe bursting layout and operation sequence.

Only joints designed for pulling are used for pipe bursting installations. Depth of pipe bursting installation and site-specific aspects of a project (e.g., groundwater levels, ground conditions, and previous pipeline installation conditions and methods) also play a role in the design of a pipe burst project.

13.7.2 Size Considerations

The diameter of pipe being burst typically ranges from 2 to 30 in., although bursting has been used on pipes of larger diameter. Pipe bursting is commonly performed size-for-size or one size above the diameter of the existing pipe. Larger upsizing (up to three pipe sizes) has been successful; however, the larger the pipe upsizing, the greater the force needed to burst the existing pipe and pull in the new pipe, thus, the greater the potential for ground movement (upheaval). The high strength of PVC relative to other thermoplastics minimizes upsizing requirements for maintaining the same flow area, since PVC provides a thinner wall for the same OD and pressure rating.

13.7.3 Types of Pipe Bursting

The two common categories of pipe bursting are:

- *Pneumatic*—In pneumatic pipe bursting, force is applied by a reciprocating hammer that is driven by compressed air. This method is not recommended for PVC pipe, since the rebound from the reciprocating action may damage the end of the pulled-in pipe.
- *Static*—In static pipe bursting, a bursting head is pulled through the existing pipe while the new pipe is pulled from behind. The pull is continuous and does not

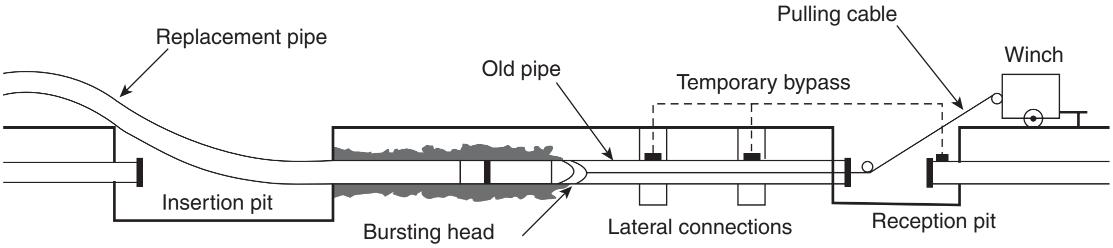

Fig. 13.13 Layout for a pipe bursting operation.

involve the reciprocating action of pneumatic methods. This method is recommended for PVC pipe and is widely used to burst failing clay, concrete, cast iron, ductile iron, and asbestos cement pipe.

13.8 Trenchless Rehabilitation—Tight Fit Structural Liners

13.8.1 Overview

Tight fit structural lining with PVC is accomplished by expanding a specially formulated PVC pipe that has been inserted into a host pipe (Fig. 13.14). The liner is brought to tight fit dimensions through a combination of heat and pressure.

13.8.2 Pressure Pipe Example: Fusible PVC Tight Fit Liner

For pressure pipe, the tight fit structural liner process is as follows:

1. Starting stock pipe is selected based on ID of host pipe and required pressure rating for new pipe. Starting stock pipe is analyzed to determine the amount of expansion needed. The pressure capacity of the expanded pipe is determined on a stand-alone, fully structural basis. No contribution from the degraded host pipe is used in this determination.
2. Starting stock sections are fused into a single length. Under most conditions, maximum recommended length is approximately 500 ft.

Fig. 13.14 Starting stock inserted into host pipe.

3. Prior to installation of the starting stock, the host pipe is cleaned and inspected. Cleaning removes any debris, sediment, or accumulated tuberculation to achieve the ID expected. Inspection is normally performed by video, allowing an assessment of host pipe for any restrictions or missing sections that could impact expansion.

   When completely expanded, the starting stock does not adhere to the host pipe, so a bondable surface is not required.

   The alignment of the host pipe must also conform to the bend radius of the selected starting stock pipe. (Bending is covered in Chapter 8.)
4. Starting stock pipe is inserted as in a slipline operation. Usually the liner is pulled into place with a winch, but it can be pushed as well.
5. Expansion hardware is installed and the line is filled with water.
6. Starting stock is heated in a controlled manner with hot water.
7. When the system reaches proper conditions, pressure is added in the form of additional hot water under pressure. This initiates the expansion.
8. Expansion completion is determined by several methods:
   - A calculated volume of expansion is determined prior to start. Although the host ID may vary, the amount of expansion achieved within a range of this calculated volume indicates that expansion is complete.
   - When expansion is completed, pressure rises (since the host pipe restricts further expansion).
   - At pipe ends and at any intermediate expansion point, visual inspection can verify that the liner has expanded against the inside wall of the host pipe.

Included in the expansion hardware is a sizing sleeve, which allows the pipe ends outside the host pipe to be expanded to a diameter that will accept a standard fitting for reconnection. In most cases this will be the OD of the host pipe, thus allowing the same size fittings to be used. Intermediate points can be exposed, host pipe removed, expansion sleeve installed, and an expanded portion of the liner sized for the cut in a tee or other fitting.

After expansion is complete (Fig. 13.16), the liner is pressure tested per standard pipe acceptance testing parameters. The application can also be used for gravity flow applications where a structural lining is needed.

13.8.3 Nonpressure Pipe Example: Folded PVC Tight Fit Liner

Lining with expanded-in-place PVC liner uses a specially formulated pipe that has been folded into a “C” shape and wound onto a coil. The length of pipe on the coil is designed to extend the length of a full manhole-to-manhole run. The lining maintains or increases flow capability by providing a Manning’s n value equal to 0.009 PVC, which offsets the slight reduction in flow area.

Fig. 13.15 Expanded structural liner with hardware removed.

Fig. 13.16 Expanded structural liner with end sized to accept host pipe fittings.

For nonpressure pipe, the process is as follows:

1. The liner pipe is heated in a steam trailer to soften the PVC material.
2. Once softened, the liner is winched down the existing manhole into the pipe to be rehabilitated (Fig. 13.17).
3. Winching continues until the liner reaches the next designated manhole.
4. After the liner pipe is winched into the existing pipeline, steam and pressure are applied to expand it tightly against the host pipe (Fig. 13.18).
5. Steam is replaced by air (while maintaining a constant pressure) and the liner is cooled.

Fig. 13.17 Heated liner being winched into a manhole.

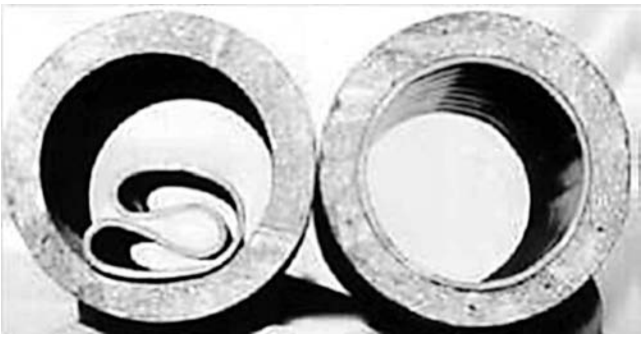

Fig. 13.18 Tight fit PVC liner; inserted is shown on left, expanded is shown on right.

6. The liner is trimmed at each pipe end and excess material is removed from the manhole.
7. House service connections are reopened with use of a robotic cutting device and closed-circuit television camera.
8. Liner installation is complete and the pipe is ready for use.

13.9 Sources

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CHAPTER 14

Molecularly Oriented Polyvinyl Chloride Pipe (PVCO)

Raw Materials
•
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Table of Contents

14.1 Notation

a = pressure wave velocity, ft/s
E = modulus of elasticity of the pipe material, psi
P_s = pressure surge, psi
t_{min} = minimum wall thickness, in.

14.2 Introduction

This chapter discusses molecularly oriented polyvinyl chloride pipe—PVCO pipe. The development parallels the previous chapters of the handbook, but rather than repeat earlier information, numerous references are made to the corresponding previous chapters and sections.

PVCO pipe is extruded from the same material used for conventional PVC pipe. However, after extrusion, the "starting stock pipe" is expanded under carefully controlled conditions to approximately twice the original outside diameter. This expansion process realigns the material's molecules, enhancing the properties of the pipe.

The concept of improving pipe materials by reorienting the molecules in PVC starting stock was developed in Europe in the early 1970s, which led to the first installation of PVCO pipe in 1974. In North America, the first test installation was done in 1979; the product was fully commercialized by the early 1990s.

The first North American standard for PVCO pipe, American Society for Testing and Materials (ASTM) F1483, was published in 1993. The American Water Works Association (AWWA) C909 standard followed five years later.

14.3 Raw Materials

14.3.1 Pipe Materials

PVCO and PVC pressure pipe are made from the same raw materials, specified as follows:

1. Equivalent PVC compounds, which meet PPI range formulation and qualify for cell class 12454 per ASTM D1784.
2. Identical hydrostatic design basis (HDB) of 4,000 psi as determined by ASTM D2837.
3. Equal conformance to toxological requirements per American National Standards Institute (ANSI)/NSF Standard 61.

The improved properties of PVCO over conventional PVC pipe are not due to differences in raw materials, but to physical changes in the PVC material caused by stretching the pipe (realigning the molecules) after the extrusion process.

14.3.2 Gasket Materials

The same gasket materials are used for both PVCO and PVC pressure pipes. Gaskets must conform to the requirements of ASTM F477 for high-head applications.

14.4 Manufacturing

Chapter 4 coverage of PVC pipe manufacturing applies to PVCO. Since the raw materials and extrusion process for PVCO and PVC are the same, production of PVCO starting stock pipe is identical to that of conventional pipe. However, PVCO undergoes an additional process, as mentioned above. The starting stock is expanded circumferentially to about twice its original diameter. This step in PVCO production can be carried out either in-line (*continuous process*) or it can be a separate step (*batch process*) to the extrusion of the starting stock. These processes are outlined next.

14.4.1 Continuous Process

In the continuous process, partially cooled stock is drawn over a mandrel (as shown in Fig. 14.1), expanding the pipe to approximately twice its original diameter. This expansion (or “stretching”) causes the long PVC polymer chains to orient in the direction of the hoop (that is, radially, around the pipe circumference). This strengthens the material in the hoop direction. There is also partial orientation in the longitudinal direction.

Fig. 14.1 PVCO – Continuous process.

14.4.2 Batch Process

In the batch process, orientation is performed separately from starting stock extrusion. A length of starting stock is placed inside a steel mold, then heated, expanded, and cooled. The batch process orients the pipe in the circumferential direction only.

14.5 Standards and Testing

Standards specific to PVCO are:

1. ASTM F1483 Specification for Oriented Polyvinyl Chloride PVCO Pressure Pipe:

   F1483 includes 4-in. through 16-in. sizes of PVCO pipe with both CIOD and IPS outside diameters; CIOD pressure ratings are PR150, PR200, and PR250 psi; IPS ratings are PR160, PR200, and PR250.

2. AWWA C909 Molecularly Oriented Polyvinyl Chloride (PVCO) Pressure Pipe, 4 in. through 24 in. (100 mm through 600 mm) for Water, Wastewater, and Reclaimed Water Service:

   C909 includes three pressure classes: PC165, PC235, and PC305 psi (same as the C900 PVC pipe standard).

3. CSA B137.3.1 Molecularly Oriented Polyvinyl Chloride (PVCO) Pipe for Pressure Applications:

   This standard contains terminology that differs from the ASTM and AWWA standards. To prevent confusion, specifics of the CSA standard are not discussed in this chapter.

These standards provide for product verification through quality control and quality assurance tests, which are the same as those performed on PVC pipe (discussed in Chapter 4). Qualification tests such as determination of cell classification for starting stock material, definition of hydrostatic design basis, and evaluation of health effects are all performed using the same standards described previously. Certifications, approvals, and third-party testing are also available for PVCO.

14.6 PVCO Pressure Pipe Design and Selection

Engineering principles discussed in Chapter 5 also apply to molecularly oriented polyvinyl chloride pipe. As described in Chapter 5, the designer may need to consider hydrostatic strength (long and short term) of PVCO pipe.

14.6.1 The Stress Regression Line

Chapter 5, Section 5.3.1, points out that visco-elastic materials cannot use the linear elastic model employed by traditional pipe materials. This section introduces and thoroughly discusses the concept of the stress regression line.

For PVCO pipe the same parameters apply. The difference is that the data for PVC pipe in Tables 5.1 and 5.2 have lower hoop stress values than those for PVCO because of PVCO's higher circumferential tensile strength.

14.6.2 Hydrostatic Design Basis (HDB)

The discussion in Chapter 5, Section 5.3.2, thoroughly covers the concept of the hydrostatic design basis. For starting stock material, the HDB is 4,000 psi (the same as PVC for pipe). Orientation of the starting stock material's molecules causes an increase in the HDB of the finished PVCO pipe. For North American standards, an HDB of 7,100 psi is required.

PVCO exhibits similar results as those for PVC in Fig. 5.4 (stress regression curve), Fig 5.5 (stress regression line), and Fig. 5.6 (stress regression line showing HDB categories). However, PVCO's y-axis values for hoop stress are higher, qualifying it for the 7,100 psi HDB category.

Because of the different HDB values, dimension ratio (DR) classification for conventional PVC is not used for PVCO. Instead, PVCO is referenced only by pressure class (PC) or pressure rating (PR).

14.6.3 Short-Term Hydrostatic Strength

Like PVC, PVCO pipe can withstand substantially higher hydrostatic pressure over a short application duration than over long periods of time. For example, to pass a short-term, quick-burst test, the hoop stress at burst must meet or exceed 11,400 psi. However, to pass the longer-term 1,000-hour sustained-pressure test, the sample is pressurized to a constant hoop stress of 7,500 psi for 1,000 hours.

The discussion of short-term strength (STS) and short-term rating (STR) of PVC pipe found in Chapter 5 is also relevant for PVCO pipe. For the C909 standard, STS and STR values are the same as found in the C900 standard for the equivalent pressure classes (see Table 5.12 for further information).

14.6.4 Temperature Effects on Hydrostatic Strength

Like conventional PVC, the hydrostatic pressure capacity of PVCO is temperature-dependent, and thermal de-rating factors need to be used when appropriate. These temperature coefficients (F_T) are the same as those found in Table 5.3 for PVC pipe; however, for PVCO pipe the maximum recommended service temperature is 130°F (54°C).

14.6.5 Surge Pressures in PVCO Pipe

The surge pressure discussion for PVC pipe that appears in Chapter 5, Section 5.3.6, also applies to PVCO pipe. Very important to note is that prevention and mitigation measures are the same for both materials (Chapter 5, Section 5.3.6.3).

14.6.5.1 Occasional Surge Pressure (P_{os})

The magnitude of surge pressure can be calculated reliably using the elastic wave theory of surge analysis. The pressure wave velocity is given by Equation 5.5 and the resulting pressure surge by Equation 5.7.

Substitution of PC235 PVCO pipe for PVC in Example in 5.1 provides interesting results. For 6-in. PC235 PVCO pipe and a velocity change of 2.0 ft/s, along with the values

$$E = 500{,}000 \text{ psi}$$
$$t_{\text{min}} = 0.221 \text{ in.}$$

the results are

$$a = 1050 \text{ ft/s}$$
$$P_s = 28.1 \text{ psi.}$$

This compares to a P_s of 109 psi for ductile iron pipe (Example 5.2). It is important to note that for the same conditions of interrupted flow, pressure surges generated in pipe with high tensile modulus (ductile iron E = 29,000,000 psi) will be significantly greater than surges in lower modulus pipe (PVCO E = 500,000 psi) of similar dimensions.

Pressure surges (P_s') in PVCO pipe of various pressure class/ratings in response to a 1.0-ft/s (0.3-m/s) instantaneous flow velocity change (ΔV) are shown in Table 14.1.

Table 14.1 Pressure class/rating vs. pressure surge for a 1.0 ft/s (0.3 m/s) instantaneous change in velocity (ΔV)

PR, PC	Pressure surge, P_s', psi (kPa)
PR160, IPS	11.7 (81)
PR200, IPS	13.0 (90)
PR250, IPS	14.5 (100)
PR150, CIOD	11.4 (79)
PR200, CIOD	13.0 (90)
PR250, CIOD	14.5 (100)
PC165, CIOD	12.0 (83)
PC235, CIOD	14.1 (97)
PC305, CIOD	15.9 (109)

Allowable short-term ratings (STR) for PVCO pipe are 1.60 times its pressure class or rating. Short-term ratings are developed by applying a safety factor (SF) = 2.0 (SF = 2.0 is equivalent to a design factor (DF) = 0.5) to the short-term strength (STS) of the pipe.

14.6.5.2 Recurring Surge Pressure (P_{rs}) and Cyclic Design

Fatigue failure due to cyclic surging is rarely a matter of concern in most water distribution systems. However, the design of some piping systems (e.g., sewer forcemains) may be controlled or limited by severe cyclic surging. If cyclic surges are not controlled or are not designed out of the system, then all pipes, fittings, and appurtenances must be designed with sufficient allowance for cyclic surging to prevent fatigue failure. In cases where cyclic fatigue is design-limiting, it is often more economical to install surge control devices to reduce the magnitude and/or frequency of the surges.

14.7 External Loads

14.7.1 Superimposed Loads

The discussion and equations found in Chapter 6 for flexible pipe are not specific to pipe material and therefore apply also to PVCO pipe.

14.7.2 Buried Pipe Design

The engineering principles presented in Chapter 7 for PVC pipe also apply to PVCO pipe. However, since PVCO pipe is intended only for pressure applications, external load is rarely a design-limiting parameter.

Pipe stiffness (PS) values to determine pipe deflection percentages are found in Table 14.2.

14.8 Installation-Specific Design Applications

Design applications covered in Chapter 8 for PVC pipe are:

- longitudinal bending
- support spacing
- thermal expansion and contraction
- flotation (buoyancy).

Table 14.2 Pipe stiffness

PR, PC	PS, psi
PR160, IPS	24
PR200, IPS	48
PR250, IPS	98
PR150, CIOD	21
PR200, CIOD	48
PR250, CIOD	98
PC165, CIOD	28
PC235, CIOD	81
PC305, CIOD	178

Stiffness values are based on E = 500,000 psi.

These same engineering principles apply to PVCO pipe, with the exception of a few modifications discussed in Sections 14.8.1 to 14.8.4 below.

14.8.1 Longitudinal Bending

If the manufacturing process provides biaxial orientation, flexural properties of PVCO pipe in the longitudinal direction may be higher than they are for PVC pipe. However, a conservative approach to determining these properties uses the same values as PVC (as found in Chapter 8):

- Flexural modulus = 400,000 psi
- Allowable bending stress, S_b (Table 8.1):
  - 1,000 psi for pressure-rated pipe
  - 800 psi for pressure-class pipe.

If PVCO flexural properties are higher and the designer elects to take advantage of this, the allowable bending radius will be tighter (by the ratio of PVC allowable flexural stress to PVCO allowable flexural stress). The PVCO pipe manufacturer should be consulted for actual strength values.

The discussion of longitudinal bending found in Chapter 8 also applies to PVCO pipe. If average wall and minimum flexural strength values are used, the tables for PVCO are the same as those for PVC (Tables 8.2 and 8.5 for the same pressure class or pressure rating), with the exception that the force required to bend PVCO pipe is approximately 60% of the force required for the same curvature in PVC pipe.

14.8.2 Support Spacing

The discussion and equations for support spacing found in Chapter 8 are also applicable to PVCO pipe. Further support spacing recommendations shown in Tables 14.3, 14.4, and 14.5 are based on the following design limitations:

- Initial pipe vertical displacement (sag) is limited to 0.2% of span length based on calculations using Equation 8.22, so that long-term sag is limited to approximately 0.5%.
- Pipe bending stress values (longitudinal) are limited to:
    - 1,000 psi for pressure-rated pipe
    - 800 psi for pressure-class pipe
- Modulus of elasticity (longitudinal) is 400,000 psi.
- All calculated values greater than 20 ft have been reduced to 20 ft, which is the maximum length for gasketed PVCO pipe.

Tabular values are given for pipe sizes 4 through 12 in. For sizes greater than 12 in., the manufacturer should be consulted for spacing and pipe availability.

14.8.3 Thermal Expansion and Contraction

Expansion and contraction of PVCO pipe is the same as for PVC pipe:

- PVCO's coefficient of thermal expansion is 3.0×10^{-5}, the same as for PVC.
- Table 8.12 provides values for length change due to change in temperature; the values are appropriate for PVCO as well as for PVC.

14.8.4 Buoyancy (Flotation)

Buoyancy properties for PVCO pipe are the same as those discussed in Chapter 8, Section 8.5, for PVC pipe.

Table 14.3 Support spacing for AWWA C909 CIOD PVCO pipe

Pipe size, in.	Pressure class, psi	73°F, ft	23°C, m	90°F, ft	32°C, m	110°F, ft	44°C, m
4	305	7.3	2.2	7.1	2.2	6.8	2.1
4	235	6.8	2.1	6.6	2.0	6.4	1.9
4	165	6.1	1.9	6.0	1.8	5.8	1.8
6	305	9.3	2.8	9.0	2.7	8.7	2.7
6	235	8.6	2.6	8.4	2.6	8.1	2.5
6	165	7.8	2.4	7.6	2.3	7.4	2.2
8	305	11.1	3.4	10.8	3.3	10.4	3.2
8	235	10.3	3.2	10.1	3.1	9.7	3.0
8	165	9.4	2.9	9.1	2.8	8.8	2.7
10	305	12.7	3.9	12.4	3.8	12.0	3.6
10	235	11.9	3.6	11.5	3.5	11.2	3.4
10	165	10.7	3.3	10.4	3.2	10.1	3.1
12	305	14.3	4.4	13.9	4.2	13.4	4.1
12	235	13.3	4.1	13.0	3.9	12.5	3.8
12	165	12.0	3.7	11.7	3.6	11.3	3.5
14	305	15.7	4.8	15.3	4.7	14.8	4.5
14	235	14.7	4.5	14.3	4.4	13.8	4.2
14	165	13.3	4.0	12.9	3.9	12.5	3.8
16	305	17.1	5.2	16.7	5.1	16.1	4.9
16	235	16.0	4.9	15.6	4.7	15.0	4.6
16	165	14.5	4.4	14.1	4.3	13.6	4.1
18	305	18.5	5.6	18.0	5.5	17.4	5.3
18	235	17.2	5.3	16.8	5.1	16.2	5.0
18	165	15.6	4.8	15.2	4.6	14.7	4.5
20	305	19.8	6.0	19.3	5.9	18.6	5.7
20	235	18.5	5.6	18.0	5.5	17.4	5.3
20	165	16.7	5.1	16.3	5.0	15.7	4.8
24	305	22.3	6.8	21.7	6.6	21.0	6.4
24	235	20.8	6.3	20.3	6.2	19.6	6.0
24	165	18.8	5.7	18.3	5.6	17.7	5.4

Table 14.4 Support spacing for ASTM F1483 CIOD PVCO pipe

Pipe size, in.	Pressure rating, psi	73°F, ft	23°C, m	90°F, ft	32°C, m	110°F, ft	44°C, m
4	250	6.9	2.1	6.7	2.0	6.5	2.0
4	200	6.5	2.0	6.3	1.9	6.1	1.9
4	150	6.0	1.8	5.8	1.8	5.6	1.7
6	250	8.8	2.7	8.6	2.6	8.3	2.5
6	200	8.3	2.5	8.0	2.5	7.8	2.4
6	150	7.6	2.3	7.4	2.3	7.1	2.2
8	250	10.5	3.2	10.2	3.1	9.9	3.0
8	200	9.9	3.0	9.6	2.9	9.3	2.8
8	150	9.1	2.8	8.9	2.7	8.6	2.6
10	250	12.1	3.7	11.7	3.6	11.4	3.5
10	200	11.3	3.5	11.0	3.4	10.7	3.3
10	150	10.4	3.2	10.1	3.1	9.8	3.0
12	250	13.5	4.1	13.2	4.0	12.7	3.9
12	200	12.7	3.9	12.4	3.8	12.0	3.6
12	150	11.7	3.6	11.4	3.5	11.0	3.4
14	250	14.9	4.5	14.5	4.4	14.0	4.3
14	200	14.0	4.3	13.7	4.2	13.2	4.0
14	150	12.9	3.9	12.6	3.8	12.2	3.7
16	250	16.3	5.0	15.8	4.8	15.3	4.7
16	200	15.3	4.7	14.9	4.5	14.4	4.4
16	150	14.1	4.3	13.7	4.2	13.2	4.0

14.9 Hydraulics

The discussion and equations for PVC pressure pipe presented in Chapter 9 also apply to PVCO pipe. The larger inside diameters of PVCO pipe provide slightly increased flow volume for the same velocity or slightly reduced velocity (and friction loss) for a constant flow volume.

Table 14.5 Support spacing for ASTM F1483 IPS PVCO pipe

Pipe size, in.	Pressure rating, psi	73°F, ft	23°C, m	90°F, ft	32°C, m	110°F, ft	44°C, m
4	250	6.6	2.0	6.4	2.0	6.2	1.9
4	200	6.2	1.9	6.0	1.8	5.8	1.8
4	160	5.8	1.8	5.7	1.7	5.5	1.7
6	250	8.5	2.6	8.3	2.5	8.0	2.5
6	200	8.0	2.5	7.8	2.4	7.6	2.3
6	160	7.5	2.3	7.3	2.2	7.1	2.2
8	250	10.2	3.1	9.9	3.0	9.6	2.9
8	200	9.6	2.9	9.3	2.8	9.0	2.7
8	160	9.0	2.7	8.7	2.7	8.4	2.6
10	250	11.8	3.6	11.5	3.5	11.1	3.4
10	200	11.1	3.4	10.8	3.3	10.4	3.2
10	160	10.4	3.2	10.1	3.1	9.8	3.0
12	250	13.2	4.0	12.9	3.9	12.4	3.8
12	200	12.4	3.8	12.1	3.7	11.7	3.6
12	160	11.6	3.6	11.3	3.5	11.0	3.3
14	250	14.1	4.3	13.7	4.2	13.2	4.0
14	200	13.2	4.0	12.9	3.9	12.4	3.8
14	160	12.4	3.8	12.1	3.7	11.7	3.6
16	250	15.4	4.7	15.0	4.6	14.5	4.4
16	200	14.4	4.4	14.1	4.3	13.6	4.1
16	160	13.6	4.1	13.2	4.0	12.8	3.9

Friction loss values calculated using Equations 9.1 through 9.4 are conservatively based on:

1. Inside diameters (D_i) using wall thicknesses equal to 106% times the minimum specified;
2. Hazen–Williams coefficient, $C = 150$.

Tables 14.6, 14.7, and 14.8 for PVCO pipe are in the same format as the tables in Chapter 9 for PVC pipe.

Table 14.6 Flow friction loss, AWWA C909 and CSA B137.3.1 CIOD PVCO pipe

4 in. CIOD (AWWA C909 and CSA B137.3.1)									
	Pressure rated 165 psi			Pressure rated 235 psi			Pressure rated 305 psi		
Flow	Velocity	Pressure drop		Velocity	Pressure drop		Velocity	Pressure drop	
gpm	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft
25	0.490	0.0236	0.0102	0.511	0.0261	0.0113	0.533	0.0289	0.0125
40	0.783	0.0562	0.0244	0.817	0.0623	0.0270	0.852	0.0690	0.0299
55	1.08	0.101	0.0439	1.12	0.112	0.0486	1.17	0.124	0.0539
70	1.37	0.158	0.0686	1.43	0.175	0.0760	1.49	0.194	0.0842
85	1.66	0.227	0.0982	1.74	0.251	0.109	1.81	0.278	0.121
100	1.96	0.306	0.133	2.04	0.339	0.147	2.13	0.376	0.163
120	2.35	0.429	0.186	2.45	0.476	0.206	2.56	0.527	0.228
140	2.74	0.571	0.247	2.86	0.633	0.274	2.98	0.701	0.303
160	3.13	0.731	0.317	3.27	0.810	0.351	3.41	0.897	0.389
180	3.53	0.909	0.394	3.68	1.01	0.436	3.84	1.12	0.483
200	3.92	1.10	0.478	4.09	1.22	0.530	4.26	1.36	0.587
225	4.41	1.37	0.595	4.60	1.52	0.659	4.79	1.69	0.730
250	4.90	1.67	0.723	5.11	1.85	0.801	5.33	2.05	0.887
275	5.39	1.99	0.862	5.62	2.21	0.955	5.86	2.44	1.06
300	5.88	2.34	1.01	6.13	2.59	1.12	6.39	2.87	1.24
350	6.86	3.11	1.35	7.15	3.45	1.49	7.46	3.82	1.65
400	7.83	3.98	1.72	8.17	4.41	1.91	8.52	4.89	2.12
450	8.81	4.95	2.14	9.19	5.49	2.38	9.59	6.08	2.63

Notes:

1. CSA values were converted from metric units.
2. Table is based on Chapter 9 Equations 9.1 through 9.4, using C = 150.
3. Friction-loss values in tables 14.6 through 14.8 are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$ where:

D_i = pipe inside diameter, in.
D_o = pipe outside diameter, in.
t_{min} = minimum wall thickness, in.

Table 14.6 Flow friction loss, AWWA C909 and CSA B137.3.1 CIOD PVCO pipe *(continued)*

6 in. CIOD (AWWA C909 and CSA B137.3.1)									
	Pressure rated 165 psi			Pressure rated 235 psi			Pressure rated 305 psi		
Flow	Velocity	Pressure drop		Velocity	Pressure drop		Velocity	Pressure drop	
gpm	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft
50	0.474	0.0146	0.00631	0.494	0.0161	0.00699	0.515	0.0179	0.00774
75	0.711	0.0309	0.0134	0.741	0.0342	0.0148	0.773	0.0378	0.0164
100	0.948	0.0525	0.0228	0.988	0.0582	0.0252	1.03	0.0644	0.0279
125	1.19	0.0794	0.0344	1.24	0.0879	0.0381	1.29	0.0973	0.0421
150	1.42	0.111	0.0482	1.48	0.123	0.0533	1.55	0.136	0.0590
175	1.66	0.148	0.0641	1.73	0.164	0.0709	1.80	0.181	0.0785
200	1.90	0.189	0.0820	1.98	0.210	0.0908	2.06	0.232	0.101
250	2.37	0.286	0.124	2.47	0.317	0.137	2.58	0.351	0.152
300	2.84	0.401	0.174	2.97	0.444	0.192	3.09	0.492	0.213
350	3.32	0.533	0.231	3.46	0.590	0.256	3.61	0.654	0.283
400	3.79	0.683	0.296	3.95	0.756	0.327	4.12	0.837	0.362
450	4.27	0.849	0.368	4.45	0.940	0.407	4.64	1.04	0.451
500	4.74	1.03	0.447	4.94	1.14	0.495	5.15	1.26	0.548
600	5.69	1.45	0.626	5.93	1.60	0.693	6.18	1.77	0.767
700	6.64	1.92	0.833	6.92	2.13	0.922	7.22	2.36	1.02
800	7.58	2.46	1.07	7.91	2.72	1.18	8.25	3.02	1.31
900	8.53	3.06	1.33	8.90	3.39	1.47	9.28	3.75	1.62
1,000	9.48	3.72	1.61	9.88	4.12	1.78	10.3	4.56	1.97

Notes:

1. CSA values were converted from metric units.
2. Table is based on Chapter 9 Equations 9.1 through 9.4, using C = 150.
3. Friction-loss values in tables 14.6 through 14.8 are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$ where:

D_i = pipe inside diameter, in.
D_o = pipe outside diameter, in.
t_{min} = minimum wall thickness, in.

Table 14.6 Flow friction loss, AWWA C909 and CSA B137.3.1 CIOD PVCO pipe *(continued)*

8 in. CIOD (AWWA C909 and CSA B137.3.1)									
	Pressure rated 165 psi			Pressure rated 235 psi			Pressure rated 305 psi		
Flow	Velocity	Pressure drop		Velocity	Pressure drop		Velocity	Pressure drop	
gpm	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft
100	0.551	0.0141	0.00609	0.575	0.0156	0.00674	0.599	0.0172	0.00747
125	0.689	0.0213	0.00920	0.718	0.0235	0.0102	0.749	0.0261	0.0113
150	0.827	0.0298	0.0129	0.862	0.0330	0.0143	0.899	0.0365	0.0158
200	1.10	0.0507	0.0220	1.15	0.0561	0.0243	1.20	0.0622	0.0269
250	1.38	0.0766	0.0332	1.44	0.0848	0.0367	1.50	0.0939	0.0407
300	1.65	0.107	0.0465	1.72	0.119	0.0514	1.80	0.132	0.0570
350	1.93	0.143	0.0618	2.01	0.158	0.0684	2.10	0.175	0.0758
400	2.20	0.183	0.0791	2.30	0.202	0.0876	2.40	0.224	0.0970
450	2.48	0.227	0.0984	2.59	0.252	0.109	2.70	0.279	0.121
500	2.76	0.276	0.120	2.87	0.306	0.132	3.00	0.339	0.147
600	3.31	0.387	0.168	3.45	0.428	0.185	3.60	0.475	0.205
700	3.86	0.515	0.223	4.02	0.570	0.247	4.20	0.631	0.273
800	4.41	0.659	0.285	4.60	0.729	0.316	4.79	0.808	0.350
1,000	5.51	1.00	0.431	5.75	1.10	0.477	5.99	1.22	0.529
1,200	6.61	1.39	0.604	6.90	1.54	0.669	7.19	1.71	0.741
1,400	7.72	1.86	0.803	8.04	2.05	0.889	8.39	2.28	0.985
1,600	8.82	2.38	1.03	9.19	2.63	1.14	9.59	2.91	1.26
1,800	9.92	2.95	1.28	10.3	3.27	1.42	10.8	3.62	1.57

Table 14.6 Flow friction loss, AWWA C909 and CSA B137.3.1 CIOD PVCO pipe *(continued)*

10 in. CIOD (AWWA C909 and CSA B137.3.1)									
	Pressure rated 165 psi			Pressure rated 235 psi			Pressure rated 305 psi		
Flow	Velocity	Pressure drop		Velocity	Pressure drop		Velocity	Pressure drop	
gpm	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft
150	0.549	0.0110	0.00478	0.573	0.0122	0.00529	0.598	0.0135	0.00586
200	0.732	0.0188	0.00813	0.764	0.0208	0.00901	0.797	0.0230	0.0100
250	0.916	0.0284	0.0123	0.955	0.0314	0.0136	1.00	0.0348	0.0151
300	1.10	0.0398	0.0172	1.15	0.0441	0.0191	1.20	0.0488	0.0211
350	1.28	0.0529	0.0229	1.34	0.0586	0.0254	1.39	0.0649	0.0281
400	1.46	0.0677	0.0293	1.53	0.0750	0.0325	1.59	0.0830	0.0360
450	1.65	0.0842	0.0365	1.72	0.0933	0.0404	1.79	0.103	0.0447
500	1.83	0.102	0.0443	1.91	0.113	0.0491	1.99	0.125	0.0543
600	2.20	0.143	0.0621	2.29	0.159	0.0688	2.39	0.176	0.0761
700	2.56	0.191	0.0826	2.67	0.211	0.0915	2.79	0.234	0.101
800	2.93	0.244	0.106	3.06	0.270	0.117	3.19	0.299	0.130
1,000	3.66	0.369	0.160	3.82	0.409	0.177	3.98	0.452	0.196
1,200	4.39	0.517	0.224	4.58	0.573	0.248	4.78	0.634	0.274
1,400	5.13	0.687	0.298	5.35	0.762	0.330	5.58	0.843	0.365
1,600	5.86	0.880	0.381	6.11	0.975	0.422	6.37	1.08	0.467
1,800	6.59	1.09	0.474	6.88	1.21	0.525	7.17	1.34	0.581
2,200	8.06	1.59	0.687	8.40	1.76	0.761	8.76	1.95	0.842
2,600	9.52	2.16	0.935	9.93	2.39	1.04	10.4	2.65	1.15

Notes:

1. CSA values were converted from metric units.
2. Table is based on Chapter 9 Equations 9.1 through 9.4, using C = 150.
3. Friction-loss values in tables 14.6 through 14.8 are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$ where:

D_i = pipe inside diameter, in.
D_o = pipe outside diameter, in.
t_{min} = minimum wall thickness, in.

Table 14.6 Flow friction loss, AWWA C909 and CSA B137.3.1 CIOD PVCO pipe *(continued)*

12 in. CIOD (AWWA C909 and CSA B137.3.1)									
	Pressure rated 165 psi			Pressure rated 235 psi			Pressure rated 305 psi		
Flow	Velocity	Pressure drop		Velocity	Pressure drop		Velocity	Pressure drop	
gpm	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft
200	0.518	0.00809	0.00350	0.540	0.00896	0.00388	0.563	0.00993	0.00430
250	0.648	0.0122	0.00530	0.675	0.0135	0.00586	0.704	0.0150	0.00650
300	0.777	0.0171	0.00742	0.810	0.0190	0.00822	0.845	0.0210	0.00910
350	0.907	0.0228	0.00987	0.945	0.0252	0.0109	0.986	0.0280	0.0121
400	1.04	0.0292	0.0126	1.08	0.0323	0.0140	1.13	0.0358	0.0155
500	1.30	0.0441	0.0191	1.35	0.0488	0.0211	1.41	0.0541	0.0234
600	1.55	0.0618	0.0267	1.62	0.0684	0.0296	1.69	0.0758	0.0328
700	1.81	0.0822	0.0356	1.89	0.0910	0.0394	1.97	0.101	0.0436
800	2.07	0.105	0.0455	2.16	0.116	0.0504	2.25	0.129	0.0559
1,000	2.59	0.159	0.0688	2.70	0.176	0.0762	2.82	0.195	0.0844
1,200	3.11	0.223	0.0964	3.24	0.247	0.107	3.38	0.273	0.118
1,400	3.63	0.296	0.128	3.78	0.328	0.142	3.94	0.363	0.157
1,600	4.14	0.379	0.164	4.32	0.420	0.182	4.51	0.465	0.201
2,000	5.18	0.573	0.248	5.40	0.634	0.275	5.63	0.703	0.304
2,400	6.22	0.803	0.348	6.48	0.889	0.385	6.76	0.985	0.426
2,800	7.25	1.07	0.462	7.56	1.18	0.512	7.89	1.31	0.567
3,200	8.29	1.37	0.592	8.64	1.51	0.655	9.02	1.68	0.726
3,600	9.32	1.70	0.736	9.72	1.88	0.815	10.1	2.09	0.903

Table 14.6 Flow friction loss, AWWA C909 and CSA B137.3.1 CIOD PVCO pipe *(continued)*

14 in. CIOD (CSA B137.3.1)									
	Pressure rated 165 psi			Pressure rated 235 psi			Pressure rated 305 psi		
Flow	Velocity	Pressure drop		Velocity	Pressure drop		Velocity	Pressure drop	
gpm	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft
300	0.578	0.00836	0.00362	0.603	0.00926	0.00401	0.629	0.0103	0.00444
450	0.867	0.0177	0.00766	0.905	0.0196	0.00849	0.944	0.0217	0.00940
600	1.16	0.0301	0.0130	1.21	0.0334	0.0144	1.26	0.0370	0.0160
800	1.54	0.0513	0.0222	1.61	0.0568	0.0246	1.68	0.0629	0.0273
1,000	1.93	0.0775	0.0336	2.01	0.0859	0.0372	2.10	0.0951	0.0412
1,200	2.31	0.109	0.0470	2.41	0.120	0.0521	2.52	0.133	0.0577
1,400	2.70	0.144	0.0625	2.81	0.160	0.0693	2.94	0.177	0.0767
1,600	3.08	0.185	0.0801	3.22	0.205	0.0887	3.35	0.227	0.0982
1,800	3.47	0.230	0.100	3.62	0.255	0.110	3.77	0.282	0.122
2,000	3.86	0.279	0.121	4.02	0.310	0.134	4.19	0.343	0.148
2,200	4.24	0.333	0.144	4.42	0.369	0.160	4.61	0.409	0.177
2,600	5.01	0.454	0.197	5.23	0.503	0.218	5.45	0.557	0.241
3,000	5.78	0.592	0.256	6.03	0.655	0.284	6.29	0.726	0.314
3,400	6.55	0.746	0.323	6.84	0.826	0.358	7.13	0.915	0.396
3,800	7.32	0.916	0.397	7.64	1.01	0.439	7.97	1.12	0.487
4,200	8.10	1.10	0.477	8.44	1.22	0.529	8.81	1.35	0.586
4,600	8.87	1.30	0.565	9.25	1.45	0.626	9.64	1.60	0.693
5,000	9.64	1.52	0.659	10.1	1.69	0.730	10.5	1.87	0.809

Notes:

1. CSA values were converted from metric units.
2. Table is based on Chapter 9 Equations 9.1 through 9.4, using C = 150.
3. Friction-loss values in tables 14.6 through 14.8 are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$ where:

   D_i = pipe inside diameter, in.
   D_o = pipe outside diameter, in.
   t_{min} = minimum wall thickness, in.

Table 14.6 Flow friction loss, AWWA C909 and CSA B137.3.1 CIOD PVCO pipe *(continued)*

16 in. CIOD (AWWA C909 and CSA B137.3.1)									
	Pressure rated 165 psi			Pressure rated 235 psi			Pressure rated 305 psi		
Flow	Velocity	Pressure drop		Velocity	Pressure drop		Velocity	Pressure drop	
gpm	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft
350	0.522	0.00595	0.00258	0.544	0.00659	0.00285	0.567	0.00730	0.00316
500	0.745	0.0115	0.00498	0.777	0.0127	0.00552	0.811	0.0141	0.00612
650	0.969	0.0187	0.00810	1.01	0.0207	0.00897	1.05	0.0229	0.00994
800	1.19	0.0275	0.0119	1.24	0.0304	0.0132	1.30	0.0337	0.0146
1,000	1.49	0.0415	0.0180	1.55	0.0459	0.0199	1.62	0.0509	0.0220
1,200	1.79	0.0581	0.0252	1.87	0.0644	0.0279	1.95	0.0713	0.0309
1,400	2.09	0.0773	0.0335	2.18	0.0856	0.0371	2.27	0.0949	0.0411
1,800	2.68	0.123	0.0533	2.80	0.136	0.0590	2.92	0.151	0.0654
2,200	3.28	0.178	0.0773	3.42	0.198	0.0856	3.57	0.219	0.0948
2,600	3.88	0.243	0.105	4.04	0.269	0.117	4.22	0.298	0.129
3,000	4.47	0.317	0.137	4.66	0.351	0.152	4.86	0.389	0.168
3,500	5.22	0.421	0.182	5.44	0.466	0.202	5.67	0.517	0.224
4,000	5.96	0.539	0.234	6.22	0.597	0.259	6.49	0.662	0.287
4,500	6.71	0.671	0.290	6.99	0.743	0.322	7.30	0.823	0.356
5,000	7.45	0.815	0.353	7.77	0.902	0.391	8.11	1.00	0.433
5,500	8.20	0.972	0.421	8.55	1.08	0.466	8.92	1.19	0.516
6,000	8.94	1.14	0.494	9.33	1.26	0.547	9.73	1.40	0.607
6,500	9.69	1.32	0.573	10.1	1.47	0.635	10.5	1.62	0.703

Table 14.6 Flow friction loss, AWWA C909 and CSA B137.3.1 CIOD PVCO pipe *(continued)*

18 in. CIOD (CSA B137.3.1)									
	Pressure rated 165 psi			Pressure rated 235 psi			Pressure rated 305 psi		
Flow	Velocity	Pressure drop		Velocity	Pressure drop		Velocity	Pressure drop	
gpm	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft
500	0.593	0.00662	0.00287	0.619	0.00733	0.00317	0.645	0.00812	0.00351
800	0.949	0.0158	0.00684	0.990	0.0175	0.00757	1.03	0.0194	0.00838
1,100	1.31	0.0285	0.0123	1.36	0.0315	0.0136	1.42	0.0349	0.0151
1,400	1.66	0.0445	0.0193	1.73	0.0492	0.0213	1.81	0.0545	0.0236
1,800	2.14	0.0708	0.0306	2.23	0.0784	0.0339	2.32	0.0868	0.0376
2,200	2.61	0.103	0.0444	2.72	0.114	0.0492	2.84	0.126	0.0545
2,600	3.09	0.140	0.0605	3.22	0.155	0.0670	3.36	0.171	0.0742
3,000	3.56	0.182	0.0788	3.71	0.202	0.0873	3.87	0.223	0.0967
3,500	4.15	0.242	0.105	4.33	0.268	0.116	4.52	0.297	0.129
4,000	4.75	0.310	0.134	4.95	0.343	0.149	5.16	0.380	0.165
4,500	5.34	0.386	0.167	5.57	0.427	0.185	5.81	0.473	0.205
5,000	5.93	0.468	0.203	6.19	0.519	0.225	6.45	0.575	0.249
5,500	6.53	0.559	0.242	6.81	0.619	0.268	7.10	0.685	0.297
6,000	7.12	0.656	0.284	7.43	0.727	0.315	7.74	0.805	0.349
6,500	7.71	0.761	0.330	8.05	0.843	0.365	8.39	0.934	0.404
7,000	8.31	0.873	0.378	8.66	0.967	0.419	9.04	1.07	0.464
7,500	8.90	0.992	0.429	9.28	1.10	0.476	9.68	1.22	0.527
8,000	9.49	1.12	0.484	9.90	1.24	0.536	10.3	1.37	0.594

Notes:

1. CSA values were converted from metric units.
2. Table is based on Chapter 9 Equations 9.1 through 9.4, using C = 150.
3. Friction-loss values in tables 14.6 through 14.8 are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$ where:
   D_i = pipe inside diameter, in.
   D_o = pipe outside diameter, in.
   t_{min} = minimum wall thickness, in.

Table 14.6 Flow friction loss, AWWA C909 and CSA B137.3.1 CIOD PVCO pipe *(continued)*

20 in. CIOD (CSA B137.3.1)									
	Pressure rated 165 psi			Pressure rated 235 psi			Pressure rated 305 psi		
Flow	Velocity	Pressure drop		Velocity	Pressure drop		Velocity	Pressure drop	
gpm	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft
600	0.580	0.00564	0.00244	0.605	0.00625	0.00270	0.631	0.00692	0.00300
1,000	0.967	0.0145	0.00628	1.01	0.0161	0.00696	1.05	0.0178	0.00771
1,400	1.35	0.0270	0.0117	1.41	0.0299	0.0130	1.47	0.0332	0.0144
1,800	1.74	0.0431	0.0186	1.82	0.0477	0.0206	1.89	0.0528	0.0229
2,200	2.13	0.0624	0.0270	2.22	0.0691	0.0299	2.31	0.0766	0.0331
2,600	2.52	0.0850	0.0368	2.62	0.0941	0.0408	2.74	0.104	0.0452
3,000	2.90	0.111	0.0480	3.03	0.123	0.0531	3.16	0.136	0.0588
3,500	3.39	0.147	0.0638	3.53	0.163	0.0706	3.68	0.181	0.0783
4,000	3.87	0.189	0.0817	4.03	0.209	0.0904	4.21	0.231	0.100
4,500	4.35	0.235	0.102	4.54	0.260	0.112	4.73	0.288	0.125
5,000	4.84	0.285	0.123	5.04	0.316	0.137	5.26	0.350	0.151
5,500	5.32	0.340	0.147	5.55	0.376	0.163	5.79	0.417	0.181
6,000	5.80	0.399	0.173	6.05	0.442	0.191	6.31	0.490	0.212
6,500	6.29	0.463	0.201	6.56	0.513	0.222	6.84	0.568	0.246
7,000	6.77	0.531	0.230	7.06	0.588	0.255	7.36	0.651	0.282
8,000	7.74	0.680	0.294	8.07	0.753	0.326	8.42	0.834	0.361
9,000	8.71	0.846	0.366	9.08	0.936	0.405	9.47	1.04	0.449
10,000	9.67	1.03	0.445	10.1	1.14	0.493	10.5	1.26	0.546

Table 14.6 Flow friction loss, AWWA C909 and CSA B137.3.1 CIOD PVCO pipe *(continued)*

24 in. CIOD (CSA B137.3.1)									
	Pressure rated 165 psi			Pressure rated 235 psi			Pressure rated 305 psi		
Flow	Velocity	Pressure drop		Velocity	Pressure drop		Velocity	Pressure drop	
gpm	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft
800	0.542	0.00405	0.00175	0.566	0.00449	0.00194	0.590	0.00497	0.00215
1,200	0.814	0.00857	0.00371	0.848	0.00950	0.00411	0.885	0.0105	0.00455
1,600	1.08	0.0146	0.00632	1.13	0.0162	0.00700	1.18	0.0179	0.00775
2,000	1.36	0.0221	0.00955	1.41	0.0244	0.0106	1.47	0.0271	0.0117
2,600	1.76	0.0358	0.0155	1.84	0.0397	0.0172	1.92	0.0440	0.0190
3,200	2.17	0.0526	0.0228	2.26	0.0583	0.0252	2.36	0.0646	0.0280
3,800	2.58	0.0723	0.0313	2.69	0.0801	0.0347	2.80	0.0887	0.0384
4,600	3.12	0.103	0.0446	3.25	0.114	0.0494	3.39	0.126	0.0547
5,400	3.66	0.139	0.0600	3.82	0.153	0.0664	3.98	0.170	0.0736
6,200	4.20	0.179	0.0775	4.38	0.198	0.0858	4.57	0.219	0.0950
7,000	4.75	0.224	0.0970	4.95	0.248	0.107	5.16	0.275	0.119
8,000	5.42	0.287	0.124	5.66	0.318	0.137	5.90	0.352	0.152
9,000	6.10	0.356	0.154	6.36	0.395	0.171	6.64	0.437	0.189
10,000	6.78	0.433	0.188	7.07	0.480	0.208	7.37	0.531	0.230
11,000	7.46	0.517	0.224	7.78	0.572	0.248	8.11	0.634	0.274
12,000	8.14	0.607	0.263	8.48	0.672	0.291	8.85	0.745	0.322
13,500	9.15	0.755	0.327	9.55	0.836	0.362	9.96	0.926	0.401
15,000	10.2	0.917	0.397	10.6	1.02	0.440	11.1	1.13	0.487

Notes:

1. CSA values were converted from metric units.
2. Table is based on Chapter 9 Equations 9.1 through 9.4, using C = 150.
3. Friction-loss values in tables 14.6 through 14.8 are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$ where:

   D_i = pipe inside diameter, in.
   D_o = pipe outside diameter, in.
   t_{min} = minimum wall thickness, in.

Table 14.7 Flow friction loss, ASTM F1483 and CSA B137.3.1 IPS OD PVCO pipe

4 in. IPS (ASTM F1483 and CSA B137.3.1)									
	Pressure rated 160 psi			Pressure rated 200 psi			Pressure rated 250 psi		
Flow	Velocity	Pressure drop		Velocity	Pressure drop		Velocity	Pressure drop	
gpm	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft
25	0.555	0.0320	0.0139	0.569	0.0339	0.0147	0.586	0.0365	0.0158
40	0.889	0.0764	0.0331	0.910	0.0809	0.0350	0.938	0.0871	0.0377
55	1.22	0.138	0.0596	1.25	0.146	0.0632	1.29	0.157	0.0680
70	1.56	0.215	0.0931	1.59	0.228	0.0987	1.64	0.245	0.106
85	1.89	0.308	0.133	1.93	0.326	0.141	1.99	0.351	0.152
100	2.22	0.416	0.180	2.28	0.441	0.191	2.34	0.475	0.205
125	2.78	0.629	0.272	2.84	0.666	0.289	2.93	0.717	0.310
150	3.33	0.881	0.381	3.41	0.934	0.404	3.52	1.00	0.435
175	3.89	1.17	0.507	3.98	1.24	0.538	4.10	1.34	0.579
200	4.44	1.50	0.650	4.55	1.59	0.688	4.69	1.71	0.741
225	5.00	1.87	0.808	5.12	1.98	0.856	5.28	2.13	0.921
250	5.55	2.27	0.981	5.69	2.40	1.04	5.86	2.59	1.12
275	6.11	2.70	1.17	6.26	2.87	1.24	6.45	3.08	1.34
300	6.66	3.18	1.38	6.83	3.37	1.46	7.03	3.62	1.57
325	7.22	3.68	1.59	7.39	3.90	1.69	7.62	4.20	1.82
350	7.78	4.22	1.83	7.96	4.48	1.94	8.21	4.82	2.09
375	8.33	4.80	2.08	8.53	5.09	2.20	8.79	5.47	2.37
400	8.89	5.41	2.34	9.10	5.73	2.48	9.38	6.17	2.67

Notes:

1. CSA values were converted from metric units.
2. Table is based on Chapter 9 Equations 9.1 through 9.4, using C = 150.
3. Friction-loss values in tables 14.6 through 14.8 are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$ where:

D_i = pipe inside diameter, in.
D_o = pipe outside diameter, in.
t_{min} = minimum wall thickness, in.

Table 14.7 Flow friction loss, ASTM F1483 and CSA B137.3.1 IPS OD PVCO pipe *(continued)*

6 in. IPS (CSA B137.3.1)									
	Pressure rated 160 psi			Pressure rated 200 psi			Pressure rated 250 psi		
Flow	Velocity	Pressure drop		Velocity	Pressure drop		Velocity	Pressure drop	
gpm	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft
50	0.513	0.0176	0.00763	0.525	0.0187	0.00810	0.541	0.0201	0.00870
75	0.769	0.0373	0.0162	0.788	0.0396	0.0171	0.811	0.0425	0.0184
100	1.03	0.0635	0.0275	1.05	0.0674	0.0292	1.08	0.0724	0.0313
125	1.28	0.0960	0.0416	1.31	0.102	0.0441	1.35	0.109	0.0474
150	1.54	0.135	0.0582	1.58	0.143	0.0618	1.62	0.153	0.0664
175	1.79	0.179	0.0775	1.84	0.190	0.0822	1.89	0.204	0.0883
200	2.05	0.229	0.0992	2.10	0.243	0.105	2.16	0.261	0.113
225	2.31	0.285	0.123	2.36	0.302	0.131	2.43	0.325	0.141
250	2.56	0.346	0.150	2.63	0.367	0.159	2.70	0.394	0.171
300	3.08	0.485	0.210	3.15	0.514	0.223	3.25	0.553	0.239
350	3.59	0.645	0.279	3.68	0.684	0.296	3.79	0.735	0.318
400	4.10	0.826	0.358	4.20	0.876	0.379	4.33	0.941	0.407
450	4.61	1.03	0.445	4.73	1.09	0.472	4.87	1.17	0.507
500	5.13	1.25	0.540	5.25	1.32	0.573	5.41	1.42	0.616
600	6.15	1.75	0.757	6.30	1.85	0.803	6.49	1.99	0.863
700	7.18	2.33	1.01	7.35	2.47	1.07	7.57	2.65	1.15
800	8.20	2.98	1.29	8.40	3.16	1.37	8.65	3.39	1.47
900	9.23	3.70	1.60	9.45	3.93	1.70	9.74	4.22	1.83

Notes:

1. CSA values were converted from metric units.
2. Table is based on Chapter 9 Equations 9.1 through 9.4, using C = 150.
3. Friction-loss values in tables 14.6 through 14.8 are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$ where:

   D_i = pipe inside diameter, in.
   D_o = pipe outside diameter, in.
   t_{min} = minimum wall thickness, in.

Table 14.7 Flow friction loss, ASTM F1483 and CSA B137.3.1 IPS OD PVCO pipe *(continued)*

8 in. IPS (CSA B137.3.1)									
	Pressure rated 160 psi			Pressure rated 200 psi			Pressure rated 250 psi		
Flow	Velocity	Pressure drop		Velocity	Pressure drop		Velocity	Pressure drop	
gpm	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft
90	0.544	0.0145	0.00628	0.557	0.0154	0.00666	0.574	0.0165	0.00716
120	0.726	0.0247	0.0107	0.743	0.0262	0.0113	0.766	0.0281	0.0122
150	0.907	0.0373	0.0162	0.929	0.0395	0.0171	0.957	0.0425	0.0184
200	1.21	0.0635	0.0275	1.24	0.0673	0.0292	1.28	0.0724	0.0314
250	1.51	0.0960	0.0416	1.55	0.102	0.0441	1.60	0.109	0.0474
300	1.81	0.135	0.0583	1.86	0.143	0.0617	1.91	0.153	0.0664
350	2.12	0.179	0.0775	2.17	0.190	0.0821	2.23	0.204	0.0883
400	2.42	0.229	0.0992	2.48	0.243	0.105	2.55	0.261	0.113
500	3.02	0.346	0.150	3.10	0.367	0.159	3.19	0.395	0.171
600	3.63	0.485	0.210	3.72	0.514	0.223	3.83	0.553	0.239
700	4.23	0.645	0.279	4.34	0.684	0.296	4.47	0.735	0.318
800	4.84	0.826	0.358	4.96	0.875	0.379	5.11	0.941	0.408
900	5.44	1.03	0.445	5.57	1.09	0.471	5.74	1.17	0.507
1,000	6.05	1.25	0.540	6.19	1.32	0.573	6.38	1.42	0.616
1,100	6.65	1.49	0.644	6.81	1.58	0.683	7.02	1.70	0.735
1,200	7.26	1.75	0.757	7.43	1.85	0.802	7.66	1.99	0.863
1,400	8.47	2.33	1.01	8.67	2.46	1.07	8.94	2.65	1.15
1,600	9.68	2.98	1.29	9.91	3.15	1.37	10.2	3.39	1.47

Table 14.7 Flow friction loss, ASTM F1483 and CSA B137.3.1 IPS OD PVCO pipe *(continued)*

10 in. IPS (CSA B137.3.1)									
	Pressure rated 160 psi			Pressure rated 200 psi			Pressure rated 250 psi		
Flow	Velocity	Pressure drop		Velocity	Pressure drop		Velocity	Pressure drop	
gpm	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft
150	0.584	0.0128	0.00554	0.598	0.0136	0.00588	0.616	0.0146	0.00632
200	0.779	0.0218	0.00944	0.798	0.0231	0.0100	0.822	0.0249	0.0108
250	0.973	0.0329	0.0143	0.997	0.0349	0.0151	1.03	0.0376	0.0163
300	1.17	0.0461	0.0200	1.20	0.0489	0.0212	1.23	0.0526	0.0228
400	1.56	0.0786	0.0340	1.60	0.0833	0.0361	1.64	0.0896	0.0388
500	1.95	0.119	0.0514	1.99	0.126	0.0545	2.05	0.135	0.0586
600	2.34	0.166	0.0720	2.39	0.176	0.0764	2.47	0.190	0.0821
700	2.73	0.221	0.0958	2.79	0.235	0.102	2.88	0.252	0.109
800	3.11	0.283	0.123	3.19	0.300	0.130	3.29	0.323	0.140
900	3.50	0.352	0.152	3.59	0.373	0.162	3.70	0.402	0.174
1,000	3.89	0.428	0.185	3.99	0.454	0.196	4.11	0.488	0.211
1,200	4.67	0.600	0.260	4.79	0.636	0.275	4.93	0.684	0.296
1,400	5.45	0.797	0.345	5.58	0.846	0.366	5.75	0.910	0.394
1,600	6.23	1.02	0.442	6.38	1.08	0.469	6.58	1.16	0.504
1,800	7.01	1.27	0.550	7.18	1.35	0.583	7.40	1.45	0.627
2,000	7.79	1.54	0.668	7.98	1.64	0.708	8.22	1.76	0.762
2,200	8.57	1.84	0.797	8.77	1.95	0.845	9.04	2.10	0.909
2,500	9.73	2.33	1.01	9.97	2.47	1.07	10.3	2.66	1.15

Notes:

1. CSA values were converted from metric units.
2. Table is based on Chapter 9 Equations 9.1 through 9.4, using C = 150.
3. Friction-loss values in tables 14.6 through 14.8 are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$ where:

   D_i = pipe inside diameter, in.
   D_o = pipe outside diameter, in.
   t_{min} = minimum wall thickness, in.

Table 14.7 Flow friction loss, ASTM F1483 and CSA B137.3.1 IPS OD PVCO pipe *(continued)*

12 in. IPS (CSA B137.3.1)									
	Pressure rated 160 psi			Pressure rated 200 psi			Pressure rated 250 psi		
Flow	Velocity	Pressure drop		Velocity	Pressure drop		Velocity	Pressure drop	
gpm	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft
200	0.554	0.00951	0.00412	0.567	0.0101	0.00436	0.584	0.0108	0.00470
300	0.830	0.0201	0.00872	0.850	0.0213	0.00924	0.876	0.0230	0.00994
400	1.11	0.0343	0.0148	1.13	0.0363	0.0157	1.17	0.0391	0.0169
500	1.38	0.0518	0.0224	1.42	0.0549	0.0238	1.46	0.0591	0.0256
600	1.66	0.0726	0.0314	1.70	0.0769	0.0333	1.75	0.0828	0.0358
700	1.94	0.0965	0.0418	1.98	0.102	0.0443	2.05	0.110	0.0477
800	2.21	0.124	0.0535	2.27	0.131	0.0567	2.34	0.141	0.0610
900	2.49	0.154	0.0665	2.55	0.163	0.0705	2.63	0.175	0.0759
1,000	2.77	0.187	0.0809	2.83	0.198	0.0857	2.92	0.213	0.0922
1,200	3.32	0.262	0.113	3.40	0.277	0.120	3.51	0.298	0.129
1,400	3.87	0.348	0.151	3.97	0.369	0.160	4.09	0.397	0.172
1,600	4.43	0.445	0.193	4.54	0.472	0.204	4.67	0.508	0.220
1,800	4.98	0.554	0.240	5.10	0.587	0.254	5.26	0.632	0.274
2,000	5.54	0.673	0.291	5.67	0.713	0.309	5.84	0.768	0.332
2,400	6.64	0.943	0.408	6.80	1.00	0.433	7.01	1.08	0.466
2,800	7.75	1.25	0.543	7.94	1.33	0.576	8.18	1.43	0.619
3,200	8.86	1.61	0.695	9.07	1.70	0.737	9.35	1.83	0.793
3,600	9.96	2.00	0.865	10.2	2.12	0.916	10.5	2.28	0.986

Table 14.7 Flow friction loss, ASTM F1483 and CSA B137.3.1 IPS OD PVCO pipe *(continued)*

14 in. IPS (CSA B137.3.1)									
	Pressure rated 160 psi			Pressure rated 200 psi			Pressure rated 250 psi		
Flow	Velocity	Pressure drop		Velocity	Pressure drop		Velocity	Pressure drop	
gpm	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft
250	0.574	0.00911	0.00394	0.588	0.00967	0.00419	0.606	0.0104	0.00450
300	0.688	0.0128	0.00552	0.705	0.0135	0.00587	0.727	0.0146	0.00631
350	0.803	0.0170	0.00735	0.823	0.0180	0.00780	0.848	0.0194	0.00839
400	0.918	0.0217	0.00941	0.941	0.0231	0.0100	0.969	0.0248	0.0107
500	1.15	0.0328	0.0142	1.18	0.0349	0.0151	1.21	0.0375	0.0162
600	1.38	0.0460	0.0199	1.41	0.0488	0.0212	1.45	0.0525	0.0227
700	1.61	0.0612	0.0265	1.65	0.0650	0.0281	1.70	0.0698	0.0302
800	1.84	0.0783	0.0339	1.88	0.0832	0.0360	1.94	0.0894	0.0387
1,000	2.29	0.118	0.0512	2.35	0.126	0.0544	2.42	0.135	0.0585
1,200	2.75	0.166	0.0718	2.82	0.176	0.0762	2.91	0.189	0.0820
1,400	3.21	0.221	0.0955	3.29	0.234	0.101	3.39	0.252	0.109
1,600	3.67	0.282	0.122	3.76	0.300	0.130	3.88	0.322	0.140
2,000	4.59	0.427	0.185	4.70	0.453	0.196	4.85	0.487	0.211
2,400	5.51	0.598	0.259	5.64	0.635	0.275	5.81	0.682	0.296
2,800	6.42	0.795	0.344	6.58	0.844	0.366	6.78	0.908	0.393
3,200	7.34	1.02	0.441	7.53	1.08	0.468	7.75	1.16	0.503
3,700	8.49	1.33	0.577	8.70	1.41	0.612	8.96	1.52	0.658
4,200	9.64	1.68	0.729	9.88	1.79	0.774	10.2	1.92	0.832

Notes:

1. CSA values were converted from metric units.
2. Table is based on Chapter 9 Equations 9.1 through 9.4, using C = 150.
3. Friction-loss values in tables 14.6 through 14.8 are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$ where:

   D_i = pipe inside diameter, in.
   D_o = pipe outside diameter, in.
   t_{min} = minimum wall thickness, in.

Table 14.7 Flow friction loss, ASTM F1483 and CSA B137.3.1 IPS OD PVCO pipe *(continued)*

16 in. IPS (CSA B137.3.1)									
	Pressure rated 160 psi			Pressure rated 200 psi			Pressure rated 250 psi		
Flow	Velocity	Pressure drop		Velocity	Pressure drop		Velocity	Pressure drop	
gpm	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft
300	0.527	0.00668	0.00289	0.540	0.00708	0.00306	0.556	0.00761	0.00330
400	0.703	0.0114	0.00493	0.720	0.0120	0.00522	0.742	0.0130	0.00561
500	0.879	0.0172	0.00745	0.900	0.0182	0.00788	0.927	0.0196	0.00848
600	1.05	0.0241	0.0104	1.08	0.0255	0.0110	1.11	0.0274	0.0119
700	1.23	0.0320	0.0139	1.26	0.0339	0.0147	1.30	0.0365	0.0158
800	1.41	0.0410	0.0178	1.44	0.0434	0.0188	1.48	0.0467	0.0202
1,000	1.76	0.0620	0.0268	1.80	0.0656	0.0284	1.85	0.0706	0.0306
1,300	2.29	0.101	0.0436	2.34	0.107	0.0462	2.41	0.115	0.0497
1,600	2.81	0.148	0.0640	2.88	0.157	0.0678	2.97	0.168	0.0729
1,900	3.34	0.203	0.0880	3.42	0.215	0.0932	3.52	0.232	0.100
2,200	3.87	0.267	0.115	3.96	0.282	0.122	4.08	0.304	0.131
2,500	4.40	0.338	0.146	4.50	0.358	0.155	4.64	0.385	0.167
3,000	5.27	0.473	0.205	5.40	0.501	0.217	5.56	0.539	0.233
3,500	6.15	0.629	0.272	6.30	0.666	0.289	6.49	0.717	0.310
4,000	7.03	0.806	0.349	7.20	0.853	0.369	7.42	0.918	0.397
4,500	7.91	1.00	0.434	8.10	1.06	0.459	8.35	1.14	0.494
5,000	8.79	1.22	0.527	9.00	1.29	0.558	9.27	1.39	0.600
5,500	9.67	1.45	0.629	9.90	1.54	0.666	10.2	1.65	0.716

Table 14.7 Flow friction loss, ASTM F1483 and CSA B137.3.1 IPS OD PVCO pipe *(continued)*

18 in. IPS (CSA B137.3.1)									
	Pressure rated 160 psi			Pressure rated 200 psi			Pressure rated 250 psi		
Flow	Velocity	Pressure drop		Velocity	Pressure drop		Velocity	Pressure drop	
gpm	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft
400	0.556	0.00642	0.00278	0.569	0.00680	0.00294	0.586	0.00731	0.00317
600	0.833	0.0136	0.00588	0.853	0.0144	0.00623	0.879	0.0155	0.00670
800	1.11	0.0231	0.0100	1.14	0.0245	0.0106	1.17	0.0264	0.0114
1,000	1.39	0.0349	0.0151	1.42	0.0370	0.0160	1.47	0.0398	0.0172
1,200	1.67	0.0490	0.0212	1.71	0.0519	0.0225	1.76	0.0558	0.0242
1,400	1.94	0.0651	0.0282	1.99	0.0690	0.0299	2.05	0.0742	0.0321
1,800	2.50	0.104	0.0449	2.56	0.110	0.0476	2.64	0.118	0.0512
2,200	3.06	0.150	0.0651	3.13	0.159	0.0690	3.22	0.171	0.0742
2,600	3.61	0.205	0.0886	3.70	0.217	0.0939	3.81	0.233	0.101
3,000	4.17	0.267	0.116	4.27	0.283	0.122	4.40	0.304	0.132
3,500	4.86	0.355	0.154	4.98	0.376	0.163	5.13	0.404	0.175
4,000	5.56	0.454	0.197	5.69	0.481	0.208	5.86	0.518	0.224
4,500	6.25	0.565	0.245	6.40	0.599	0.259	6.60	0.644	0.279
5,000	6.94	0.686	0.297	7.11	0.727	0.315	7.33	0.782	0.339
5,500	7.64	0.819	0.354	7.82	0.868	0.376	8.06	0.933	0.404
6,000	8.33	0.962	0.416	8.53	1.02	0.441	8.79	1.10	0.475
6,500	9.03	1.12	0.483	9.24	1.18	0.512	9.53	1.27	0.550
7,000	9.72	1.28	0.554	9.96	1.36	0.587	10.3	1.46	0.631

Notes:

1. CSA values were converted from metric units.
2. Table is based on Chapter 9 Equations 9.1 through 9.4, using C = 150.
3. Friction-loss values in tables 14.6 through 14.8 are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$ where:

   D_i = pipe inside diameter, in.

   D_o = pipe outside diameter, in.

   t_{min} = minimum wall thickness, in.

Table 14.7 Flow friction loss, ASTM F1483 and CSA B137.3.1 IPS OD PVCO pipe *(continued)*

20 in. IPS (CSA B137.3.1)									
	Pressure rated 160 psi			Pressure rated 200 psi			Pressure rated 250 psi		
Flow	Velocity	Pressure drop		Velocity	Pressure drop		Velocity	Pressure drop	
gpm	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft
500	0.562	0.00581	0.00252	0.576	0.00616	0.00267	0.594	0.00662	0.00287
800	0.900	0.0139	0.00600	0.922	0.0147	0.00636	0.950	0.0158	0.00684
1,100	1.24	0.0250	0.0108	1.27	0.0265	0.0115	1.31	0.0285	0.0123
1,400	1.57	0.0390	0.0169	1.61	0.0414	0.0179	1.66	0.0445	0.0193
1,700	1.91	0.0559	0.0242	1.96	0.0592	0.0257	2.02	0.0637	0.0276
2,000	2.25	0.0755	0.0327	2.30	0.0800	0.0346	2.37	0.0861	0.0373
2,500	2.81	0.114	0.0494	2.88	0.121	0.0524	2.97	0.130	0.0563
3,000	3.37	0.160	0.0692	3.46	0.169	0.0734	3.56	0.182	0.0789
3,500	3.94	0.213	0.0921	4.03	0.225	0.0976	4.15	0.242	0.105
4,000	4.50	0.272	0.118	4.61	0.288	0.125	4.75	0.310	0.134
4,500	5.06	0.338	0.147	5.18	0.359	0.155	5.34	0.386	0.167
5,000	5.62	0.411	0.178	5.76	0.436	0.189	5.94	0.469	0.203
5,500	6.19	0.491	0.212	6.34	0.520	0.225	6.53	0.559	0.242
6,000	6.75	0.576	0.250	6.91	0.611	0.264	7.12	0.657	0.284
6,500	7.31	0.668	0.289	7.49	0.708	0.307	7.72	0.762	0.330
7,000	7.87	0.766	0.332	8.06	0.812	0.352	8.31	0.874	0.378
7,500	8.44	0.871	0.377	8.64	0.923	0.400	8.90	0.993	0.430
8,000	9.00	0.981	0.425	9.22	1.04	0.450	9.50	1.12	0.484

Table 14.7 Flow friction loss, ASTM F1483 and CSA B137.3.1 IPS OD PVCO pipe *(continued)*

24 in. IPS (CSA B137.3.1)									
	Pressure rated 160 psi			Pressure rated 200 psi			Pressure rated 250 psi		
Flow	Velocity	Pressure drop		Velocity	Pressure drop		Velocity	Pressure drop	
gpm	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft
700	0.547	0.00446	0.00193	0.560	0.00473	0.00205	0.577	0.00509	0.00220
1,100	0.859	0.0103	0.00446	0.880	0.0109	0.00473	0.907	0.0117	0.00508
1,500	1.17	0.0183	0.00792	1.20	0.0194	0.00839	1.24	0.0208	0.00902
2,000	1.56	0.0311	0.0135	1.60	0.0330	0.0143	1.65	0.0355	0.0154
2,500	1.95	0.0471	0.0204	2.00	0.0498	0.0216	2.06	0.0536	0.0232
3,000	2.34	0.0659	0.0285	2.40	0.0698	0.0302	2.47	0.0751	0.0325
3,500	2.73	0.0877	0.0380	2.80	0.0929	0.0402	2.89	0.100	0.0433
4,000	3.13	0.112	0.0486	3.20	0.119	0.0515	3.30	0.128	0.0554
4,500	3.52	0.140	0.0604	3.60	0.148	0.0640	3.71	0.159	0.0689
5,000	3.91	0.170	0.0734	4.00	0.180	0.0778	4.12	0.193	0.0837
5,500	4.30	0.202	0.0876	4.40	0.214	0.0928	4.53	0.231	0.100
6,000	4.69	0.238	0.103	4.80	0.252	0.109	4.95	0.271	0.117
7,000	5.47	0.316	0.137	5.60	0.335	0.145	5.77	0.360	0.156
8,000	6.25	0.405	0.175	6.40	0.429	0.186	6.60	0.461	0.200
9,000	7.03	0.503	0.218	7.20	0.533	0.231	7.42	0.573	0.248
10,000	7.81	0.611	0.265	8.00	0.648	0.280	8.24	0.697	0.302
11,000	8.59	0.729	0.316	8.80	0.773	0.335	9.07	0.831	0.360
12,000	9.38	0.857	0.371	9.60	0.907	0.393	9.89	0.976	0.423

Notes:

1. CSA values were converted from metric units.
2. Table is based on Chapter 9 Equations 9.1 through 9.4, using C = 150.
3. Friction-loss values in tables 14.6 through 14.8 are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$ where:

D_i = pipe inside diameter, in.
D_o = pipe outside diameter, in.
t_{min} = minimum wall thickness, in.

Table 14.8 Flow friction loss, ASTM F1483 and CSA B137.3.1 CIOD PVCO pipe

4 in. CIOD (ASTM F1483 and CSA B137.3.1)									
	Pressure rated 150 psi			Pressure rated 200 psi			Pressure rated 250 psi		
Flow	Velocity	Pressure drop		Velocity	Pressure drop		Velocity	Pressure drop	
gpm	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft
25	0.485	0.0231	0.0100	0.500	0.0248	0.0108	0.515	0.0267	0.0115
40	0.776	0.0550	0.0238	0.800	0.0593	0.0257	0.824	0.0636	0.0276
55	1.07	0.0991	0.0429	1.10	0.107	0.0462	1.13	0.115	0.0497
70	1.36	0.155	0.0671	1.40	0.167	0.0723	1.44	0.179	0.0776
85	1.65	0.222	0.0960	1.70	0.239	0.103	1.75	0.257	0.111
100	1.94	0.300	0.130	2.00	0.323	0.140	2.06	0.347	0.150
120	2.33	0.420	0.182	2.40	0.452	0.196	2.47	0.486	0.210
140	2.72	0.558	0.242	2.80	0.602	0.260	2.88	0.646	0.280
160	3.10	0.715	0.309	3.20	0.770	0.333	3.30	0.827	0.358
180	3.49	0.889	0.385	3.60	0.958	0.415	3.71	1.03	0.445
200	3.88	1.08	0.468	4.00	1.16	0.504	4.12	1.25	0.541
225	4.37	1.34	0.582	4.50	1.45	0.627	4.64	1.55	0.673
250	4.85	1.63	0.707	5.00	1.76	0.761	5.15	1.89	0.818
275	5.34	1.95	0.843	5.50	2.10	0.908	5.67	2.25	0.975
300	5.82	2.29	0.990	6.00	2.46	1.07	6.18	2.65	1.15
350	6.79	3.04	1.32	7.00	3.28	1.42	7.21	3.52	1.52
400	7.76	3.89	1.69	8.00	4.20	1.82	8.24	4.50	1.95
450	8.73	4.84	2.10	9.00	5.22	2.26	9.27	5.60	2.43

Notes:

1. CSA values were converted from metric units.
2. Table is based on Chapter 9 Equations 9.1 through 9.4, using C = 150.
3. Friction-loss values in tables 14.6 through 14.8 are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$ where:

   D_i = pipe inside diameter, in.
   D_o = pipe outside diameter, in.
   t_{min} = minimum wall thickness, in.

Table 14.8 Flow friction loss, ASTM F1483 and CSA B137.3.1 CIOD PVCO pipe *(continued)*

6 in. CIOD (ASTM F1483 and CSA B137.3.1)									
	Pressure rated 150 psi			Pressure rated 200 psi			Pressure rated 250 psi		
Flow	Velocity	Pressure drop		Velocity	Pressure drop		Velocity	Pressure drop	
gpm	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft
50	0.470	0.0143	0.00617	0.484	0.0153	0.00664	0.499	0.0165	0.00714
75	0.705	0.0302	0.0131	0.726	0.0325	0.0141	0.748	0.0349	0.0151
100	0.940	0.0514	0.0223	0.968	0.0553	0.0239	1.00	0.0595	0.0258
125	1.17	0.0777	0.0336	1.21	0.0835	0.0362	1.25	0.0899	0.0389
150	1.41	0.109	0.0471	1.45	0.117	0.0507	1.50	0.126	0.0545
175	1.64	0.145	0.0627	1.69	0.156	0.0674	1.75	0.167	0.0725
200	1.88	0.185	0.0802	1.94	0.199	0.0863	2.00	0.214	0.0928
250	2.35	0.280	0.121	2.42	0.301	0.130	2.49	0.324	0.140
300	2.82	0.392	0.170	2.90	0.422	0.183	2.99	0.454	0.197
350	3.29	0.522	0.226	3.39	0.561	0.243	3.49	0.604	0.261
400	3.76	0.668	0.289	3.87	0.718	0.311	3.99	0.773	0.335
450	4.23	0.831	0.360	4.36	0.893	0.387	4.49	0.961	0.416
500	4.70	1.01	0.437	4.84	1.09	0.470	4.99	1.17	0.506
600	5.64	1.41	0.612	5.81	1.52	0.658	5.99	1.64	0.709
700	6.58	1.88	0.815	6.78	2.02	0.876	6.98	2.18	0.943
800	7.52	2.41	1.04	7.74	2.59	1.12	7.98	2.79	1.21
900	8.46	2.99	1.30	8.71	3.22	1.39	8.98	3.47	1.50
1,000	9.40	3.64	1.58	9.68	3.91	1.69	9.98	4.21	1.82

Notes:

1. CSA values were converted from metric units.
2. Table is based on Chapter 9 Equations 9.1 through 9.4, using C = 150.
3. Friction-loss values in tables 14.6 through 14.8 are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$ where:

D_i = pipe inside diameter, in.
D_o = pipe outside diameter, in.
t_{min} = minimum wall thickness, in.

Table 14.8 Flow friction loss, ASTM F1483 and CSA B137.3.1 CIOD PVCO pipe *(continued)*

8 in. CIOD (ASTM F1483 and CSA B137.3.1)									
	Pressure rated 150 psi			Pressure rated 200 psi			Pressure rated 250 psi		
Flow	Velocity	Pressure drop		Velocity	Pressure drop		Velocity	Pressure drop	
gpm	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft
100	0.546	0.0137	0.00595	0.563	0.0148	0.00640	0.580	0.0159	0.00689
125	0.682	0.0208	0.00899	0.703	0.0224	0.00968	0.725	0.0240	0.0104
150	0.819	0.0291	0.0126	0.844	0.0313	0.0136	0.870	0.0337	0.0146
200	1.09	0.0496	0.0215	1.13	0.0533	0.0231	1.16	0.0574	0.0248
250	1.36	0.0749	0.0324	1.41	0.0806	0.0349	1.45	0.0867	0.0375
300	1.64	0.105	0.0454	1.69	0.113	0.0489	1.74	0.121	0.0526
350	1.91	0.140	0.0604	1.97	0.150	0.0650	2.03	0.162	0.0699
400	2.18	0.179	0.0774	2.25	0.192	0.0832	2.32	0.207	0.0895
450	2.46	0.222	0.0962	2.53	0.239	0.103	2.61	0.257	0.111
500	2.73	0.270	0.117	2.81	0.290	0.126	2.90	0.312	0.135
600	3.28	0.378	0.164	3.38	0.407	0.176	3.48	0.438	0.190
700	3.82	0.503	0.218	3.94	0.541	0.234	4.06	0.582	0.252
800	4.37	0.644	0.279	4.50	0.693	0.300	4.64	0.746	0.323
1,000	5.46	0.973	0.421	5.63	1.05	0.453	5.80	1.13	0.488
1,200	6.55	1.36	0.590	6.75	1.47	0.635	6.96	1.58	0.683
1,400	7.64	1.81	0.785	7.88	1.95	0.845	8.12	2.10	0.909
1,600	8.74	2.32	1.01	9.00	2.50	1.08	9.28	2.69	1.16
1,800	9.83	2.89	1.25	10.1	3.11	1.35	10.4	3.34	1.45

Table 14.8 Flow friction loss, ASTM F1483 and CSA B137.3.1 CIOD PVCO pipe *(continued)*

10 in. CIOD (ASTM F1483 and CSA B137.3.1)									
	Pressure rated 150 psi			Pressure rated 200 psi			Pressure rated 250 psi		
Flow	Velocity	Pressure drop		Velocity	Pressure drop		Velocity	Pressure drop	
gpm	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft
150	0.544	0.0108	0.00467	0.561	0.0116	0.00503	0.578	0.0125	0.00541
200	0.726	0.0184	0.00795	0.748	0.0198	0.00856	0.771	0.0213	0.00921
250	0.907	0.0278	0.0120	0.935	0.0299	0.0129	0.964	0.0321	0.0139
300	1.09	0.0389	0.0168	1.12	0.0418	0.0181	1.16	0.0450	0.0195
350	1.27	0.0517	0.0224	1.31	0.0557	0.0241	1.35	0.0599	0.0259
400	1.45	0.0662	0.0287	1.50	0.0713	0.0309	1.54	0.0767	0.0332
450	1.63	0.0823	0.0356	1.68	0.0886	0.0384	1.73	0.0954	0.0413
500	1.81	0.100	0.0433	1.87	0.108	0.0466	1.93	0.116	0.0502
600	2.18	0.140	0.0607	2.24	0.151	0.0653	2.31	0.162	0.0703
700	2.54	0.186	0.0807	2.62	0.201	0.0869	2.70	0.216	0.0935
800	2.90	0.239	0.103	2.99	0.257	0.111	3.08	0.276	0.120
1,000	3.63	0.361	0.156	3.74	0.388	0.168	3.85	0.418	0.181
1,200	4.35	0.505	0.219	4.49	0.544	0.235	4.63	0.585	0.253
1,400	5.08	0.672	0.291	5.24	0.723	0.313	5.40	0.778	0.337
1,600	5.81	0.860	0.373	5.98	0.926	0.401	6.17	1.00	0.432
1,800	6.53	1.07	0.463	6.73	1.15	0.499	6.94	1.24	0.537
2,200	7.98	1.55	0.672	8.23	1.67	0.723	8.48	1.80	0.778
2,600	9.44	2.11	0.915	9.72	2.27	0.984	10.0	2.45	1.06

Notes:

1. CSA values were converted from metric units.
2. Table is based on Chapter 9 Equations 9.1 through 9.4, using C = 150.
3. Friction-loss values in tables 14.6 through 14.8 are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$ where:

D_i = pipe inside diameter, in.
D_o = pipe outside diameter, in.
t_{min} = minimum wall thickness, in.

Table 14.8 Flow friction loss, ASTM F1483 and CSA B137.3.1 CIOD PVCO pipe *(continued)*

12 in. CIOD (ASTM F1483 and CSA B137.3.1)									
	Pressure rated 150 psi			Pressure rated 200 psi			Pressure rated 250 psi		
Flow	Velocity	Pressure drop		Velocity	Pressure drop		Velocity	Pressure drop	
gpm	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft
200	0.513	0.00792	0.00343	0.529	0.00852	0.00369	0.545	0.00916	0.00397
250	0.642	0.0120	0.00518	0.661	0.0129	0.00557	0.681	0.0138	0.00599
300	0.770	0.0168	0.00726	0.794	0.0180	0.00781	0.818	0.0194	0.00840
350	0.898	0.0223	0.00965	0.926	0.0240	0.0104	0.954	0.0258	0.0112
400	1.03	0.0285	0.0124	1.06	0.0307	0.0133	1.09	0.0330	0.0143
500	1.28	0.0431	0.0187	1.32	0.0464	0.0201	1.36	0.0499	0.0216
600	1.54	0.0604	0.0262	1.59	0.0650	0.0282	1.64	0.0699	0.0303
700	1.80	0.0804	0.0348	1.85	0.0865	0.0374	1.91	0.0930	0.0403
800	2.05	0.103	0.0445	2.12	0.111	0.0479	2.18	0.119	0.0515
1,000	2.57	0.155	0.0673	2.65	0.167	0.0724	2.73	0.180	0.0779
1,200	3.08	0.218	0.0943	3.17	0.234	0.101	3.27	0.252	0.109
1,400	3.59	0.290	0.125	3.70	0.312	0.135	3.82	0.335	0.145
1,600	4.11	0.371	0.161	4.23	0.399	0.173	4.36	0.429	0.186
2,000	5.13	0.560	0.243	5.29	0.603	0.261	5.45	0.648	0.281
2,400	6.16	0.785	0.340	6.35	0.845	0.366	6.54	0.909	0.393
2,800	7.19	1.04	0.452	7.41	1.12	0.487	7.63	1.21	0.523
3,200	8.21	1.34	0.579	8.46	1.44	0.623	8.72	1.55	0.670
3,600	9.24	1.66	0.720	9.52	1.79	0.775	9.81	1.92	0.833

Table 14.8 Flow friction loss, ASTM F1483 and CSA B137.3.1 CIOD PVCO pipe *(continued)*

14 in. CIOD (ASTM F1483 and CSA B137.3.1)									
	Pressure rated 150 psi			Pressure rated 200 psi			Pressure rated 250 psi		
Flow	Velocity	Pressure drop		Velocity	Pressure drop		Velocity	Pressure drop	
gpm	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft
300	0.573	0.00818	0.00354	0.591	0.00880	0.00381	0.609	0.00946	0.00410
450	0.860	0.0173	0.00750	0.886	0.0186	0.00806	0.913	0.0200	0.00867
600	1.15	0.0295	0.0128	1.18	0.0317	0.0137	1.22	0.0341	0.0148
800	1.53	0.0502	0.0217	1.57	0.0540	0.0234	1.62	0.0581	0.0251
1,000	1.91	0.0759	0.0329	1.97	0.0816	0.0353	2.03	0.0877	0.0380
1,200	2.29	0.106	0.0460	2.36	0.114	0.0495	2.43	0.123	0.0532
1,400	2.68	0.141	0.0612	2.76	0.152	0.0658	2.84	0.164	0.0708
1,600	3.06	0.181	0.0784	3.15	0.195	0.0843	3.25	0.209	0.0906
1,800	3.44	0.225	0.0975	3.54	0.242	0.105	3.65	0.260	0.113
2,000	3.82	0.274	0.118	3.94	0.294	0.127	4.06	0.316	0.137
2,200	4.20	0.326	0.141	4.33	0.351	0.152	4.46	0.377	0.163
2,600	4.97	0.445	0.192	5.12	0.478	0.207	5.27	0.514	0.223
3,000	5.73	0.579	0.251	5.91	0.623	0.270	6.09	0.670	0.290
3,400	6.50	0.730	0.316	6.69	0.785	0.340	6.90	0.844	0.366
3,800	7.26	0.897	0.388	7.48	0.964	0.418	7.71	1.04	0.449
4,200	8.03	1.08	0.467	8.27	1.16	0.502	8.52	1.25	0.540
4,600	8.79	1.28	0.553	9.06	1.37	0.595	9.33	1.48	0.639
5,000	9.55	1.49	0.645	9.84	1.60	0.694	10.1	1.72	0.746

Notes:

1. CSA values were converted from metric units.
2. Table is based on Chapter 9 Equations 9.1 through 9.4, using C = 150.
3. Friction-loss values in tables 14.6 through 14.8 are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$ where:

   D_i = pipe inside diameter, in.
   D_o = pipe outside diameter, in.
   t_{min} = minimum wall thickness, in.

Table 14.8 Flow friction loss, ASTM F1483 and CSA B137.3.1 CIOD PVCO pipe *(continued)*

16 in. CIOD (ASTM F1483 and CSA B137.3.1)									
	Pressure rated 150 psi			Pressure rated 200 psi			Pressure rated 250 psi		
Flow	Velocity	Pressure drop		Velocity	Pressure drop		Velocity	Pressure drop	
gpm	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft
350	0.517	0.00582	0.00252	0.533	0.00626	0.00271	0.549	0.00674	0.00292
500	0.739	0.0113	0.00488	0.761	0.0121	0.00525	0.784	0.0130	0.00564
650	0.960	0.0183	0.00792	0.989	0.0197	0.00852	1.02	0.0212	0.00917
800	1.18	0.0269	0.0116	1.22	0.0289	0.0125	1.25	0.0311	0.0135
1,000	1.48	0.0406	0.0176	1.52	0.0437	0.0189	1.57	0.0470	0.0203
1,200	1.77	0.0569	0.0246	1.83	0.0612	0.0265	1.88	0.0658	0.0285
1,400	2.07	0.0757	0.0328	2.13	0.0814	0.0352	2.20	0.0876	0.0379
1,800	2.66	0.120	0.0522	2.74	0.130	0.0561	2.82	0.139	0.0604
2,200	3.25	0.175	0.0756	3.35	0.188	0.0813	3.45	0.202	0.0875
2,600	3.84	0.238	0.103	3.96	0.256	0.111	4.08	0.275	0.119
3,000	4.43	0.310	0.134	4.57	0.333	0.144	4.71	0.359	0.155
3,500	5.17	0.412	0.178	5.33	0.443	0.192	5.49	0.477	0.207
4,000	5.91	0.528	0.229	6.09	0.568	0.246	6.27	0.611	0.264
4,500	6.65	0.656	0.284	6.85	0.706	0.306	7.06	0.759	0.329
5,000	7.39	0.797	0.345	7.61	0.858	0.371	7.84	0.923	0.400
5,500	8.12	0.951	0.412	8.37	1.02	0.443	8.63	1.10	0.477
6,000	8.86	1.12	0.484	9.13	1.20	0.520	9.41	1.29	0.560
6,500	9.60	1.30	0.561	9.89	1.39	0.604	10.2	1.50	0.649

Table 14.8 Flow friction loss, ASTM F1483 and CSA B137.3.1 CIOD PVCO pipe *(continued)*

18 in. CIOD (CSA B137.3.1)									
	Pressure rated 150 psi			Pressure rated 200 psi			Pressure rated 250 psi		
Flow	Velocity	Pressure drop		Velocity	Pressure drop		Velocity	Pressure drop	
gpm	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft
500	0.588	0.00647	0.00280	0.606	0.00697	0.00302	0.624	0.00749	0.00324
800	0.941	0.0154	0.00669	0.970	0.0166	0.00720	0.999	0.0179	0.00774
1,100	1.29	0.0278	0.0121	1.33	0.0300	0.0130	1.37	0.0322	0.0139
1,400	1.65	0.0435	0.0188	1.70	0.0468	0.0203	1.75	0.0503	0.0218
1,800	2.12	0.0692	0.0300	2.18	0.0745	0.0323	2.25	0.0801	0.0347
2,200	2.59	0.100	0.0434	2.67	0.108	0.0468	2.75	0.116	0.0503
2600	3.06	0.137	0.0592	3.15	0.147	0.0637	3.25	0.158	0.0685
3000	3.53	0.178	0.0771	3.64	0.192	0.0830	3.75	0.206	0.0892
3500	4.12	0.237	0.103	4.24	0.255	0.110	4.37	0.274	0.119
4000	4.70	0.303	0.131	4.85	0.326	0.141	5.00	0.351	0.152
4500	5.29	0.377	0.163	5.45	0.406	0.176	5.62	0.436	0.189
5000	5.88	0.458	0.198	6.06	0.493	0.214	6.24	0.530	0.230
5500	6.47	0.547	0.237	6.67	0.588	0.255	6.87	0.632	0.274
6000	7.06	0.642	0.278	7.27	0.691	0.299	7.49	0.743	0.322
6500	7.64	0.745	0.322	7.88	0.801	0.347	8.12	0.861	0.373
7000	8.23	0.854	0.370	8.49	0.919	0.398	8.74	0.988	0.428
7500	8.82	0.970	0.420	9.09	1.04	0.452	9.37	1.12	0.486
8000	9.41	1.09	0.473	9.70	1.18	0.509	10.0	1.26	0.548

Notes:

1. CSA values were converted from metric units.
2. Table is based on Chapter 9 Equations 9.1 through 9.4, using C = 150.
3. Friction-loss values in tables 14.6 through 14.8 are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$ where:

D_i = pipe inside diameter, in.
D_o = pipe outside diameter, in.
t_{min} = minimum wall thickness, in.

Table 14.8 Flow friction loss, ASTM F1483 and CSA B137.3.1 CIOD PVCO pipe *(continued)*

20 in. CIOD (CSA B137.3.1)									
	Pressure rated 150 psi			Pressure rated 200 psi			Pressure rated 250 psi		
Flow	Velocity	Pressure drop		Velocity	Pressure drop		Velocity	Pressure drop	
gpm	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft
600	0.575	0.00552	0.00239	0.593	0.00594	0.00257	0.611	0.00639	0.00276
1,000	0.959	0.0142	0.00615	0.988	0.0153	0.00661	1.02	0.0164	0.00711
1,400	1.34	0.0265	0.0115	1.38	0.0285	0.0123	1.43	0.0306	0.0133
1,800	1.73	0.0421	0.0182	1.78	0.0453	0.0196	1.83	0.0487	0.0211
2,200	2.11	0.0611	0.0264	2.17	0.0657	0.0284	2.24	0.0706	0.0306
2,600	2.49	0.0832	0.0360	2.57	0.0895	0.0387	2.65	0.0962	0.0417
3,000	2.88	0.108	0.0469	2.96	0.117	0.0505	3.05	0.125	0.0543
35,000	33.55	10.204	4.4183	34.57	10.975	4.7524	35.63	11.806	5.1121
4,000	3.83	0.185	0.0799	3.95	0.198	0.0859	4.07	0.213	0.0924
4,500	4.31	0.229	0.0994	4.45	0.247	0.107	4.58	0.265	0.115
5,000	4.79	0.279	0.121	4.94	0.300	0.130	5.09	0.323	0.140
5,500	5.27	0.333	0.144	5.43	0.358	0.155	5.60	0.385	0.167
6,000	5.75	0.391	0.169	5.93	0.420	0.182	6.11	0.452	0.196
6,500	6.23	0.453	0.196	6.42	0.487	0.211	6.62	0.524	0.227
7,000	6.71	0.520	0.225	6.91	0.559	0.242	7.13	0.601	0.260
8,000	7.67	0.665	0.288	7.90	0.716	0.310	8.14	0.770	0.333
9,000	8.63	0.827	0.358	8.89	0.890	0.385	9.16	0.957	0.414
10,000	9.59	1.01	0.435	9.88	1.08	0.468	10.2	1.16	0.504

Table 14.8 Flow friction loss, ASTM F1483 and CSA B137.3.1 CIOD PVCO pipe *(continued)*

24 in. CIOD (CSA B137.3.1)									
	Pressure rated 150 psi			Pressure rated 200 psi			Pressure rated 250 psi		
Flow	Velocity	Pressure drop		Velocity	Pressure drop		Velocity	Pressure drop	
gpm	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft	ft/s	ft H_2O/ 100 ft	psi/100 ft
800	0.537	0.00396	0.00171	0.554	0.00426	0.00185	0.571	0.00458	0.00199
1,200	0.806	0.00839	0.00363	0.831	0.00902	0.00391	0.856	0.00971	0.00420
1,600	1.07	0.0143	0.00618	1.11	0.0154	0.00665	1.14	0.0165	0.00716
2,000	1.34	0.0216	0.00934	1.38	0.0232	0.0101	1.43	0.0250	0.0108
2,600	1.75	0.0351	0.0152	1.80	0.0377	0.0163	1.86	0.0406	0.0176
3,200	2.15	0.0515	0.0223	2.22	0.0554	0.0240	2.28	0.0596	0.0258
3,800	2.55	0.0707	0.0306	2.63	0.0761	0.0330	2.71	0.0819	0.0355
4,600	3.09	0.101	0.0436	3.18	0.108	0.0469	3.28	0.117	0.0505
5,400	3.63	0.136	0.0587	3.74	0.146	0.0631	3.85	0.157	0.0679
6,200	4.17	0.175	0.0758	4.29	0.188	0.0815	4.42	0.203	0.0877
7,000	4.70	0.219	0.0948	4.85	0.236	0.102	4.99	0.254	0.110
8,000	5.37	0.280	0.121	5.54	0.302	0.131	5.71	0.325	0.141
9,000	6.05	0.349	0.151	6.23	0.375	0.162	6.42	0.404	0.175
10,000	6.72	0.424	0.183	6.92	0.456	0.197	7.13	0.490	0.212
11,000	7.39	0.505	0.219	7.62	0.544	0.235	7.85	0.585	0.253
12,000	8.06	0.594	0.257	8.31	0.639	0.277	8.56	0.687	0.298
13,500	9.07	0.738	0.320	9.35	0.794	0.344	9.63	0.854	0.370
15,000	10.1	0.897	0.388	10.4	0.965	0.418	10.7	1.04	0.450

Notes:

1. CSA values were converted from metric units.
2. Table is based on Chapter 9 Equations 9.1 through 9.4, using C = 150.
3. Friction-loss values in tables 14.6 through 14.8 are based on average $D_i = D_o - (2 \times 106\% \times t_{min}) = D_o - (2.12 \times t_{min})$ where:
   D_i = pipe inside diameter, in.
   D_o = pipe outside diameter, in.
   t_{min} = minimum wall thickness, in.

14.10 Installation

14.10.1 General Construction

The construction practices described in Chapter 10 apply to PVCO pipe with the following modifications:

1. *Cutting and beveling*: It is recommended that an abrasive disk be used to cut PVCO pipe.
2. *Grouting pressures*: Maximum recommended pressures are found in Table 14.9

14.10.2 Pressure Pipe Installation

The installation practices described in Chapter 11 apply to PVCO pipe with the following modification:

1. *Direct tapping*: Direct tapping of PVCO is not permitted. This is similar to the prohibition of direct tapping for thinner-walled C900 products such as 4-in. DR14, 4-in. DR18, and all sizes of DR25.

Table 14.9 Maximum recommended grouting pressures

PC, PR	$P_{critical}$ (psi)	$P_{allowable}$ (psi)
PR160, IPS	13.4	6.7
PR200, IPS	26.0	13
PR250, IPS	50.8	25
PR150, CIOD	11.0	5.5
PR200, CIOD	26.0	13
PR250, CIOD	50.8	25
PC165, CIOD	14.8	7.4
PC235, CIOD	42.4	21
PC305, CIOD	93.0	46

$P_{allowable}$ is based on a safety factor against buckling of 2.0 (equal to a design factor = 0.5) at temperature of 73° F, using E = 500,000 psi.
Grouting pressures must be reduced for increased wall temperatures.
Grout temperatures are not to exceed 130°F.

Fig. 14.2 Lightweight PVCO pipe at a job site

14.10.3 Nonpressure Pipe Installation

PVCO pipe is not intended for nonpressure applications. As Chapter 12 covers installation of nonpressure pipe, it does not apply to PVCO pipe.

14.10.4 Trenchless Construction

PVCO pipe is not intended for trenchless installations at this time. As Chapter 13 covers trenchless construction, it does not apply to PVCO pipe.

14.11 Sources

ASTM D1784, Standard Specification for Rigid Polyvinyl Chloride PVC and Chlorinated Polyvinyl Chloride (CPVC) Compounds. ASTM International, West Conshohocken, PA (2008).

ASTM D2837, Standard Test Method for Obtaining Hydrostatic Design Basis for Thermoplastic Pipe Materials or Pressure Design Basis for Thermoplastic Pipe Products. ASTM International (2011).

ASTM F477, Standard Specification for Elastomeric Seals (Gaskets) for Joining Plastic Pipe. ASTM International (2010).

ASTM F1483, Standard Specification for Oriented Polyvinyl Chloride, PVCO, Pressure Pipe. ASTM International (2005).

AWWA C900, Standard for Polyvinyl Chloride (PVC) Pressure Pipe and Fabricated Fittings, 4 in. through 12 in. (100 mm through 300 mm), for Water Transmission and Distribution. American Water Works Association, Denver, CO (2007).

AWWA C909, Standard for Oriented Polyvinyl Chloride (PVCO) Pressure Pipe, 4 in. through 24 in. (100 mm through 600 mm) for Water, Wastewater, and Reclaimed Water Service. American Water Works Association (2009).

CSA Standard B137.3.1 Molecularly Oriented Polyvinyl Chloride (PVCO) Pipe for Pressure Applications. Canadian Standards Association, Mississauga, ON (2009).

NSF Standard 61, Drinking Water System Components—Health Effects. NSF International, Ann Arbor, MI (2010).

APPENDIX

PVC Pipe Dimensions

PVC Pressure Pipe
•
PVC Nonpressure Pipe — Solid-Wall Sewer Pipe
•
PVC Nonpressure Pipe — Profile-Wall Sewer Pipe
•
PVCO Pressure Pipe

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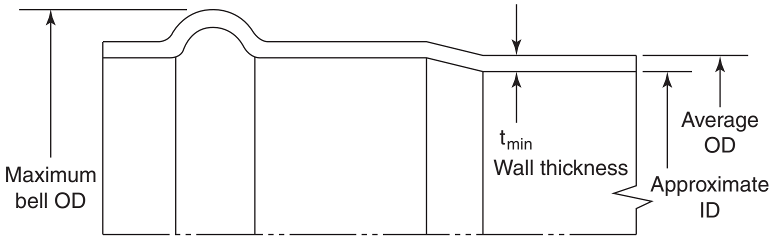
Appendix — PVC Pipe Dimensions

Abbreviations used in this appendix:

ID = pipe inside diameter
OD = pipe outside diameter
t_{min} = minimum pipe wall thickness

In sections A, B, and D of this appendix, the figure below illustrates the dimensions for all types of PVC pressure pipe, PVC solid-wall sewer pipe, and PVCO pressure pipe, as listed in the tables:



A. PVC Pressure Pipe

For all tables in this section, "maximum bell OD" indicates that the dimensions are on the high side of the industry average, making them suitable for casing design. The manufacturer should be consulted for the exact dimensions.

Pipe outside-diameter (OD) regimen abbreviations used in this section:

CIOD = cast iron OD
IPS = iron pipe size OD
PIP = plastic irrigation pipe OD

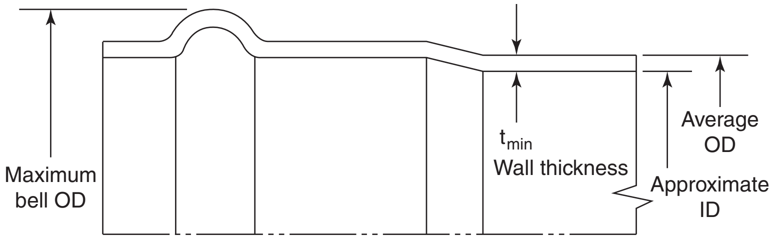


Fig. A.1

Table A.1 AWWA C900 (CIOD) — DR25 PVC Pressure Pipe
Pressure Class 165

Pipe size, in.	*Average OD, in.	*Min. wall thickness (t_{min}), in.	Approx. ID, in.	Max. bell OD, in.
4	4.800	0.192	4.39	6.00
6	6.900	0.276	6.31	8.25
8	9.050	0.362	8.28	10.50
10	11.100	0.444	10.16	13.25
12	13.200	0.528	12.08	15.50

* Specified by AWWA C900 standard
Note: Calculation for approximate ID uses wall thickness = 1.06 × t_{min}

Table A.2 AWWA C900 (CIOD) — DR18 PVC Pressure Pipe
Pressure Class 235

Pipe size, in.	*Average OD, in.	*Min. wall thickness (t_{min}), in.	Approx. ID, in.	Max. bell OD, in.
4	4.800	0.267	4.23	6.13
6	6.900	0.383	6.09	8.50
8	9.050	0.503	7.98	10.75
10	11.100	0.617	9.79	13.50
12	13.200	0.733	11.65	16.00

* Specified by AWWA C900 standard
Note: Calculation for approximate ID uses wall thickness = 1.06 × t_{min}

Table A.3 AWWA C900 (CIOD) — DR14 PVC Pressure Pipe
Pressure Class 305

Pipe size, in.	*Average OD, in.	*Min. wall thickness (t_{min}), in.	Approx. ID, in.	Max. bell OD, in.
4	4.800	0.343	4.07	6.50
6	6.900	0.493	5.86	9.25
8	9.050	0.646	7.68	11.75
10	11.100	0.793	9.42	14.25
12	13.200	0.943	11.20	16.75

* Specified by AWWA C900 standard
Note: Calculation for approximate ID uses wall thickness = 1.06 × t_{min}

Table A.4 AWWA C905 (CIOD) — DR51 PVC Pressure Pipe
Pressure Class 80

Pipe size, in.	*Average OD, in.	*Min. wall thickness (t_{min}), in.	Approx. ID, in.	Max. bell OD, in.
18	19.500	0.382	18.69	22.25
20	21.600	0.424	20.70	24.50
24	25.800	0.506	24.73	29.50
30	32.000	0.627	30.67	36.00
36	38.300	0.751	36.71	43.00
42	44.500	0.873	42.65	49.00
48	50.800	0.996	48.69	55.50

* Specified by AWWA C905 standard
Note: Calculation for approximate ID uses wall thickness = 1.06 × t_{min}

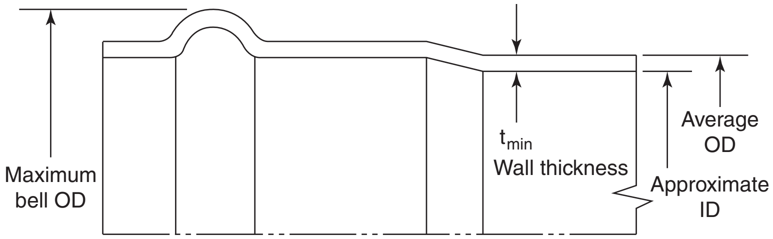


Fig. A.2

Table A.5 AWWA C905 (CIOD) — DR41 PVC Pressure Pipe
Pressure Class 100

Pipe size, in.	*Average OD, in.	*Min. wall thickness (t_{min}), in.	Approx. ID, in.	Max. bell OD, in.
14	15.300	0.373	14.51	17.75
16	17.400	0.424	16.50	20.00
18	19.500	0.476	18.49	22.25
20	21.600	0.527	20.48	25.00
24	25.800	0.629	24.47	29.50
30	32.000	0.780	30.35	36.00
36	38.300	0.934	36.32	42.75
42	44.500	1.085	42.20	49.50
48	50.800	1.239	48.17	56.25

* Specified by AWWA C905 standard
Note: Calculation for approximate ID uses wall thickness $= 1.06 \times t_{min}$

Table A.6 AWWA C905 (CIOD) — DR32.5 PVC Pressure Pipe
Pressure Class 125

Pipe size, in.	*Average OD, in.	*Min. wall thickness (t_{min}), in.	Approx. ID, in.	Max. bell OD, in.
14	15.300	0.471	14.30	17.75
16	17.400	0.535	16.26	20.50
18	19.500	0.600	18.23	22.50
20	21.600	0.665	20.19	25.25
24	25.800	0.794	24.12	29.75
30	32.000	0.985	29.91	36.50
36	38.300	1.178	35.80	43.75
42	44.500	1.369	41.60	51.00
48	50.800	1.563	47.49	58.00

* Specified by AWWA C905 standard
Note: Calculation for approximate ID uses wall thickness = 1.06 × t_{min}

Table A.7 AWWA C905 (CIOD) — DR25 PVC Pressure Pipe
Pressure Class 165

Pipe size, in.	*Average OD, in.	*Min. wall thickness (t_{min}), in.	Approx. ID, in.	Max. bell OD, in.
14	15.300	0.612	14.00	18.50
16	17.400	0.696	15.92	21.00
18	19.500	0.780	17.85	23.50
20	21.600	0.864	19.77	26.00
24	25.800	1.032	23.61	31.00
30	32.000	1.280	29.29	37.25
36	38.300	1.532	35.05	44.75
42	44.500	1.780	40.73	51.00
48	50.800	2.032	46.49	58.00

* Specified by AWWA C905 standard
Note: Calculation for approximate ID uses wall thickness = 1.06 × t_{min}

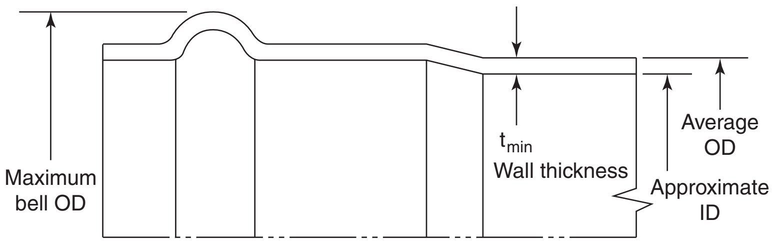


Fig. A.3

Table A.8 AWWA C905 (CIOD) — DR21 PVC Pressure Pipe Pressure Class 200

Pipe size, in.	*Average OD, in.	*Min. wall thickness (t_{min}), in.	Approx. ID, in.	Max. bell OD, in.
14	15.300	0.729	13.76	18.75
16	17.400	0.829	15.64	21.00
18	19.500	0.929	17.53	23.00
20	21.600	1.029	19.42	25.50
24	25.800	1.229	23.20	30.50
30	32.000	1.524	28.77	37.25
36	38.300	1.824	34.43	43.75

* Specified by AWWA C905 standard
Note: Calculation for approximate ID uses wall thickness = 1.06 × t_{min}

Table A.9 AWWA C905 (CIOD) — DR18 PVC Pressure Pipe Pressure Class 235

Pipe size, in.	*Average OD, in.	*Min. wall thickness (t_{min}), in.	Approx. ID, in.	Max. bell OD, in.
14	15.300	0.850	13.50	18.75
16	17.400	0.967	15.35	21.00
18	19.500	1.083	17.20	23.50
20	21.600	1.200	19.06	26.25
24	25.800	1.433	22.76	31.25
30	32.000	1.778	28.23	38.00

* Specified by AWWA C905 standard
Note: Calculation for approximate ID uses wall thickness = 1.06 × t_{min}

Table A.10 AWWA C905 (CIOD) — DR14 PVC Pressure Pipe
Pressure Class 305

Pipe size, in.	*Average OD, in.	*Min. wall thickness (t_{min}), in.	Approx. ID, in.	Max. bell OD, in.
14	15.300	1.093	12.98	19.50
16	17.400	1.243	14.77	22.00
18	19.500	1.393	16.55	24.50

* Specified by AWWA C905 standard
Note: Calculation for approximate ID uses wall thickness = 1.06 × t_{min}

Table A.11 AWWA C905 (IPS) — DR41 PVC Pressure Pipe
Pressure Class 100

Pipe size, in.	*Average OD, in.	*Min. wall thickness (t_{min}), in.	Approx. ID, in.	Max. bell OD, in.
14	14.000	0.341	13.28	16.25
16	16.000	0.314	15.33	18.50
18	18.000	0.353	17.25	20.75
20	20.000	0.392	19.17	23.00
24	24.000	0.471	23.00	27.50
30	30.000	0.588	28.75	33.50
36	36.000	0.706	34.50	40.00

* Specified by AWWA C905 standard
Note: Calculation for approximate ID uses wall thickness = 1.06 × t_{min}

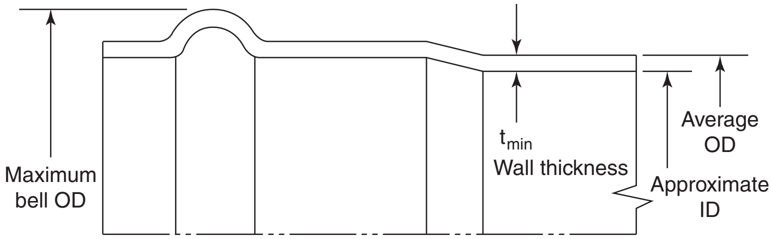


Fig. A.4

Table A.12 AWWA C905 (IPS) — DR32.5 PVC Pressure Pipe Pressure Class 125

Pipe size, in.	*Average OD, in.	*Min. wall thickness (t_{min}), in.	Approx. ID, in.	Max. bell OD, in.
14	14.000	0.431	13.09	16.50
16	16.000	0.492	14.96	18.75
18	18.000	0.554	16.83	21.00
20	20.000	0.615	18.70	23.25
24	24.000	0.738	22.43	27.75
30	30.000	0.923	28.04	33.75
36	36.000	1.108	33.65	40.50

* Specified by AWWA C905 standard
Note: Calculation for approximate ID uses wall thickness = 1.06 × t_{min}

Table A.13 AWWA C905 (IPS) — DR26 PVC Pressure Pipe Pressure Class 160

Pipe size, in.	*Average OD, in.	*Min. wall thickness (t_{min}), in.	Approx. ID, in.	Max. bell OD, in.
14	14.000	0.538	12.86	16.75
16	16.000	0.615	14.70	19.00
18	18.000	0.692	16.53	21.25
20	20.000	0.769	18.37	23.75
24	24.000	0.923	22.04	28.00
30	30.000	1.154	27.55	34.00
36	36.000	1.385	33.06	40.75

* Specified by AWWA C905 standard
Note: Calculation for approximate ID uses wall thickness = 1.06 × t_{min}

Table A.14 AWWA C905 (IPS) — DR21 PVC Pressure Pipe
Pressure Class 200

Pipe size, in.	*Average OD, in.	*Min. wall thickness (t_{min}), in.	Approx. ID, in.	Max. bell OD, in.
14	14.000	0.667	12.59	17.00
16	16.000	0.762	14.38	19.25
18	18.000	0.857	16.18	21.50
20	20.000	0.952	17.98	24.00
24	24.000	1.143	21.58	28.50
30	30.000	1.429	26.97	34.50
36	36.000	1.714	32.37	41.50

* Specified by AWWA C905 standard
Note: Calculation for approximate ID uses wall thickness = 1.06 × t_{min}

Table A.15 ASTM D2241 (IPS) — DR41 PVC Pressure Pipe
Pressure Rated 100

Pipe size, in.	*Average OD, in.	*Min. wall thickness (t_{min}), in.	Approx. ID, in.	Max. bell OD, in.
3	3.500	0.085	3.32	4.25
4	4.500	0.110	4.27	5.50
5	5.563	0.136	5.28	7.00
6	6.625	0.162	6.28	7.75
8	8.625	0.210	8.18	10.00
10	10.750	0.262	10.19	12.50
12	12.750	0.311	12.09	14.75
14	14.000	0.341	13.28	16.25
16	16.000	0.314	15.33	18.50
18	18.000	0.353	17.25	20.75
20	20.000	0.392	19.17	23.00
24	24.000	0.471	23.00	27.50
30	30.000	0.588	28.75	33.50
36	36.000	0.706	34.50	40.00

* Specified by ASTM D2241 standard

Note: Calculation for approximate ID uses wall thickness = 1.06 × t_{min}

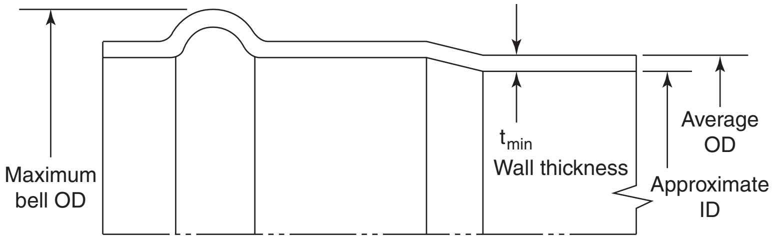


Fig. A.5

Table A.16 ASTM D2241 (IPS) — DR32.5 PVC Pressure Pipe Pressure Rated 125

Pipe size, in.	*Average OD, in.	*Min. wall thickness (t_{min}), in.	Approx. ID, in.	Max. bell OD, in.
3	3.500	0.108	3.27	4.25
4	4.500	0.138	4.21	5.75
5	5.563	0.171	5.20	7.00
6	6.625	0.204	6.19	8.00
8	8.625	0.265	8.06	10.25
10	10.750	0.331	10.05	12.75
12	12.750	0.392	11.92	15.00
14	14.000	0.431	13.09	16.50
16	16.000	0.492	14.96	18.75
18	18.000	0.554	16.83	21.00
20	20.000	0.615	18.70	23.25
24	24.000	0.738	22.43	27.75
30	30.000	0.923	28.04	34.00
36	36.000	1.108	33.65	40.50

* Specified by ASTM D2241 standard

Note: Calculation for approximate ID uses wall thickness = 1.06 × t_{min}

Table A.17 ASTM D2241 (IPS) — DR26 PVC Pressure Pipe
Pressure Rated 160

Pipe size, in.	*Average OD, in.	*Min. wall thickness (t_{min}), in.	Approx. ID, in.	Max. bell OD, in.
3	3.500	0.135	3.21	4.50
4	4.500	0.173	4.13	5.75
5	5.563	0.214	5.11	7.25
6	6.625	0.255	6.08	8.25
8	8.625	0.332	7.92	10.50
10	10.750	0.413	9.87	13.00
12	12.750	0.490	11.71	15.25
14	14.000	0.538	12.86	17.00
16	16.000	0.615	14.70	19.25
18	18.000	0.692	16.53	21.50
20	20.000	0.769	18.37	24.00
24	24.000	0.923	22.04	28.50
30	30.000	1.154	27.55	34.50
36	36.000	1.385	33.06	41.00

* Specified by ASTM D2241 standard
Note: Calculation for approximate ID uses wall thickness $= 1.06 \times t_{min}$

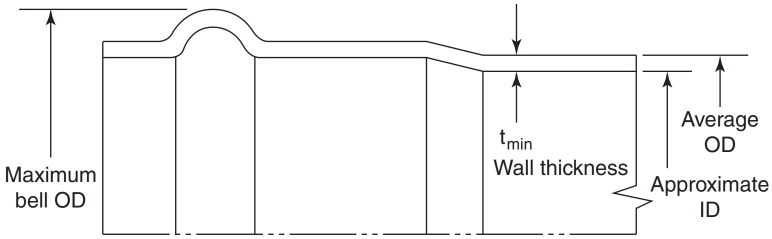


Fig. A.6

Table A.18 ASTM D2241 (IPS) — DR21 PVC Pressure Pipe Pressure Rated 200

Pipe size, in.	*Average OD, in.	*Min. wall thickness (t_{min}), in.	Approx. ID, in.	Max. bell OD, in.
3	3.500	0.167	3.15	4.50
4	4.500	0.214	4.05	5.75
5	5.563	0.265	5.00	7.25
6	6.625	0.315	5.96	8.25
8	8.625	0.411	7.75	10.50
10	10.750	0.512	9.66	13.25
12	12.750	0.607	11.46	15.50
14	14.000	0.667	12.59	16.75
16	16.000	0.762	14.38	19.25
18	18.000	0.857	16.18	21.50
20	20.000	0.952	17.98	24.00
24	24.000	1.143	21.58	28.50
30	30.000	1.429	26.97	35.00
36	36.000	1.714	32.37	41.50

* Specified by ASTM D2241 standard

Note: Calculation for approximate ID uses wall thickness = 1.06 × t_{min}

Table A.19 ASTM D2241 (IPS) — DR17 PVC Pressure Pipe
Pressure Rated 250

Pipe size, in.	*Average OD, in.	*Min. wall thickness (t_{min}), in.	Approx. ID, in.	Max. bell OD, in.
3	3.500	0.206	3.06	4.50
4	4.500	0.265	3.94	6.00
5	5.563	0.327	4.87	7.50
6	6.625	0.390	5.80	8.25
8	8.625	0.507	7.55	10.75
10	10.750	0.632	9.41	13.50
12	12.750	0.750	11.16	15.75
14	14.000	0.824	12.25	17.25
16	16.000	0.941	14.00	19.75
18	18.000	1.059	15.76	22.00
20	20.000	1.176	17.51	24.50
24	24.000	1.412	21.01	29.00
30	30.000	1.765	26.26	35.75
36	36.000	2.118	31.51	42.50

* Specified by ASTM D2241 standard

Note: Calculation for approximate ID uses wall thickness = $1.06 \times t_{min}$

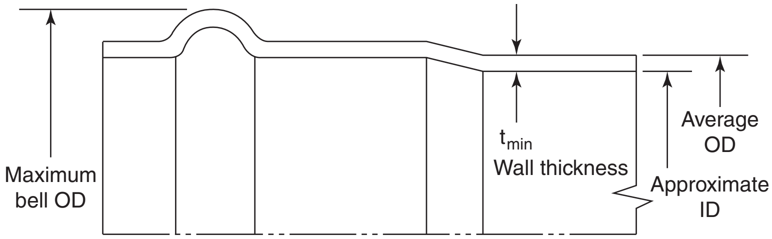


Fig. A.7

Table A.20 ASTM D2241 (IPS) — DR13.5
Pressure Rated 315

Pipe size, in.	*Average OD, in.	*Min. wall thickness (t_{min}), in.	Approx. ID, in.	Max. bell OD, in.
3	3.500	0.259	2.95	4.50
4	4.500	0.333	3.79	6.00
5	5.563	0.412	4.69	7.50
6	6.625	0.491	5.58	8.25
8	8.625	0.639	7.27	10.75
10	10.750	0.796	9.06	13.50
12	12.750	0.944	10.75	15.75
14	14.000	1.037	11.80	17.25
16	16.000	1.185	13.49	19.75
18	18.000	1.333	15.17	22.00
20	20.000	1.481	16.86	24.50
24	24.000	1.778	20.23	29.00
30	30.000	2.222	25.29	35.75
36	36.000	2.667	30.35	42.50

* Specified by ASTM D2241 standard
Note: Calculation for approximate ID uses wall thickness = 1.06 × t_{min}

Table A.21 ASTM D2241 (PIP) — DR51 PVC Pressure Pipe
Pressure Rated 80

Pipe size, in.	*Average OD, in.	*Min. wall thickness (t_{min}), in.	Approx. ID, in.	Max. bell OD, in.
6	6.140	0.120	5.88	7.25
8	8.160	0.160	7.82	9.50
10	10.200	0.200	9.78	11.75
12	12.240	0.240	11.73	14.25
15	15.300	0.300	14.66	17.75
18	18.701	0.367	17.92	–
21	22.047	0.432	21.13	–
24	24.803	0.486	23.77	–
27	27.953	0.548	26.79	–

* Specified by ASTM D2241 standard
Note: Calculation for approximate ID uses wall thickness = 1.06 × t_{min}

Table A.22 ASTM D2241 (PIP) — DR41 PVC Pressure Pipe
Pressure Rated 100

Pipe size, in.	*Average OD, in.	*Min. wall thickness (t_{min}), in.	Approx. ID, in.	Max. bell OD, in.
6	6.140	0.150	5.82	7.25
8	8.160	0.199	7.74	9.50
10	10.200	0.249	9.67	11.75
12	12.240	0.299	11.61	14.25
15	15.300	0.373	14.51	17.75
18	18.701	0.456	17.73	–
21	22.047	0.538	20.91	–
24	24.803	0.605	23.52	–
27	27.953	0.682	26.51	–

* Specified by ASTM D2241 standard
Note: Calculation for approximate ID uses wall thickness = 1.06 × t_{min}

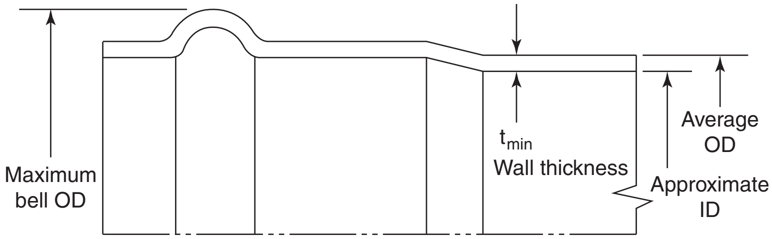


Fig. A.8

Table A.23 ASTM D2241 (PIP) — DR32.5 PVC Pressure Pipe Pressure Rated 125

Pipe size, in.	*Average OD, in.	*Min. wall thickness (t_{min}), in.	Approx. ID, in.	Max. bell OD, in.
6	6.140	0.189	5.74	7.25
8	8.160	0.251	7.63	9.50
10	10.200	0.314	9.53	11.75
12	12.240	0.377	11.44	14.25
15	15.300	0.471	14.30	17.75
18	18.701	0.575	17.48	–
21	22.047	0.678	20.61	–
24	24.803	0.763	23.19	–
27	27.953	0.860	26.13	–

* Specified by ASTM D2241 standard
Note: Calculation for approximate ID uses wall thickness = 1.06 × t_{min}

Table A.24 ASTM D2241 (PIP) — DR26 Pressure Pipe
Pressure Rated 160

Pipe size, in.	*Average OD, in.	*Min. wall thickness (t_{min}), in.	Approx. ID, in.	Max. bell OD, in.
15	15.300	0.588	14.05	7.25
18	18.701	0.719	17.18	9.50
21	22.047	0.848	20.25	11.75
24	24.803	0.954	22.78	14.25
27	27.953	1.075	25.67	17.75

* Specified by ASTM D2241 standard
Note: Calculation for approximate ID uses wall thickness = $1.06 \times t_{min}$

Table A.25 ASTM D2241 (PIP) — DR21 Pressure Pipe
Pressure Rated 200

Pipe size, in.	*Average OD, in.	*Min. wall thickness (t_{min}), in.	Approx. ID, in.	Max. bell OD, in.
15	15.300	0.729	13.76	7.25

* Specified by ASTM D2241 standard
Note: Calculation for approximate ID uses wall thickness = $1.06 \times t_{min}$

B. PVC Nonpressure Pipe — Solid-Wall Sewer Pipe

Pipe outside-diameter regimen abbreviation used in this section:

PSM = sewer pipe OD

For all tables in this section, "maximum bell OD" indicates that the dimensions are on the high side of the industry average, making them suitable for casing design. The manufacturer should be consulted for exact dimensions.

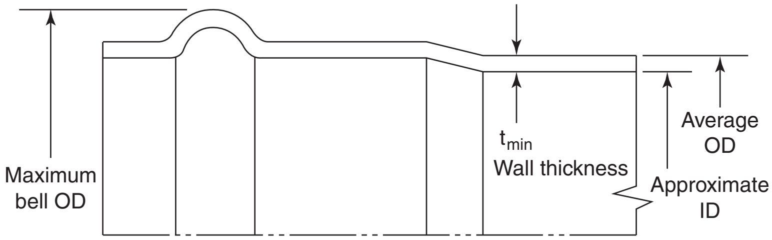


Fig. B.1

Table B.1 ASTM D3034 (PSM) — DR35 PVC solid-wall sewer pipe
Pipe Stiffness 46

Pipe size, in.	*Average OD, in.	*Min. wall thickness (t_{min}), in.	Approx. ID, in.	Max. bell OD, in.
4	4.215	0.120	3.96	5.25
6	6.275	0.179	5.89	7.50
8	8.400	0.240	7.89	10.00
10	10.500	0.300	9.86	12.25
12	12.500	0.357	11.74	14.25
15	15.300	0.437	14.37	17.25

* Specified by ASTM D3034 standard
Note: Calculation for approximate ID uses wall thickness = 1.06 × t_{min}

Table B.2 ASTM D3034 (PSM) — DR26 PVC solid-wall sewer pipe
Pipe Stiffness 115

Pipe size, in.	*Average OD, in.	*Min. wall thickness (t_{min}), in.	Approx. ID, in.	Max. bell OD, in.
4	4.215	0.162	3.87	5.25
6	6.275	0.241	5.76	7.63
8	8.400	0.323	7.72	10.25
10	10.500	0.404	9.64	12.50
12	12.500	0.481	11.48	14.50
15	15.300	0.588	14.05	17.75

* Specified by ASTM D3034 standard
Note: Calculation for approximate ID uses wall thickness = 1.06 × t_{min}

Table B.3 ASTM F679 — Solid-wall PVC sewer pipe
Pipe Stiffness 46

Pipe size, in.	*Average OD, in.	*Min. wall thickness (t_{min}), in.	Approx. ID, in.	Max. bell OD, in.
18	18.701	0.499	17.64	21.50
21	22.047	0.588	20.80	25.00
24	24.803	0.661	23.40	28.00
27	27.953	0.745	26.37	33.00
30	32.000	0.853	30.19	36.50
36	38.300	1.021	36.14	43.62
42	44.500	1.187	41.98	49.80
48	50.800	1.355	47.93	56.50

* Specified by ASTM F679 standard
Note: Calculation for approximate ID uses wall thickness = 1.06 × t_{min}

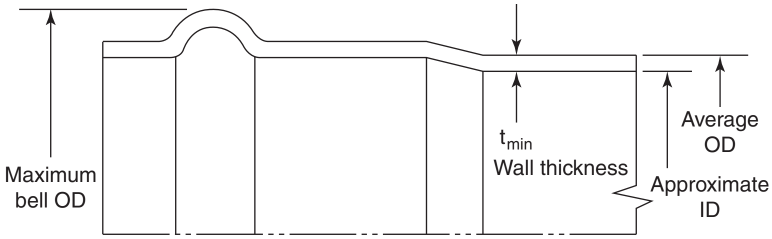


Fig. B.2

Table B.4 ASTM F679 — Solid-wall PVC sewer pipe
Pipe Stiffness 75

Pipe size, in.	*Average OD, in.	*Min. wall thickness (t_{min}), in.	Approx. ID, in.	Max. bell OD, in.
18	18.701	0.584	17.46	21.50
21	22.047	0.689	20.59	25.00
24	24.803	0.775	23.16	28.00
27	27.953	0.874	26.10	33.00
30	32.000	1.000	29.88	36.50
36	38.300	1.197	35.76	43.62
42	44.500	1.391	41.55	49.80
48	50.800	1.588	47.43	56.50

* Specified by ASTM F679 standard
Note: Calculation for approximate ID uses wall thickness = $1.06 \times t_{min}$

Table B.5 ASTM F679 — Solid-wall PVC sewer pipe
Pipe Stiffness 115

Pipe size, in.	*Average OD, in.	*Min. wall thickness (t_{min}), in.	Approx. ID, in.	Max. bell OD, in.
18	18.701	0.671	17.28	21.50
21	22.047	0.791	20.37	25.00
24	24.803	0.889	22.92	28.00
27	27.953	1.002	25.83	33.00
30	32.000	1.148	29.57	36.50
36	38.300	1.373	35.39	43.62
42	44.500	1.596	41.12	49.80
48	50.800	1.822	46.94	56.50

* Specified by ASTM F679 standard
Note: Calculation for approximate ID uses wall thickness = $1.06 \times t_{min}$

C. PVC Nonpressure Pipe — Profile-Wall Sewer Pipe

Profile-wall pipe abbreviations used in this section:

CP = closed profile
DWCP = dual-wall closed profile
OP = open profile

For all tables in this section, “maximum bell OD” indicates that the dimensions are on the high side of the industry average, making them suitable for casing design. The manufacturer should be consulted for exact dimensions.

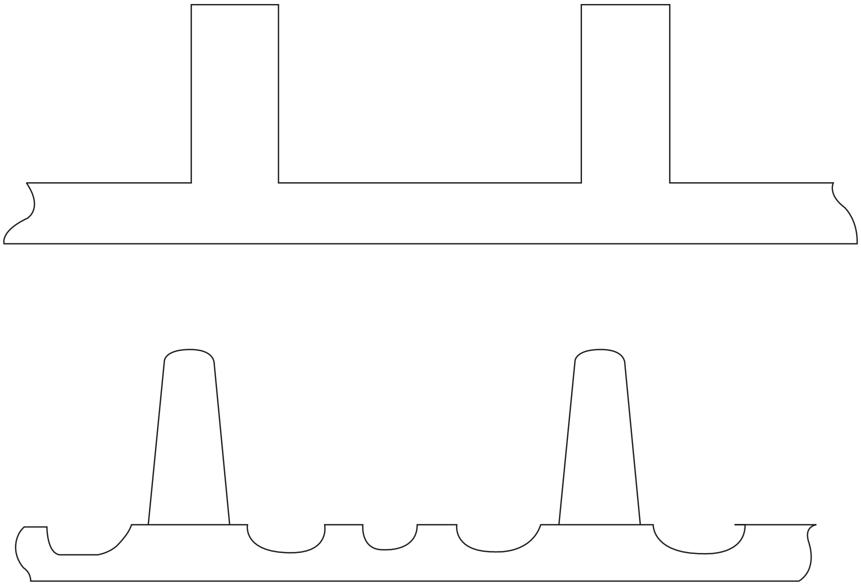


Fig. C.1 Typical open-profile vertical ribs.

Table C.1 ASTM F794 — Vertical-rib open-profile (OP) PVC sewer pipe
Pipe Stiffness 46 psi

Pipe size, in.	*Minimum ID, in.	Average ID, in.	*Min. waterway wall, in.	Approx. pipe OD, in.	Max. bell OD, in.
8	7.863	7.89	0.060	8.80	9.76
10	9.825	9.86	0.070	11.00	12.22
12	11.687	11.73	0.085	13.10	14.60
15	14.303	14.36	0.105	16.04	17.84
18	17.510	17.61	0.130	19.63	21.95
21	20.656	20.76	0.160	23.10	26.20
24	23.412	23.51	0.180	26.14	28.50
27	26.371	26.48	0.205	29.56	32.76
30	29.388	29.50	0.235	32.93	36.62
33	32.405	32.52	0.260	36.29	38.13
36	35.370	35.49	0.290	39.61	43.32
39	38.380	38.50	0.315	42.99	48.50
42	41.370	41.50	0.345	46.33	54.63
45	44.365	44.50	0.370	49.69	61.35
48	47.355	47.50	0.400	53.04	69.00

* Specified by ASTM F794 standard

Notes:

1. ODs of OP pipes are not standardized. For proprietary information on dimensions of ODs and gasketed bells, consult the pipe manufacturer.
2. OP pipe has a smooth waterway braced by external ribs.

Table C.2 ASTM F794 — Vertical-rib open-profile (OP) PVC sewer pipe
Pipe Stiffness 10 psi

Pipe size, in.	*Minimum ID, in.	Average ID, in.	*Min. waterway wall, in.	Approx. pipe OD, in.	Max. bell OD, in.
18	17.510	17.61	0.070	19.63	21.95
21	20.656	20.76	0.085	23.10	26.20
24	23.412	23.51	0.105	26.14	28.50
27	26.371	26.48	0.115	29.56	32.76
30	29.388	29.50	0.130	32.93	36.62
33	32.405	32.52	0.150	36.29	38.13
36	35.370	35.49	0.165	39.61	43.32
39	38.380	38.50	0.195	42.99	48.50
42	41.370	41.50	0.215	46.33	54.63
45	44.365	44.50	0.225	49.69	61.35
48	47.355	47.50	0.230	53.04	69.00

* Specified by ASTM F794 standard

Notes:

1. ODs of OP pipes are not standardized. For proprietary information on dimensions of ODs and gasketed bells, consult the pipe manufacturer.
2. OP pipe has a smooth waterway braced by external ribs.

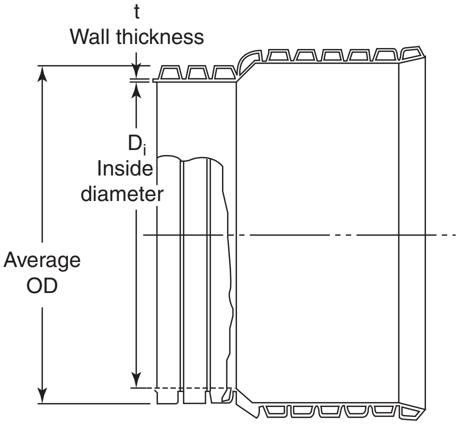


Fig. C.2 Dual wall corrugated profile wall PVC pipe

Table C.3 ASTM F794 — Dual-wall corrugated-profile (DWCP) PVC sewer pipe
Pipe Stiffness 46 psi

Pipe size, in.	*Minimum ID, in.	Average ID, in.	*Min. waterway wall, in.	Approx. pipe OD, in.	Max. bell OD, in.
8	7.863	7.89	0.035	8.80	9.30
10	9.825	9.86	0.045	11.00	11.70
12	11.687	11.73	0.058	13.10	13.90
15	14.303	14.36	0.077	16.04	16.90
18	17.510	17.61	0.084	19.63	20.60
21	20.656	20.76	0.095	23.10	24.60
24	23.412	23.51	0.110	26.14	28.45
27	26.371	26.48	0.120	29.56	32.10
30	29.388	29.50	0.130	32.93	35.76
33	32.405	32.52	0.150	36.29	38.13
36	35.370	35.49	0.155	39.61	43.32
39	38.380	38.50	0.200	42.99	48.50
42	41.370	41.50	0.200	46.33	54.63
45	44.365	44.50	0.200	49.69	61.35
48	47.355	47.50	0.200	53.04	69.00

* Specified by ASTM F794 standard

Notes:

1. ODs of OP pipes are not standardized. For proprietary information on dimensions of ODs and gasketed bells, consult the pipe manufacturer.
2. OP pipe has a smooth waterway braced by external ribs.

Table C.4 ASTM F794 — Dual-wall corrugated-profile (DWCP) PVC sewer pipe
Pipe Stiffness 10 psi

Pipe size, in.	*Minimum ID, in.	Average ID, in.	*Min. waterway wall, in.	Approx. pipe OD, in.	Max. bell OD, in.
18	17.510	17.61	0.070	19.63	20.60
21	20.656	20.76	0.070	23.10	24.60
24	23.412	23.51	0.070	26.14	28.45
27	26.371	26.48	0.070	29.56	32.10
30	29.388	29.50	0.085	32.93	35.76
33	32.405	32.52	0.095	36.29	38.13
36	35.370	35.49	0.105	39.61	43.32
39	38.380	38.50	0.120	42.99	48.50
42	41.370	41.50	0.130	46.33	54.63
45	44.365	44.50	0.145	49.69	61.35
48	47.355	47.50	0.160	53.04	69.00

* Specified by ASTM F794 standard

Notes:

1. ODs of OP pipes are not standardized. For proprietary information on dimensions of ODs and gasketed bells, consult the pipe manufacturer.
2. OP pipe has a smooth waterway braced by external ribs.

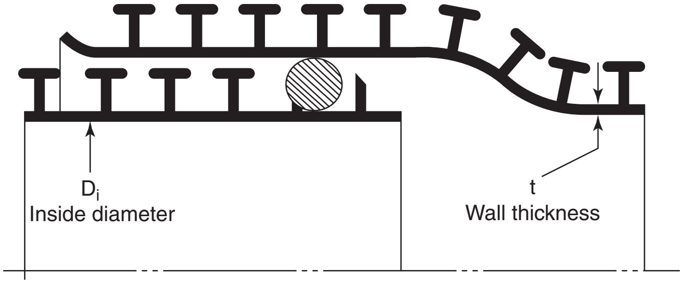


Fig. C.3 Typical open-profile T-rib pipe

Table C.5 ASTM F794 — T-rib open-profile (OP) PVC sewer pipe
Pipe Stiffness 46 psi

Pipe size, in.	*Minimum ID, in.	Average ID, in.	*Min. waterway wall, in.	Approx. pipe OD, in.	Max. bell OD, in.
18	17.510	17.51	0.130	19.13	20.98
21	20.656	20.66	0.160	22.47	24.36
24	23.412	23.41	0.180	25.42	27.72
27	26.371	26.37	0.205	28.70	31.10
30	29.388	29.39	0.235	31.94	34.56
33	32.405	32.41	0.260	–	–
36	35.370	35.37	0.290	38.46	41.30
39	38.380	38.38	0.315	–	–
42	41.370	41.37	0.345	45.00	–
45	44.365	44.37	0.370	–	–
48	47.355	47.36	0.400	51.50	–

* Specified by ASTM F794 standard

Notes:

1. ODs of OP pipes are not standardized. For proprietary information on dimensions of ODs and gasketed bells, consult the pipe manufacturer.
2. OP pipe has a smooth waterway braced by external ribs.

Table C.6 ASTM F794 — T-rib open-profile (OP) PVC sewer pipe
Pipe Stiffness 10 psi

Pipe size, in.	*Minimum ID, in.	Average ID, in.	*Min. waterway wall, in.	Approx. pipe OD, in.	Max. bell OD, in.
18	17.510	17.51	0.070	19.13	20.98
21	20.656	20.66	0.085	22.47	24.36
24	23.412	23.41	0.105	25.42	27.72
27	26.371	26.37	0.115	28.70	31.10
30	29.388	29.39	0.130	31.94	34.56
33	32.405	32.41	0.150	–	–
36	35.370	35.37	0.165	38.46	41.30
39	38.380	38.38	0.195	–	–
42	41.370	41.37	0.215	45.00	–
45	44.365	44.37	0.225	–	–
48	47.355	47.36	0.230	51.50	–

* Specified by ASTM F794 standard

Notes:

1. ODs of OP pipes are not standardized. For proprietary information on dimensions of ODs and gasketed bells, consult the pipe manufacturer.
2. OP pipe has a smooth waterway braced by external ribs.

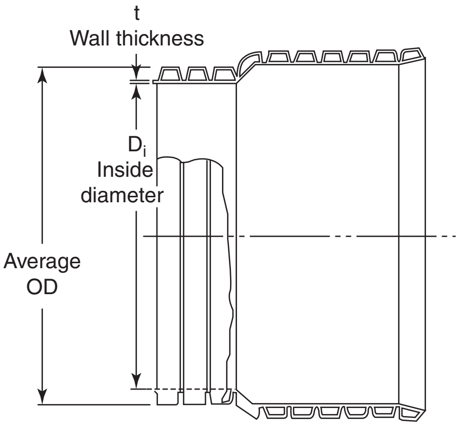


Fig. C.4 Dual wall corrugated profile wall PVC pipe

Table C.7 ASTM F949 — Dual-wall corrugated profile (DWCP) PVC sewer pipe
Pipe Stiffness 46 psi

Pipe size, in.	*Average OD, in.	*Average ID, in.	*Min. waterway wall, in.	Max. bell OD, in.
4	4.300	3.95	0.022	4.90
6	6.420	5.91	0.025	6.90
8	8.600	7.88	0.035	9.30
10	10.786	9.85	0.045	11.70
12	12.795	11.72	0.058	13.90
15	15.658	14.34	0.077	16.90
18	19.152	17.55	0.084	20.60
21	22.630	20.71	0.095	24.60
24	25.580	23.47	0.110	28.45
27	28.860	26.44	0.120	32.10
30	32.150	29.47	0.130	35.76
36	38.740	35.48	0.150	43.32
42	45.800	41.50	0.160	–
48	52.800	47.50	0.165	–

* Specified by ASTM F949 standard

Notes:

1. Both ODs and IDs of ASTM F949 DWCP pipes are specified in the standard.
2. DWCP pipe has a smooth waterway braced by external corrugations.

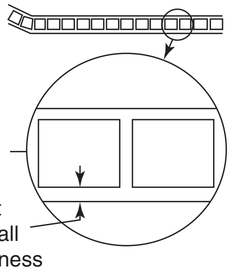


Fig. C.5 Closed-profile wall PVC pipe cross-section

Table C.8 ASTM F1803 — Closed-profile (CP) PVC sewer pipe
Pipe Stiffness 46 psi

Pipe size, in.	*Minimum ID, in.	Average ID, in.	*Min. waterway wall, in.	Approx. pipe OD, in.	Max. bell OD, in.
18	17.6	17.65	0.070	18.81	20.69
21	20.690	20.75	0.080	22.11	24.32
24	23.430	23.50	0.100	25.04	27.54
27	26.420	26.50	0.115	28.23	31.05
30	29.410	29.50	0.125	31.43	34.57
33	32.405	32.50	0.140	34.60	38.06
36	35.395	35.50	0.150	37.80	41.58
39	38.385	38.50	0.165	41.00	45.10
42	41.375	41.50	0.180	44.20	48.62
45	44.370	44.50	0.195	47.40	52.14
48	47.360	47.50	0.210	50.57	55.63
54	53.350	53.50	0.225	59.96	65.96
60	59.340	59.50	0.240	63.40	69.74

* Specified in ASTM F1803 standard

Notes:

1. Slipliner pipe has bell OD equal to pipe OD.
2. ODs of CP pipes are not standardized. For proprietary information on dimensions of ODs and gasketed bells, consult the pipe manufacturer.
3. CP pipe has a smooth waterway braced circumferentially or spirally with ribs that are joined by a smooth outer wall.

D. PVCO Pressure Pipe

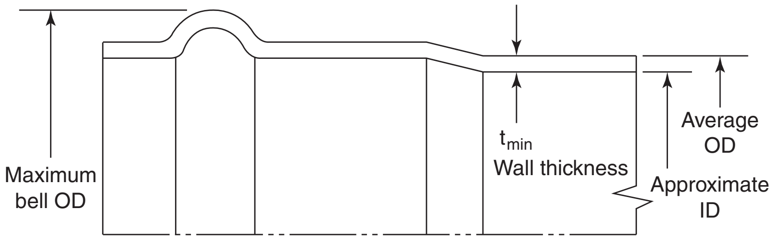


Fig. D.1

Table D.1 AWA C909 and CSA B137.3.1 (CIOD) PVCO Pressure Class / Pressure Rated 165

Pipe size, in.	*Average OD, in.	*Min. wall thickness (t_{min}), in.	Approx ID, in.	Maxbell OD, in.
4	4.800	0.109	4.57	–
6	6.900	0.157	6.57	–
8	9.050	0.206	8.61	–
10	11.100	0.252	10.57	–
12	13.200	0.300	12.56	–
14	15.300	0.347	14.56	–
16	17.400	0.395	16.56	–
18	19.500	0.443	18.56	–
20	21.600	0.491	20.56	–
24	25.800	0.586	24.56	–

*Specified by AWA C909 or CSA B137.3.1 standard

Note: Calculation for approximate ID uses wall thickness $= 1.06 \times t_{min}$

Table D.2 AWA C909 and CSA B137.3.1 (CIOD) PVCO Pressure Class / Pressure Rated 235

Pipe size, in.	*Average OD, in.	*Min. wall thickness (t_{min}), in.	Approx ID, in.	Maxbell OD, in.
4	4.800	0.154	4.47	–
6	6.900	0.221	6.43	8.40
8	9.050	0.290	8.44	10.75
10	11.100	0.356	10.35	13.23
12	13.200	0.423	12.30	15.48
14	15.300	0.490	14.26	–
16	17.400	0.557	16.22	–
18	19.500	0.625	18.18	–
20	21.600	0.692	20.13	–
24	25.800	0.827	24.05	–

*Specified by AWA C909 or CSA B137.3.1 standard
Note: Calculation for approximate ID uses wall thickness $= 1.06 \times t_{min}$

Table D.3 AWWA C909 and CSA B137.3.1 (CIOD) PVCO Pressure Class / Pressure Rated 305

Pipe size, in.	*Average OD, in.	*Min. wall thickness (t_{min}), in.	Approx ID, in.	Maxbell OD, in.
4	4.800	0.198	4.38	–
6	6.900	0.284	6.30	–
8	9.050	0.373	8.26	–
10	11.100	0.457	10.13	–
12	13.200	0.544	12.05	–
14	15.300	0.630	13.96	–
16	17.400	0.717	15.88	–
18	19.500	0.803	17.80	–
20	21.600	0.890	19.71	–
24	25.800	1.063	23.55	–

*Specified by AWA C909 or CSA B137.3.1 standard
Note: Calculation for approximate ID uses wall thickness $= 1.06 \times t_{min}$

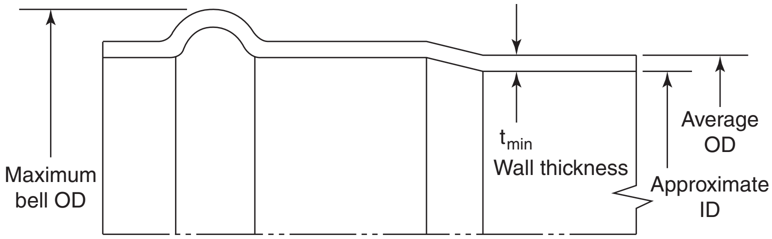


Fig. D.2

Table D.4 ASTM F1483 and CSA B137.3.1 (IPS) PVCO Pressure Rated 160

Pipe size, in.	*Average OD, in.	*Min. wall thickness (t_{min}), in.	Approx ID, in.	Maxbell OD, in.
4	4.500	0.099	4.29	–
6	6.625	0.146	6.32	–
8	8.625	0.190	8.22	–
10	10.750	0.237	10.25	–
12	12.750	0.281	12.15	–
14	14.000	0.309	13.35	–
16	16.000	0.353	15.25	–
18	18.000	0.397	17.16	–
20	20.000	0.441	19.06	–
24	24.000	0.530	22.88	–

*Specified by ASTM F1483 or CSA B137.3.1 standard
Note:Calculation for approximate IDuses wall thickness $= 1.06 \times t_{min}$

Table D.5 ASTM F1483 and CSA B137.3.1 (IPS) PVCO Pressure Rated 200

Pipe size, in.	*Average OD, in.	*Min. wall thickness (t_{min}), in.	Approx ID, in.	Maxbell OD, in.
4	4.500	0.123	4.24	–
6	6.625	0.182	6.24	7.94
8	8.625	0.236	8.12	10.04
10	10.750	0.295	10.12	12.45
12	12.750	0.349	12.01	14.63
14	14.000	0.384	13.19	–
16	16.000	0.438	15.07	–
18	18.000	0.493	16.95	–
20	20.000	0.548	18.84	–
24	24.000	0.657	22.61	–

*Specified by ASTM F1483 or CSA B137.3.1 standard
Note:Calculation for approximate ID uses wall thickness $= 1.06 \times t_{min}$

Table D.6 ASTM F1483 and CSA B137.3.1 (IPS) PVCO Pressure Rated 250

Pipe size, in.	*Average OD, in.	*Min. wall thickness (t_{min}), in.	Approx ID, in.	Maxbell OD, in.
4	4.500	0.153	4.18	–
6	6.625	0.225	6.15	–
8	8.625	0.293	8.00	–
10	10.750	0.366	9.97	–
12	12.750	0.434	11.83	–
14	14.000	0.476	12.99	–
16	16.000	0.544	14.85	–
18	18.000	0.612	16.70	–
20	20.000	0.680	18.56	–
24	24.000	0.816	22.27	–

*Specified by ASTM F1483 or CSA B137.3.1 standard
Note:Calculation for approximate ID uses wall thickness $= 1.06 \times t_{min}$

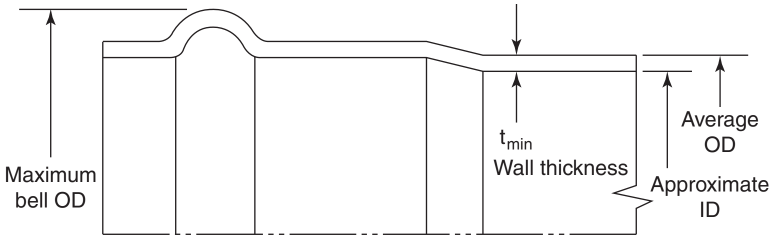


Fig. D.3

Table D.7 ASTM F1483 and CSA B137.3.1 (CIOD) PVCO Pressure Rated 150

Pipe size, in.	*Average OD, in.	*Min. wall thickness (t_{min}), in.	Approx ID, in.	Maxbell OD, in.
4	4.800	0.099	4.59	–
6	6.900	0.143	6.60	–
8	9.050	0.187	8.65	–
10	11.100	0.229	10.61	–
12	13.200	0.273	12.62	–
14	15.300	0.317	14.63	–
16	17.400	0.360	16.64	–
18	19.500	0.403	18.65	–
20	21.600	0.447	20.65	–
24	25.800	0.533	24.67	–

*Specified by ASTM F1483 or CSA B137.3.1 standard

Note:Calculation for approximate ID uses wall thickness $= 1.06 \times t_{min}$

Table D.8 ASTM F1483 and CSA B137.3.1 (CIOD) PVCO Pressure Rated 200

Pipe size, in.	*Average OD, in.	*Min. wall thickness (t_{min}), in.	Approx ID, in.	Maxbell OD, in.
4	4.800	0.189	4.40	–
6	6.900	0.248	6.37	7.94
8	9.050	0.304	8.41	10.04
10	11.100	0.362	10.33	12.45
12	13.200	0.419	12.31	14.63
14	15.300	0.477	14.29	–
16	17.400	0.438	16.47	–
18	19.500	0.535	18.37	–
20	21.600	0.592	20.34	–
24	25.800	0.707	24.30	–

*Specified by ASTM F1483 or CSA B137.3.1 standard
Note: Calculation for approximate ID uses wall thickness = 1.06 × t_{min}

Table D.9 ASTM F1483 and CSA B137.3.1 (CIOD) PVCO Pressure Rated 250

Pipe size, in.	*Average OD, in.	*Min. wall thickness (t_{min}), in.	Approx ID, in.	Maxbell OD, in.
4	4.800	0.163	4.45	–
6	6.900	0.235	6.40	–
8	9.050	0.308	8.40	–
10	11.100	0.378	10.30	–
12	13.200	0.449	12.25	–
14	15.300	0.520	14.20	–
16	17.400	0.592	16.14	–
18	19.500	0.663	18.09	–
20	21.600	0.735	20.04	–
24	25.800	0.878	23.94	–

*Specified by ASTM F1483 or CSA B137.3.1 standard
Note: Calculation for approximate ID uses wall thickness = 1.06 × t_{min}

Unit Conversion Tables

The tables in this section give algorithms (× conversion factor) for converting SI to English units of measurement and vice versa. Conversion factors for units within a system are also given.

Abbreviations

SI

atm = atmosphere
cm = centimeter
dm = decimeter
g = gram
J = joule
kg = kilogram
kgf = kilogram force
km = kilometer
kPa = kilopascal
L = liter
m = meter
mL = milliter
mm = millimeter
MPa = megapascal
N = newton
Pa = pascal

English

Btu = British thermal unit
ft = foot
gal = U.S. gallon
Igal = Imperial gallon
in. = inch
lb = pound
lbf = pound force
mgd = million gallons per day
mi = mile
oz = ounce
pt = pint
qt = quart
yd = yard

Miscellaneous

accel = acceleration
temp = temperature
H_2O = water
Hg = mercury
C = Celsius
F = Fahrenheit

Conversion Tables—These tables give the conversion algorithm from one measure system to the other (SI to English or vice versa); there are algorithms also for conversion within a system.

Unit	× conversion factor	Unit
Length		
mm	0.0394 0.00328	in. ft
cm	0.394 0.0328	in. ft
m	3.28 1.09 0.00062	ft yd mi
km	0.621	mi
in.	25.4 2.54	mm cm
ft	305 30.5 0.305	mm cm m
yd	0.914	m
mi	1,610 1.61 5,280 1,760	m km ft yd
Area		
mm^2	0.00155 0.0000108	$in.^2$ ft^2
cm^2	0.155 0.00108	$in.^2$ ft^2
m^2	10.8 1.20 0.00025 0.0001	ft^2 yd^2 acre hectare
hectare	10,000 2.47	m^2 acre

Area		
in.^{2}	4050	mm^2
	0.405	cm^2
ft^2	43.560	mm^2
	929	cm^2
	0.0929	m^2
	0.111	yd^2
	0.0000223	acre
yd^2	0.836	m^2
	9	ft^2
	0.00021	acre
acre	4050	m^2
	0.405	hectare
	43,600	ft^2
	4,840	yd^2
	0.00156	mi^2
mi^2	640	acre
Volume		
mm^3	0.000061	in.^{3}
cm^3	0.0610	in.^{3}
dm^3	61.0	in.^{3}
	1	L
m^3	35.3	ft^3
	264	gal
	1.31	yd^3
	1000	L
L	0.264	gal
	0.0353	ft^3
	0.001	m^3
	1000	mL
	2.11	pt
	1.06	qt
	1	dm^3
in.^{3}	16,400	mm^3
	16.4	cm^3
	0.0164	dm^3

VOLUME		
ft^3	0.0283 28.3 7.48 0.0370	m^3 L gal yd^3
m^3	0.00081	acre·ft
acre·ft	1,230 326,000	m^3 gal
acre·ft	1,230 326,000	m^3 gal
pt	0.473	L
qt	0.946	L
gal	0.00379 3.79 0.134	m^3 L ft^3
Igal	0.833	gal
MASS/WEIGHT		
g	0.0353 0.0022	oz lb
kg	35.3 2.20 0.001	oz lb tonne
tonne	2,200 1.10 1,000	lb ton kg
oz	28.3 0.0625 0.0284	g lb kg
lb	454 0.454 0.000454 0.0005 16	g kg tonne ton oz
ton	0.907 2,000 907	tonne lb kg

PRESSURE		
Pa	1 0.000145	N·m^2 lbf/$in.^2$
kPa	1,000 0.01 0.145 0.335 0.296 0.001 0.00987	Pa bar lbf/$in.^2$ ft H_2O in. Hg MPa atm
MPa	1,000 145 9.87 10	kPa bar atm bar
kgf/m^2	9.81	Pa
kgf/cm^2	98.1 14.2	kPa lbf/$in.^2$
N/m^2	0.00015	lbf/$in.^2$
bar	100 0.1 14.5	kPa MPa lbf/$in.^2$
lbf/$in.^2$	6,890 6.89 0.00689 0.0703 6,890 0.0689 0.0681 2.31 2.04	Pa kPa MPa kgf/cm^2 N/m^2 bar atm ft H_2O in. Hg
atm	101 0.101 14.7	kPa MPa lbf/$in.^2$
ft H_2O	2.99 0.433	kPa lbf/$in.^2$
in. Hg	3.37 0.491	kPa lbf/$in.^2$

Density		
g/cm^3	1,000	kg/m^3
kg/m^3	0.0624	lb/ft^3
	1.69	lb/yd^3
	0.00835	lb/gal
	0.00084	ton/yd^3
	0.001	tonne/m^3
tonne/m^3	0.843	ton/yd^3
lb/ft^3	16.02	kg/m^3
	0.0135	ton/yd^3
lb/yd^3	0.593	kg/m^3
lb/gal	120	kg/m^3
ton/yd^3	1,190	kg/m^3
	1.19	tonne/m^3
	74.1	lb/ft^3
Flow		
m^3/s	35.3	ft^3/s
	15,850	gal/min
	1,000	L/s
	22.8	mgd
L/s	0.001	m^3/s
	0.0353	ft^3/s
	15.9	gal/min
ft^3/s	0.0283	m^3/s
	28.3	L/s
	449	gal/min
gal/min	0.00006	m^3/s
	0.063	L/s
	0.00223	ft^3/s
	0.00144	mgd
mgd	694	gal/min
	0.225	m^3/s

FORCE		
lbf	4.45	N
N	0.225 0.102	lbf
kgf	9.81	N
TORQUE		
N·m	0.738 8.85	ftlbf in.lbf
ftlbf	1.36	N·m
in.lbf	0.113	N·m
ENERGY		
J	0.738 0.000948	ftlbf Btu
ftlbf	1.36 0.00128	J Btu
Btu	1060 778 252	J ftlbf cal
TEMPERATURE		
temp C	1.8 (°C) + 32	temp Fahrenheit
temp F	0.556 (°F – 32)	temp Celsius
°C	1.8	°F
°F	0.556	°C
MISCELLANEOUS		
accel gravity	9.81 32.2	m/s^2 ft/s^2
L/mm/km/day	10.8	gal/in./min/day
gal/in./min/day	0.0926	L/mm/km/day
gal H_2O	3.79 8.35	kg lb
ft^3 H_2O	28.3 62.4	kg lb
kg/m	0.672	lb/ft
lb/ft	1.49	kg/m

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