Dynamics of Offshore Structures

James F. Wilson, Editor

John Wiley & Sons, Inc.

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Cover photograph. This historical Argus Island Tower was a U.S. Navy facility, located 39 km off the southwest coast of Bermuda in a water depth of 58 m. Built in 1960, the Tower was used for about 10 years for underwater acoustic research and for submarine detection. The two enclosed levels on top of this four legged jacket structure had space for diesel generators, living quarters, and laboratories. During the first few years of the Tower's existence, it was subjected to storm-generated waves approaching 21 m, which was also the wave height upon which the Tower design was based. The 1969 inspections of the Tower revealed storm damage to many of its subsurface welded brace connections, damage that was deemed too closely to repair and subsequently maintain. Thus, demolition using shaped charges toppled the Tower in 1976, and its remains now rest on the coral floor of the sea.

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Contents

Preface

This book is intended for three groups: (1) students and professors of structural and ocean engineering; (2) engineers and scientists in academic institutions, government laboratories, and industries involved in research on offshore installations, especially fluid-structure-soil interactions; and (3) practicing professional engineers who consider conceptual designs and need to employ dynamic analysis to evaluate facilities constructed offshore. The material herein was originally prepared by the three contributors for short courses attended by engineering practitioners, and for university courses taken by engineering seniors and graduate students.

Compared to the first edition, this second edition includes more example problems to illustrate the dynamic modeling, analysis, and solution of deterministic and stochastic responses for a wide variety of structures offshore, which include buoys, moored ships, and platforms of the fixed-bottom, cable-stayed, and gravity-type designs. Also, the extensive references of the first edition are updated, especially source material involving offshore waves, structural modal damping, and fluid-structure-soil interactions.

As in the first edition, this second edition addresses the basic physical ideas, structural modeling, and mathematical methods needed to analyze the dynamic behavior of structures offshore. Chapter 1 summarizes existing installations and points out future challenges. In subsequent chapters, careful attention is given to the many and sometimes subtle assumptions involved in formulating both the structural model and the natural forces imposed by the often hostile environment. The analyses in these chapters focus on plane motions of elastic structures with linear and nonlinear restraints, motions induced by the forces of currents, winds, waves, and earthquakes. Chapters 2 through 5 address single degree of freedom structural models that, together with plane wave loading theories, lead to time history predictions of structural responses. Chapters 6 and 7 extend these analyses to statistical descriptions of both wave loading and structural motion. Chapters 8 and 9 include the analysis and examples of multi-degree of freedom linear structures. Chapter 10 deals with continuous system analysis, including the motion of cables and pipelines. Chapter 11 addresses current practice related to submerged pile design for structures offshore.

I sincerely hope that this book will be useful and serve as an inspiration to engineers and researchers who design and analyze structures for the offshore environment.

JAMES F. WILSON
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Contributors

Bruce J. Muga, Professor Emeritus of Civil and Environmental Engineering at Duke University, received his B.S. in Civil Engineering from the University of Texas, and his M.S. and Ph.D. degrees in Civil Engineering (Hydrodynamics) from the University of Illinois.

From 1961 to 1967 he was employed as a Project Engineer in the Port and Harbor Division of the U.S. Naval Civil Engineering Laboratory, Port Hueneme, California. In 1964, he was assigned as Consultant to the U.S. Military Assistance Command, Vietnam, to advise on coastal and harbor engineering projects.

In 1967, Dr. Muga accepted a position in teaching and research at Duke University and was Chairman of the Department of Civil Engineering in 1974. He has served as a consultant to many international corporations engaged in offshore and deep ocean engineering activities. He has written numerous technical papers and for seventeen years served on the North Carolina Marine Sciences Council. Prior to retirement, Dr. Muga was a Registered Professional Engineer in California, a member of the American Society of Civil Engineers and the Marine Technology Society. He is a life member of the Permanent International Association of Navigational Congresses.

Lymon C. Reese is the Nasser I. Al-Rashid Chair Emeritus and Professor, Department of Civil Engineering, The University of Texas, Austin, Texas, and is principal at Ensoft, Inc., a distributor of engineering software. Some of his consulting activities are carried out through Lymon C. Reese & Associates, a subsidiary of Ensoft.

He received his Bachelor's and Master's degrees in Civil Engineering from The University of Texas at Austin and his Ph.D. from The University of California at Berkeley. Dr. Reese has had several years of industrial experience and has been a consultant to a number of companies and governmental agencies. He was formerly Assistant Professor of Civil Engineering at Mississippi State University.

Dr. Reese has done extensive research in the field of geotechnical engineering, principally concerning the behavior of deep foundations. He has pioneered in performing field studies of instrumented piles and has developed analytical methods now widely used in the design of major structures. He has authored over 400 technical papers and reports and presented a number of invited lectures and talks in North and South America, Australia, Africa, Asia, and Europe.

Dr. Reese is an Honorary Member of the American Society of Civil Engineers and was selected as Terzaghi Lecturer in 1976; he received the Terzaghi Award in 1983. He received the Distinguished Achievement Award for Individuals from the Offshore Technology Conference in 1985 and was elected to membership in the National Academy of Engineering in 1975. He is a registered professional engineer in Texas and Louisiana.

James F. Wilson earned an A.B. degree from the College of Wooster, a B.S. degree in Mechanical Engineering from MIT in 1956, and a Ph.D. degree in applied mechanics from The Ohio State University, where he was a Ford Foundation Fellow and a Freeman Scholar. He worked in research and development for several companies and government agencies before joining the faculty at Duke University in 1967.

During his academic career, Dr. Wilson was a NASA-ASEE Faculty Fellow, a lecturer at three NATO Advanced Study Institutes, and a Visiting Scholar at Colorado State University and the University of Melbourne, Australia. He has been active in national committees for the American Society of Mechanical Engineers (ASME) and the American Society of Civil Engineers (ASCE), and received national awards for innovative experimental research (ASME, 1977), and the year's best state-of-the-art civil engineering journal publication (ASCE, 1987). He is a Life Fellow in ASME and a retired Fellow of the National Academy of Forensic Engineers. As a registered professional engineer, he regularly serves as an expert witness, testifying on structural failures, product performance, and vehicle accident reconstruction.

He is author or coauthor of over 200 works, which include technical reports on forensic engineering, refereed symposium papers and journal articles, two books on structural dynamics, a three-volume work on experiments in engineering, and two U.S. patents. His experimental research on robotics was highlighted in the 1989 BBC documentary, *Nature's Technology.*

During Dr. Wilson's career at Duke University, he has taught courses in applied mechanics, structural dynamics, and experimental systems, and was the major research advisor for over 35 graduate students, including postdoctoral fellows. He also served as the Director of Graduate Studies for the Department of Civil and Environmental Engineering. As Professor Emeritus since 1998, Dr. Wilson continues to pursue his research and writing interests and consulting practice.

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I am grateful to those who have made this edition possible: to Robert E. Sandstrom for his contributions to Chapter 1; to Academic Press, Inc., for permission to use parts of Chapter 1, first published in the *Encyclopedia of Physical Science and Technology, III, 2001;* and to Gary Orgill and David M. Wilson who performed many of the calculations for the sample problems.

I especially acknowledge the patience and careful scholarship of the two guest contributors: Bruce J. Muga for Chapters 3 and 6 on fluid mechanics, and Lymon C. Reese for Chapter 11 on soil mechanics. Only by including the mechanics of fluids and soils can realistic analyses of offshore structures be made.

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1

Structures in the Offshore Environment

James F. Wilson

Offshore structures, constructed on or above the continental shelves and on the adjacent continental slopes, take many forms and serve a multitude of purposes: towers for microwave transmission, installations for power generation, portable pipeline systems for mining the ocean floor, and a few platforms and floating islands that serve as resort hotels. Most structures offshore, however, have been built to support the activities of petroleum industries—activities that include the exploration, drilling, production, storage, and transportation of oil. Exploratory drilling is done from mobile platforms or carefully positioned ships; production and storage operations involve more permanent structures; and pipelines, buoys, and mooring systems for floating structures and ships support all oil acquisition activities.

The design of marine structures compatible with the extreme offshore environmental conditions is a most challenging and creative task for the contemporary ocean engineer. The engineer involved in designing these marine structures must rely on the knowledge and experience of meteorologists, oceanographers, naval architects, geologists, and material scientists. The marine engineer's goal is to conceive and design a lasting structure that can withstand the adverse conditions of high winds and waves, earthquakes, and ice, remaining in harmony with its environment. Mulcahy (1979) expressed this design philosophy as follows:

> Offshore platforms are a bit like space capsules—for each pound of unnecessary deck space that can be trimmed from the structure, the magnitude of the structure needed to support it can be reduced. This is true for a guyed tower, a fixed platform, or a tension leg structure. Decreasing the wave load leads to lower overturning moments, a lesser requirement for pilings, and a smaller number of strength members in the structure. When this is accomplished, smaller launch barges can transport the structure to the work site.

In perspective, offshore structures include a great deal more than the towers and platforms. They include moored or mobile ships whose positions may be precisely controlled. They include the guy lines for compliant towers, the cables for buoys and for tension-leg platforms, and the associated pipelines without which the platforms and submerged oil production systems would be useless. Detailed descriptions of such installations may be found in the references at the end of this chapter. Of particular note is the review article on compliant offshore structures by Adrezin et al.(1996), with its 130 citations to the world literature on the subject up to the mid-1990s. For descriptions of current practice in all types of offshore installations, the reader is referred to the yearly conference proceedings such as found in the References at the end of this chapter.

This chapter begins with a short history of offshore structures, describes typical state-of-the-art installations, and concludes with a discussion of engineering challenges for future designs. Subsequent chapters address in some detail both the mathematical modeling and the environmental loading of offshore structures, together with ways to predict their dynamic responses and structural integrity, from both the deterministic and the statistical viewpoints.

1.1 HISTORICAL PERSPECTIVE

The earliest offshore structure for oil drilling was built about 1887 off the coast of southern California near Santa Barbara. This was simply a wooden wharf outfitted with a rig for drilling vertical wells into the sea floor. More elaborate platforms supported by timber piers were then built for oil drilling, including installations for the mile-deep well in Caddo Lake, Louisiana (1911) and the platform in Lake Maracaibo, Venezuela (1927). Soon after these early pier systems were built, it became apparent that the lifetime of timber structures erected in lakes or oceans is severely limited because of attacks by marine organisms. For this reason, reinforced concrete replaced timber as the supporting structure for many offshore platforms up to the late 1940s. Over the next 50 years about 12,000 platform structures were built offshore, usually of steel but more recently of precast concrete. The chief features of these structures, together with their supporting components such as mooring systems and pipelines, are discussed in this chapter. See also Gerwick (1999) and Will (1982).

Offshore mooring systems have a variety of configurations. All have anchors or groups of piles in the seabed with flexible lines (cables, ropes, chains) leading from them to buoys, ships, or platform structures. The function of a mooring system is to keep the buoy, ship, or platform structure at a relatively fixed location during engineering operations. Engineering efforts in mooring systems have focused in recent years on the development of new anchor configurations with higher pullout loads, larger capacity and lower cost of installation for deeper water applications.

When pipelines were first laid offshore, no extraordinary analyses or deployment techniques were needed since they were in shallow water and were of small diameter, somewhat flexible, and made of relatively ductile steel. As platforms were built in deeper and deeper water with multiple well slots, larger diameter pipelines of higher strength were required. During the 1960s, engineers met this challenge with new designs and with refined methods of analysis and deployment. Pipeline systems evolved into two main types: sea floor and vertical configurations. Both are used to transport gas and oil, but the vertical systems also include risers to carry drilling tools, electric power lines, dredge pipes for deep sea mining, and cold water pipes (CWP) for ocean thermal energy conversion (OTEC).

Throughout the world there are at present about 80,000 km of marine pipelines. Since 1986, the rate of building new marine pipelines has been about 1000 km per year. Individual pipelines on the sea floor vary in length from 1 to 1000 km and in diameter from 7 to 152 cm. For instance, a Norwegian project features a 1000 km line extending from the Troll field to Belgium, which was completed in 1992. At present, Kuwait has the loading line of largest diameter, 152 cm. The pipelines of smaller diameter are used to transport oil and gas from wellheads, and those of larger diameter are used to load and unload oil from tankers moored at offshore terminals. The deepest sea floor pipelines at present are the 46 cm diameter gas lines in the Gulf of Mexico, for which the

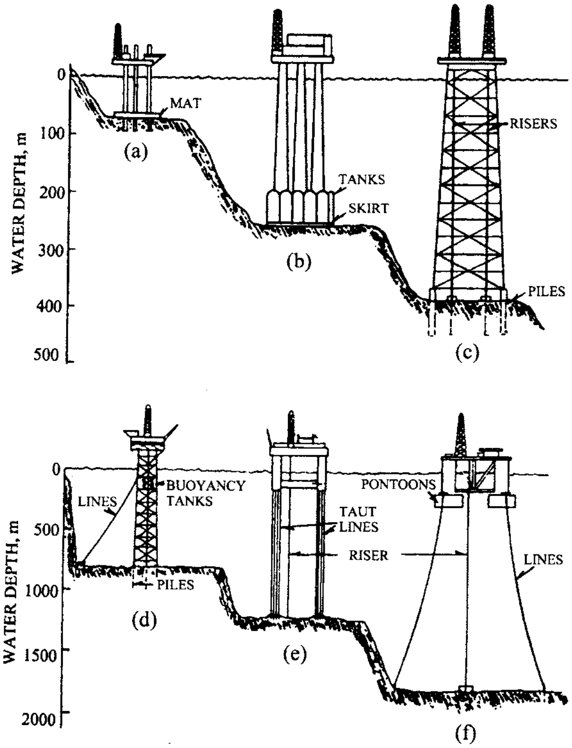

Figure 1.1 Six offshore platforms at their maximum depths: (a) jackup rig; (b) gravity platform; (c) jacket structure; (d) compliant tower; (e) tension leg platform; (f) semisubmersible.

maximum depth is 1400 m. Sea floor pipelines are often anchored to the seabed or buried in trenches for protection from erosion and the undermining effects of currents. Some seabed pipelines have a coating of concrete to add protection and to reduce buoyancy.

Figure 1.2 A mat-type jackup rig at a Louisiana dock.

1.2 PLATFORMS

Six general types of offshore platforms are depicted in Figure 1.1. The first three are designed for depths up to about 500 m, and the last three are for depths to 2000 m. Not shown are subsea production platforms, which are presently rated for 3000 m depths.

Fixed-Bottom Platforms

A mobile structure often used for exploratory oil-drilling operations is the self-elevating platform commonly called a jackup or mat-supported rig. A constructed version of this platform, depicted schematically in Figure 1.1a, is shown in Figure 1.2. Typically, such a platform is supported by three to six legs that are attached to a steel mat resting on the sea floor. In soft soils, the legs pass through the mat and may penetrate the soil to depths of up to 70 m. To the bottom of each leg is attached a steel saucer or *spud can* to help stabilize the structure and to minimize leg penetration into the soil. The height of the platform above the seafloor, up to 100 m, may be adjusted by using motor drives attached to each leg.

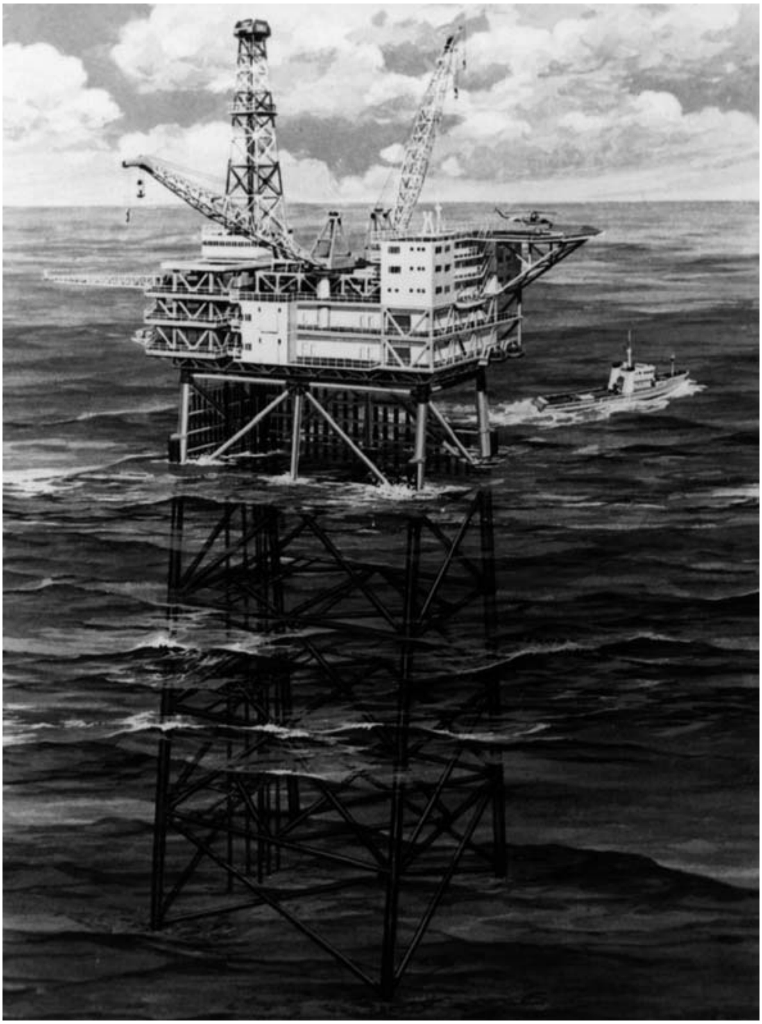

Figure 1.3 A jacket-template platform (courtesy of IHI Co. Ltd., Japan).

A platform designed to be used in a fixed location as a production unit is shown in Figure 1.1b. Such a unit, called a gravity platform, consists of a cluster of concrete oil-storage tanks surrounding hollow, tapered concrete legs that extend above the water line to support a steel deck. See Graff and Chen (1981). A typical unit, of which there were 28 operating in the North Sea in 1999, has one to four legs and rests directly on a concrete mat on the sea floor.

With ballast consisting of sand in the bottom of the tanks and seawater in the legs, these structures depend on self-weight alone to maintain an upright position when subjected to the highest waves that are expected to occur in a 100 year time period. A realistic 100 year wave that may occur in the northern North Sea is 27.8 m. At present, the largest concrete gravity platform is the Troll structure, and one of moderate size is the Statfjord-A Condeep structure, both located in the North Sea. The latter structure is 250 m high and has three legs. Located off the coast of Norway, the Statfjord-A Condeep unit has slots for 42 oil wells that reach to depths of 2800 m. When in operation, it accommodates a crew of 200 people who live and work on this structure.

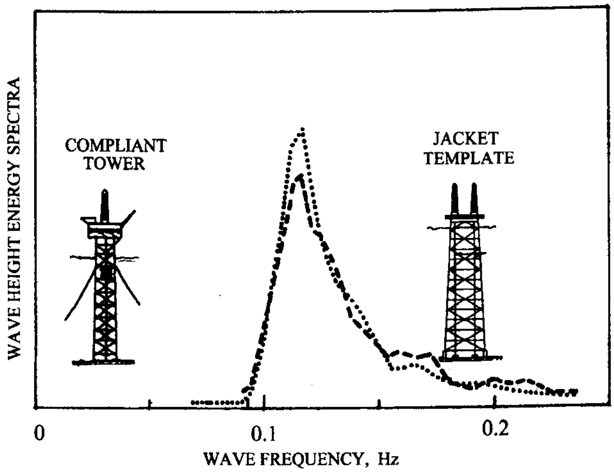

Figure 1.4 Two storm wave height spectra in the Gulf of Mexico, showing two offshore structures with natural frequencies beyond the frequencies of the highest energy waves.

Found more frequently among the permanent, fixed-bottom structures, however, is the steel truss or jacket template structure shown schematically in Figure 1.1c, where an installed structure is depicted in Figure 1.3. As for the gravity platform, each steel jacket unit is designed for a fixed location and a fixed water depth. The first such structure was operational in 1955 in water 30 m deep. By 1999 there were approximately 6500 jacket structures, the tallest of which was the Bullwinkle unit located in the Gulf of Mexico. The common characteristics of these jacket structures are their tubular legs, somewhat inclined to the vertical, and reinforced with tubular braces in K or X patterns. Piles driven through these legs into the sea floor and clusters of piles around some of the legs maintain structural stability in adverse weather. One of the largest jacket structures is the 380 m high Cognac unit, which has 10 legs with 24 piles extending 140 m into the soft clay of the Gulf of Mexico. As with all jacket template structures, its natural or fundamental bending frequency of 0.17 Hz is *above* the 0.11 Hz frequency of the highest energy sea waves in the Gulf of Mexico during storm conditions, as depicted in Figure 1.4.

Compliant Platforms

An alternative class of offshore structures meant for depths from 300 to 800 m is the compliant tower such as that shown in Figure 1.1d. Such a tower may or may not have mooring lines. It is a pile-supported steel truss structure designed to comply or flex with the waves and has considerably less structural material per unit height when compared with a common jacket template tower.

The first compliant tower was the Lena, which was installed in the early 1980s in the Gulf of Mexico. Including its three-level drilling and production deck and its drilling rigs, this tower reaches a total height of 400 m. Each of the 20 stabilizing cables, attached 25 m below the water line and arranged symmetrically about the structure, extends a horizontal distance of about 1000 m to a line of clumped weights that rest on the sea floor, to an anchor cable and an anchor pile. Under normal weather or small storm conditions, the cables act as hard springs, but with severe storms or hurricanes, the cable restraints become softer or compliant. That is, the amplitude of tower rotation increases at a rate greater than that of the loading, since the clumped weights lift off the sea floor to accommodate the increased storm loads on the tower. When storms or hurricane conditions are anticipated, operations on compliant towers cease and the crew is evacuated.

Installation of the Lena cables was more difficult and costly than anticipated. Subsequently, compliant towers without cables have been designed by Exxon, and two such designs were installed in 1999 in the Gulf of Mexico. Unlike the jacket-template structures, the compliant towers have natural frequencies in bending or sway near 0.03 Hz, or well *below* the 0.05 Hz frequency of the highest energy sea waves in the Gulf of Mexico during storm conditions. Thus, an important feature of such structures is that they are designed to have natural sway frequencies well removed from the frequency range of the highest energy waves for normal seas (0.1 to 0.15 Hz) and for storm seas (0.05 to 0.1 Hz). This frequency spread is necessary to avoid platform resonance, which can lead to failure. The sway frequencies of two platforms in comparison to the frequency range for the spectrum of the highest energy storm waves in the Gulf of Mexico are depicted graphically in Figure 1.4. The measurement and meaning of this wave height spectra, which is highly site-dependent, will be discussed in detail in subsequent chapters.

Buoyant Platforms

The tension leg platform (TLP) can be economically competitive with compliant towers for water depths between 300 m and 1200 m. The schematic design of the TLP is depicted in Figure 1.1e. In such designs, the total buoyant force of the submerged pontoons exceeds the structure's total gravity or deadweight loading. Taut, vertical tethers extending from the columns and moored to the foundation templates on the ocean floor keep the structure in position during all weather conditions. The heave, pitch, and roll motion are well restrained by the tethers; but the motions in the horizontal plane, or surge, sway, and yaw, are quite compliant with the motion of the waves. The first production TLP was built 150 km off the coast of Scotland in the mid-1980s. Conoco installed the Julliet in 1989, and Saga Petroleum installed the Snorre near Norway in 1991. The tethers for the Snorre are 137 cm in diameter. By the late 1990s, a total of eleven TLPs were installed, three in the North Sea and eight in the Gulf of Mexico.

For water depths of about 1500 m, a subsea production system provides an excellent alternative to a fixed surface facility. Much of a subsea system rests on the ocean floor, and its production of oil and gas is controlled by computer from a ship or other buoyant structure above the subsea unit. The buoyant structure and the subsea unit are often connected by a marine riser, which will be discussed presently.

Figure 1.5 A semisubmersible platform (courtesy of the builder, Mitsubishi, Ltd., Tokyo and the owner, Japan Drilling Co.).

A popular buoyant structure is the floating production system. Such a structure is practical for water depths up to 3000 m, and also at lesser depths where the field life of the structure is to be relatively short. An example of a buoyant structure is the semisubmersible with fully submerged hulls, shown schematically in Figure 1.1f , with an installed design shown in Figure 1.5. Other examples include ships converted to floating production systems. In the late 1960s, companies initiated research and design for these semisubmersible, multihull tubular structures and ships that would remain relatively stable in rough seas. In the late 1990s, the first three draft caisson vessels, or *spars*, were installed for use in 180 m water depths. Spars are floating vertical cylinders that support production decks above storm waves. These structures are controlled to remain essentially still in stormy seas. Some need to be towed from place to place; others are self-propelled. During drilling and production operations, these structures are kept in place with mooring lines and thrusters. The computer-controlled thrusters monitor the mooring line forces and accurately position the structure over the wellhead. One of the first semisubmersible structures was the Sedco 709 with a water depth rating of 1800 m. By the year 2000, semisubmersibles using dynamic positioning were designed for 3000 m water depths.

1.3 MOORINGS

Temporary Anchor Moorings

A classical example of temporary offshore mooring is the spread mooring configuration for a ship in relatively shallow water. Six to eight cables of wire rope or chain are unreeled from onboard winches symmetrically placed around the perimeter of the ship. Tug boats aid in spread mooring installations. In place, each cable hangs as a catenary curve and is attached either directly to a drag embedment anchor in the seabed or to a buoy that is anchored. An example of a spread mooring configuration is shown in Figure 1.6. Particular mooring configurations were reported by Baar et al. (2000) and O'Brian and Muga (1964).

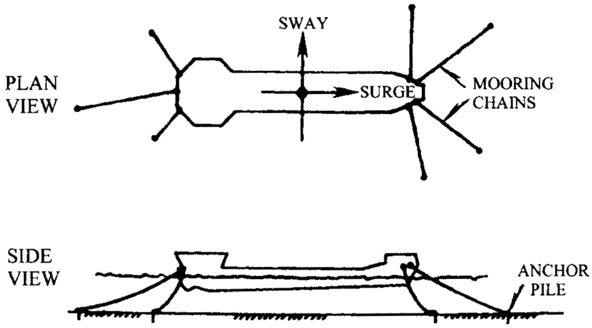

Figure 1.6 A spread mooring configuration.

In a typical spread mooring operation for a semisubmersible in deep water, a work vessel transports each anchor while pulling out its cable attached to the semisubmersible. The vessel lowers the anchor and installs a locating surface buoy just above it. At present, temporary systems for semisubmersible drilling rigs and construction barges are used in water depths of up to 2000 m. An example of an early and successful drilling rig is the Ocean Victory installed at a water depth of 450 m. This rig employed 12 anchors, each with a holding power of 200,000 newton (N) or about 45,000 lb. Each catenary line was about 2500 m long and consisted of two equal segments: one of 8.9 cm diameter steel wire cable and the other of 8.3 cm diameter chain. Newer generation rigs designed for deep water have ten times the anchor-holding capacity of the Ocean Victory. An anchor design based on suction is shown schematically in Figure 1.7.

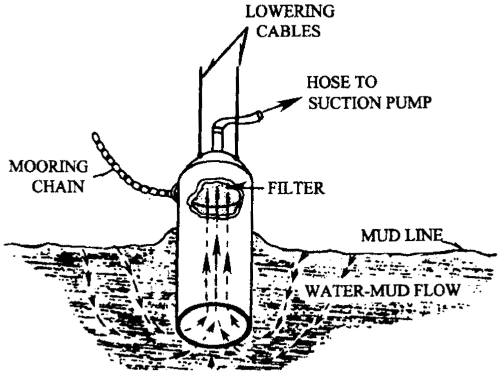

Figure 1.7 A suction anchor showing water flow during embedment.

Platform Pile and Single-Point Moorings

For installing piles for platform moorings, specially fitted derrick barges may use hydraulic hammers, drilling equipment, or possibly a jetting system. In jetting, seawater is forced around the base of a pile, blasting away the soil to make way for pile embedment. When installing mooring piles for tension leg platforms, template structures are carefully positioned at the site, and piles are hammered through the template that serves as a pile guide. Suction piles are employed in deep water where the use of hydraulic hammers is impractical or too costly. Suction piles employ hydrostatic pressure to push the piles to full penetration.

Single-point mooring (SPM) systems are designed to accommodate deep-draft tankers while they transfer crude oil and fuel oil to and from shore. Two typical designs are shown in Figure 1.8: the single anchor leg mooring (SALM), and the catenary anchor leg mooring (CALM). By the year 2000, there were about 50 SALM systems and 150 CALM systems in operation throughout the world. Their common features are the rotating head on the buoy and the vertical chain that anchors the buoy to the sea floor. While a few SALM systems may have taut mooring lines for added buoy stability, all CALM systems have multiple catenary lines (anchor legs). A third type of SPM system, the articulated column, has been designed and laboratory-tested but has yet to be installed offshore.

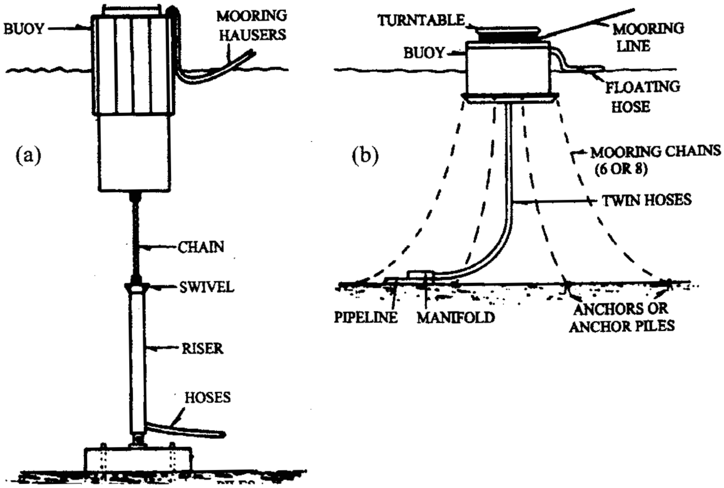

Figure 1.8 Two single-point mooring systems: (a) a single anchor leg mooring (SALM); (b) a catenary anchor leg mooring (CALM).

Successful SPMs are found at the world's largest terminals. One of these is Saudi Arabia's Ju'aymah exporting terminal, which has two SALM buoys and four CALM systems. For this SPM system, crude oil and fuel oil are loaded simultaneously to a moored tanker through the swivel assembly on the seabed. A second example is the CALM system for service vessels associated with the Cognac platform in the Gulf of Mexico. This SPM buoy has 12 catenary lines, each anchored to 0.76 m diameter piles. The water depth here is 275 m.

1.4 PIPELINES

Sea Floor Pipelines

Most of the 80,000 km of offshore pipelines have been installed by one of the following three methods. In these methods, the deployed pipeline forms an S-shape between the vessel and the sea floor.

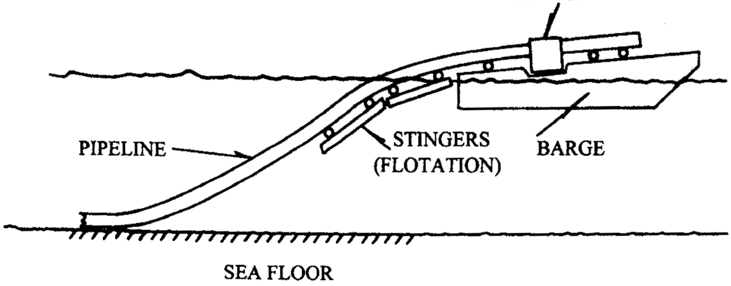

Figure 1.9 The laybarge method of pipeline construction offshore.

1. *Laybarge method.* Pipe sections, which sometimes have been coated previously with concrete for protection, are welded together on the deck of a barge and deployed on rollers over the stern. Near the stern, the pipeline passes over pontoons called stingers that relieve excess bending in the pipeline as it is deployed to the seabed. See Figure 1.9.

2. *Reel barge method.* Small to medium diameter pipe sections (up to 41 cm in diameter) are prewelded and coiled onto a reel mounted to the deployment vessel. As the pipeline is unreeled at sea, it passes through straightening rollers and then deployed as in the laybarge method.

3. *Bottom pull method.* Pipe sections are assembled on shore, and the pipe string is towed into the sea by a barge. During the launch to its place on the seabed, pontoons are often used under the string to avoid excess pipeline bending.

The following two methods of pipeline deployment have been studied extensively but have yet to be used.

1. *J-lay method.* A dynamically positioned vessel such as a drill ship, a converted pipelaying vessel, or a semisubmersible may be used in this operation. On board the vessel a derrick is used to hold the pipeline vertically as it is lowered, and the pipeline forms a J-shape between the vessel and the seafloor. An efficient single station pipe welding procedure has to be developed before this method can be adapted to common practice.

2. *Floating string method.* According to this concept, the pipeline is floated on pontoons at the water surface. Then the pontoons are released successively so that the pipe string gradually sinks to the sea floor.

Vertical Pipelines

One type of vertical offshore pipeline is the marine riser, which is shown for several of the structures in Figure 1.1. Although marine risers make up a fraction of the 80,000 km network, they are nonetheless key components of offshore structures and serve a variety of functions. For example, a riser may contain a bundle of smaller pipelines connecting a wellhead to its platform, or it may transport oil directly from its platform to a sea floor pipeline. A riser may act as a drilling sleeve, or it may contain electric power lines for operating seafloor mining vehicles or other subsea facilities. A typical drilling riser, with a ball joint at the bottom and a telescoping joint at the top, is maintained under tension to ensure stability and is kept to within 8 degrees of the vertical by computer-controlled positioning of its parent drilling vessel. In the mid-1980s, the longest riser was operating off the east coast of the United States, where depths of 2100 m were reached. At present, risers for depths approaching 3000 m are becoming a reality.

Vertical pipelines are used in deep-sea dredging operations. A most challenging engineering problem, which began to receive serious attention in the late 1960s, was that of designing dredge pipes to suck up and transport manganese nodules from depths of 3000 to 5500 m to the ship. See Lecourt and Williams (1971).These nodules, about the size of a man's fist and found in a