

MODULUS OF SOIL REACTION (E') VALUES FOR BURIED FLEXIBLE PIPE

**Engineering and Research Center
Bureau of Reclamation**

January 1977

TA
160.44
.R4
No.77-1



TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO. REC-ERC-77-1	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.	
4. TITLE AND SUBTITLE 3 Modulus of Soil Reaction (E') Values for Buried Flexible Pipe 3		5. REPORT DATE January 1977	6. PERFORMING ORGANIZATION CODE
		8. PERFORMING ORGANIZATION REPORT NO. 7 REC-ERC-77-1	
7. AUTHOR(S) 6 A. K. Howard 6	10. WORK UNIT NO. 7		
9. PERFORMING ORGANIZATION NAME AND ADDRESS Engineering and Research Center Bureau of Reclamation, Denver Denver, Colorado 80225		11. CONTRACT OR GRANT NO.	
		13. TYPE OF REPORT AND PERIOD COVERED	
12. SPONSORING AGENCY NAME AND ADDRESS Same		14. SPONSORING AGENCY CODE	
15. SUPPLEMENTARY NOTES			
<p>16. ABSTRACT</p> <p>A table of modulus of soil reaction (E') values for use in the Iowa formula has been empirically developed by the Bureau of Reclamation. Use of the methods and values suggested can reasonably predict the initial (no time effect) deflection of buried flexible pipe under fills up to 15 m (50 ft). The E' values vary according to the type of soil placed beside the pipe and the degree of compaction. The accuracy of predicted deflections varies according to the degree of compaction. Laboratory soil container tests and data from over 100 field installations were used in the investigation.</p> <p>LIBRARY</p> <p>1978</p> <p>Bureau of Reclamation Denver, Colorado</p>			
<p>17. KEY WORDS AND DOCUMENT ANALYSIS</p> <p>a. DESCRIPTORS-- / backfills / soil mechanics / buried pipes / flexible pipes / steel pipes / deflection / laboratory tests / plastic pipes / cohesionless soils / pipes / pipe bedding / pipelines / field tests / pipe tests / bedding materials / construction methods / trenches / compaction / pipe laying / pipe design</p> <p>b. IDENTIFIERS-- / fiberglass reinforced plastic pipe / reinforced plastic mortar pipe / thermoplastic pipe / ductile iron pipe / Iowa formula / soil-structure interaction / modulus of soil reaction</p> <p>c. COSATI Field/Group 13B COWRR: 1313.3</p>			
18. DISTRIBUTION STATEMENT Available from the National Technical Information Service, Operations Division, Springfield, Virginia 22151.		19. SECURITY CLASS (THIS REPORT) UNCLASSIFIED	21. NO. OF PAGES 60
		20. SECURITY CLASS (THIS PAGE) UNCLASSIFIED	22. PRICE



92024979

REC-ERC-77-1

**MODULUS OF SOIL REACTION (E')
VALUES FOR BURIED FLEXIBLE PIPE**

by
Amster K. Howard

January 1977

Earth Sciences Branch
Division of General Research
Engineering and Research Center
Denver, Colorado

DATE DUE

AUG 08 1978			
JUL 23 1980			
MAY 11 1984			
MAR 01 1988			
NOV 23 2000			
6/25/01			
OCT 12 2005	12068613		
NOV - 6 2006			
JUL 19 2007			



ACKNOWLEDGMENTS

This study was conducted under the supervision of C. W. Jones, Head, Special Investigations and Research Section. P. C. Knodel is Chief of the Earth Sciences Branch. The report was reviewed by:

J. J. Walker (retired), Head, Steel Pipe and Special Equipment Section, Mechanical Branch

J. L. Warden, Tunnels Section, Water Conveyance Branch

R. A. Simonds, Tunnels and Pipeline Section, Water Conveyance Branch

R. D. Richmond, Earth Sciences Branch, made significant contributions to the concepts and representation of information.

The information contained in appendix D was drawn from documents prepared by R. A. Simonds.

Reprint or republication of any of this material shall give appropriate credit to the Bureau of Reclamation, U.S. Department of the Interior.

Final editing and preparation of the manuscript for publication was performed by J. M. Tilsley of the Technical Services and Publication Branch.

CONTENTS

	Page
Introduction	1
Iowa formula	1
Rearranged Iowa formula	1
Load factor	1
Deflection lag factor (D_l)	4
Bedding constant (K)	4
Load on the pipe (W)	4
Ring stiffness factor	4
Soil stiffness factor	4
Laboratory tests	5
Varied pipe modulus—Constant soil modulus	5
Constant pipe modulus—Varied soil modulus	5
Field investigations	5
Development of table for E' values	5
Range of deflections along pipelines	14
Reliability of table 1	14
Limitations of table 1	17
Summary and conclusions	17
Applications	21
Bibliography	21

TABLES

Table

1	Bureau of Reclamation values for E' for Iowa formula	2
2	European PVC pipe deflection survey	16

FIGURES

Figure

1	Typical load-deflection curves for steel and thermoplastic pipe of various stiffnesses in 90 percent density clay	6
2	Load-deflection curves for steel pipe of various stiffnesses in 100 percent density clay	7
3	Typical load-deflection curves for RPM (reinforced plastic mortar) pipe in 90 percent density clay	8
4	Load-deflection curves for steel pipe of identical stiffness in 90 percent and 100 percent density clay	9
5	Load-deflection curves for RPM (reinforced plastic mortar) pipe of identical stiffness in 90 percent and 100 percent density clay	10

CONTENTS—Continued

Figure		Page
6	Load-deflection curves for steel pipe of identical stiffness in dumped and in compacted sand	11
7	Load-deflection curves for steel pipe of identical stiffness in different soil types compacted to same density	12
8	Deflections of RPM pipe on Yuma project, Ariz.	13
9	Range of deflections measured along pipelines	15
10	Comparison of actual and predicted deflections for dumped and slightly compacted beddings	18
11	Comparison of actual and predicted deflections for moderately compacted beddings	19
12	Comparison of actual and predicted deflections for highly compacted beddings and crushed rock	20

APPENDIXES

Appendix		
A	Survey of buried pipe deflection data	25
	Bibliography, Appendix A	34
B	Descriptions of deflection survey tests	37
C	Pipe buried under high fills	53
	Bibliography, Appendix C	57
D	Recommended pipe installation procedures	59

INTRODUCTION

The Earth Sciences Branch of the USBR (Bureau of Reclamation) has been investigating the load-deflection relationship of buried flexible pipe for several years, using laboratory soil container tests and special field installations. The result is a table of modulus of soil reaction (E') values for use in the Iowa formula for predicting the deflection of buried flexible pipe. At this point in its development, use of the table of E' values along with a simplified method of calculating the back-fill load on a pipe can reasonably predict the initial (no time effect) deflection of flexible pipe under fills up to 15 m (50 ft).

The soil load on a flexible pipe causes a decrease in the vertical diameter and an increase in the horizontal diameter of the pipe. In the design of structural members, the strain or deformation of an element of the material being used can be determined from the ratio of the load or stress on the member to its modulus of elasticity (strain = stress/modulus of elasticity). The modulus of elasticity for the material is either known or it can be determined from laboratory tests.

The deflection of a buried circular conduit can be predicted in a similar fashion. The cross-sectional ring deflects (deforms) according to the ratio of the load on the ring to the modulus of elasticity of the material. However, the material modulus becomes more complicated because a soil-structure interaction takes place. The material modulus becomes a combination of the structural modulus (stiffness) of the pipe and the modulus (stiffness) of the soil, so that:

$$\text{Pipe deflection} = \frac{\text{load on pipe}}{\text{pipe stiffness} + \text{soil stiffness}}$$

This is basically the form of the Iowa formula, widely used for predicting deflections of buried flexible pipe. A constant value for the soil stiffness has been used for all compacted soil types. The originator of the formula and others are now recognizing that the soil stiffness varies according to soil type and degree of compaction. However, there has been no successful effort to organize the information on buried flexible pipe deflections to determine what soil modulus values should be used for various pipe support conditions.

Reclamation experience with laboratory and field tests of buried flexible pipe has resulted in an empirical relationship between pipe deflection and soil stiffness values for different pipe bedding construction conditions. In table 1 are the values of the soil stiffness (modulus of soil reaction, E') found to represent the types of soils and degrees of compaction for buried flexible pipe.

¹Numbers in brackets refer to references in the bibliography.

IOWA FORMULA

In 1941, M. G. Spangler, of the Iowa State Engineering Experiment Station, published a design procedure [1]¹ for the underground installation of flexible pipe. Spangler and Watkins [2] later modified the formula to include a more realistic value for the soil parameter. The modified Iowa formula is given as:

$$\Delta X = D_1 \frac{KW r^3}{EI + 0.061 E' r^3}$$

where:

- ΔX = horizontal deflection of the pipe, inches
- D_1 = deflection lag factor to compensate for the volume change of the soil with time, dimensionless
- K = bedding constant which varies with the angle of the bedding, dimensionless
- W = load on the pipe per unit length, pounds per linear inch
- r = pipe radius, inches
- EI = pipe wall stiffness per inch length, in-lb
- E' = modulus of soil reaction, pounds per square inch

Rearranged Iowa Formula

If the Iowa formula is rearranged as:

$$\Delta X = \frac{(D_1 KW)}{(EI/r^3) + (0.061 E')}$$

$$\Delta X = \frac{\text{load factor}}{\text{ring stiffness factor} + \text{soil stiffness factor}}$$

then the following terms can be used to describe the three separate factors that affect the pipe deflection:

$$\begin{aligned} \text{Load factor} &= D_1 KW \\ \text{Ring stiffness factor} &= EI/r^3 \\ \text{Soil stiffness factor} &= 0.061 E' \end{aligned}$$

Load Factor ($D_1 KW$)

The load factor incorporates the parameters that determine the magnitude and distribution of the soil pressures on a buried pipe.

The pipe deflection is directly proportional to the load factor and, yet, less is known about its components than any others in the Iowa formula. Changes in construction procedures or bedding materials along a pipeline could significantly vary the load factor.

Table 1A.—Bureau of Reclamation values of E' for Iowa formula
(for initial flexible pipe deflection) [Customary units]

Soil type-pipe bedding material (Unified Classification System) ¹	E' for degree of compaction of bedding (lb/in ²)			
	Dumped	Slight <85% Proctor <40% relative density	Moderate 85-95% Proctor 40-70% relative density	High >95% Proctor >70% relative density
<i>Fine grained soils</i> (LL > 50) ² Soils with medium to high plasticity CH, MH, CH-MH	No data available; consult a competent soils engineer; otherwise use $E' = 0$			
<i>Fine-grained soils</i> (LL < 50) Soils with medium to no plasticity CL, ML, ML-CL, with less than 25 percent coarse-grained particles	50	200	400	1000
<i>Fine-grained soils</i> (LL < 50) Soils with medium to no plasticity CL, ML, ML-CL, with more than 25 percent coarse-grained particles	100	400	1000	2000
<i>Coarse-grained soils with fines</i> GM, GC, SM, SC ³ contains more than 12 percent fines				
<i>Coarse-grained soils with little or no fines</i> GW, GP, SW, SP ³ contains less than 12 percent fines	200	1000	2000	3000
<i>Crushed rock</i>	1000	3000		
Accuracy in terms of percent deflection ⁴	±2%	±2%	±1%	±0.5%

¹ ASTM Designation D 2487, USBR Designation E-3.

² LL = liquid limit.

³ Or any borderline soil beginning with one of these symbols (i.e., GM-GC, GC-SC).

⁴ For ± 1 percent accuracy and predicted deflection of 3 percent, actual deflection would be between 2 percent and 4 percent.

Note: A. Values applicable only for fills less than 50 ft.

B. Table does not include any safety factor.

C. For use in predicting initial deflections only, appropriate deflection lag factor must be applied for long-term deflections.

D. If bedding falls on the borderline between two compaction categories, select lower E' value or average the two values.

E. Percent Proctor based on laboratory maximum dry density from test standards using about 12 500 ft-lb/ft³ (ASTM D-698, AASHTO T-99, USBR Designation E-11).

Table 1B.—Bureau of Reclamation values of E' for Iowa formula
(for initial flexible pipe deflection) [SI Metric units]

Soil type-pipe bedding material (Unified Classification System) ¹	E' for degree of compaction of bedding (MPa)			
	Dumped	Slight <85% Proctor <40% relative density	Moderate 85-95% Proctor 40-70% relative density	High >95% Proctor >70% relative density
<i>Fine-grained soils</i> (LL > 50) ² Soils with medium to high plasticity CH, MH, CH-MH	No data available; consult a competent soils engineer; otherwise use $E' = 0$			
<i>Fine-grained soils</i> (LL < 50) Soils with medium to no plasticity CL, ML, ML-CL, with less than 25 percent coarse-grained particles	0.3	1.4	2.8	7
<i>Fine-grained soils</i> (LL < 50) Soils with medium to no plasticity CL, ML, ML-CL, with more than 25 percent coarse-grained particles <i>Coarse-grained soils with fines</i> GM, GP, SM, SC ³ contains more than 12 percent fines	0.7	2.8	7	14
<i>Coarse-grained soils with little or no fines</i> GW, GP, SW, SP ³ contains less than 12 percent fines	1.4	7	14	21
<i>Crushed rock</i>	7	21		
Accuracy in terms of percent deflection ⁴	± 2%	± 2%	± 1%	± 0.5%

¹ ASTM Designation D 2487, USBR Designation E-3.

² LL = liquid limit.

³ Or any borderline soil beginning with one of these symbols (i.e., GM-GC, GC-SC).

⁴ For ± 1 percent accuracy and predicted deflection of 3 percent, actual deflection would be between 2 percent and 4 percent.

- Note:*
- A. Values applicable only for fills less than 15 m.
 - B. Table does not include any safety factor.
 - C. For use in predicting initial deflections only, appropriate deflection lag factor must be applied for long-term deflections.
 - D. If bedding falls on the borderline between two compaction categories, select lower E' value or average the two values.
 - E. Percent Proctor based on laboratory maximum dry density from test standards using about 598 000 J/m³ (ASTM D-698, AASHTO T-99, USBR Designation E-11).

Deflection lag factor (D_1). — After soil has been initially loaded, it continues to reduce in volume with time. The deflection lag factor converts the immediate deflection of the pipe to the deflection of the pipe after many years. Spangler [1] recommends a value of 1.5 for D_1 . The actual value, however, depends on when the immediate deflection is measured, the volume change rate of the soil, and the load on the soil. D_1 is basically an empirical factor and ranges from 1 to 6 in observed tests.

Bedding constant (K). — The bedding constant, K , ranges from 0.110 for a 0° bedding angle (line load on the bottom of the pipe) to 0.083 for a 90° bedding angle (full support under the bottom half of the pipe). The angle of bedding describes the load resisting area of the bedding under the pipe. As the angle of bedding increases, the loaded area increases and the pipe deflects less. No further study has been done on this constant since its conception, even though it can influence the results of the Iowa formula by as much as 25 percent. Most investigators of the behavior of flexible pipe now use a K of 0.1 as a typical value.

Load on the Pipe (W). — The Marston theory is the most common method of calculating the load on the pipe and is recommended by Spangler [1] for the Iowa formula. In the Marston theory, the load depends on whether the pipe is in a trench or embankment (or combination), the type of backfill soil, the settlement of the pipe in relation to the backfill material, and the distance that the pipe projects into the natural soil foundation.

The trend in recent years has been to assume the load on the pipe to be the weight of the column of earth above the pipe, with the width equal to the pipe diameter.

Ring Stiffness Factor (EI/r^3)

In most cases the ring stiffness has very little influence on the pipe deflection because the soil stiffness factor is much larger. Considering the magnitude of the variations that can occur in the load factor and in the soil stiffness and the small influence of the ring stiffness, the use of nominal values for E , I , and r provide sufficient accuracy for the Iowa formula.

The ring stiffness is the product of the modulus of elasticity of the pipe wall material (pounds per square inch) and the moment of inertia (inch⁴ per inch) of a 25.4-mm (1-in) length of pipe divided by the pipe radius cubed. The moment of inertia is equal to $t^3/12$ where t is the wall thickness. The EI value may be found using assumed or empirical values for E and t or EI can be determined by conducting three-edge bearing

tests on a section of pipe. During the test, deflections due to line loads on the top and bottom of the pipe are measured and EI calculated from either:

$$EI = 0.149 \frac{Pr^3}{\Delta Y}$$

or

$$EI = 0.136 \frac{Pr^3}{\Delta X}$$

where P is the load per linear inch, r is the pipe radius in inches, ΔY is the vertical deflection in inches, and ΔX is the horizontal deflection in inches. In the three-edge bearing test the pipe deforms elliptically with the horizontal deflection theoretically about 91 percent of the vertical deflection.

Soil Stiffness Factor ($0.061E'$)

The soil load on a flexible pipe causes a decrease in the vertical diameter and an increase in the horizontal diameter. The horizontal movement develops a passive soil resistance that acts to help support the pipe. The magnitude of the pipe deflection then depends on the vertical soil load on the pipe and the passive resistance of the soil at the sides of the pipe. The passive soil resistance is expressed as "modulus of passive resistance," e , and is defined as the ratio of the pressure on the soil to the horizontal movement of the soil. It is usually expressed in unit pressure per unit of movement and it is similar to the coefficient of subgrade reaction. The coefficient of subgrade reaction is the ratio of the pressure on an element of soil under a footing to the corresponding settlement. Spangler [1] used a constant value for this modulus in the original Iowa formula. Watkins and Spangler [2] later modified the e value to E' ($E' = er$, where r = pipe radius) so that it would be dimensionally correct and similar to the compressive modulus of elasticity of soil. This results in E' becoming more of a pipe-soil interaction modulus rather than a soil modulus alone. A constant $E' = 4.8$ MPa (700 lb/in²) was suggested for soils placed at over 90 percent of their maximum laboratory dry density.

Spangler now regards E' as a semiempirical constant that is difficult to obtain from laboratory tests [3]. Rather than using a constant E' , he now recommends values based on experience and judgment. Recent literature reveals attempts to correlate the modulus of soil reaction to other soil parameters, especially the confined compression modulus. This is the slope of the stress-strain curve from a one-dimensional consolidation test.

LABORATORY TESTS

Bureau of Reclamation laboratory soil container tests have demonstrated the effects of the pipe modulus, the soil type, and degree of compaction on the deflections of buried flexible pipe. These tests have been described in a series of reports and papers [4, 5, 6, 7, 8, 9, 10, and 11].

The analysis of the test results took two approaches:

1. Comparing the pipe with various pipe modulus values for a constant soil modulus value.
2. Comparing pipe of equal pipe modulus for various soil modulus values.

The pipe modulus was varied by using different types of pipe [steel, FRP (fiberglass reinforced plastic), RPM (reinforced plastic mortar), PE (polyethylene), and PVC (poly(vinyl chloride))] of varying diameters and wall thicknesses.

The soil modulus was varied by bedding the pipe in different soils, a sandy clay (fine-grained — CL) and a clean, poorly graded sand (coarse-grained — SP) at various degrees of compaction (90 percent and 100 percent of the laboratory maximum density for the sandy clay, and dumped and 80 percent relative density for the sand).

The pipe was buried in a large steel soil container and surcharge loads applied to the soil surface over the pipe. Pipe deflections, soil pressures, and soil strains were measured as the load was increased over the pipe.

Varied Pipe Modulus — Constant Soil Modulus

Figure 1 shows the deflection of steel, PVC, and PE pipe with various pipe moduli tested in the sandy clay at 90 percent of maximum density. When the soil was placed around the pipe at 100 percent of maximum density, the effect of the pipe modulus was much less pronounced as shown in figure 2. The deflections of reinforced plastic mortar pipe and fiberglass reinforced plastic pipe of varying pipe moduli buried in the 90-percent density sandy clay are shown on figure 3.

When steel, RPM, and FRP pipe of various pipe moduli, 31 to 159 kPa (4.5 to 23.0 lb/in²), were buried and tested in the high density cohesionless soil, there was no significant difference in deflection due to the high soil modulus.

Constant Pipe Modulus — Varied Soil Modulus

Figure 4 shows the difference in deflection for steel pipe of equal pipe moduli in the 90-percent and the 100-percent density sandy clay. Figure 5 shows a similar relationship for RPM pipe.

Figure 6 shows the difference in deflection for a steel pipe tested in the highly compacted cohesionless soil (relative density over 80 percent) and the same pipe tested with a cohesionless material dumped in without compaction.

The effect of the type of soil is shown on figure 7. The sandy clay compacted to 100 percent density and the compacted cohesionless soil had about the same density, 1922 kg/m³ (120 lb/ft³). However, the cohesionless soil provided much better support for pipe of the same pipe modulus.

Field Investigations

A 180-m (600-ft) test section of 762-mm (30-in) diameter RPM pipe was installed on the Yuma Project (Arizona) using five different kinds of bedding [12]. As illustrated on figure 8, the type of soil and degree of compaction had a significant effect on the pipe deflections.

At the Denver Federal Center, 6.1-m (20-ft) sections of steel, RPM, and PT (pretensioned concrete) 1200-mm (48-in) diameter pipe were buried in a 4.6-m (15-ft) deep trench. A sand (cohesionless) bedding compacted to 70 percent relative density and a cohesive bedding compacted to 95 percent of Proctor maximum dry density were used. The pipe had pipe moduli ranging from 8.3 to 39 kPa (1.2 to 5.7 lb/in²). All three types of pipe in the cohesive bedding deflected about the same (average = 1.1 percent); and all three pipes in the cohesionless bedding deflected about the same (average = 0.7 percent), illustrating that when the soil modulus is high, the pipe modulus has very little effect. The cohesionless bedding also provided better support.

DEVELOPMENT OF TABLE FOR E' VALUES

Data from over 100 field installations (listed in appendix A) were collected and E' values back-calculated. The E' values showed similarities for certain categories of soil type and degrees of compaction and these categories were used to develop table 1. A representative, single E' value was selected for each category of soil type and compaction.

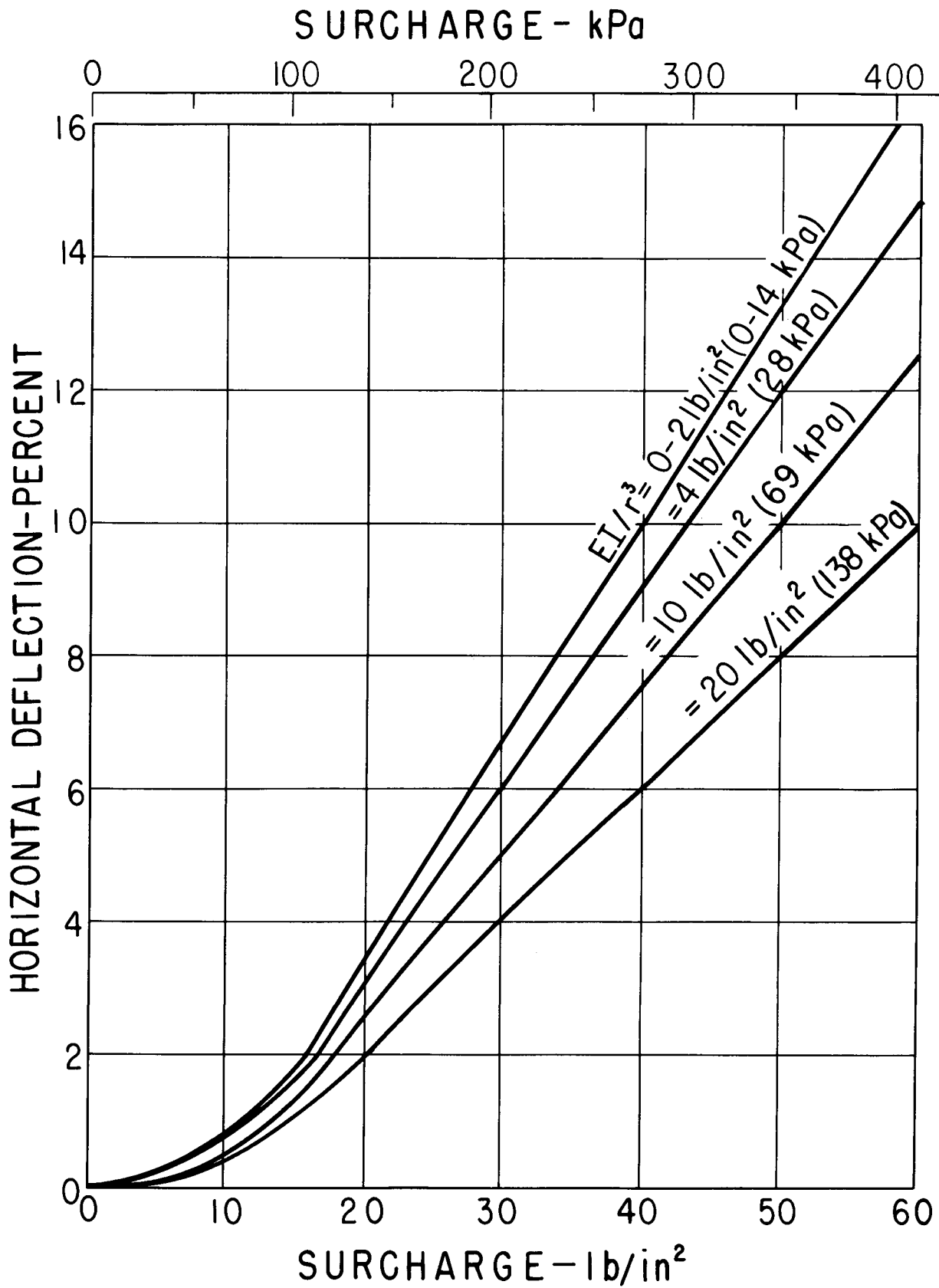


Figure 1.—Typical load-deflection curves for steel and thermoplastic pipe of various stiffnesses in 90 percent density clay.

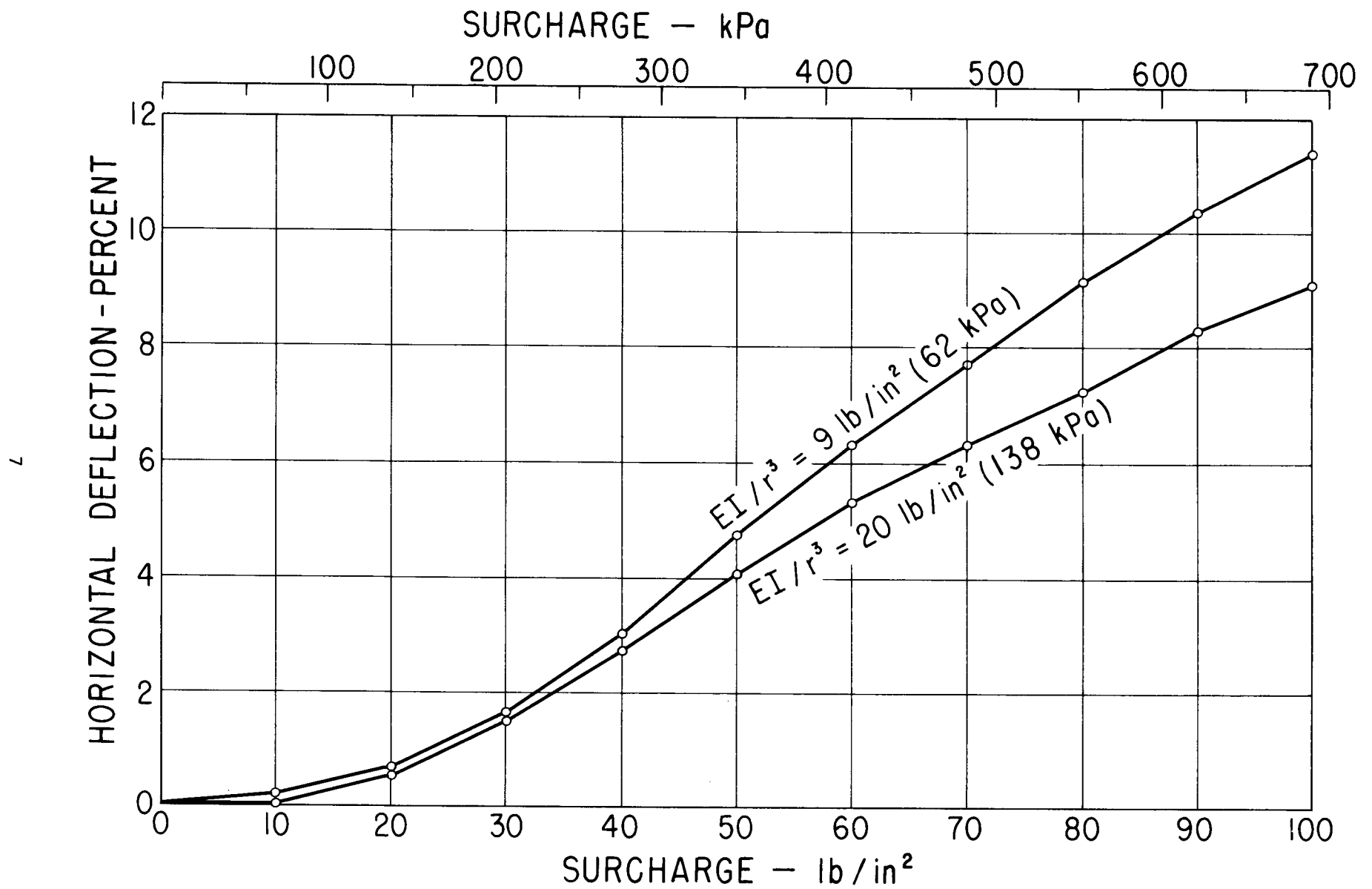


Figure 2.—Load-deflection curves for steel pipe of various stiffnesses in 100 percent density clay.

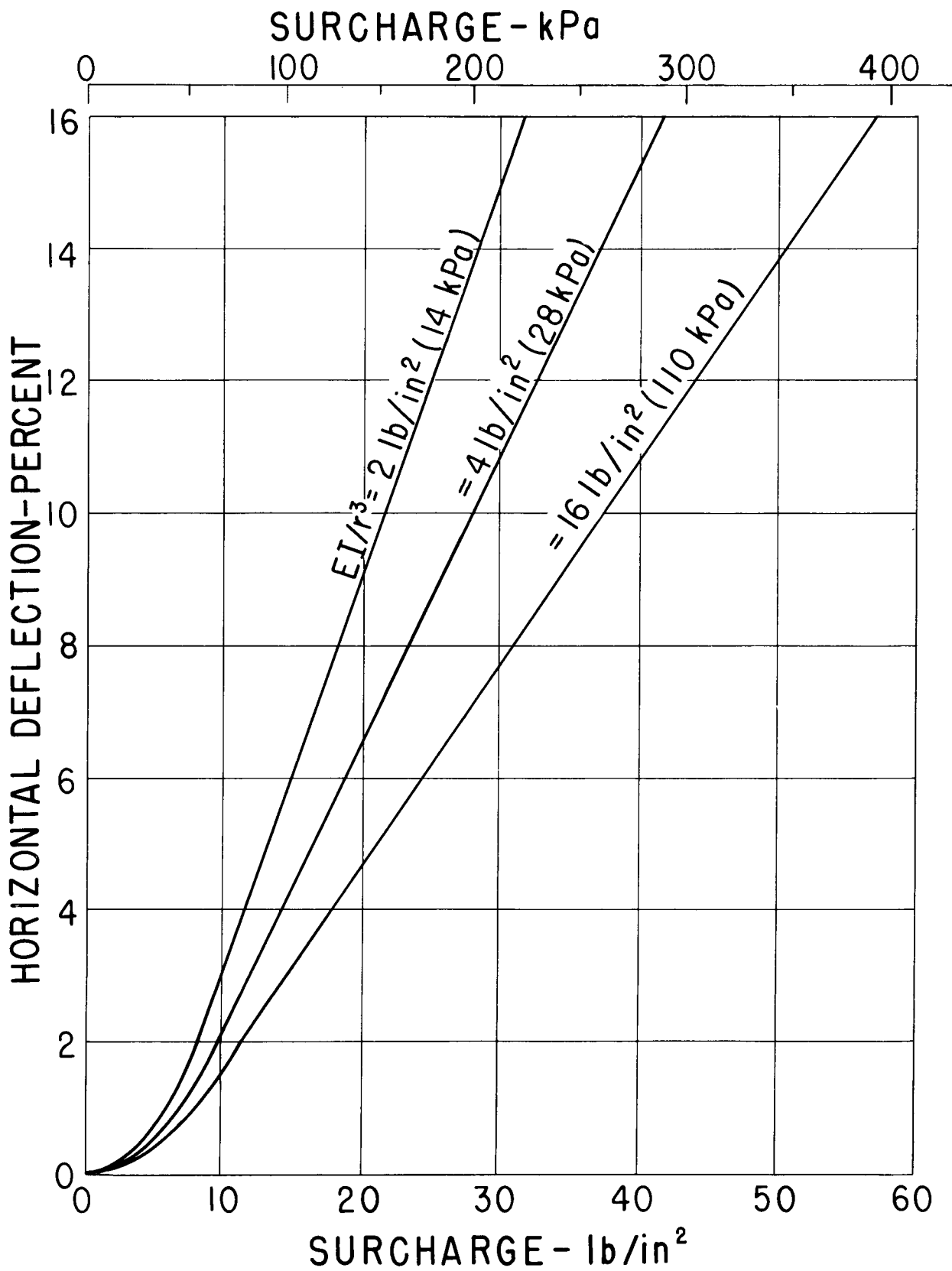


Figure 3.—Typical load-deflection curves for RPM (reinforced plastic mortar) pipe in 90 percent density clay.

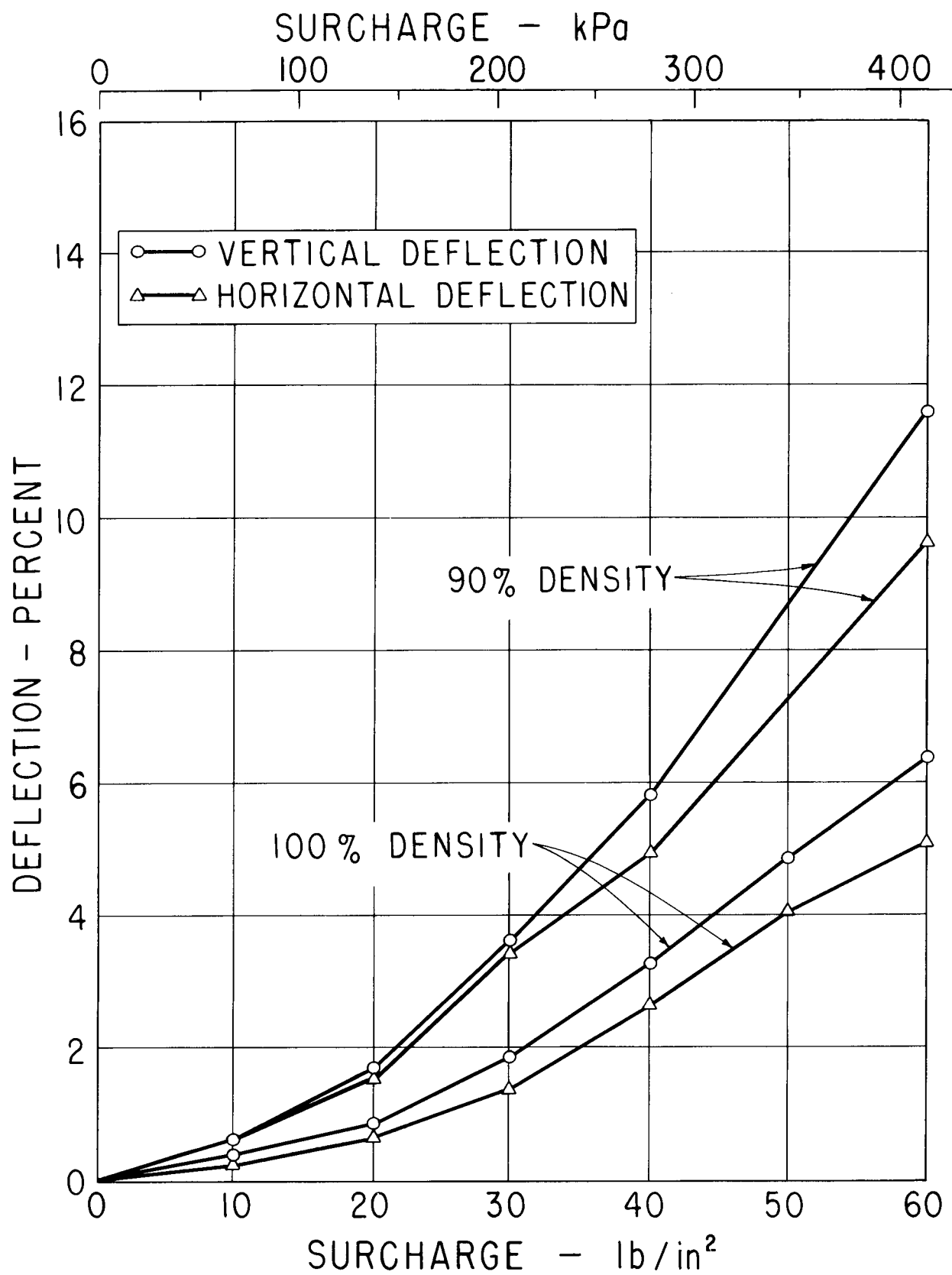


Figure 4.—Load-deflection curves for steel pipe of identical stiffness in 90 percent and 100 percent density clay.

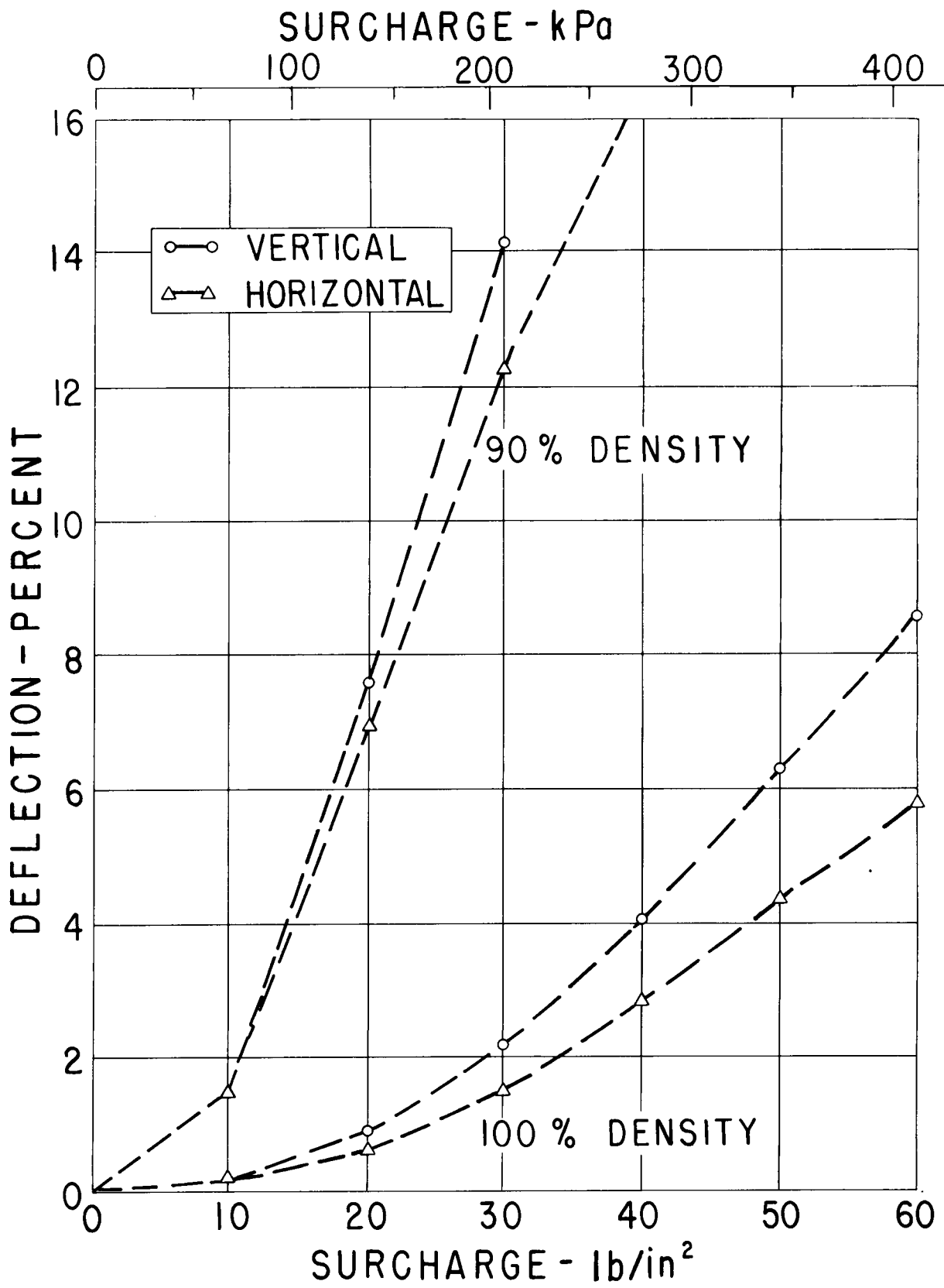


Figure 5.—Load-deflection curves for RPM (reinforced plastic mortar) pipe of identical stiffness in 90 percent and 100 percent density clay.

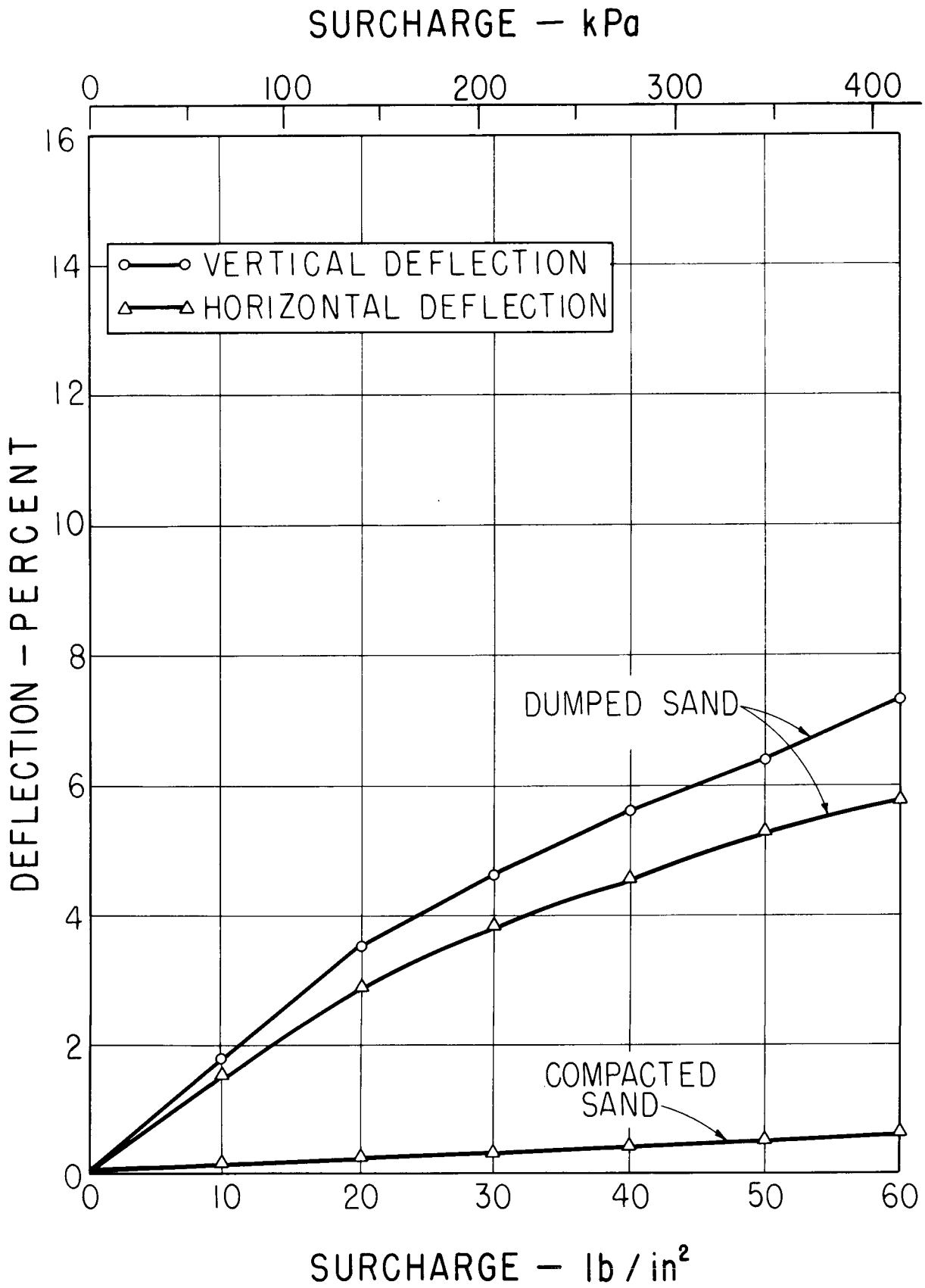


Figure 6.—Load-deflection curves for steel pipe of identical stiffness in dumped and in compacted sand.

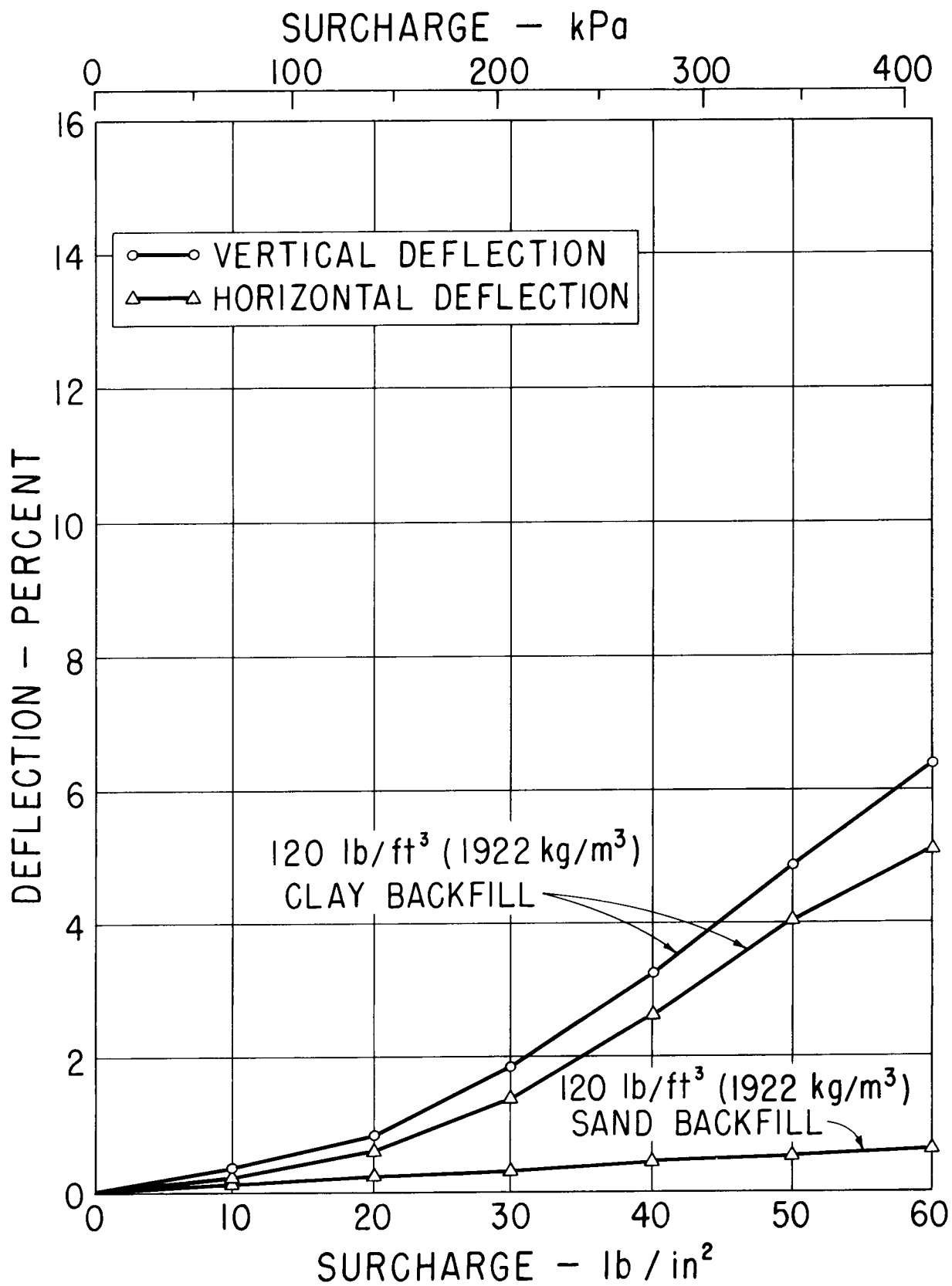


Figure 7.—Load-deflection curves for steel pipe of identical stiffness in different soil types compacted to same density.

FIELD TEST OF RPM PIPE ON TORONTO LATERAL YUMA PROJECT

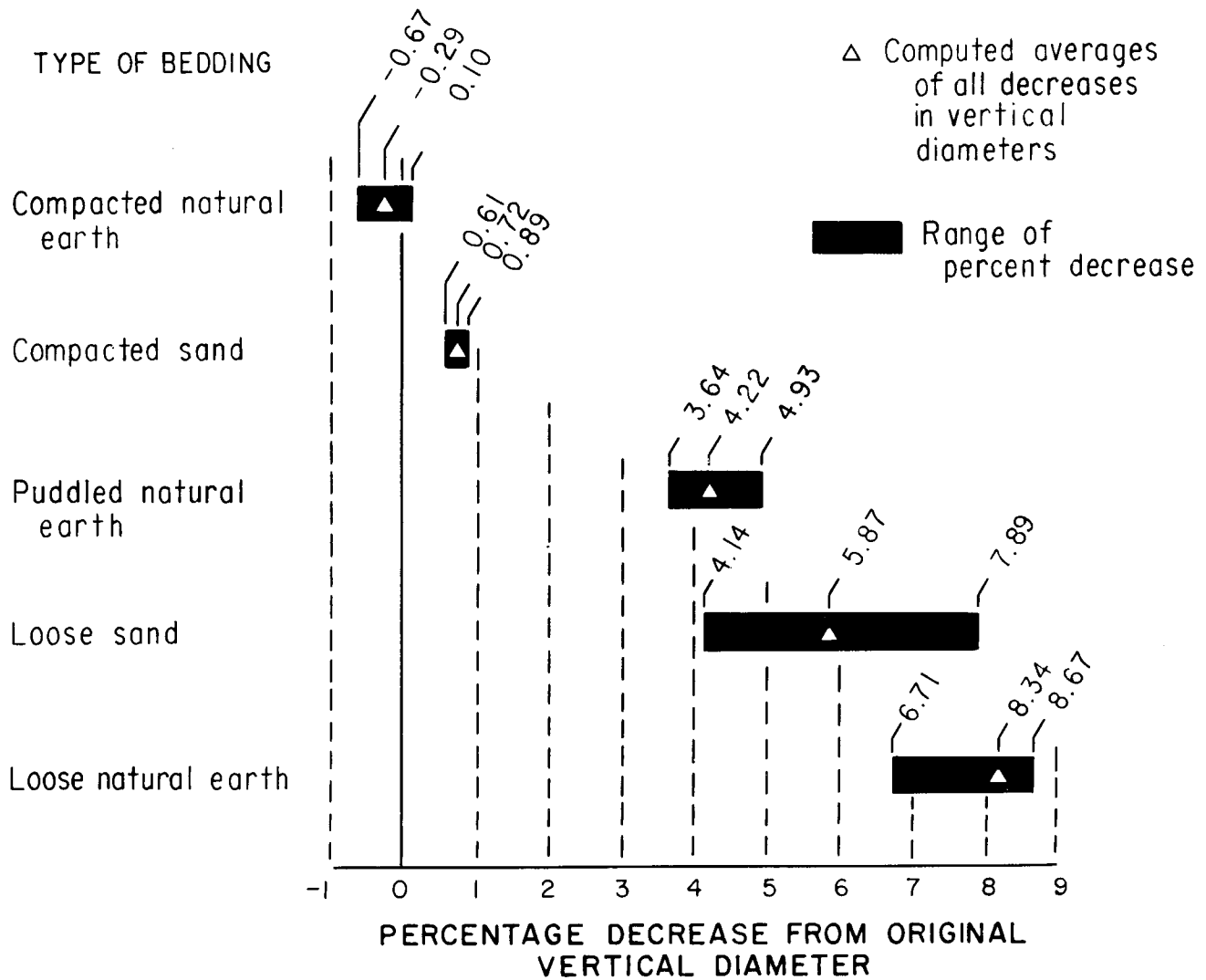


Figure 8.—Deflections of RPM pipe on Yuma Project, Ariz.

The value of the actual deflections used to calculate E' represents:

1. The initial deflection measured after construction.
2. The deflection of the pipe between the time the soil was placed to the top of the pipe and the time of completion of backfilling (when reported).
3. The measured horizontal deflection, ΔX , or if that was not measured, $\Delta X = 0.913 \Delta Y$, where ΔY is the measured vertical deflection. The value 0.913 is the ratio between the vertical and horizontal diameter changes as a circular section deforms elliptically.
4. The average deflection if numerous measurements were made along the pipeline.

The initial deflections were made any time from 1 day to a few months after construction. Data in the literature, when the deflections were measured a year or more after construction, were not used since the deflection lag factor for pipe is quite varied. In the cases studied, D_1 ranged from 1 to 4. In some of the tests, a difference of even a few days increased the deflection 20 to 30 percent. In a few cases, deflection data measured after several years were used in this comparison because the deflections were quite small and had no effect on the basic conclusions.

The various types of pipe and construction conditions in the field tests surveyed included:

- Types of pipe — CMP, steel and aluminum
 - Cast iron
 - Smooth iron
 - Ductile iron
 - Straight steel
 - Reinforced plastic mortar (RPM)
 - Fiberglass reinforced plastic (FRP)
 - Poly(vinyl chloride) (PVC)
 - Pretensioned concrete (PT)
- Pipe diameters — 300 mm (12 in) to 4570 mm (180 in)
- Backfill depths — 0.6 m (2 ft) to 13 m (42 ft)
- Trench and embankment installations
- Soft to hard soil beneath the pipe
- Various projection conditions
- Varying water table conditions

RANGE OF DEFLECTIONS ALONG PIPELINES

The deflections along a pipeline can vary considerably due to normal soil variations and inherent differences in compacting soil along a pipeline. The data from installations where measurements were made along a stretch of pipeline showed a wide range of deflections. For the field tests where measurements were made over a 30 m (100 ft) or more length of pipeline, the range of deflections are plotted about the average deflections for each line on figure 9. A deflection range of about ± 2 percent deflection can be expected, particularly when the pipe stiffness is much less than the soil stiffness. The value \pm percent deflection is used here to mean that if the average deflection was found to be 3 percent, the deflections would range between 1 percent and 5 percent.

Surprisingly, this wide range in deflection appears to be independent of the pipe type, soil type, and degree of compaction. The stiffer pipe did, however, show less variation in deflection.

Gehrels [13] reported on the measurements of 14 km (9 mi) of PVC pipe in Europe using a deformation gage pulled through the pipe as shown in table 2. Generally, the differences below the low and high deflections were about 6 percent deflection (± 3 percent deflection about the average) although he reported differences as high as 18 percent in the 200- to 400-mm (8- to 16-in) PVC pipe.

RELIABILITY OF TABLE 1

Although the back-calculated E' values varied within each category shown in table 1, a single E' value was selected to represent each category. The data from the field installations were reviewed again to see if the single E' value could have been used to predict the actual measured deflection within an acceptable degree of accuracy.

To calculate the predicted deflection, 1.0 was used for the deflection lag factor, 0.1 for the bedding constant, and nominal values for the modulus of elasticity, E ; wall thickness, t (or I , moment of inertia); and pipe radius, r ; were used. The load on the pipe was assumed to be a vertical prism of soil. The soil type and degree of compaction for the soil *beside the pipe* were used to get the appropriate E' value from table 1.

The predicted deflection was then calculated using the Iowa formula rearranged as:

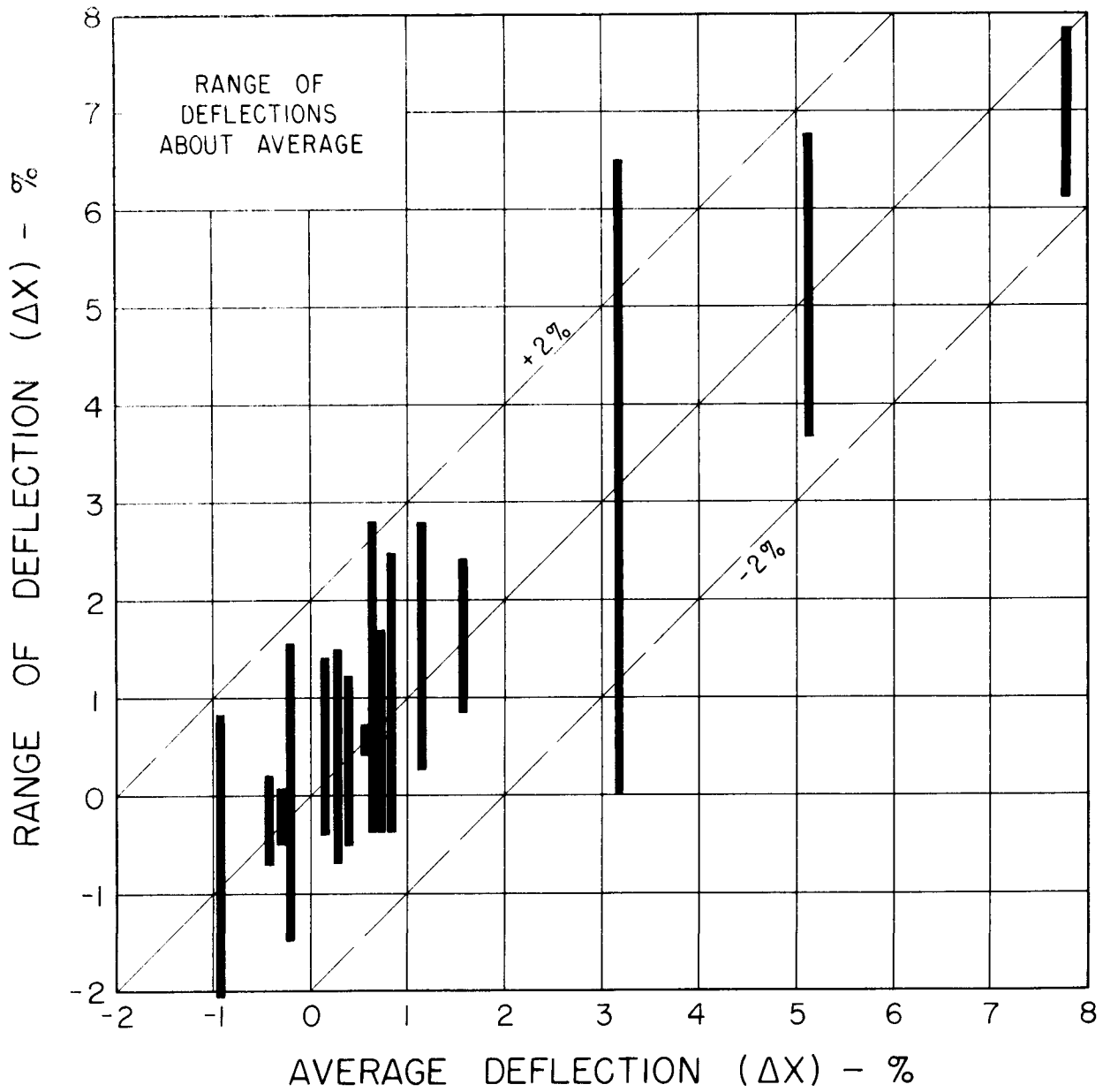


Figure 9.—Range of deflections measured along pipelines.

Table 2.—European PVC pipe deflection survey

PVC pipe size, mm	Avg. ΔY , %	ΔY range — %		Bedding material	Compaction	When measured
		Low	High			
315	5	2	9	Sand	"by treading"	5 years
250	1.5	0	4	Sand	"by treading"	5 days
	3	0	6.5			2 years
400	-2	-5	2	Sand	"with detonation rammer"	1 year
315	5.5	2.5	10	Sand	"by treading"	3-1/2 years
450	2	0	2.5	Pea gravel		2 years
400	1	0	1.5	Pea gravel		2 years
250	1.5	0	2.5	Pea gravel		2 years
400	2.5	-1	7	Sand	"by treading"	4 months
	3.5	1.5	7			1 year
250	4	3	5	Sand	"by treading"	2 years
315	4.5	2	7	Sand		1 year
200	2	0	3.5	Sand	"by treading"	3 months
	2.5	0.5	3.5			1-1/2 years
315	6	3	12	Sand	"by treading"	1 year
315	2.5	0	5	Sand	"with hand rammers"	1 year
315	2.5	1	5	Sand	"by treading"	3 years
250	4	2.5	7	Sand	"in layers with hand rammers"	1 year
225	0.6	0	0.8	Silt	"with hand rammer and by treading"	2 days
	1 to 1.5	0	2	Silt	"with hand rammer"	1 year
315	5.5	2	12	Peat		5 years
	5.5	2	12	Peat		8 years
315	5.5	1	8.5	Peat		4 years
315	3.5	2	5	Sand	"by treading"	3 years
315	15	7	22	Sand	"by treading"	3 years
315	8	4	12.5	Sand	"by treading"	2 years
	9	5	13	Sand	"by treading"	4 years
315	6.5	4.5	10.5	Sand	"by treading"	3 years
	7	2	20.5	Sand	"by treading"	6 years
315	5.5	-2	13	On wooden piles		2 years
	6.5	2	20	On wooden piles		4 years
250	3	0	11	Sand	"with hand rammers"	1-1/2 years

$$\Delta X(\%) = 0.0694 \frac{\gamma h}{EI/r^3 + 0.061 E'}$$

where:

$\Delta X(\%)$ = percent deflection, change in diameter divided by nominal diameter times 100

γ = soil density, lb/ft³

h = fill height, ft

EI/r^3 = ring stiffness factor, lb/in²

E' = modulus of soil reaction, lb/in²

The variations between the actual measured deflection and the deflection predicted using E' values from table 1 appear to be affected more by the degree of compaction than any other factor.

The comparisons between the actual and predicted deflections are shown on figure 10 for the dumped and slightly compacted field tests. Over 90 percent of the comparisons showed the actual deflection was within ± 2 percent deflection of the predicted deflection. The value, ± 2 percent deflection, means that if the predicted deflection were 3 percent, the actual deflection was between 1 and 5 percent.

Figure 11 shows the comparison of the actual deflection versus the predicted deflection for the field tests with moderate degrees of compaction. About 90 percent of the actual deflections were within ± 1 percent deflection of the predicted value.

The comparison of actual deflection versus predicted deflection for the tests with a high degree of compaction is shown on figure 12. Over 80 percent of the actual deflections were within ± 0.5 percent deflection of the predicted deflection. However, all those tests that had more than a 0.5 percent deflection variation were those where the actual deflections were *less* than the predicted deflection. One hundred percent of the comparisons were within ± 1 percent deflection.

Therefore, the use of E' values from table 1 to predict the pipe deflections in over 100 field tests surveyed would have predicted the deflection of the tests as follows:

- Dumped or slight compaction to within ± 2 percent deflection.
- Moderate compaction to within ± 1 percent deflection
- High compaction to within ± 0.5 percent deflection

The expected reliability of using the E' values from table 1 is summarized in the bottom line of table 1.

LIMITATIONS OF TABLE 1

Obviously, this is an empirical method of determining E' values and the values reported will probably be modified by the collection and evaluation of more field installation data, especially for those categories of soil type and compaction where data from only a few tests were available.

These results apply only to the initial deflections, deflections measured soon after construction. A similar study is now underway to evaluate the time-lag effect on the deflection.

These results are not applicable for flexible pipe buried under fills over 15 m (50 ft). Evaluation of data on high fills in the literature showed the actual deflections reported to be much less than deflections calculated using the E' values from table 1. Values of E' have been reported as high as 138 MPa (20 000 lb/in²) for high fills. (See appendix C.)

Caution should be used when applying values from table 1 when the trench walls are more compressible than the bedding material. The bedding material needs firm support. When trenching through highly compressible in situ material, a minimum of two pipe diameters should be excavated on either side of the pipe and the bedding material placed at a high degree of compaction so that the resistance to the pipe deflection will come from the bedding material without depending on support from the trench walls.

When the trench wall material is fine-grained soil and the bedding material is gravel, the possibility of infiltration of the fines into the gravel should be considered.

Recommended procedures for installation of buried flexible pipe are given in appendix D.

SUMMARY AND CONCLUSIONS

A table of E' (modulus of soil reaction) values has been empirically developed for use in the Iowa formula for predicting buried flexible pipe initial (no time effect) deflections for fills less than 15 m (50 ft).

A series of laboratory soil container load tests on flexible pipe established the effect of the load on the pipe, the pipe stiffness, the soil type, and the degree of

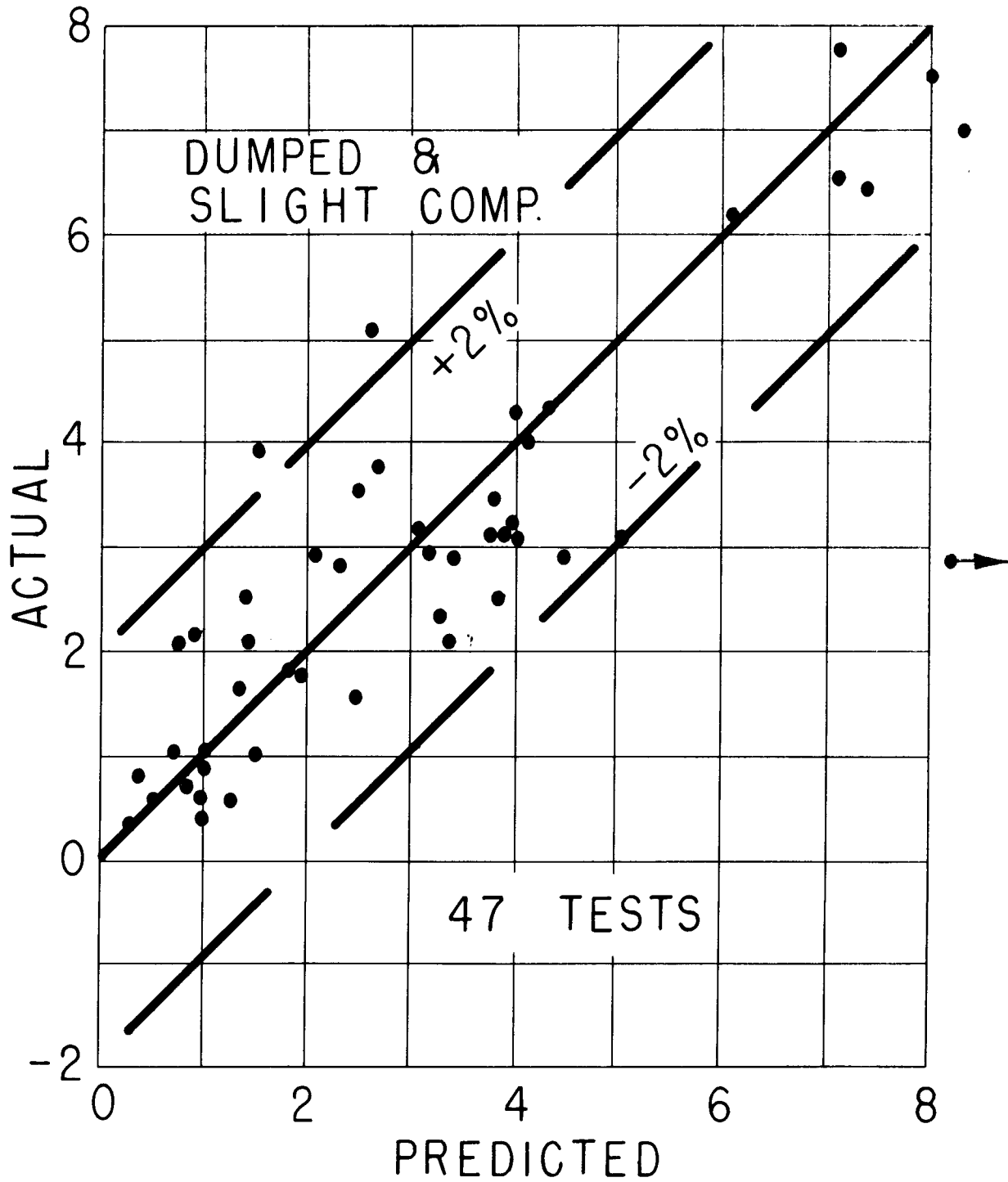


Figure 10.—Comparison of actual and predicted deflections for dumped and slightly compacted beddings.

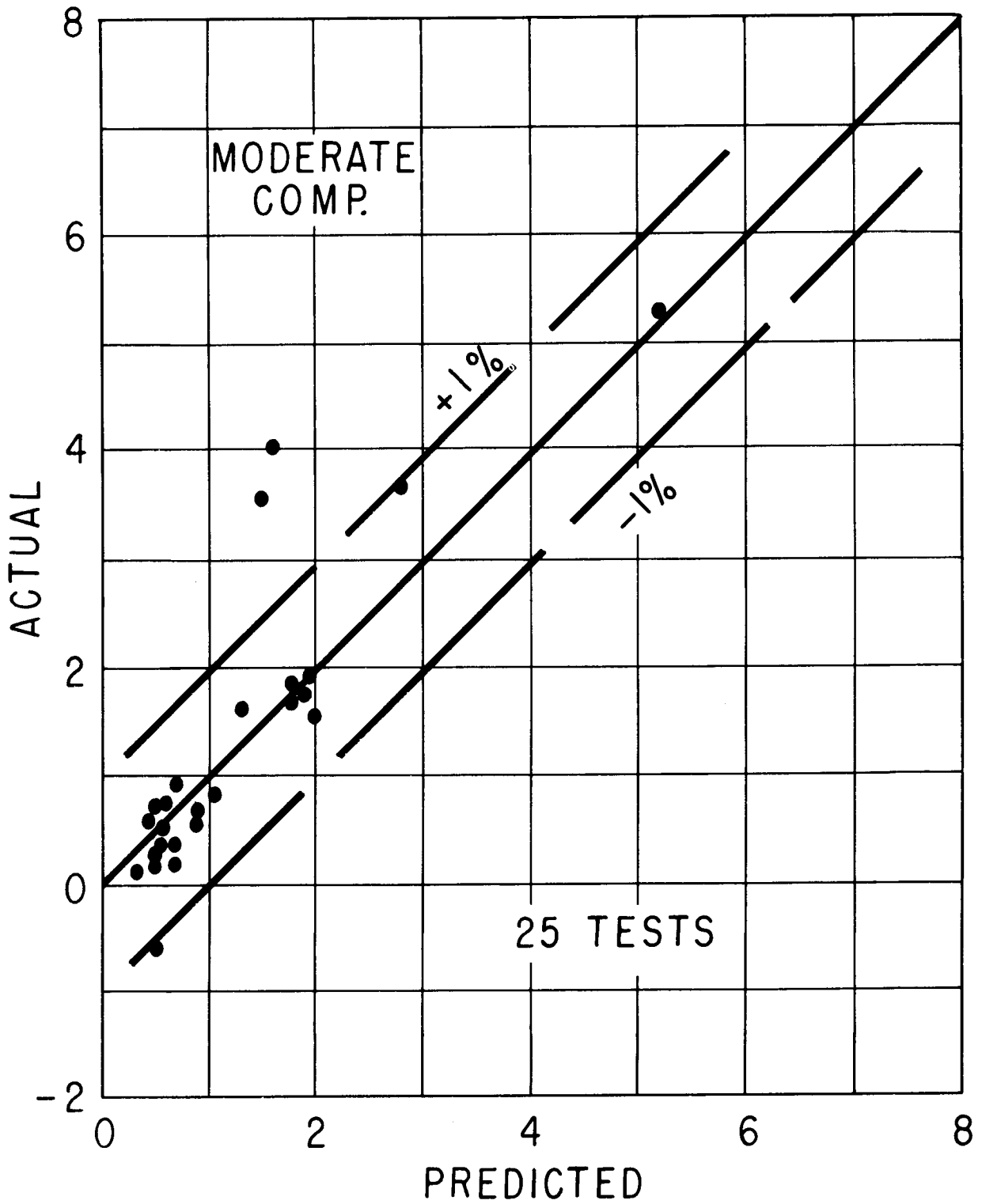


Figure 11.—Comparison of actual and predicted deflections for moderately compacted beddings.

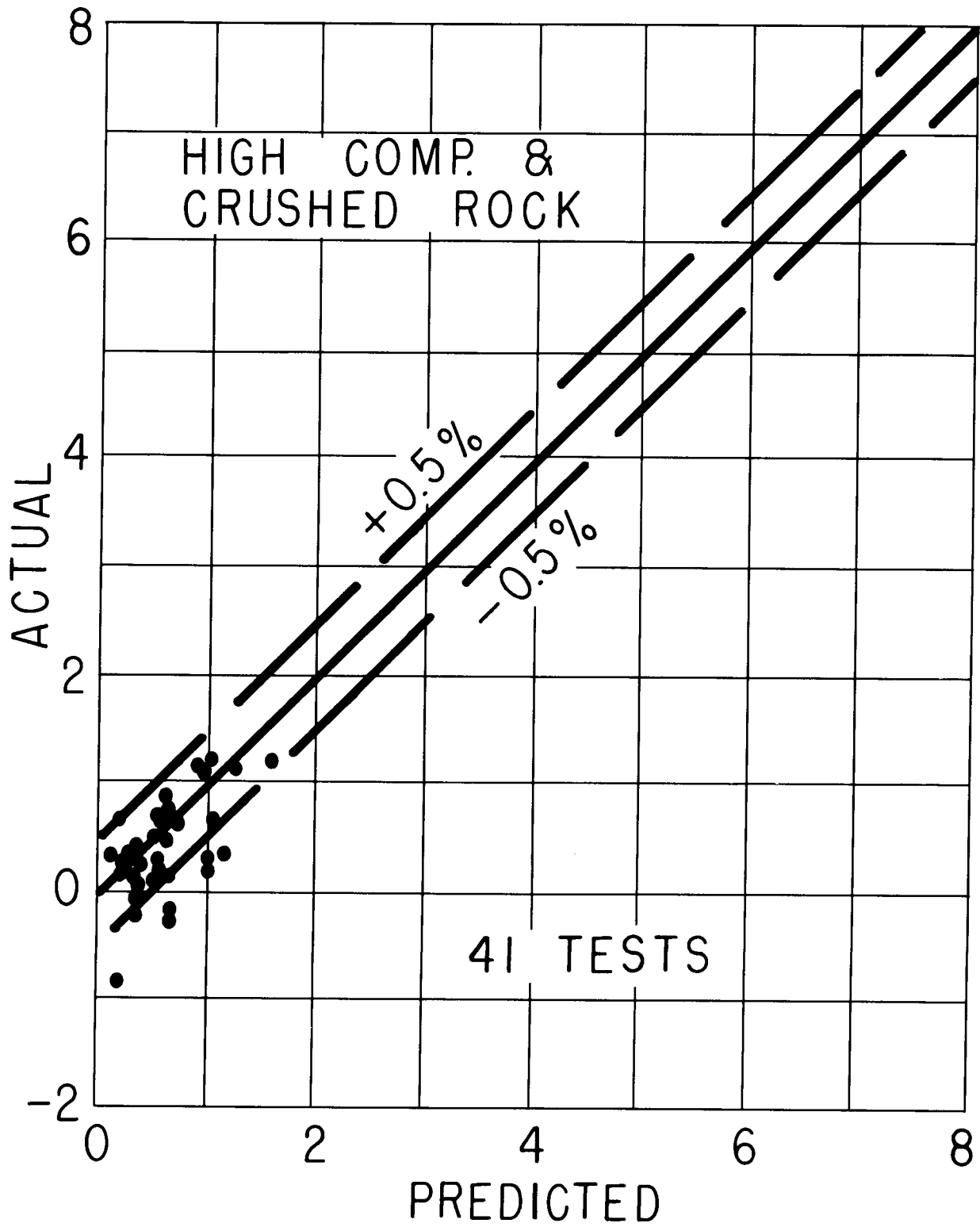


Figure 12.—Comparison of actual and predicted deflections for highly compacted beddings and crushed rock.

compaction of the soil beside the pipe on the pipe deflection.

After using data from over 100 field tests to establish representative E' values for specific soil types and degrees of compaction, the E' values were used in the Iowa formula to show that the representative values of E' could have been used to predict the actual pipe deflection for dumped backfill and slight degrees of compaction to within ± 2 percent, for moderate degrees of compaction to within ± 1 percent deflection, and for high degrees of compaction to within ± 0.5 percent deflection. The percent deflection refers here to the variation in the actual deflection from the predicted deflection. For ± 1 percent deflection accuracy, if the predicted deflection were 3 percent, the actual deflection would be between 2 and 4 percent.

The data from the field measurements of buried pipe showed that the deflection along a pipeline can vary ± 2 percent deflection about the average deflection for any soil type or degree of compaction.

APPLICATIONS

The Bureau of Reclamation table of modulus of soil reaction values can be used to reasonably predict initial buried flexible pipe deflection for fills less than 15 m (50 ft). Designers of flexible pipe should expect a range of deflections of ± 2 percent about the average deflection.

BIBLIOGRAPHY

- [1] Spangler, M. G., "The Structural Design of Flexible Pipe Culverts," Iowa Engineering Experiment Station Bulletin No. 153, 1941.
- [2] Watkins, R. K., and Spangler, M. G., "Some Characteristics of the Modulus of Passive Resistance of Soil: A Study of Similitude," Highway Research Board Proceedings, vol. 37, 1958.
- [3] Spangler, M. G., Discussion of "Rebuilt Wolf Creek Culvert Behavior," by A. C. Scheer and G. A. Willet, Jr., Highway Research Record 185, 1967.
- [4] Howard, A. K., "Laboratory Load Tests on Buried Flexible Pipe — Progress Report No. 1," Report No. EM-763, Bureau of Reclamation, Denver, Colorado, June 1968.
- [5] Howard, A. K., "Laboratory Load Tests on Buried Flexible Pipe — Progress Report No. 2," Report No. REC-OCE-70-24, Bureau of Reclamation, Denver, Colorado, June 1970.
- [6] Howard, A. K., "Laboratory Load Tests on Buried Flexible Pipe — Progress Report No. 3, Steel Pipe in High Density Cohesive Soil," Report No. REC-ERC-71-35, Bureau of Reclamation, Denver, Colorado, June 1971.
- [7] Howard, A. K., "Laboratory Load Tests on Buried Flexible Pipe — Progress Report No. 4, Reinforced Plastic Mortar (RPM) Pipe," Report No. REC-ERC-72-38, Bureau of Reclamation, Denver, Colorado, November 1972.
- [8] Howard, A. K., "Laboratory Load Tests on Buried Flexible Pipe — Progress Report No. 5, Fiberglass Reinforced Plastic, Polyethylene, and Polyvinyl Chloride Pipe," REC-ERC-73-16, Bureau of Reclamation, Denver, Colorado, July 1973.
- [9] Howard, A. K., "Laboratory Load Tests on Buried Flexible Pipe — Progress Report No. 6, Pipe Buried in Cohesionless Backfill," Report No. REC-ERC-73-9, Bureau of Reclamation, Denver, Colorado, April 1973.
- [10] Howard, A. K., "Laboratory Load Tests on Buried Flexible Pipe," AWWA Journal, vol. 64, No. 10, Part 1, October 1972.
- [11] Howard, A. K., and Selander, C. E., "Laboratory Load Tests on Buried Reinforced Thermosetting, Thermoplastic, and Steel Pipe," Proceedings, 28th Annual Technical Conference, Reinforced Plastics/Composites Institute, The Society of the Plastics Industry, Inc., 1973; also AWWA Journal, vol. 66, No. 9, September 1974.
- [12] Howard, A. K., and Metzger, H. G., "RPM Pipe Deflections on Yuma Project Field Test," Report No. REC-ERC-73-7, Bureau of Reclamation, Denver, Colorado, April 1973.
- [13] Gehrels, J. R., "Experience with Plastic Sewers and Drainage Pipes," Proceedings, 2nd International Plastic Pipes Symposium, September 1972.



APPENDIXES



APPENDIX A

SURVEY OF BURIED PIPE DEFLECTION DATA

Table A-1 includes data collected from published reports. Table A-2 is data that are unpublished and are used with permission of the various sources. The column heading "No. of measurements" refers to the number of different locations where deflections were measured. In the "comments" column the length covered by the number of location measurements is reported.

A more complete discussion of each test case is described in appendix B. The references listed in tables A-1 and A-2 refer to bibliography at the end of appendix A.



Table A-1.—Predicted versus actual pipe deflection — flexible pipe field data — published reports

Test No.	Ref. No.	Test site	Pipe stiffness factor			Soil stiffness factor			Load factor		Horiz. (ΔX) deflection		Deflection range		No. of measurements	Comments	
			Pipe type	Diameter, in	Wall thickness, ² in	El/r ³ lb/in ²	Soil type ¹	Degree of compaction	Theo. E', lb/in ²	Fill ht, ft	Fill density, lb/ft ³	Pre-dicted %	Actual %	Low %			High %
PUBLISHED REPORTS																	
1	1	Farina, Ill.	CMP	24	14 ga.	37.5	III	Slight	400	33.1	105	3.9	3.2		1	Their test No. 4	
2	1	Farina, Ill.	CMP	42	12 ga.	10.3	III	Slight	400	33.5	105	7.1	6.6		1	Their test No. 5	
3	1	Farina, Ill.	Cast iron	42	1.25	160.9	III	Slight	400	34.2	105	1.3	0.6		1	Their test No. 6	
4	1	Farina, Ill.	CMP	42	12 ga.	10.3	III	Slight	400	34.9	105	7.4	6.5		1	Their test No. 7	
5	1	Farina, Ill.	CMP	48	10 ga.	9.3	III	Slight	400	27.9	105	6.1	6.2		1	Their test No. 8	
6	2	Chapel Hill, N.C.	Smooth iron	30	0.109	0.9	V	Slight	1,000	12	107	1.4	2.1		1	Their test No. 1	
7	2	Chapel Hill, N.C.	CMP	30	12 ga.	27.1	V	Slight	1,000	12	107	1.0	1.0		1	Their test No. 2	
8	2	Chapel Hill, N.C.	Steel	30	0.349	32.6	V	Slight	1,000	12	107	1.0	0.8		1	Their test No. 3	
9	2	Chapel Hill, N.C.	Cast iron	30	1.00	229.3	V	Slight	1,000	12	107	0.3	0.3		1	Their test No. 4	
10	2	Chapel Hill, N.C.	Smooth iron	20	0.076	1.0	V	Slight	1,000	12	107	1.4	2.5		1	Their test No. 7	
11	2	Chapel Hill, N.C.	CMP	20	14 ga.	65.5	V	Slight	1,000	12	107	0.7	1.0		1	Their test No. 8	
12	3	Ames, Iowa	CMP	42	8 ga.	16.6	IV	Slight	400	15	121	3.1	3.2	3.1	3.5	4	Exp. No. 1
13	3	Ames, Iowa	CMP	42	10 ga.	13.2	IV	Mod.	1,000	16	130	1.9	1.8	1.5	2.1	4	Exp. No. 2
14	3	Ames, Iowa	CMP	36	16 ga.	8.8	IV	Mod.	1,000	15	121	1.8	1.8			4	Exp. No. 3, no range given
15	3	Ames, Iowa	CMP	36	16 ga.	8.8	IV	Slight	400	15	121	3.8	3.5			3	Exp. No. 3, no range given

¹ Type I — Fine-grained soil (LL > 50) — soil with medium to high plasticity.

Type II — Fine-grained soil (LL < 50) — soil with medium to no plasticity with less than 25 percent coarse-grained particles.

Type III — Fine-grained soil (LL < 50) — soil with medium to no plasticity with more than 25 percent coarse-grained particles.

Type IV — Coarse-grained soil with fines — contains more than 12 percent fines.

Type V — Coarse-grained soil with little or no fines — contains less than 12 percent fines.

Type VI — Crushed rock.

² CMP wall thickness is given by gage number, e.g. 14 ga.

Table A-1.—Predicted versus actual pipe deflection — flexible pipe field data — published reports (Continued)

Test No.	Ref. No.	Test site	Pipe stiffness factor			Soil stiffness factor			Load factor		Horiz. (ΔX) deflection		Deflection range		No. of measurements	Comments	
			Pipe type	Diameter, in	Wall thickness, ² in	El/r ³ , lb/in ²	Soil type ¹	Degree of compaction	Theo. E', lb/in ²	Fill ht, ft	Fill density, lb/ft ³	Pre-dicted %	Actual %	Low %			High %
16	3	Ames, Iowa	CMP	42	14 ga.	7.0	IV	Mod.	1,000	15	121	1.9	1.8		4	Exp. No. 3, no range given	
17	3	Ames, Iowa	CMP	42	14 ga.	7.0	IV	Slight	400	15	121	4.0	3.2		3	Exp. No. 3, no range given	
18	3	Ames, Iowa	CMP	48	14 ga.	4.8	IV	Mod.	1,000	15	121	1.9	1.8		4	Exp. No. 3, no range given	
19	3	Ames, Iowa	CMP	48	14 ga.	4.8	IV	Slight	400	15	121	4.3	4.3		3	Exp. No. 3, no range given	
20	3	Ames, Iowa	CMP	60	12 ga.	3.5	IV	Mod.	1,000	15	121	2.0	1.6		4	Exp. No. 3, no range given	
21	3	Ames, Iowa	CMP	60	12 ga.	3.5	IV	Slight	400	15	121	4.5	2.9		3	Exp. No. 3, no range given	
22	3	Coal Creek Canyon, Colo.	CMP	180	1 ga.	6.8	IV	Mod.	1,000	42	≈ 120	5.2	5.3				
23	4	D&RGWRR	CMP	180	1 ga.	3.2	V	Mod.	2,000	41.5	≈ 120	2.8	3.7		1		
24	4	D&RGWRR	CMP	120	3/16		IV	Mod.	1,000	13	110	1.6	4.0	3.7	4.3	2	
25	5	Birmingham, Ala.	Ductile iron	36	0.46	29	II	Dump	50	5	94	1.0	0.6	0.5	0.8	4	
26	6	Richmond, Va.	Alum. CMP	25-54	16 ga.-12 ga.	2-12	III	High	2,000	6	130	0.4	0.3	0	0.3	7	
27	7	Gallup, N. Mex.	Steel	34	0.41	35	IV	High	2,000	6	≈ 120	0.3	0.3	0.2	0.4	2	
28	7	Gallup, N. Mex.	Steel	34	0.41	35	IV	High	2,000	8.5	≈ 120	0.4	0.4	0.4	0.4	2	
29	8	Kirtling, Gr. Brit.	Steel	72	0.5	6.7	V	Mod.	2,000	4.4	111	0.3	0.1			1	
30	9	Yuma, Ariz.	RPM	30		2	II	Dump	50	4.5	115	7.1	7.8	6.1	7.9	15	Along 180 ft
31	9	Yuma, Ariz.	RPM	30		2	II	Slight	200	4.5	115	2.5	3.5	3.0	4.2	3	
32	9	Yuma, Ariz.	RPM	30		2	II	High	1,000	4.5	115	0.6	0.1	-0.3	0.7	3	
33	9	Yuma, Ariz.	RPM	30		2	V	Dump	200	4.5	115	2.6	5.1	3.6	6.8	20	Along 240 ft
34	9	Yuma, Ariz.	RPM	30		2	V	Slight	1,000	4.5	115	0.6	0.6	0.6	0.6	3	
35	10	Marlow-Bisham Bypass, Gr. Brit.	PVC	12	0.32		V	Slight	1,000	2.5	124	0.4	0.8	0.4	1.3	3	Trench

Table A-1.—Predicted versus actual pipe deflection — flexible pipe field data — published reports (Continued)

Test No.	Ref. No.	Test site	Pipe stiffness factor			Soil stiffness factor			Load factor		Horiz. (ΔX) deflection		Deflection range		No. of measurements	Comments	
			Pipe type	Diameter, in	Wall thickness, ² in	El/r, ³ lb/in ²	Soil type ¹	Degree of compaction	Theo. E', lb/in ²	Fill ht, ft	Fill density, lb/ft ³	Pre-dicted %	Actual %	Low %			High %
36	11	St. Paul, Minn.	Steel	60	0.38	4.9	II	High	1,000	4.6-5.8	110	0.5	0.3	-0.2	1.2	3	
37	11	St. Paul, Minn.	Steel	60	0.38	4.9	V	High	3,000	6.0-7.5	110	0.2	0.1	-0.2	0.3	3	
38	11	St. Paul, Minn.	Steel	60	0.38	4.9	V	High	3,000	9.0-10.1	110	0.5	0.3	-0.2	0.7	3	
39	11	St. Paul, Minn.	Steel	60	0.50	11.6	V	High	3,000	9.0	110	0.4	0			1	
40	11	St. Paul, Minn.	Steel	60	0.38	4.9	V	High	3,000	11.7	110	0.5	0.5			1	
41	11	St. Paul, Minn.	Steel	60	0.44	7.8	V	High	3,000	13.8	110	0.6	0.5			1	
42	11	St. Paul, Minn.	Steel	60	0.44	7.8	V	High	3,000	15.3	110	0.6	0.7			1	
43	11	St. Paul, Minn.	Steel	90	0.44	2.3	II	High	1,000	5	110	0.6	0.2	0.1	0.7	8	
44	11	St. Paul, Minn.	Steel	90	0.44	2.3	V	High	3,000	6-7	110	0.3	0.2	0	0.2	4	
45	11	St. Paul, Minn.	Steel	90	0.44	2.3	V	High	3,000	9-10	110	0.4	0.4	0.4	0.4	2	
46	11	St. Paul, Minn.	Steel	90	0.44	2.3	V	High	3,000	12-16	110	0.6	0.2	0.1	0.3	3	
47	11	St. Paul, Minn.	Steel	90	0.50	3.4	V	High	3,000	40	110	1.6	1.2			1	
48	12,13	Winn Parish, La.	Steel	34	5/16	186	III	High	2,000	5.6	≈120	0.2	0.7	0	1.8	7	Along 64 ft
49	12,13	Jackson Parish, La.	Steel	34	5/16	186	III	High	2,000	5.5	≈120	0.2	-0.9	-2.2	0.8	7	Along 60 ft
50	12	San Bernardino County, Calif.	Steel	42	3/8	171	V	High	3,000	10	≈120	0.2	0.1	-0.4	1.3	23	Along 240 ft

Table A-2.— Predicted versus actual pipe deflection — flexible pipe field data — unpublished reports

Test No.	Ref. No.	Test site	Pipe stiffness factor			Soil stiffness factor			Load factor		Horiz. (ΔX) deflection		Deflection range		No. of measurements	Comments	
			Pipe type	Diameter, in	Wall thickness, in	EI/r^3 , lb/in ²	Soil type ¹	Degree of compaction	Theo. E' , lb/in ²	Fill ht, ft	Fill density, lb/ft ³	Pre-dicted %	Actual %	Low %			High %
UNPUBLISHED DATA																	
51	14	Santa Ana, Calif.	Steel	126	0.60	2.1	IV	High	2,000	10	≈120	0.7	0.6	0.5	0.7	4	USBR data, different pipe measured along unknown length
52	14	Santa Ana, Calif.	Steel	126	0.60	2.1	IV	Mod.	1,000	10	≈120	1.3	1.6	0.9	2.4	6	USBR data, different pipe measured along unknown length
53	15	San Diego, Calif.	RPM	24		7	IV	Slight	400	19	≈120	5.0	3.1	0	6.5	23	w/30% rock along 230 ft
54	15	San Diego, Calif.	RPM	24		7	IV	High	2,000	18	≈120	1.2	1.1	0.3	2.8	13	Along 130 ft
55	15	San Diego, Calif.	RPM	24		3 & 7	IV	High	2,000	17.5	≈120	1.1	0.3	-0.7	1.5	34	Along 340 ft
56	15	San Diego, Calif.	RPM	24		3 & 7	VI	Com-pacted	3,000	17	≈120	0.7	-0.2	-0.5	0.1	10	Along 100 ft
57	15	San Diego, Calif.	RPM	24		3 & 7	VI	Com-pacted	3,000	17	≈120	0.7	-0.3	-0.7	0.3	12	Along 120 ft
58	15	San Diego, Calif.	RPM	24		3 & 7	IV	High	2,000	16	≈120	1.0	0.2	-1.5	1.6	88	Along 880 ft
59	15	San Diego, Calif.	RPM	24		3	VI	Com-pacted	3,000	15	≈120	0.7	0.7	-0.4	2.8	90	Along 900 ft
60	15	San Diego, Calif.	RPM	24		3	VI	Com-pacted	3,000	14	≈120	0.6	0.4	-0.5	1.2	29	Along 290 ft
61	15	San Diego, Calif.	RPM	24		3	VI	Com-pacted	3,000	13	≈120	0.6	0.7	-0.5	1.6	25	Along 250 ft

¹ Type I — Fine-grained soil ($LL > 50$) — soil with medium to high plasticity.
 Type II — Fine-grained soil ($LL < 50$) — soil with medium to no plasticity with less than 25 percent coarse-grained particles.
 Type III — Fine-grained soil ($LL < 50$) — soil with medium to no plasticity with more than 25 percent coarse-grained particles.
 Type IV — Coarse-grained soil with fines — contains more than 12 percent fines.
 Type V — Coarse-grained soil with little or no fines — contains less than 12 percent fines.
 Type VI — Crushed rock.

Table A-2.— Predicted versus actual pipe deflection — flexible pipe field data — unpublished reports (Continued)

Test No.	Ref. No.	Test site	Pipe stiffness factor			Soil stiffness factor			Load factor		Horiz. (ΔX) deflection		Deflection range		No. of measurements	Comments	
			Pipe type	Diameter, in	Wall thickness, in	EI/r^3 lb/in ²	Soil type ¹	Degree of compaction	Theo. E' , lb/in ²	Fill ht, ft	Fill density, lb/ft ³	Pre-dicted %	Actual %	Low %			High %
62	16	Sunnyvale, Calif.	RPM	24		3.8	III	Mod.	1,000	8	105	0.9	0.6	0.5	0.7	2	
63	16	Sunnyvale, Calif.	RPM	24		2.6	III	Mod.	1,000	8	102	0.9	0.7	0.4	1.1	2	
64	16	Sunnyvale, Calif.	RPM	24		3.8	II	Slight	200	8	110	3.8	2.5	1.6	3.4	2	
65	16	Sunnyvale, Calif.	RPM	24		2.6	II	Slight	200	3	106	4.0	3.2			1	
66	16	Sunnyvale, Calif.	RPM	24		3.8	III	High	2,000	18	103	1.0	0.3	0	0.5	2	
67	16	Sunnyvale, Calif.	RPM	24		2.6	III	High	2,000	18	102	1.0	0.7	0.6	0.7	2	
68	16	Sunnyvale, Calif.	RPM	24		2.6	II	Slight	200	18	101	8.5	7.0	5.8	8.2	2	
69	16	Sunnyvale, Calif.	RPM	24		3.8	II	Slight	200	18	103	8.0	7.6	7.5	7.6	2	
70	17	Sidney, Mont.	RPM	39		1.6	V	Slight	1,000	4	122	0.8	0.7	-0.4	2.4	14	Along 1,100 ft, USBR Data
71	18	Denver, Colo.	RPM	48	0.5	2.0	IV	High	2,000	15	120	1.0	1.1			2	USBR Data
72	18	Denver, Colo.	RPM	48	0.5	2.0	V	High	3,000	15	120	0.7	0.8			2	USBR Data
73	18	Denver, Colo.	Steel	48	0.19	1.2	IV	High	2,000	15	120	1.0	1.1			2	USBR Data
74	18	Denver, Colo.	Steel	48	0.19	1.2	V	High	3,000	15	120	0.7	0.7			2	USBR Data
75	18	Denver, Colo.	PT	48	2.0	5.7	IV	High	2,000	15	120	1.0	1.1			2	USBR Data
76	18	Denver, Colo.	PT	48	2.0	5.7	V	High	3,000	15	120	0.7	0.6			2	USBR Data
77	19	Logan, Utah	Steel	24	0.20	13	II	Dump	50	11	83	4.0	4.3			1	
78	19	Logan, Utah	Steel	24	0.20	13	II	Slight	200	11	83	2.5	1.6	0.4	2.3	3	
79	19	Logan, Utah	Steel	24	0.20	13	IV	Dump	100	11	83	3.3	2.3	2.2	2.4	3	
80	19	Logan, Utah	Steel	24	0.20	13	IV	Mod.	1,000	11	83	0.9	0.3	0.1	0.6	3	
81	19	Logan, Utah	Steel	24	0.20	13	IV	High	2,000	11	83	0.3	0.1			1	
82	19	Logan, Utah	Steel	16	0.11	21	IV	Dump	100	11	83	2.3	1.8	1.6	1.9	2	
83	19	Logan, Utah	Steel	16	0.11	21	IV	Mod.	1,000	11	83	0.8	0.6			1	
84	19	Logan, Utah	Steel	30	0.21	7	IV	Dump	100	11	83	4.8	2.9			1	
85	19	Logan, Utah	Steel	30	0.21	7	IV	Slight	400	11	83	2.0	2.2	1.6	2.8	2	
86	19	Logan, Utah	Steel	36	0.27	11	IV	Dump	100	11	83	3.7	3.8			1	
87	19	Logan, Utah	Steel	36	0.27	11	IV	Slight	400	11	83	1.8	2.2	1.3	3.0	2	
88	19	Logan, Utah	Steel	24	0.27	13	IV	Dump	100	8	83	2.4	1.8	1.7	1.9	3	Trench
89	20	Grande Prairie, Alberta, Can.	FRP	42	Ribbed	20	VI	Com-pacted	3,000	6.0	125	0.3	-0.3			1	

Table A-2.— Predicted versus actual pipe deflection — flexible pipe field data — unpublished reports (Continued)

Test No.	Ref. No.	Test site	Pipe stiffness factor			Soil stiffness factor			Load factor		Horiz. (ΔX) deflection		Deflection range		No. of measurements	Comments	
			Pipe type	Diameter, in	Wall thickness, in	EI/r^3 , lb/in ²	Soil type ¹	Degree of compaction	Theo. E' , lb/in ²	Fill ht, ft	Fill density, lb/ft ³	Pre-dicted %	Actual %	Low %			High %
90	20	Grande Prairie, Alberta, Can.	FRP	42	Ribbed	20	VI	Dump	1,000	6.0		0.6	0.4			1	
91	21,22	Carrington, N. Dak.	PVC	12	0.12	0.3	II	Dump	50	3.0	55	3.4	2.1	1.8	2.5	3	Their test No. 1
92	21,22	Carrington, N. Dak.	PVC	12	0.12	0.3	II	Dump	50	2.5	75	3.9	7.6	5.3	9.4	2	Their test No. 2
93	21,22	Carrington, N. Dak.	PVC	12	0.12	0.3	II	Dump	50	2.5	79	4.1	4.0	3.0	4.9	3	Their test No. 3
94	21,22	Carrington, N. Dak.	PVC	12	0.12	0.3	II	Dump	50	2.0	78	3.2	2.9	2.5	3.2	3	Their test No. 5
95	21,22	Carrington, N. Dak.	PVC	12	0.12	0.3	II	Slight	200	3.0	80	1.3	1.7	1.3	2.1	3	Their test No. 4
96	21,22	Carrington, N. Dak.	PVC	12	0.12	0.3	II	High	1,000	2.0	50	0.1	0.3	0.1	0.5	3	Their test No. 6
97	21,22	Carrington, N. Dak.	PVC	12	0.12	0.3	II	Dump	50	2.0	50	2.1	2.9	2.6	3.7	3	Their test No. 7
98	23	New Jersey	RPM	24		2.1	III	Mod.	1,000	10	89	1.0	0.9	0.4	1.5	3	Sec. I, pipe 1, 6-ft-wide trench
99	23	New Jersey	RPM	24		2.1	V	Mod.	2,000	10	89	0.5	0.3	0.2	0.3	3	Sec. I, pipe 2, 6-ft-wide trench
100	23	New Jersey	RPM	24		2.1	V	Mod.	2,000	10	89	0.5	-0.6	-0.7	-0.4	3	Sec. I, pipe 3, 6-ft-wide trench
101	23	New Jersey	RPM	24		2.1	V	Mod.	2,000	10	89	0.5	0.7	0.5	1.0	3	Sec. I, pipe 4, 6-ft-wide trench
102	23	New Jersey	RPM	24		2.1	V	Mod.	2,000	10	89	0.5	0.5	0.4	0.6	3	Sec. I, pipe 5, 4-ft-wide trench
103	23	New Jersey	RPM	24		2.1	V	High	3,000	10	89	0.3	-0.1	-0.3	0.1	3	Sec. I, pipe 6, 4-ft-wide trench
104	23	New Jersey	RPM	24		2.1	V	Mod.	2,000	10	89	0.5	0.2	0.1	0.3	3	Sec. I, pipe 7, 4-ft-wide trench

Table A-2.— Predicted versus actual pipe deflection — flexible pipe field data — unpublished reports (Continued)

Test No.	Ref. No.	Test site	Pipe stiffness factor			Soil stiffness factor			Load factor		Horiz. (ΔX) deflection		Deflection range		No. of measurements	Comments	
			Pipe type	Diameter, in	Wall thickness, in	EI/r^3 , lb/in ²	Soil type ¹	Degree of compaction	Theo. E' , lb/in ²	Fill ht, ft	Fill density, lb/ft ³	Pre-dicted %	Actual %	Low %			High %
105	23	New Jersey	RPM	24		2.1	III	Slight	400	10	89	2.3	2.8	1.4	3.6	3	Sec. I, pipe 8, 4-ft-wide trench
106	23	New Jersey	RPM	24		2.1	III	Mod.	1,000	15	89	1.5	3.6	2.3	4.5	3	Sec. II, pipe 1, 4-ft-wide trench
107	23	New Jersey	RPM	24		2.1	V	Slight	1,000	15	89	1.5	1.0	0.4	1.5	3	Sec. II, pipe 2, 4-ft-wide trench
108	23	New Jersey	RPM	24		2.1	V	Mod.	2,000	15	89	0.7	0.3	-0.2	0.9	3	Sec. II, pipe 3, 4-ft-wide trench
109	23	New Jersey	RPM	24		2.1	V	Mod.	2,000	15	89	0.7	0.9	0.8	1.0	3	Sec. II, pipe 4, 4-ft-wide trench
110	23	New Jersey	RPM	24		2.1	V	Mod.	2,000	15	89	0.7	0.2	1.0	1.4	3	Sec. II, pipe 5, 6-ft-wide trench
111	23	New Jersey	RPM	24		2.1	V	Mod.	2,000	15	89	0.7	0.8	0.6	1.2	3	Sec. II, pipe 6, 6-ft-wide trench
112	23	New Jersey	RPM	24		2.1	V	Slight	1,000	15	89	1.5	3.9	3.1	4.5	3	Sec. II, pipe 7, 6-ft-wide trench
113	23	New Jersey	RPM	24		2.1	III	Dump	100	15	89	11.3	2.9	2.5	3.3	3	Sec. II, pipe 8, 6-ft-wide trench

BIBLIOGRAPHY — APPENDIX A

Published

- [1] American Railway Engineering Association Committee, "Corrugated Metal Culverts for Railroad Purposes," Proceedings, American Railway Engineering Association, vol. 27, p. 794, 1926.
- [2] Braune, G. M., Cain, W., and Janda, H. F., "Earth Pressure Experiments on Culvert Pipe," Public Roads, vol. 10, No. 9, November 1929.
- [3] Spangler, M. G., "The Structural Design of Flexible Pipe Culverts," Bulletin No. 153, Iowa State Engineering Experiment Station, 1941.
- [4] Peck, O. K., and Peck, R. B., "Experience with Flexible Culverts through Railroad Embankments," Proceedings, Second International Conference on Soil Mechanics and Foundation Engineering, vol. II, Rotterdam, 1948.
- [5] Sears, E. C., "Engineering Properties and Design of Ductile-Iron Pipe in Underground Pressure Service," ASME Journal, 1963.
- [6] Valentine, H. E., "Structural Performance and Load Reaction Patterns of Flexible Aluminum Culvert," Highway Research Record No. 56, p. 47, 1964.
- [7] Research Council on Pipeline Crossings of Railroads and Highways, "Performance of Casing Pipe Under Railroads and Highways," Journal of the Pipeline Division, ASCE, vol. 91, July 1965.
- [8] Trott, J. J., and Gaunt, J., "Experimental Work on Large Steel Pipeline at Kirtling," TRRL Report LR 472, Transport and Road Research Laboratory, 1972.
- [9] Howard, A. K., and Metzger, H. G., "RPM Pipe Deflections on Yuma Project Field Test," Report No. REC-ERC-73-7, Bureau of Reclamation, Denver, Colorado, April 1973.
- [10] Trott, J. J., and Gaunt, J., "A Study of an Experimental PVC Pipeline Laid Beneath a Major Road, During and After Construction," Third International Plastics Pipes Symposium, 1974.
- [11] Proudfit, D. P., "Performance of Large-Diameter Steel Pipe at St. Paul," AWWA Journal, March 1963.
- [12] Research Council on Pipeline Crossings of Railroads and Highways, "Performance of Casing Pipe under Railroads and Highways," Journal of the Pipeline Division, ASCE, vol. 91, No. PL1, July 1965.
- [13] Spangler, M. G., "Pipeline Crossings under Railroads and Highways," AWWA Journal, vol. 56, No. 8, August 1964.

BIBLIOGRAPHY — APPENDIX A

Unpublished

- [14] Bureau of Reclamation, "Deflections of Welded Steel Pipe, Santa Ana River Siphon, Metropolitan Water District," Internal Memorandum, Denver, Colorado, January 1936.
- [15] Glascock, B. C., "Barnett Avenue Sewer, Performance Analysis of an RPM Pipe Installation," Engineering Report No. 3a01016, United Technology Center, Sunnyvale, California, October 12, 1970.
- [16] Glascock, B. C., "Three Year Data, Techite In-Ground Test Program at Sunnyvale," Engineering Report No. 3a-01015, United Technology Center, Sunnyvale, California, October 12, 1970.
- [17] Howard, A. K., "Deflection of 39-inch-inside-diameter RPM Pipe — Lateral E — Lower Yellowstone Irrigation District, Sidney, Montana," Earth Sciences Reference 74-41-2, Internal Memorandum, Bureau of Reclamation, Denver, Colorado, June 1974.
- [18] Richmond, R. D., "OCCS Flexible Pipe Installation, Denver Federal Center," Report in preparation, Bureau of Reclamation, Denver, Colorado.
- [19] Watkins, R. K., and Loosle, D., "Deflection of Cement — Mortar Lined Spiral — Welded Steel Pipe Embedded in Soil," Report submitted to Armco Steel Corporation, Middletown, Ohio, April 1965.
- [20] The Proctor and Gamble Company, private correspondence, 1973, 1975.
- [21] Olson, H. M., Busch, L. A., and Miller, E. R., "Performance of Irrigation Pipelines Buried Within the Frost Zone," Paper presented at 1974 Winter Meeting, American Society of Agricultural Engineers, December 1974.

BIBLIOGRAPHY – Continued

Unpublished

- [22] North Dakota State University, "Report on Buried Irrigation Pipe at the Carrington Irrigation Station," Private Report to the Bureau of Reclamation, Contract No. 14-06-600-9990, May 31, 1970.
- [23] Private Corporation (name withheld by request), private correspondence, 1972, 1975.



APPENDIX B

DESCRIPTIONS OF DEFLECTION SURVEY TESTS

The field tests summarized in tables A-1 and A-2 are described in more detail in this appendix. Some of the information is quoted from the original reports. Reference numbers refer to the bibliography at the end of appendix A.

Much of the data on type of soil and degree of compaction were incomplete and the assignment of categories were at the discretion of the author after consultation with engineers familiar with soil classification and construction of pipe beddings.



- **Test No. 1-5** **Reference No. 1**
American Railway Engineering Association Committee, "Corrugated Metal Culverts for Railroad Purposes," Proc. American Railway Engineering Association, vol. 27, p. 794, 1926.
FARINA, ILLINOIS

Pipe stiffness factor — Eight pipes were buried in a special installation under a railroad embankment near Farina, Illinois. The deflection data were reported for the following five pipes:

Line No.	Diameter and description	Height of fill, ft	E , lb/in ²	Wall thickness, in	I , in ⁴ /in	EI/r^3 , lb/in ²
4	24" 14 ga. corrugated	33.1	30(10) ⁶		0.0023	37.5
5	42" 12 ga. corrugated	33.5	30(10) ⁶		.0033	10.3
6	42" extra heavy cast iron	34.2	10(10) ⁶	1.25	---	160.9
7	42" 12 ga. corrugated	34.9	30(10) ⁶		.0033	10.3
8	48" 10 ga. corrugated (second sheets)	34.6	30(10) ⁶		.0044	9.3

¹ Assume 2-2/3 by 1/2 corrugations.

Soil stiffness factor — Soil type: "The material for approximately the first 8 feet of filling consisted of a very loose-grained top soil."

Assume FINE-GRAINED SOIL (LL < 50)

Degree of compaction: "The embankment material was tamped (by hand) to three-fourths the height of the pipes and at least 14 inches out from the sides." "It was not possible to tamp this material very much as it was very fine and dry at the time of placing."

SLIGHT

E' from table 1 = 400 lb/in².

Load factor — Fill height = 28 to 35 feet. Fill density = 105 lb/ft³. The first 8 feet weighed 85 lb/ft³ and the remainder about 112 lb/ft³.

Actual deflection — See table A-1. The vertical readings were reported. There are slight discrepancies between deflections shown on graphs and those mentioned in text. Deflection readings were immediate. Rainfall during embankment construction increased deflections 0.5 percent for two pipe.

Deflection lag — No time-deflection data presented.

Comments — The culverts were placed at projection ratios from 0.65 to 0.8. Load-deflection curves during embankment construction presented in original report.

Immediate deflections measured.

Embankment condition.

- **Test No. 6-11** **Reference No. 2**
Braune, G. M., Cain, W., and Janda, H. F., "Earth Pressure Experiments on Culvert Pipe," Public Roads, vol. 10, no. 9, p. 153, November 1929.
CHAPEL HILL, NORTH CAROLINA

Pipe stiffness factor — Nine pipe were tested in a special embankment installation. Six of the pipe were flexible, described as follows:

¹ Test No.	Diameter and description	E , lb/in ²	Wall thickness, in	I , in ⁴ /in	EI/r^3 , lb/in ²
1	30-inch smooth iron	27(10) ⁶	0.109		0.9
2	30-inch (12 ga.) corrugated metal	30(10) ⁶	0.105	0.0035	27.1
3	30-inch steel tube	30(10) ⁶	0.349		32.6
4	30-inch cast iron	10(10) ⁶	1.00		229.3
7	20-inch smooth iron	27(10) ⁶	0.076		1.0
8	20-inch (14 ga.) corrugated metal	30(10) ⁶	0.079	0.0025	65.5

¹ Assume 2-2/3 by 1/2 corrugations.

Soil stiffness factor — Soil type: Well-graded sand with 1 percent fines. (SW). Gradation was reported.
COARSE-GRAINED SOIL WITH LITTLE OR NO FINES

Degree of compaction: "The fill . . . was placed with drag pans. The teams moved in a direction parallel to the pipe until the 1-foot level (over the pipe) was reached. Up to this level the sand was thrown around and over the pipe by hand and lightly tamped with shovel handles."

SLIGHT

E' from table 1 = 1,000 lb/in².

Load factor — Fill height = 12 feet. Fill density = 107 lb/ft³. Backfill density and moisture tests made about every foot. Densities varied from 99 lb/ft³ to 114 lb/ft³ and moisture from 3.9 percent to 14.6 percent.

Actual deflection — See table A-1. Immediate ΔX values were reported. High quality data taken.

Deflection lag — None reported.

Comments — All pipe placed in 100 percent projection condition. Pipes were laid on weighing platforms. Load-deflection data and curves during embankment construction included.

Immediate deflections measured.

Embankment condition.

Load-deflection curves presented by Spangler, M.G., "Stresses and Deflections in Flexible Pipe Culverts," Highway Research Board Proceedings, 28th Annual Meeting, vol. 28, p. 249, 1948.

* * * * *

- **Test No. 12** **Reference No. 3**
Spangler, M. G., "The Structural Design of Flexible Pipe Culverts," Bulletin No. 153, Iowa State Engineering Experiment Station, 1941.
AMES, IOWA

See also: Spangler, M. G., "Long-time Measurements of Loads on Three Pipe Culverts," Paper, Highway Research Board Annual Meeting, 1973.

Pipe stiffness factor —

Pipe type:	CMP (2-2/3 by 1/2)
Diameter =	42-in
Wall thickness =	8 gage
$I =$	0.0055 in ⁴ /in
$EI/r^3 =$	16.6 lb/in ²

Soil stiffness factor — Soil type: "The embankment material was a sandy loam top soil with considerable gravel and some light clay intermixed. It was composed of the stripping from several gravel pits . . . and had been moved and removed 2 or 3 times." A sandy loam in the PRA classification system is a SM or SC material in the Unified Classification system.

COARSE-GRAINED SOIL WITH FINES

Degree of compaction: "The embankment was constructed by teams and wheeled scrapers and was not formally compacted except by the team and scraper traffic." The density measured 13 years later was 88 percent of Proctor.

SLIGHT (considering the consolidation over 13 years)

E' from table 1 = 400 lb/in².

Load factor — Fill height = 15 feet. Fill density = 120 lb/ft³ (Measured by sinking two shafts down through the embankment).

Actual deflection — ΔX for the four pipe ranged from 3.1 to 3.5 percent with an average of 3.2 percent.

Deflection lag — After 14 years the horizontal deflection was 6.2 percent. $D_1 = 6.2/3.2 = 1.9$.

Comments — Experiment No. 1. Four independent 4-foot sections were placed on weighing platforms and an embankment constructed over them. Pressures were measured with friction ribbons. Load-deflection values given for construction period and 14 years afterward.

Immediate deflections measured.

Embankment condition.

* * * * *

- **Test No. 13** **Reference No. 3**
Spangler, M. G., "The Structural Design of Flexible Pipe Culverts," Bulletin 153, Iowa State Engineering Experiment Station, 1941.
AMES, IOWA

Pipe stiffness factor —

Pipe type:	CMP (2-2/3 by 1/2)
Diameter =	42 in
Wall thickness =	10 gage
$I =$	0.0044 in ⁴ /in
$EI/r^3 =$	13.2 lb/in ²

Soil stiffness factor — Soil type: Pit-run gravel, maximum size 1-1/2 inch

COARSE-GRAINED SOIL WITH FINES

Degree of compaction: "It was placed around and over the culvert by teams and drag scrapers and no effort was made to compact the material by means

other than the traffic of the teams during construction." Estimated by Spangler at 93 percent Proctor.
MODERATE

E' from table 1 = 1000 lb/in².

Load factor — Fill height = 16 feet. Fill density = 130 lb/ft³. Measured by sinking two shafts through the embankment.

Actual deflection — ΔX for the four pipe ranged from 1.5 to 2.1 percent with an average of 1.8 percent.

Deflection lag — After 1 year the average ΔX was 3.1 percent, $D_1 = 3.1/1.8 = 1.7$.

Comments — Experiment No. 2. Four independent 4-foot-long sections were placed on weighing platforms and an embankment constructed over them. Pressures on the pipe were measured with friction ribbons. Load-deflection data given for construction period and 1 year afterwards.

Immediate deflections measured.

Embankment condition.

* * * * *

- **Test No. 14-21** **Reference No. 3**
 Spangler, M. G., "The Structural Design of Flexible Pipe Culverts," Bulletin No. 153, Iowa State Engineering Experiment Station, 1941.
 AMES, IOWA

Pipe stiffness factor —

Diameter and wall thickness =
 36 in 16 gage, 42 in 14 gage,
 48 in 14 gage, 60 in 12 gage
 $EI/r^3 =$ 8.8, 7.0, 4.8, 3.5 lb/in²

Soil stiffness factor — Soil type: Sandy clay loam, a "sandy clay loam" in the PRA classification system is equivalent to a SC in the Unified Classification System.

COARSE-GRAINED SOIL WITH FINES

Degree of compaction: "The fill on each side of the south half of the test sections in each culvert was hand-tamped in about 6-inch layers for a distance out from the sides equal to the diameter of the pipe, and for a depth equal to three fourths of the distance which the pipe projected above the sub-grade. The fill at the sides of the north half of the

test sections and at all other places outside this tamped zone was simply dumped from the scrapers and shovel-placed."

Average density for tamped and untamped soil was 90 percent, 4 years later.

MODERATE AND SLIGHT

E' from table 1 = 1,000 lb/in² and 400 lb/in².

Load factor — Fill height = 15 feet. Fill density = 120 lb/ft³.

Actual deflection — See table 1. Average deflection of four pipe for the tamped and three for the untamped reported with no range of deflections given.

Deflection lag — The average ΔX values 4 years later were:

Pipe	Compaction	Initial $\Delta X - \%$	4-year $\Delta X - \%$	D_1
36-16	tamped	1.8	2.7	1.5
	untamped	3.5	4.6	1.3
42-14	tamped	1.8	2.7	1.5
	untamped	3.2	4.7	1.5
48-14	tamped	1.8	2.5	1.4
	untamped	3.3	4.4	1.3
60-12	tamped	1.6	2.4	1.5
	untamped	2.9	4.3	1.5

Comments — Experiment No. 3. Pipe bedded in sand for a bedding angle of 90°. Projection ratio = 0.85.

Immediate deflections measured.

Embankment condition.

* * * * *

- **Test No. 22** **Reference No. 3**
 Spangler, M. G., "The Structural Design of Flexible Pipe Culverts," Iowa Engineering Experiment Station Bulletin 153, Ames, Iowa, 1941.
 COAL CREEK CANYON, COLORADO

Pipe stiffness factor —

Pipe type: 6 by 2 corrugated steel
 Diameter = 15 ft
 Wall thickness = 1 gage (9/32 in) 0.2813 in
 $I =$ 0.166 in⁴/in
 $EI/r^3 =$ 6.8 lb/in²

Soil stiffness factor — Soil type: "granular plastic"
 Assume COARSE-GRAINED SOIL WITH FINES

Degree of compaction: "The backfill around the culvert was shoved into place in 1-foot layers by a bulldozer, and each layer was compacted by repeated trips back and forth by the tractor." Compaction of 6-12 inch soil layers by equipment travel usually results in densities about 85-95 percent of Proctor maximum.

MODERATE

E' from table 1 = 1000 lb/in².

Load factor — Fill height = 42 feet. Fill density = "Fill was placed by dumping from railroad cars on the trestle" \approx 120 lb/ft³.

Actual deflection — With struts, 2 months after construction, $\Delta X = \Delta Y = 0$ percent. 3 months after struts removed, $\Delta x = 5.3$ percent, $\Delta Y = 3.7$ percent.

Deflection lag — After 2 years, $\Delta X = 6.2$ percent, $\Delta Y = 4.5$ percent, horizontal $D_1 = 6.2/5.3 = 1.2$, vertical $D_1 = 4.5/3.7 = 1.2$.

Comments — Pipe was initially vertically elongated 6 in. (3.3 percent) with vertical struts. Struts removed 2 months after construction. A cradle for the "lower quadrant of the culvert" was trimmed into in-place material.

Embankment condition.

* * * * *

- **Test No. 23** **Reference No. 4**
Peck, O. K., and Peck, R. B., "Experience with Flexible Culverts through Railroad Embankments," Proc. Second International Conference on Soil Mechanics and Foundation Engineering, vol. II, p. 95, Rotterdam, 1948.
D&RGW RR

Pipe stiffness factor —

Pipe type: 6 by 1½ corrugated steel or iron
Diameter = 15 ft
Wall thickness = 0.2813 in (1 gage)
 $I = 0.080$ in⁴/in
 $EI/r^3 = 3.2$ lb/in²

Soil stiffness factor — Soil type: "On either side of the remainder of the culvert a fill consisting of disintegrated (*granite*) was pushed against the pipe in 6-inch to 12-inch layers and compacted by means of

a 20-ton bulldozer." "All the backfill material was granular in nature."

COARSE-GRAINED SOIL WITH LITTLE OR NO FINES

Degree of compaction: Compaction of a 6-12 in. soil layers by equipment travel usually results in densities about 85-95 percent of Proctor maximum.

MODERATE

E' from table 1 = 2000 lb/in².

Load factor — Fill height = 41.5 feet. Fill density = "Above the top of the pipe, the fill was placed by dumping from a trestle" \approx 120 lb/ft³.

Actual deflection — With struts in place, pipe had deflected 0.5 percent after 2 months. After the struts were removed, the pipe deflected an additional 3.6 percent vertically over 3 months.

$\Delta X = 0.913$ ($\Delta Y = 0.913$ (3.6) = 3.3 percent

Deflection lag — 3 months after struts removed, $\Delta Y = 4.1$ percent. After 2 years, deflection leveled off at 4.8 percent. $D_1 = 4.8/4.1 = 1.2$.

Comments — Structure A in paper. Pipe was initially vertically elongated 3 inches by vertical struts. Struts removed 2 months after construction. Cradle for bottom of 90° of pipe trimmed out of in-place foundation material.

* * * * *

- **Test No. 24** **Reference No. 4**
Peck, O. K., and Peck, R. B., "Experience with Flexible Culverts through Railroad Embankments," Proc. Second International Conference on Soil Mechanics and Foundation Engineering, vol. II, p. 95, Rotterdam, 1948.
D&RGW RR

Pipe stiffness factor —

Pipe type: 6 by 1½ corrugated steel or iron
Diameter = 10 ft
Wall thickness = 0.1875 in
 $I = 0.050$ in⁴/in
 $EI/r^3 = 3.0$ lb/in²

Soil stiffness factor — Soil type: "The backfill consisted of a residual silty sand derived from shale and contained numerous rather large fragments of unweathered shale. The effective size was about

0.25 mm and the uniformity coefficient 20. The liquid limit of the material passing a No. 28 sieve was 44.1 percent and the plastic limit 26.8 percent. Binder is ML.

COARSE-GRAINED SOIL WITH FINES

Degree of compaction: Material immediately against pipe hand-tamped. Rest of material beside pipe placed in "1-foot layers rolled parallel to pipe by 17-ton caterpillar tractor."

MODERATE

E' from table 1 = 1 000 lb/in²

Load factor -- Fill height = 13 feet. Fill density = "1-foot layers placed under grading specifications. After placement of 5 feet of cover, 15-ton scraper routed over fill" \approx 110 lb/ft³.

Actual deflection -- With struts, after 1 month, ΔY = 3 percent, after 2 months 3.6 and 4.1 percent; after struts removed, immediate ΔY was an additional 0.5 and 0.6 percent (two locations).

Deflection lag -- Average ΔY right after struts removed = 4.4 percent. After 5 years, deflection leveled off at average ΔY = 9.7 percent. D_1 = 9.7/4.4 = 2.2.

Comments -- Structure B in paper. Pipe was initially elongated vertically 3 percent by vertical struts. Struts removed after about 2 months after construction. Pipe rested on a 18-in. gravel bed over 4 feet of an "organic sandy clay." Center of section settled about 3 inches.

* * * * *

● Test No. 25 **Reference No. 5**

Sears, E. C., "Engineering Properties and Design of Ductile-Iron Pipe in Underground Pressure Service," ASME Journal, 1963; plus private correspondence.

BIRMINGHAM, ALABAMA

Pipe stiffness factor --

Pipe type: Ductile iron ($E = 23.5 (10)^6$ lb/in²)

Diameter = O. D. = 38.3 in

Wall thickness = 0.46 in

$EI/r^3 = 29$ lb/in²

Soil stiffness factor -- Soil type: Sandy clay (CL)

Gradation: 1 percent retained on No. 4

79 percent passing No. 200

Consistency limits: LL = 39, PI = 17

FINE-GRAINED SOIL (LL < 50)

Degree of compaction: In-place density = 79 lb/ft³, moisture = 19 percent. Material was dumped in-place and not tamped. Measured densities averaged about 70 percent Proctor maximum dry density.

DUMPED

E' from table 1 = 50 lb/in²

Load factor -- Fill height = 5 feet. Fill density = 94 lb/ft³.

Actual deflection -- The deflections in the center of 8 pipe were measured. ΔX for 5 feet of cover ranged from 0.5 to 0.8 with an average of 0.6 percent. After a heavy rain, ΔX increased an additional 0.7 percent. Another 3 feet of cover increased the ΔX by 0.5 percent for a total deflection of 1.8 percent.

Deflection lag -- No data.

Comments -- Line was pressurized after backfilling. High quality data were taken during construction. SR-4 strain readings and soil pressures also measured.

* * * * *

● Test No. 26 **Reference No. 6**

Valentine, H. E., "Structural Performance and Load Reaction Patterns of Flexible Aluminum Culvert," Highway Research Record No. 56, p. 47, 1964; plus private correspondence.

RICHMOND, VIRGINIA

Pipe stiffness factor --

Pipe type: Aluminum CMP (2-2/3 by 1/2)

Diameter and wall thickness =

24 in 16 gage, 36 in 14 gage,

54 in 12 gage

$EI/r^3 = 11.6, 4.3, \text{ and } 1.8$ lb/in²

Soil stiffness factor -- Soil type: "Brown sandy silt" "silty loam"

Gradation: 45 percent sand, 55 percent fines

Consistency tests: LL = 26, PI = 2

Sandy silt (ML)

FINE-GRAINED SOIL (LL < 50) WITH MORE THAN 25 PERCENT COARSE-GRAINED PARTICLES

Degree of compaction: Tamped in 6- to 9-inch layers, densities ranged from 91.4 to 106 percent Proctor based on AASHTO T-99-57 Method A with an average of 98 percent

NOTE

E' from table 1 = 2,000 lb/in².

Load factor — Fill height = 6 feet. Fill density = 130 lb/ft³; measured.

Actual deflection — Data erratic with no deflection pattern apparent for either differences in pipe stiffness or backfill load increases. Minimum deflection was 0.01 percent and maximum was 0.3 percent. Maximum deflection was used (0.3 percent) for actual deflection.

Deflection lag — No data.

Comments — Seven different pipe were tested, 3 of which were vertically elongated 5 percent. Each pipe was bedded on 6 inches of sand. Dynamic loading tests were also conducted.

* * * * *

- **Test No. 27-28** **Reference No. 7**
Research Council on Pipeline Crossings of Railroads and Highways, "Performance of Casing Pipes Under Railroads and Highways," Journal of the Pipeline Division, ASCE, vol. 91, July 1965.
GALLUP, NEW MEXICO

Pipe stiffness factor —

Pipe type: Steel
Diameter = 34 in
Wall thickness = 13/32 in
 $EI/r^3 = 35.4 \text{ lb/in}^2$

Soil stiffness factor — Soil type: Silty sand (SM)
Gradation: 33 percent passing No. 200
Consistency limits: LL = 19, PI = 3

COARSE-GRAINED SOIL WITH FINES

Degree of compaction: Assumed to be a high degree of compaction since it was a casing pipe under an embankment.

HIGH

E' from table 1 = 2,000 lb/in².

Load factor — Fill height = 6 feet and 8.5 feet. Fill density = Assumed to be 120 lb/ft³.

Actual deflection — Two locations (0+40, 0+50) were measured in test No. 27 and ΔX varied from 0.2 percent to 0.4 percent with an average of 0.3 percent immediately after backfilling. Two locations (1+00, 1+10) were measured on test No. 28 with a resulting $\Delta X = 0.4$ percent for both.

Deflection lag — Horizontal deflections measured after 4 years were 0.6 percent for test 27 and 28. $D_1 = 0.6/0.3 = 2$ (No. 27) and $0.6/0.4 = 1.5$ (No. 28).

Comments — The pipe was installed in three sections with the center section bored under a railroad embankment. Sections on either end were installed in open cuts and these were the pipe used in this analysis.

* * * * *

- **Test No. 29** **Reference No. 8**
Trott, J. J., and Gaunt, J., "Experimental Work on Large Steel Pipeline at Kirtling," TRRL Report LR 472, Transport and Road Research Laboratory, 1972.
KIRTLING, GREAT BRITAIN

Pipe stiffness factor —

Pipe type: Steel
Diameter = 72 in
Wall thickness = 0.5 in
 $EI/r^3 = 6.7 \text{ lb/in}^2$

Soil stiffness factor — Soil type: Sand with few fines, "uniformly graded fine sand."

COARSE-GRAINED SOIL WITH LITTLE OR NO FINES

Degree of compaction: "A small vibrating tamper was used to compact the sand around the sides of the pipe" in 10-inch layers. Measured densities were 93-95 percent of Proctor at 4 percent over optimum.
MODERATE

E' from table 1 = 2,000 lb/in².

Load factor — Fill height = 4.4 feet. Fill density = 111 lb/ft³.

Actual deflection — Readings were rather erratic, but for the backfill load, the deflection was about 0.1 percent or less. A static surcharge of 6 lb/in² over the pipe increased the deflection to about 0.2 percent. Static and dynamic vehicle loading tests made only slight differences in the deflections.

Comments — Pipe was laid in a 9-foot-wide trench on a shaped sand bed for a bedding angle of 30°. Compaction of the bedding on the sides of the pipe resulted in a vertical elongation of 0.2 percent.

* * * * *

- **Test No. 30-34** **Reference No. 9**
Howard, A. K., and Metzger, H. G., "RPM Pipe Deflections on Yuma Project Field Test," Report No. REC-ERC-73-7, Bureau of Reclamation, Denver, Colorado, April 1973.
YUMA, ARIZONA

Pipe stiffness factor –

Pipe type: RPM (reinforced plastic mortar)
Diameter = 30 in
 $EI/r^3 = 2 \text{ lb/in}^2$ (reported by manufacturer)

Soil stiffness factor – Soil type: Test 30, 31, 32, ML, CL with 2 to 31 percent sand, consistency ranged from non-plastic to LL = 33, PI = 9.

FINE-GRAINED SOIL (LL < 50)

Test 33, 34 soil was a poorly graded sand (SP) with 1 percent fines.

COARSE-GRAINED SOIL WITH LITTLE OR NO FINES

Degree of compaction:

Test 30, dumped, no compaction
Test 31, puddled to 82-87 percent Proctor SLIGHT
Test 32, tamped to 95-97 percent Proctor HIGH
Test 33, was dumped in, no compaction
Test 34, R. D. = 30-38 percent SLIGHT

Load factor – Fill height = 4.5 feet. Fill density = 115 lb/ft³.

Actual deflection –

Test 30 $\Delta X = 6.1$ to 7.9 percent, avg. = 7.8 percent
Test 31 $\Delta X = 3.0$ to 4.2 percent, avg. = 3.5 percent
Test 32 $\Delta X = -0.3$ to 0.7 percent, avg. = 0.1 percent
Test 33 $\Delta X = 3.6$ to 6.8 percent, avg. = 5.1 percent
Test 34 $\Delta X = 0.6$ percent in all three pipes

Deflection lag – Over 16 months, Test 30 = 1.1
Test 31 = 1.1
Test 32 = 1.0
Test 33 = 1.1
Test 34 = 1.5

* * * * *

- **Test No. 35** **Reference No. 10**
Trott, J. J., and Gaunt, J., "A Study of an Experimental PVC Pipeline Laid Beneath a Major Road, During and After Construction," Third International Plastic Pipe Symposium, 1974.
MARLOW-BISHAM BY-PASS,
GREAT BRITAIN

Pipe stiffness factor –

Pipe type: PVC
Diameter = 12 in
Wall thickness = 0.32 in
 $EI/r^3 = 5.1 \text{ lb/in}^2$

Soil stiffness factor – Soil type: 10-mm single-size gravel.

COARSE-GRAINED SOIL WITH LITTLE OR NO FINES

Degree of compaction: "Granular bed and surround not compacted." Backfill over pipe was compacted providing some compaction down to the material beside the pipe.

SLIGHT

E' from table 1 = 1,000 lb/in².

Load factor – Fill height = 2.5 feet. Fill density = 124 lb/ft³.

Actual deflection –

ΔY at three locations = 0.5, 1.0, and 1.5 percent
 ΔX at three locations = 0.4, 0.8, and 1.3 percent

Comments – Pipe subsequently loaded with loaded scrapers and deflections measured. After 15 months of traffic $\Delta Y = 1.6, 2.5,$ and 3.0 percent.

* * * * *

- **Test No. 36-47** **Reference No. 11**
Proudfit, D. P., "Performance of Large-Diameter Steel Pipe at St. Paul," AWWA Journal, March 1963.
ST. PAUL, MINNESOTA

Pipe stiffness factor –

Pipe type: Steel
Diameter = 60 to 90 in
Wall thickness = 0.38 to 0.50 in
 $EI/r^3 = 2.3$ to 11.6 lb/in²

Soil stiffness factor – Soil type: Granular-natural rounded grain gravel, 95 percent passing 1/2-inch sieve and 95 percent retained on No. 4 sieve.

COARSE-GRAINED SOIL WITH LITTLE OR NO FINES

Other material reported only as "earth," no data available.

Assume FINE-GRAINED SOIL (LL < 50)

Degree of compaction: Embedment materials placed in 4-inch layers, if compacted by tamping, or 8-inch layers if vibrated. Compacted to 95 percent standard density as per ASTM D-698.

HIGH

E' from table 1 = See table A-1.

Load factor -- Fill height = See table A-1. Fill density = 110 lb/ft³.

Actual deflection -- See table A-1.

Deflection lag -- Data too erratic to calculate.

Comments -- All 7/16-inch to 1/2-inch wall pipe were strutted 3.3 percent vertically.

* * * * *

● **Test No. 48-50**

Reference No. 12

Research Council on Pipeline Crossings of Railroads and Highways, "Performance of Casing Pipe under Railroads and Highways," Journal of the Pipeline Division, ASCE, vol. 91, No. PL 1, July 1965.

Reference No. 13

Spangler, M. G., "Pipeline Crossings under Railroads and Highways," AWWA Journal, vol. 56, No. 8, August 1964.
WINN PARISH, LA.; JACKSON PARISH, LA.;
SAN BERNARDINO CO., CALIF.

Pipe stiffness factor --

Pipe type: Steel
Diameter = 34 in
Wall thickness = 5/16 in
 $EI/r^3 = 186 \text{ lb/in}^2$

Soil stiffness factor -- Soil type:

Winn Parish = sandy clay FINE-GRAINED SOIL (LL < 50) WITH MORE THAN 25 PERCENT COARSE-GRAINED PARTICLES
Jackson Parish = sandy clay FINE-GRAINED SOIL (LL < 50) WITH MORE THAN 25 PERCENT COARSE-GRAINED PARTICLES
San Bernardino = desert sand COARSE-GRAINED SOIL WITH LITTLE OR NO FINES

Degree of compaction: Assumed to be HIGH since they were all highway crossings.

E' from table 1 = See table A-1.

Load factor -- Fill height = See table A-1. Fill density = See table A-1.

Actual deflection -- See table A-1, data not reduced for deflection lag.

Deflection lag -- No initial deflections reported.

Comments -- Deflection readings taken every 10 feet, deflections calculated using average diameter as initial diameter.

* * * * *

● **Test No. 51, 52**

Reference No. 14

Bureau of Reclamation, "Deflections of Welded Steel Pipe, Santa Ana River Siphon, Metropolitan Water District," Internal Memorandum, Denver, Colorado, January 1936.
SANTA ANA, CALIFORNIA

Pipe stiffness factor --

Pipe type: Steel
Diameter = 126 in
Wall thickness = 12/32 in
 $EI/r^3 = 2.1 \text{ lb/in}^2$

Soil stiffness factor -- Soil type: "Sand and gravel, with an admixture of clay equal to one-fourth to one-half of volume of the sand and gravel" from specifications circa 1936.

COARSE-GRAINED SOIL WITH FINES

Degree of compaction: Case 1 "material deposited in layers of 6 inches or less and compacted by tamping . . . with the smallest quantity of water that will insure consolidation." HIGH
Case 2 "deposited in water." Puddling usually results in a MODERATE degree of compaction.

E' from table 1 = Case 1, $E' = 2,000$; Case 2, $E' = 1,000$.

Load factor -- Fill height = 10 feet. Fill density = ≈ 120 .

Actual deflection -- Case 1, Vertical diameters measured in four different "sections". Average ΔY with struts in place = 0.6 percent. Pipe deflected an additional 0.1 percent after struts removed. $\Delta X = 0.913$

$(\Delta Y) = 0.913 (0.6 + 0.1) = 0.6$ percent.
 Case 2, Vertical diameters measured in six different "sections". Average ΔY after struts removed = 1.7 percent. $\Delta X = 0.913$ ($\Delta Y) = 0.913 (1.7) = 1.6$ percent.

Comments — Pipe had 3/4" thick gunite exterior. Struts were 4" x 6" posts, every 33 feet. Time lapse unknown, assumed to be soon after construction.

Trench condition.

* * * * *

● **Test No. 53-61** **Reference No. 15**
 Glascock, B. C., "Barnett Avenue Sewer, Performance Analysis of an RPM Pipe Installation," Engineering Report No. 3a01016, United Technology Center, Sunnyvale, California, October 12, 1970.
 SAN DIEGO, CALIFORNIA

Pipe stiffness factor —
 Pipe type: RPM sewer pipe
 Diameter = 24 in
 $EI/r^3 = 3.3$ and 7.0 lb/in²

Soil stiffness factor — Soil type: The exact soil used for bedding is described in the table below. The material with a sand equivalent of 84 percent would have about 16 percent plastic fines and the material with a S.E. (sand equivalent) = 65 percent would have 35 percent fines.

COARSE-GRAINED SOIL WITH FINES
 The other material is **CRUSHED ROCK**

Degree of compaction:

Test No.	Station	Backfill (Construction) Description	% Proctor
3	0+00 to 2+34	Mixture of 30% 3/4" rock and 70% sand equivalent 65%. Placed in one lift to 6 inches above top of pipe, then flooded and poled. Poor compaction due to depth of lift and not fully covered. SLIGHT	—
4	2+34 to 3+65	Sand equivalent 84%: First lift placed to above the springline, second lift to 6 inches over top of pipe. Each lift flooded and stung with 3-inch concrete rod-vibrator. HIGH	85 below and 99 above springline
5	3+65 to 7+10	Sand equivalent 84%: First lift placed to just below springline, two more lifts to 6	99

inches over top of pipe. Each lift flooded and mechanically tamped with a whacker-type compactor. HIGH

8	9+30 to 18+10	Sand equivalent 84%: First lift placed to just below springline, two more lifts to 6 inches over top of pipe. Each lift flooded and mechanically tamped with a whacker-type compactor. HIGH	99
6	7+10 to 8+10	3/8" washed crushed rock: First lift to just below springline, second lift to 6 inches over pipe. Each lift tamped, no tamping directly over pipe. COMPACTED	—
7	8+10 to 9+30	3/4" washed crush rock, placed in same way as test 6 above. COMPACTED	—
9	18+10 to 27+60	First lift 3/8" unwashed crushed rock to just below springline, mechanically tamped. Second lift S.E. 84% to 6 inches over pipe, flooded and mechanically tamped. No tamping directly over pipe. COMPACTED	—
10	27+60 to 30+50	First lift 3/4" unwashed crushed rock to just below springline, mechanically tamped. Second lift S.E. 84% to 6 inches above pipe, flooded and tamped. No tamping directly over pipe. COMPACTED	—
11	30+50 to 33+20 (end)	First lift 1/2" washed crushed rock to just below springline, mechanically tamped. Second lift S.E. 84% to 6 inches over top of pipe, flooded and tamped. No tamping directly over pipe. COMPACTED	—

E' from table 1 = See table A-2.

Load factor — Fill height = See table A-2. Fill density ≈ 120 lb/ft³.

Actual deflection — See table A-2. Vertical deflections reported. Values in table A-2 calculated from $\Delta X = 0.913 (\Delta Y)$.

Deflection lag — None reported.

Comments — Well points used to dry the area and removed after backfilling. Deflections measured before and after well points removed. The subgrade was stabilized with 6" to 24" of 1" rock.

Immediate deflections measured.

Trench condition.

* * * * *

- **Test No. 62-69** **Reference No. 16**
 Glascock, B. C., "Three Year Data, Techite In-Ground Test Program at Sunnyvale," Engineering Report No. 3a-01015, United Technology, Center, Sunnyvale, California, October 12, 1970. SUNNYVALE, CALIFORNIA

Pipe stiffness factor —

Pipe type: RPM
 Diameter = 24 in
 $EI/r^3 = 2.6$ and 3.8 lb/in²

Soil stiffness factor — Soil type: Tests 62, 63, 66, and 67 soil had a sand equivalent = 48 percent (52 percent plastic fines).

FINE-GRAINED SOIL (LL < 50) WITH MORE THAN 25 PERCENT COARSE-GRAINED PARTICLES

Tests 64, 65, 68 and 69 "native silt clay".

FINE-GRAINED SOIL (LL < 50) WITH LESS THAN 25 PERCENT COARSE-GRAINED PARTICLES

Degree of compaction: Tests 62, 63 tamped to 91 percent Proctor. MODERATE

Tests 66, 67 tamped to 95 percent Proctor. HIGH
 Tests 64, 65, 68, 69 soil was jetted into place, usually higher density than dumped. SLIGHT

E' from table 1 = See table A-2.

Load factor — Fill height = See table A-2. Fill density = See table A-2.

Actual deflection — Vertical deflections measured at center of 10-foot pipe sections. See table A-2 for values which are averages of two pipe for each bedding condition. ΔX values calculated from $\Delta X = 0.913 (\Delta Y)$.

Deflection lag —

Test No.	Initial ΔX -%	3-year ΔX -%	D_1
62	0.6	0.9	1.5
63	0.7	1.0	1.4
64	2.5	2.6	1.0
65	3.2	3.7	1.2
66	0.3	0.6	2.0
67	0.7	0.8	1.1
68	7.0	7.2	1.0
69	7.6	7.6	1.0

Immediate deflections measured.

Comments — Trench condition.

* * * * *

- **Test No. 70** **Reference No. 17**
 Howard, A. K., "Deflections of 39-inch-inside-diameter RPM Pipe — Lateral E — Lower Yellowstone Irrigation District, Sidney, Montana," Earth Sciences Reference 74-41-2, Internal Memorandum, Bureau of Reclamation, Denver, Colorado, June 1974. SIDNEY, MONTANA

Pipe stiffness factor —

Pipe type: RPM
 Diameter = 39 in
 $EI/r^3 = 1.6$ lb/in² (from manufacturer)

Soil stiffness factor — Soil type: Poorly graded sand (SP) with 48 percent gravel and 2 percent fines. Maximum size was 1½ inch.

COARSE-GRAINED SOIL WITH LITTLE OR NO FINES

Degree of compaction: Pneumatically tamped. In-place densities were about 114 lb/ft³ which is about 0 to 40 percent relative density based on relative density tests of similar soils from the area.

SLIGHT

E' from table 1 = 1,000 lb/in².

Load factor — Fill height = 3 to 5 feet. Fill density = 122 lb/ft³, measured.

Actual deflection — 14 vertical and horizontal diameters measured along 1,100 foot 5 years after construction.

Average $\Delta Y = 1.3$ percent, range from -0.7 to 4.5 percent
 Average $\Delta X = 1.0$ percent, range from -0.6 to 3.6 percent

Pipe had been initially elongated vertically about 0.6 percent from bedding construction.

Deflection lag — Two locations were measured right after construction and 5 years later showing an increase in deflection of 50 percent. $D_1 = 1.5$. This factor was applied to the 5-year deflection data for use as immediate deflections.

ΔX average for table A-2 = 1.0/1.5 = 0.7 percent.

* * * * *

- **Test No. 71-76** **Reference No. 18**
Richmond, R. D., "OCCS Flexible Pipe Installation, Denver Federal Center," Report in preparation. DENVER, COLORADO

Pipe stiffness factor –

Pipe type: RPM, steel, PT concrete
Diameter = 48 in
Wall thickness = 0.5, 0.19, 2.0 in
 $EI/r^3 = 2.0, 1.2, 5.7 \text{ lb/in}^2$

Soil stiffness factor – Soil type: Test 72, 74, 76 bedded in a poorly graded sand (SP) with 2 percent fines.

COARSE-GRAINED SOIL WITH LITTLE OR NO FINES

Tests 71, 73, 75 soil was clayey sand (SC) with 56 percent sand. The fines had a LL = 34 and a PI = 23. Maximum density was 113 lb/ft³ at an optimum water content of 15 percent.

COARSE-GRAINED SOIL WITH FINES

Degree of compaction: Test 72, 74, 76 "material placed in thin lifts, slurried with water, and compacted with a mechanical tamper.

Nineteen density tests showed a range of 105 lb/ft³ to 117 lb/ft³ with an average of 111 lb/ft³ or 75 percent relative density. HIGH

Tests 71, 73, 75 mechanically tamped.

Fourteen density ranged from 99 lb/ft³ to 117 lb/ft³ with an average of 107 lb/ft³ or 95 percent of Proctor. HIGH

E' from table 1 – Test 72, 74, 76, $E' = 3,000 \text{ lb/in}^2$; Test 71, 73, 75, $E' = 2,000 \text{ lb/in}^2$.

Load factor – Fill height = 15 feet. Fill density $\approx 120 \text{ lb/ft}^3$.

Actual deflection and deflection lag –

Test No.	71	72	73	74	75	76
ΔX due to backfill (%) =	1.1	0.8	1.1	0.7	1.1	0.6
3 years later (%) =	2.7	1.0	2.3	1.0	1.6	0.7
$D_1 =$	2.5	1.25	2.1	1.4	1.5	1.2

Comments – Soil pressures, pipe settlement, and soil movement around the pipe also measured. Three years after construction, the backfill was saturated to increase the load on the pipe. Measurements made 24 days after saturation showed no differences in pipe deflection.

* * * * *

- **Test No. 77-88** **Reference No. 19**
Watkins, R. K., and Loosle, D., "Deflection of Cement-Mortar Lined Spiral-Welded Steel Pipe Embedded in Soil," Report submitted to Armco Steel Corporation, Middletown, Ohio, April 1965. LOGAN, UTAH

Pipe stiffness factor –

Pipe type: Cement-mortar lined steel
Diameter = See table A-2
Wall thickness = See table A-2
 $EI/r^3 =$ See table A-2, values are from 3-edge bearing tests

Soil stiffness factor – Soil type: Tests 77, 78, "silt". FINE-GRAINED SOIL (LL < 50) LESS THAN 25 PERCENT COARSE-GRAINED PARTICLES Tests 79-88 "Fine sand with 18% fines." COARSE-GRAINED SOIL WITH FINES

Degree of compaction:

Test No.	% Proctor		No. of Tests	% Compaction
	Avg.	Range		
77	57		1	DUMPED ¹
78	70	68-75	3	SLIGHT
79	73	71-75	3	DUMPED ¹
80	89	84-92	3	MODERATE
81	96		1	HIGH
82	73	66-79	2	DUMPED ¹
83	85		1	MODERATE ¹
84	68		1	DUMPED ¹
85	82	79-85	2	SLIGHT
86	65		1	DUMPED ¹
87	82	80-84	2	SLIGHT
88	72	70-77	3	DUMPED ¹

¹ Described as either "uncompacted", "loose", or "untamped". All others were tamped.

E' from table 1 = See table A-2.

Load factor – Fill height = 11 ft. Fill density = 83 lb/ft³.

Actual deflection – See table A-2. Both vertical and horizontal deflections measured.

Deflection lag – "After two days, the deflection was greater by 20 to 30 percent than the same fill height during a continuous fill operation."

Comments – Except for test 78, load was applied through soil in "nesting hoops" placed over the bedded pipe. Load-deflection curves presented.

Immediate deflections.

* * * * *

● **Test No. 89,90** **Reference No. 20**

The Proctor and Gamble Company, private correspondence, 1973, 1975.

GRANDE PRAIRIE, ALBERTA, CANADA

Pipe stiffness factor –

Pipe type: Ribbed FRP
 Diameter = 42 in
 Wall thickness = 0.37 in plus 2" by 5" ribs
 on 24-in centers
 $EI/r^3 = 20 \text{ lb/in}^2$

Soil stiffness factor – Soil type: 7/8 inch crushed gravel, pit run gravel run through a crusher 7/8 inch max size, placed at 5 to 8 percent moisture.

CRUSHED ROCK

Degree of compaction: Case 39 compacted by hand-operated roller at 7-in. lifts and 30-in. wide adjacent to pipe.

COMPACTED

Case 40

DUMPED

E' from table 1 Test 89, $E' = 3,000 \text{ lb/in}^2$; Test 90 $E' = 1,000 \text{ lb/in}^2$.

Load factor – Fill height = 6 feet. Fill density $\approx 125 \text{ lb/ft}^3$. Backfill was compacted with 10-ton vibratory roller in 1-foot lifts to about 90 percent relative density.

Actual deflection – Test 89 $\Delta Y = \Delta X = -0.3$ percent (Pipe initially elongated vertically from bedding compaction).

Test 90 $\Delta Y = 0.6$ percent, $\Delta X = 0.4$ percent.

Static load deflection – About 11 lb/in^2 static load (65 tons) applied on soil surface over pipe.

Test 89 $\Delta Y = \Delta X = 0.1$ percent.

Test 90 $\Delta Y = 0.2$ percent, $\Delta X = 0.1$ percent.

Comments – Pipeline served as an effluent line from pulp mill. 65-ton load over pipe cycled 300 times. Pipe laid in 6" of compacted fine silty sand.

Immediate deflections measured.

Trench condition.

* * * * *

● **Test No. 91-97**

Reference No. 21

Olson, H. M., Busch, L. A., and Miller, E. R., "Performances of Irrigation Pipe Lines Buried Within the Frost Zone," Paper at 1974 Winter Meeting, American Society of Agricultural Engineering, December, 1974.

Reference No. 22

North Dakota State University, "Report on Buried Irrigation Pipe at the Carrington Irrigation Station," Private Report to the Bureau of Reclamation, Contract No. 14-06-600-9990, May 31, 1970.

CARRINGTON, NORTH DAKOTA

Pipe stiffness factor –

Pipe type: Poly(vinyl chloride)
 Diameter = 12 in
 Wall thickness = 0.12 in
 $EI/r^3 = 0.3 \text{ lb/in}^2$

Soil stiffness factor – Soil type: Two soil samples taken (CL).

	No. 1	No. 2
Gradation:	21 percent sand 79 percent fines	24 percent sand 76 percent fines
Consistency	LL = 30 PI = 12	LL = 29 PI = 12

FINE-GRAINED SOIL (LL < 50) LESS THAN 25 PERCENT COARSE-GRAINED PARTICLES

Degree of compaction, load factor parameters, E' values –

Their test No.	Backfill & bedding description	Measured backfill density, lb/ft^3	Degree of compaction	E' selected, lb/in^2
1	"First 6-inch backfill hand placed, rest of backfill dumped" bedding hand placed but not compacted 3.0' of cover	55	dumped	50
2	"Backfill dumped then ponded with water" 2.5' of cover	75 before (118 after)	dumped	50
3	"Same as No. 2 except pipe filled with water (a 3-foot ponding head) then back-filled" 2.5' of cover	79 before (128 after)	dumped	50

4	"U.S. Soil Conservation Service Recommended Procedure" "backfilling 6" over pipe and puddling with water" 2.0' of cover	78	slight	200
5	"Backfill completely dumped" 3.0' of cover	80	dumped	50
6	"Soil compacted to 1/2 dia. of pipe, backfill dumped 3.0' of cover	50	high	1,000
7	"2-inch cradle formed in trench backfill dumped" 2.0' of cover	50	dumped	50

Vertical Deflections

Their test No.	Measurement No. 1, %	Measurement No. 2, %	Measurement No. 3, %	Avg. %	
1	2.0	2.3	2.7	2.3	
2	5.8	8.9	10.3	8.3	Backfill load due to ponding
	10.6	9.6	7.9	9.4	
3	3.3	5.4	4.7	4.4	Backfill load due to ponding
	8.3	9.5	8.0	8.6	
4	3.5	3.3	2.7	3.2	
5	2.3	2.2	1.4	1.9	
6	0.5	0.1	0.5	0.3	
7	4.0	2.8	2.9	3.3	

Comments — Two 20-foot-long trenches were dug with observation pits at each end. Twenty-foot sections of PVC pipe were buried under various bedding conditions and depths of backfill. After determining the deflections due to backfill loads, the pipes were subjected to vehicular traffic.

* * * * *

Actual deflections — Immediate vertical deflections were measured at 3 locations along each 20' section. From the original data, the deflections due to the backfill load were calculated plus deflections due to ponding after the backfill was in place. The ΔX values shown in table A-2 were calculated from $\Delta X = 0.913 \Delta Y$.

- Test No. 98-113 Reference No. 23
 Private Corporation (name withheld by request),
 private correspondence, 1972, 1975.

Pipe stiffness factor –
 Pipe type: RPM
 Diameter = 24 in
 $EI/r^3 =$ 2.1 lb/in²

Soil type
 Degree of compaction
 Actual deflections
 Deflection lag

Section and pipe No.	Soil type	How Compacted ¹	% Proctor	Trench width, ft	Backfill Depth ³ ft	Degree of compaction	$\Delta X - \%$		D_1
							initial	2 yrs	
I – 1	ML ⁴	mechanically	91	6	10	mod.	0.9	3.8	4.2
2	SW-SM	mechanically	95	6	10	mod.	0.3	0.9	3.0
3	SW	mechanically	"dense"	6	10	mod. ²	0	0.3	–
4	GP	mechanically	"dense"	6	10	mod. ²	0.7	0.7	1.0
5	GP	hand tamped	"dense"	4	10	mod. ²	0.5	0.8	1.6
6	SW	hand tamped	97	4	10	high	0	0.3	–
7	SW-SM	mechanically	94	4	10	mod.	0.2	0.4	2.0
8	ML	hand tamped	83	4	10	slight	2.8	11.4	4.1
II – 1	ML ⁴	mechanically	91	4	15	mod.	3.6	7.8	2.2
2	SW-SM	hand tamped	79	4	15	slight	1.0	1.4	1.4
3	SW	hand tamped	"dense"	4	15	mod. ²	0.3	0.2	1.0
4	GP	hand tamped	"dense"	4	15	mod. ²	0.9	0.6	1.0
5	GP	hand tamped	"dense"	6	15	mod. ²	1.2	0.9	1.0
6	SW	hand tamped	"dense"	6	15	mod. ²	0.8	1.1	1.4
7	SW-SM	hand tamped	86	6	15	slight	3.9	6.6	1.7
8	ML ⁴	dumped	57	6	15	dump	2.9	12.1	4.2

¹ All compaction done in 6" to 12" lifts.

² Since tamping is a less efficient method than saturation and vibration for compacting cohesionless soil, degree of compaction assumed only moderate. Where densities were measured, average was 90 percent (79 percent to 97 percent) for tamped cohesionless soil.

³ Backfill density measured at 89 lb/ft³.

⁴ w/45 percent sand.

Comments – Heavy rainfall a few months after construction increased the deflections of pipe I-1, 300 percent; pipe I-8, 400 percent; pipe II-1, 200 percent; pipe II-8, 300 percent; and the rest only moderately.

Immediate deflections measured.

Trench condition.

APPENDIX C

PIPE BURIED UNDER HIGH FILLS

The Reclamation E' table is not applicable for flexible pipe buried under high fills [over about 15 m (50 ft)]. Deflections of pipe under high fills were found to be much less than predicted using table 1. The actual deflections probably were less for two reasons:

1. The "prism of soil load" assumption only approximates the loading conditions sufficiently to provide a deflection prediction to within, ± 2 percent deflection. A fill height of about 15 m or over is the limit where the soil prism load assumption no longer provides reasonable answers.

2. Pipe under high fills are generally short-span culverts under railroads or highways. High-quality bedding can be afforded for these shorter lengths,

whereas the construction costs for that type of bedding would not be economically feasible for longer pipelines. Imported high-quality soil and carefully controlled compaction (in many cases over 100 percent of maximum density) can result in E' values as high as 138 MPa (20 000 lb/in²). E' becomes more difficult to apply in these cases because the deflections are quite small and a difference of 2.5 mm (0.1 in) in deflection readings can change back-calculated E' values by as much as 6.9 MPa (1000 lb/in²).

This appendix includes information from the literature that may be useful for anticipating the deflections for flexible pipe under high fills when a high quality bedding material is used. Each case is described and the information summarized in table C-1.

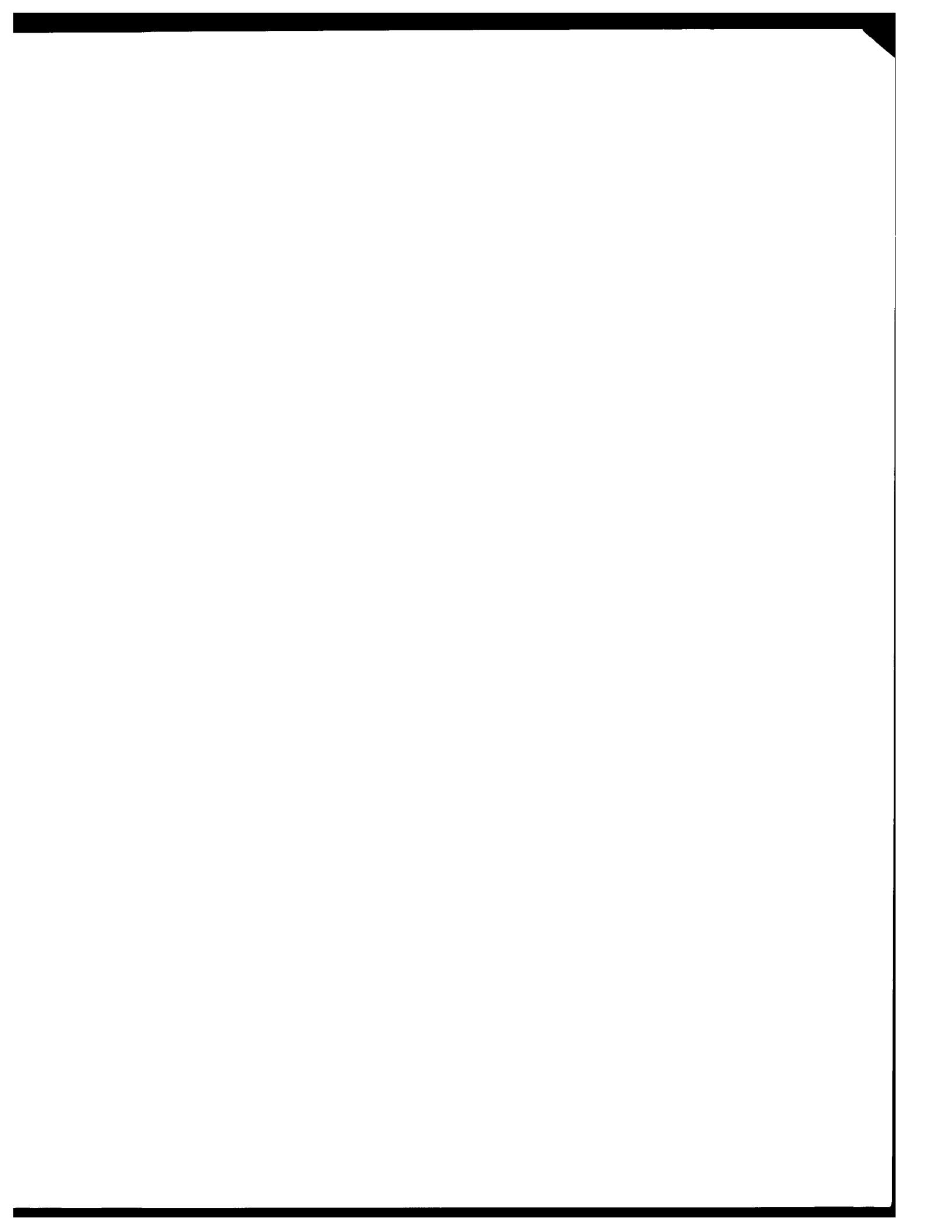


Table C-1.— E' for pipe buried under high fills.

Test No.	Reference No.	Location	Pipe diameter, in	Corrugation	Wall thickness	Soil type	Fill height, ft	ΔX , %	E' , lb/in ²
C-1	1, 2	Lethbridge, Alberta, Canada	108	6 x 2	1 ga.	medium-plastic clay and gravel-clay mixture	99	3.7	3,100
C-2	3, 4	Cullman County, Ala.	84			crumbly sandstone	137	0.9	8,000
C-3	5, 6	McDowell County, N.C.	66	6 x 2	1 ga.	silty sand (SM) 89% compaction	170	≈ 4	3,500
C-4	7	Duisburg-Hamborn, Germany	Pipe Arch 20' 7" span, 13' 2" rise		7 ga.	sandy-gravel	150 ton sur-charge	0.3 of rise	
C-5	8	Wolf Creek Culvert, Mont.	222			crushed rock 1-1/2" maximum	83	0.9	6,300
C-6	9	Chadd Creek, Calif.	114	6 x 2	1 ga.	well-graded, granular	89	-0.4 to 0.4	16,000- to 20,500
C-7	9	Apple Canyon, Calif.	108	6 x 2	12 ga. to 3/8"	well-graded, granular	160	0.9	16,400

Test No. C-1 LETHBRIDGE, ALBERTA, CANADA

"The culvert at Lethbridge consists of No. 1 gage corrugated steel with 6-inch by 2-inch corrugations and is installed in medium-plastic clay compacted to about 94 percent of standard Proctor density above mid-height of the culvert and compact gravel-clay mixture below. The maximum deflection is about 4.0 inches" [1]¹. The fill height = 99 feet and diameter = 108 inches. E' was calculated to be 3,100 lb/in², for an $I = 0.166 \text{ in}^4/\text{in}$ and a fill density of 120 lb/ft³.

* * * * *

Test C-2 CULLMAN COUNTY, ALABAMA

A 7-foot-diameter corrugated metal pipe culvert was constructed using the *imperfect ditch* method under a 137-foot highway embankment in Cullman County, Alabama. The pipe was initially elongated vertically 3 percent using vertical struts [3].

The fill material around the pipe was a crumbly sandstone compacted by power hand tampers to 100 percent standard AASHTO density [3]. The average deflection was 0.72 inches (0.9 percent). Spangler has calculated E' to be about 8,000 lb/in² [4].

¹ Numbers in brackets refer to bibliography at the end of this appendix.

* * * * *

Test No. C-3 McDOWELL COUNTY, NORTH CAROLINA

A 66-inch-diameter CMP with 6-inch by 2-inch corrugations was buried under a 170-foot-high highway embankment in McDowell County, North Carolina. The pipe was initially elongated 3 percent vertically using vertical struts. The select material beside the pipe was compacted in 6-inch layers by pneumatic tamping up to a height equal to 3/4 of the pipe diameter. The *imperfect ditch* method of construction was used for the placement of the backfill over the pipe [5].

On the center section, under the high portion of the fill, the horizontal deflections ranged from 3 to 5 percent after the struts were removed. The average was about 4 percent [5]. A back-calculated $E' = 3,500 \text{ lb/in}^2$ results if a 120 lb/ft³ density for the backfill is assumed.

* * * * *

Test No. C-4 DUISBURG-HAMBORN, GERMANY

"The test described in this report conducted on a multiplate pipe-arch conduit of 20-foot 7-inch span, 13-foot 2-inch rise, and 7 gage wall thickness, showed the following results:

1. With a cover height of one-sixth the span = 3.44 feet and a loaded area 8.53 feet wide and 10.33 feet long = 88.11 square feet, the pipe-arch-soil structure proved capable of carrying a load of $P = 151.32$ tons applied both axially and off-center showing but slight deformation (0.386 inches = $1/640$ of span).

2. With a cover height of one-fourth the span and the same axial loaded area a load of 953.75 tons was applied and, with an enlarged loaded area of approximately 16.4 by 9.84 = 161.4 square feet resulting from settlement, a load of 1,079.77 tons could be reached in this test without the pipe arch being crushed" [7].

Backfilling Material.

"Sandy gravel was used as backfilling material for the pipe arch. Its single Proctor density at an optimum moisture content of 6.8 percent was determined to be 120 lb/ft³. The results of the triaxial pressure tests indicate a friction angle of 37.5 deg for the sandy gravel at this density" [7].

"During backfilling the compactness obtained at the 7 points was determined by the calibrated sand method. This showed an average dry density of 128 lb/ft³, which means that by compaction of fill in 8-inch lifts with surface vibrators, a compactness of 107 percent of the single Proctor density was obtained. The results of the drop-penetration test with 70 to 90 blows for 8 inches of penetration depth also indicate the good compaction of the fill" [7].

* * * * *

Test No. C-5 WOLF CREEK CULVERT, MONTANA

An 18.5-foot-diameter corrugated metal culvert was constructed using the *imperfect trench* method under an 83-foot embankment. The average deflection was 1.9 inches (0.9 percent) and Spangler has calculated E' to be 6,300 lb/in² [8].

The backfill adjacent to the pipe was a crushed granular material of base course quality. It was classified as a well-graded gravel, maximum size 1-1/2 inches. It was compacted by pneumatic tire rollers, supplemented by hand tamping, in 6-inch layers to a minimum of 95 percent of AASHTO T-99 [8].

* * * * *

Test No. C-6 CHADD CREEK, CALIFORNIA and No. C-7 APPLE CANYON, CALIFORNIA

"Two large-diameter, structural steel plate pipes embedded in deep embankments were instrumented and tested to assess circumferential soil stress distributions, deformations, and internal strains. Construction techniques included the *imperfect trench* method (method B backfill) and *positive projection* (method A backfill). Method B uses layers of baled straw over a 114-in (290-cm) pipe under 89 ft (72 m) of overfill. Method A consists of ordinary embankment material surrounding twin, 108-in. (274-cm) pipes under 160 feet (49 m) of overfill" [9].

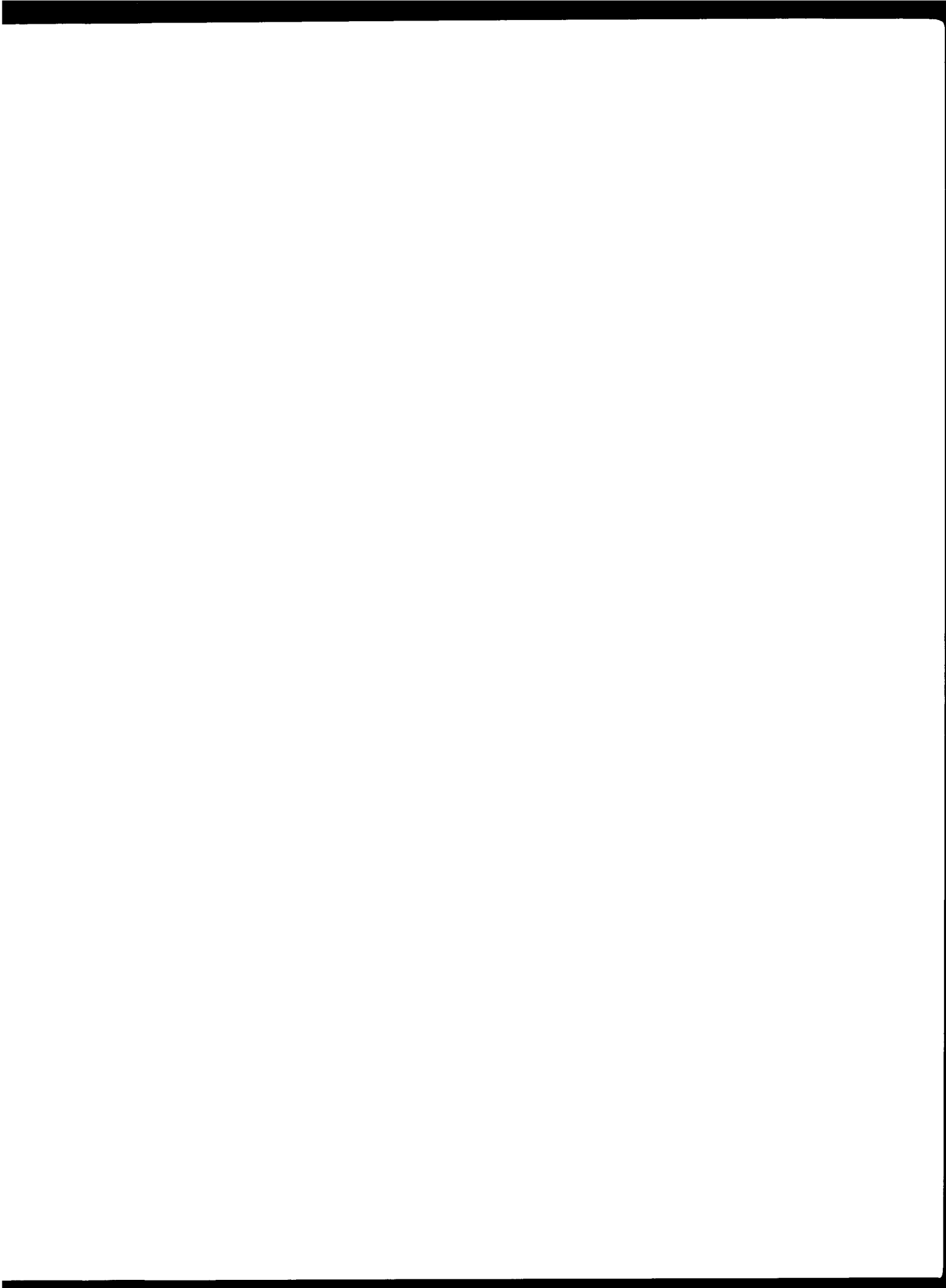
"Method B backfill was employed in a prototype culvert in Chadd Creek canyon in Humboldt County, California, during the fall of 1965 and spring of 1966. The culvert was a 114-in.- (290-cm-) diameter, number 1 gauge, structural steel plate pipe having 6- by 2-in (15.2- by 5.0-cm) corrugations. An initial ellipticity was produced by a 5 percent vertical diameter elongation. The culvert periphery comprised 6 segments of 60-deg arc each with longitudinal seams at the horizontal diameter. The pipe was installed in a 7-ft- (2.1-m-) deep trench having shaped bedding; it was backfilled with well-graded, granular backfill to a height of 1 to 2 ft (0.3 to 0.6 m) above the pipe crown. Baled straw was placed in layers 3 to 5 ft (0.9 to 1.5 m) thick, above the structure backfill. The maximum fill height, measured from the culvert crown, was 89 ft (27.1 m)" [9].

"Method A backfill was used in the second prototype culvert, which was constructed at Apple Canyon in Los Angeles County, California, during the spring of 1966. This culvert comprised twin 108-in.- (274-cm-) nominal-diameter, structural steel plate pipes, which were elongated 5 percent in the vertical dimension. Both pipes were constructed from six 6- by 2-in. (15.2- by 5.0-cm) corrugated plates formed into 60-deg arcs. However, various plate thicknesses, ranging from 0.109 in [2.77 mm (number 12 gauge)] to 3/8 in. (9.5 mm), were used along the culvert axis. The twin pipes were placed 4 ft (1.2 m) apart on shaped bedding in an 8-ft- (2.4-m-) deep by 24-ft- (7.3-m-) wide trench with sloping sides. Structure backfill surrounding the pipes was well-graded, granular material placed to a height of 1 ft (0.3 m) above the culvert crowns" [9].

E' for the Chadd Creek installation was calculated to be from 110 to 141 MPa (16,000 to 20,500 lb/in²) and for Apple Canyon about 113 MPa (16,400 lb/in²). The bedding was placed at 95 percent AASHTO compaction [9].

BIBLIOGRAPHY

- [1] Meyerhof, G. G., and Fisher, C. L., "Composite Design of Underground Steel Structures," *The Engineering Journal*, September 1963.
- [2] Prairie Farm Rehabilitation Administration, "First Progress Report on Flexible Culvert Investigations," Saskatoon, 1957.
- [3] Timmers, J. H., "Load Study of Flexible Pipe Under High Fills," *Highway Research Board Bulletin* 125, 1956 (discussion by M. G. Spangler).
- [4] Spangler, M. G., and Phillips, D. L., "Deflections of Timber-Strutted Corrugated Metal Pipe under Earth Fills," *Highway Research Board Bulletin* 102, 1955.
- [5] Costes, N. C., and Proudley, C. E., "Performance Study of Multi-Plate Corrugated-Metal Pipe Culvert under Embankment. — North Carolina," *Highway Research Board Proceedings*, 39th Annual Meeting, 1960.
- [6] Watkins, R. K., and Spangler, M. G., "Some Characteristics of the Modulus of Passive Resistance of Soil: A Study in Similitude," *Highway Research Board Proceedings*, vol. 37, 1958.
- [7] Demmin, J., "Field Verification of Ring Compression Conduit Design," *Highway Research Record* No. 116, 1966 (discussion by M. G. Spangler).
- [8] Scheer, A. C., and Willett, G. A., "Rebuilt Wolf Creek Culvert Behavior," *Highway Research Record* No. 262, 1969 (discussion by M. G. Spangler).
- [9] Spannagel, D. W., Davis, R. E., and Bacher, A. E., "Effects of Methods A and B Backfill on Flexible Culverts Under High Fills," *Transportation Research Record* No. 510, 1974.



APPENDIX D

RECOMMENDED PIPE INSTALLATION PROCEDURES

Pipeline installation terminology varies throughout the country. In this appendix, *foundation* will refer to the in situ or replaced material beneath the pipe, *bedding* to the material placed beside the pipe, and *backfill* to the material placed over the pipe.

A soils exploration program should be conducted prior to excavation to determine in advance soil conditions which relate to trench construction and pipe installation. The results of the exploration program should not only indicate the proper backfill and compaction procedures to be followed, but also determine the areas of unsuitable material so that unnecessary importation of select material may be avoided. Fine-grained soils with medium to high plasticity (CH, MH) and organic soils, such as OL, OH, and Pt (Unified Classification System), are generally considered to be unsuitable for bedding materials.

The soil surface at the trench grade should be continuous, smooth, and free of rocks or other protrusions which may cause point loading on the pipe.

Where rock, cobbles, or hardpan excavation is encountered, the trench bottom should be overexcavated to provide a minimum of 150 mm (6 in) of bedding for pipe 300 mm (12 in) in diameter or greater, or a minimum of 100 mm (4 in) of bedding for pipe less than 300 mm (12 in) in diameter. Occasionally, organic soils or soils that exhibit a volume change with a change in moisture content may be encountered in the bottom of the trench, in which case the engineer should require further excavation and specify a firm replaced foundation material. Each such situation must be evaluated to determine the extent of overexcavation and the type of replaced foundation material to be used. Where overexcavation is performed, including overexcavation done inadvertently during construction, any required replaced foundation material should be uniformly compacted to at least the density of the native soil at the sides of the trench or to a greater density if required by the design procedure. For pipe 300 mm (12 in) in diameter or larger, the material should be uniformly compacted to at least the density of the native soil at the sides of the trench or to a greater density if required by the design procedure. For pipe less than 300 mm (12 in) in diameter, the material need not be compacted.

Where ground-water conditions are such that running or standing water occurs in the bottom of the trench, the water should be removed by suitable means such as well points or side drains. Care should be taken that the gradation of the backfill, bedding, and foundation material is such that under saturated conditions, fines from these areas will not migrate into the adjacent soil of the trench bottom or walls, nor material from the trench bottom or walls migrate into these areas.

Where the bedding is compacted by tamping or with surface vibrators, the soil surface at the trench grade should be shaped to fit the outside diameter of the pipe. The soil surface should be shaped to a depth of at least 5 percent of the outside diameter of the pipe. Shaping is not necessary if the backfill is compacted by saturation and internal vibration or if uncompacted bedding material is used.

When the pipe being installed is provided with joints that form an offset on the outside of the pipe, "bell holes" should be dug beneath the joint to allow for proper assembly of the joint and to prevent the weight of the pipe from being carried on the joint. Care should be taken that the bell hole is no larger than necessary to accomplish proper joint assembly. When the joint has been made, the bell hole should be carefully filled with bedding material to provide for continuous support of the pipe throughout its entire length.

The width of the trench at any point below the top of the pipe should not be greater than necessary to provide adequate room for joining the pipe in the trench and compacting the bedding at the sides of the pipe. However, if the trench wall material is a soil that will not provide the side support for the pipe required by the design procedure, the trench width should be five pipe diameters and the bedding material highly compacted.

The pipe should be laid in the trench so that it bears evenly on the bedding or the bottom of the trench throughout its entire length. Blocking should not be used to bring the pipe to grade.

The bedding material should be placed in layers on each side of the pipe and compacted. Care should be taken to compact the material under the haunches of the pipe. The compacted bedding should be placed to a minimum depth of 70 percent of the outside diameter of the pipe. The bedding should be brought up uniformly on both sides of the pipe with no rocks or clods greater than 25 mm (1 in) in diameter being placed within 150 mm (6 in) of the pipe. The backfill above the bedding may be placed without compaction by spreading in approximately uniform layers in such a manner to fill the trench completely so that there will be no voids.

The following compaction methods are recommended to obtain the maximum practicable density of the material.

- Coarse-grained soils containing less than 5 percent fines, such as GW, GP, SW, SP, GW-GP, and SW-SP, should be compacted by saturation and vibration. If internal vibrators are used, the height of successive lifts of backfill shall be limited to the penetrating depth of the vibrator. If surface vibrators are used, the backfill should be placed in 150- to 300-mm (6- to 12-in) lifts.
- Coarse-grained soils containing more than 12 percent fines, such as GM, GC, SM, SC, and any borderline cases in this group (e.g., GM-SM), should be compacted by tamping. The backfill should be placed in 100- to 150-mm (4- to 6-in) lifts.
- Coarse-grained soils containing between 5 and 12 percent fines, such as GW-GM, SW-SM, GW-GC, SW-SC, GP-GM, SP-SM, GP-GC, and SP-SC, should be compacted by either tamping or by saturation and vibration, whichever method results in the highest density meeting the design requirements.
- Fine-grained soils with low to medium plasticity, such as ML, CL, SC-CL, SM-ML, and ML-CL, should be compacted by tamping in lifts of 100 to 150 mm (4 to 6 in).

The minimum and maximum dry densities of soils compacted by saturation and vibration should be

determined in accordance with ASTM D 2049, "Relative Density of Cohesionless Soils," or Designation E-12 in the *Earth Manual*, Second Edition, 1974.

The maximum dry density of the minus No. 4 fraction of materials compacted by tamping should be determined by ASTM D 698, "Moisture-Density Relations of Soils," or Designation E-11 in the *Earth Manual*.

The minimum in-place densities of the compacted material shall not be less than that required by the design procedure.

When saturation is used during the installation procedure, care should be taken to avoid flotation of the pipe. Precautions should also be taken to avoid displacement of the pipe while placing material under the haunches of the pipe.

In the process of backfilling the trench, care should be exercised to protect the pipe from falling rocks, direct impact of compaction equipment, or other sources of potential damage. When the backfill is to be compacted up to the ground surface, the compaction should be done in such a way so that the compaction equipment is not used directly above the pipe until sufficient backfill has been placed to ensure that such compaction equipment will not have a damaging effect on the pipe. Rolling equipment or heavy tampers should be used to consolidate the final backfill only if recommended by the manufacturer and at least 760 mm (30 in) of cover, or a greater amount if recommended by the manufacturer, over the top of the pipe should be provided before their use. Precautions should be taken when using a hydrohammer to compact the backfill material to avoid damage to the pipe.

Parallel piping systems laid within a common trench should be spaced sufficiently far apart to allow for the use of compaction equipment to compact the soil between the pipes. The soil between the pipes shall be compacted in the same manner as the soil between the pipe and the trench wall, with special care being taken to compact the soil underneath the haunches of each pipe.

Where practicable, the engineer should make periodic measurements of the deflection of the installed pipe to ensure compliance with the design assumptions.