Installation of Submarine Pipelines

15.1 General

This Chapter will address the installation of submarine pipelines used for the transmission of petroleum products, gas, water, slurries, and effluents.

The diameter of steel submarine pipelines typically runs from 75 mm (3 in.) up to 150 mm (54 in.) with occasional lines running 1800 mm (72 in.). Diameters of steel pipe worldwide are often expressed in inches, even though all other units are metric; this is due to their historical tie to the U.S. petroleum industry.

The steel for these lines is usually of relatively high yield strength, 350–500 MPa (50,000–70,000 psi), and is selected for weldability. Wall thickness will normally run from 10 to 75 mm (3/8–3 in.) with the upper limit again being constrained by weldability.

Almost all steel pipelines have been joined by full-penetration welds, especially in the petroleum industry, where pressures typically run 1500 psi (10 MPa) and leakage of oil or gas is unacceptable. Consideration is being given, however, to the use of mechanical joints, for example, joints similar to those used with well casing. Developmental work continues on explosively and hydraulically expanded connections. In a few cases, flanged connections are used, but these are for lower pressures, which are used in off-loading of tankers.

Since most submarine pipelines are installed empty, they are subjected during installation to high hydrostatic pressure, along with whatever bending may be taking place. They are laid under axial tension. Buckling under combined loading becomes a principal design consideration. Tolerances are consequently of great importance, out-of-roundness and wall thickness being the most critical.

The steel is protected from external corrosion by coatings such as bitumastic or epoxy, supplemented by cathodic protection, usually sacrificial anodes. Internally, the line may be uncoated if it is to be in petroleum service, or it may be internally coated with epoxy, polyurethane, or polyethylene or cement lined when it will carry seawater or corrosive substances. The external coating may be further protected from abrasion by concrete or fiberglass wrapping. To give stability to the line when in service, especially those lines which must be emptied at some stage of their life or which carry a low-density material like gas, the line must have net negative buoyancy. This is usually supplied by concrete weight coating (which can also serve to protect the anticorrosion coatings) or by increasing the wall thickness of steel (see Figure 15.1). A number of pipelines have experienced “floating up” off the seafloor due to spalling and shedding of their concrete coat. This indicates that the reinforcing mesh may have been underdesigned or that the pipelines may have been subjected to excessive overstress during installation.

The latter is within the purview of this book. It appears that most such cases of damage have occurred during the more severe sea states when the pipe laying barge was subjected...
to severe dynamic surge. If the coating was not only cracked but delaminated from the pipe, then transient pore pressures under the storm waves break the coating off in progressive failure. This type of failure has occurred a number of times during pipe-pulling operations. The most obvious solution is to increase the amount of circumferential reinforcing in the coating. Since the coated pipe is usually furnished by the oil company, this obviously presents a contractual problem to pipeline installation contractors. Nevertheless, contractors may often find it in their best interests to verify the amount of circumferential reinforcing and, where necessary, recommend increased reinforcement.

Pipelines are basically designed to lie on the seafloor or in a trench in the seafloor, with more or less continuous support. However, unsupported spans may occur in rough, rocky seafloors or where the sands move under the action of currents and waves. The designer will have set limits on the unsupported span lengths, which the contractor must not exceed; this may require either prior seafloor leveling or post-installation support.
Lines are buried beneath the seafloor in many areas of the world to protect them from fishing trawl boards, from dragging anchors, and from fatigue due to vortex shedding in a current. Usually, the trenches are backfilled with the excavated soil or covered with rock, but in many cases, natural sedimentation is counted on to fill the trench. Cyclic oscillation of pore pressures due to the passing of long period wave crests and troughs may “pump” the pipeline out of the trench. For this reason, pipelines in the North Sea are laid in trenches that are then filled with crushed rock.

As noted earlier, the pipeline usually sees its most severe stresses during installation; thus, very close integration is required between the designer and the installation contractor. The designer needs to be aware of and to address the needs of the contractor during installation. The contractor, conversely, must be aware of the limitations and constraints imposed by the installation procedures, taking into account the sea state (waves and current), the varying water depths, and the varying seafloor.

In addition, all parties must be cognizant of other pipelines, cables, and facilities in the area, recognizing the tolerances in location both of the previously laid lines and facilities, and the tolerances that are inherent in the contractor’s procedure for the new line.

Submarine pipelines are typically laid in a “corridor” whose centerline and width are given by the client and shown on the approved permit. The installation contractor must have an adequate survey system to enable the contractor to comply. This system is usually an electronic positioning system or real-time differential GPS but may include lasers, ranges, and preset spar buoys.

The installer must verify to the satisfaction of the client and the regulatory body that the line has been satisfactorily installed. Externally, this is done by side-scan sonar and ROVs, using video or acoustic imaging. Internally, the line is pigged and then tested with hydrostatic pressure to a pressure in excess of the design pressure.

A pipeline “pig” is a short cylinder, of slightly smaller diameter than the pipeline, with several sets of squeegee wipers. When the pig is entered in the pipeline and excess pressure is applied to one face, it travels along the pipeline. The diameter of the pig and its length verify that there is no dent, crimp, or buckle more than the small annular space. The squeegees restrict the loss of pressure yet allow the pig to move. The pig is usually equipped with an acoustic transponder or radioactive marker so that if it does get stuck, its position can be determined. For short lines, an umbilical line “fishing line” can be unreeled behind it (see Figure 15.2). Guidance for the design and installation of submarine pipelines is given in the DNV Rules for Submarine Pipeline Systems.

Many methods of pipe laying have been employed, selected on the basis of environmental conditions during installation, availability and cost of equipment, length and size of line, depth of water and constraints of adjacent lines and structures. The following are those most commonly employed:

1. Conventional S-lay barge (see Section 15.2)
2. Bottom-pull method (see Section 15.3)
3. Reel barge (see Section 15.4)
4. Surface float (see Section 15.5)
5. Controlled subsurface float (see Section 15.6)
6. Controlled above-bottom pull (see Section 15.7)
7. J-tube from platform (see Section 15.8)
8. J-lay from barge (see Section 15.9)
9. S-curve with collapsible buoyancy (see Section 15.10)
These lines have almost all been installed empty, so as to reduce the weight. The exceptions have been small-diameter lines in relatively shallow water. When laid empty, the pipe must have an adequate wall thickness to withstand the combined stresses, that is, longitudinal installation force, plus the circumferential hydrostatic force, plus bending. These will be described in the following sections.

### 15.2 Conventional S-Lay Barge

The offshore lay barge has grown up from the specially modified cargo barge of the 1950s to become one of the most sophisticated, efficient, and expensive vessels in the world. Lay barges are often characterized as first-, second-, third-, and fourth-generation to denote major “quantum jumps” that have been made in extending the ability to lay lines in deep water, with current achievements being the successful installation in depths over 1700 m in the Gulf of Mexico and in such adverse environments as the North Sea (see Figure 15.3). Also, See Chapter 22, Section 22.10.

First-generation lay barges have a conventional barge hull, with the pipe-laying assembly mounted on one side. The stinger is hinged but rigid. The inclination of the stinger is controlled by buoyancy tanks at the outer end. Second-generation lay barges have a semisubmersible hull, with the pipe laying assembly on one side and an articulated stinger. Third-generation lay barges lay pipe on the centerline, over a fixed cantilevered stinger. First-, second-, and third-generation barges all have deck engines and mooring lines. Fourth-generation lay barges use dynamic thrusters and a fixed cantilevered stinger. They are usually equipped for both S-lay and J-lay operations. These arbitrary distinctions are descriptive of the rapid advances that have been made in pipe laying technology.

The lay barge is a system that comprises the following principal operations and systems:

1. Seaborne work platform vessel
2. Mooring and positioning systems, either lines or dynamic positioning
3. Pipe delivery, transfer, and storage facilities
4. Double-ending of pipe, conveying to lineup station, and lineup equipment
5. Welding of joints
6. X-ray
7. Joint coating
8. Tensioning of line during laying
9. Support of line into water either by “stinger” or cantilevered ramp
10. Survey and navigation
11. Anchor-handling boats
12. Communications
13. Personnel transfers—helicopter and crew boat
14. Diver or ROV for underwater inspection
15. Control center
16. Crew housing and feeding
17. Power generation
18. Repair facilities and shops

A typical second-generation lay barge is shown in Figure 15.4. The layout of equipment is shown in Figure 15.5 through Figure 15.7. The basic operations of the lay barge can be outlined as follows:

1. The lay barge is positioned on its anchors, eight to twelve in number, holding it aligned with the pipeline route, with a “crab” or slight orientation angle as needed to accommodate the effects of the current. Its position is determined by an electronic positioning system or GPS, augmented by laser in some cases. Its orientation is by gyroscope.
2. The anchors will be progressively moved forward as the laying takes place, usually in 500–600 m jumps. One anchor-handling boat on the starboard side will move each anchor ahead in succession; another anchor-handling boat will move each of the port anchors ahead in succession (see Figure 15.8).
FIGURE 15.4
Second-generation pipe-laying barge.

FIGURE 15.5
Layout of equipment on third generation lay barge. (Courtesy of Western Gear Corp.)
FIGURE 15.6
Equipment on third generation lay barge. (Courtesy of Western Gear Corp.)

FIGURE 15.7
Arrangement of conveyors and winches at line-up station. (Courtesy of Western Gear Corp.)
Typically, the anchor-handling boat maneuvers close to the anchor buoy to enable the deckhand to hook an eye in the end of the pendant. The deckhand attaches a wire line from the deck engine of the tug, which either pulls the buoy aboard or pulls the pendant through the buoy, thus lifting the anchor clear of the bottom 5 m or so. The boat then runs forward, setting the anchor as directed in its new position and releasing the buoy. The boat turns outboard and goes back for the next anchor in the cycle. The new position of the anchor is given by voice radio command from the control house, which is based on radar, gyro, and the reading on the remote mooring line length counters, reading the line length paid out by the winch.

Anchor handling is a very dangerous operation. Hydraulically operated ramps and booms have been developed to enable these operations to be carried out safely. The proper paying out and taking in of each mooring line on the winch drum is monitored by video in the control house to ensure against crossed lines on the drum or fouling of the line.

3. From a supply boat or barge alongside the port side, the crawler crane on the lay barge snags (picks) one pipe length (12 m) at a time, turns, and sets it in storage. From storage, the crane picks a pipe length and sets it on the end-O conveyor, which moves it to the transverse conveyor at the bow. This conveyor feeds it onto the lineup station, where it is positioned, usually semi-automatically, in correct alignment and then run forward to the end of the preceding segment (see Figure 15.9).

4. The internal lineup clamp positions it in exact spacing and holds it for the hot-pass weld.

5. The hot-pass weld is made and ground or gouged (see Figure 15.10).

6. The segment moves forward successively to weld stations 2, 3, and 4, with one or more passes being applied at each station, and then chipped or gouged.

7. The fully welded line now passes through the tensioner, where it is gripped by polyurethane cleats on caterpillar-like treads. Hydraulic rams push the pads against the coating, adjusting their pressure so as not to deform the pipe or crush.

FIGURE 15.8
Typical lay barge operational spread. (Courtesy of Western Gear Corp.)

Note: Numbering of anchor lines varies on different barges.
the coating, while still developing frictional resistance. The tensioners run on torque converters or similar devices to pay out under a set tension. This tension or tensioner typically has a rather wide tolerance on external pipeline diameter (see Figure 15.11).

8. The joint now goes to the x-ray station, where it is x-rayed, and the films are developed and checked. If a flaw is found, it must be cut out, re-welded, and re-x-rayed. For a cutout, the barge must be moved astern and the line brought back up on board one or two lengths so that the cutout is forward, i.e., on the untensioned side, of the tensioner.
9. The pipe section now moves astern, where the joint is coated with the special corrosion-protective coating. A bracelet of zinc–aluminum or other anode is affixed. Concrete mortar coating is applied to protect the corrosion-protective coating at the joint. This fresh concrete is protected by a sheet-metal wrap-around (see Figure 15.12).

10. The completed pipeline now passes down the ramp and over the stern of the barge and bends downward. This downward bend is called the “overbend” (see Figure 15.13).

11. The line rides down the stinger or ramp to a point of departure, where it leaves the stinger due to the tension in the line. The stinger has a hinged connection to the barge. It has built-in flotation to support the pipeline while still allowing a downward inclination and some flexibility to accommodate surge. The stinger may be articulated to permit continuous curvature or may have a fixed vertical curve. Load cells on the roller supports, plus depth indicators such as bubble gauges, enable the stinger to be ballasted for optimum support.

12. The line now moves downward through the water and bends back to the horizontal at the seafloor. This bend is called the “sag” bend. At this bend, the pipeline is usually subjected to its maximum stresses and potential buckling due to the combined axial tension, vertical bend, and circumferential hydrostatic pressure.

13. As the line lays out on the seafloor, its integrity is checked either by divers and video or by ROV.
From the above sequence, it can be seen that the typical lay barge system described at the beginning of this section has the following physical components:

- Lay barge
- Anchor-handling boats (usually two)
- Supply boats (usually three) or supply barges (usually two) with tug
- Helicopter service and/or crew boat
- Shore base
- Pipe storage racks
- Pipe conveyors
- Lineup station
- Internal line up device and clamp
- Welding stations
- Tracked tensioner
- X-ray equipment
- Joint-coating equipment
Constant-tension winch for abandonment and recovery
Stinger and stinger control
Winches with mooring lines
Control room
Radio circuits to shore and boats
Voice and indicator circuits to welding stations, stinger control, and x-ray
Gyrocompass
Radar
DGPS and/or electronic positioning
Tensioner force readout
Mooring line tension readout and video display
Mooring line length-out readout
Diver shack
Decompression tank

FIGURE 15.13
Pipeline in overbend, passing down stinger.
The crew required to operate an offshore pipe-laying vessel may be 150 or more per shift. Normal operations use two twelve-hour shifts. A third shift will be off on leave. Work schedule is usually two weeks on, one week off, or one week on, one week off.

Tension is maintained in the pipeline from the barge to the seafloor in order to reduce the vertical bending and the tendency to buckle. Values of applied tension range from a low of perhaps 100–150 kN (20,000–30,000 lb) in shallow water and calm seas to 300 kN (70,000 lb) or more in deep water and rough seas.

The lay barge is subject to dynamic surge motions, depending on the relationship between wavelength, barge length, and depth of water. This surge is usually too fast for the tensioner and the welder to follow. Thus, under low sea states, the pipe is locked in fixed position in relation to the barge. Therefore, the tension in the pipeline varies cyclically about the steady-state force. Typical ranges of variation are of the order of 100 kN (20,000 lb) each way in a moderate sea. Heave and pitch also have some effect on the tension, but generally to a much lesser degree than surge. This tension must also be introduced and maintained during the startup and lay-down of the pipe. The skill of the welders is critical to the operation. They are working on a rolling and heaving barge, often with a moving joint, yet must produce essentially perfect welds.

The actual performance of the welds is also of serious concern to the pipeline installation contractor, because of the responsibility to ensure a sound, leak-free pipe on completion. The combination of axial tension and overbend stresses on the weld are very severe, especially since the latter is dynamic. Not only the toughness of the weld itself is involved, but also that of the heat-affected zone (HAZ), which in turn is influenced by the parent steel quality as well as the welding procedures. The constructor may therefore find it prudent to test the pipe steel and welding procedures under dynamic tension loads prior to finalizing procedures.

In a typical offshore operation, the barge will move one pipe length every fifteen minutes. On the most modern third-generation barges, using advanced welding techniques and double- or triple-ended pipe joints, rates of a mile per day are achieved. This means that all the work must be completed at each station within that same time frame. This translates to 100 or more 12 m lengths per twenty-four-hour day. These performances have been exceeded by topnotch crews on good days, even with manual welding.

Stresses in the pipe in the laying operation are controlled not only by axial tension but also by the net submerged weight of the pipe. This latter is the difference between two large numbers, the one being the air weight of the pipe, the other being the buoyancy due
to the displaced volume. The major variable is the thickness of mortar coating, which affects both air weight and displacement, but not equally.

In a typical case, a pipe may have an air weight of 15 kN/m (1000 lb/ft.) and a displacement of 14.3 kN/m (950 lb/ft.) leaving a net (buoyant) weight of 0.7 kN/m (50 lb/ft.). If the coating increases the weight by 5%, the displacement may increase by only 2%. These numbers may sound small, but they develop an increase in net buoyant weight of 0.45 kN/m or a 60% increase in the force causing the bending. Thus, while weight control is normally not as critical with lay barge operations as it is with bottom pulls, it nevertheless is of great importance and must be monitored.

The pipe is generally furnished in double-random lengths, which are normally 12 m (40 ft.). Most sections will run 11.4–12.6 m. However, generalized pipe procurement specifications allow a few sections which vary widely from the norm, even as short as 3 m and long as 17 m. While this may be accommodated on land pipelines, it is unworkable at sea. Such sections should be cut or spliced to the normative length of 12 m (40 ft.) at the shore base, or else the procurement order should exclude these variances. Experienced pipeline contractors will require that the pipe be furnished in 40 foot (12 m) lengths, plus-or-minus 2 ft. (0.6 m).

As previously noted, rates of progress with third-generation lay barges may reach one mile per day or more. This means that one hundred or more sections must be loaded out each day from the shore base, transported to the site, and then unloaded to the deck of the barge. This last is a critical operation when the seas are running high and may, along with anchor handling, be the controlling operation. The transfer at sea of the pipe is a typical case of operations involving two vessels alongside each other, of different characteristics, each responding in its own way to the seas, in each of six degrees of freedom. The relative positions in plan can usually be maintained in a moderate sea state by tying the transport barge alongside the lay barge, with suitable fendering, so that the major individual responses are limited to heave, roll, and pitch. In heavier sea states, barges can no longer be kept alongside, and so supply boats are used. By running a line from the boat and keeping power on, a good skipper can hold the boat in reasonably close position, although now the boat will develop some relative sway, surge, and yaw motions as well as heave, pitch, and roll (see Figure 15.14).

The typical lay barge is restrained from lateral motion by the mooring lines; it is also moved periodically one pipe length ahead. These lines, while catenary in scope in deep water, are kept under tension by the winches. The line tensions are measured by tension meters on the wire rope or on the winch drum or both. In the typical second-generation lay barge, the tension may be 400 kN (80,000 lb) with a variance in a moderate sea of ±100 kN. This variance is due to the long-period sway plus surge built up by the waves, storing energy in the wire lines as the barge gradually moves to one extreme of its transverse range. The lines on the far side gradually become more taut, so that eventually the barge changes direction and starts its sway excursion to the other end of the range. The sudden reversal at the end of its excursion causes a shudder effect in the overall system, and translates into a severe horizontal whip of the stinger and of the pipe. The surge excursions cause cyclic bending in the pipe at the overbend and in high sea states can lead to low-cycle fatigue in the pipe.

The mooring lines must provide the horizontal and longitudinal restraint against wave drift, wind drift, and current drift. They also react against one another and especially must counter the tension on the pipe, which in effect is like a mooring line of relatively equal tension, leading directly astern. Balancing out the tensions in eight to twelve mooring lines plus one pipeline is a complex problem, especially when these line forces are not steady but subject to the significant ranges introduced by the long-period excursions.
Typically, the tensions in the mooring lines are set so that under the maximum design surges, the force will not exceed 50%–60% of the guaranteed minimum breaking strength. To offset the pipeline tension requires additional mooring line forces in the lines leading forward. The system must be balanced, which is difficult enough with one positioning of the anchors, but which is rendered more complex due to the constant lifting and relocation of anchors. The system can be satisfactorily resolved by preparing calculations of typical and extreme positions for each permutation; it, of course, lends itself to the use of an on-board mini- or microcomputer, which can then solve for intermediate situations. The most modern lay barges (of this generation) use dynamic positioning by means of thrusters to maintain lateral position and heading. These are controlled by computer and connected to the GPS system. However, reaction lines to the pipe tension, usually two forward leading lines, are usually still required because of the large forces involved when laying by the S-curve method, especially in deep water for which high tension is required in the pipeline. Dynamic thrusters eliminate the long-period sway and the consequent kick back of the barge, making it practical to continue welding operations in higher sea states.

The cost of pipe laying is related to the progress, since the cost per day is more or less the same whether any pipe is laid or not. The rate of progress has until recently been controlled by the time required for welding. There is a specific amount of weld metal, which must be applied. Only two welders (one on each side) can work at any station. Therefore, the rate of progress depends on the number of stations. Typically, these are placed one pipe length (40 ft.) apart. There is only room enough for a certain number of welding stations on a barge; therefore, the longer the barge, the greater the rate of progress. This explains why prior double-ending of the pipe does not speed the operation. Another means of accelerating the welding is by the use of microwire welding, but this is usually only acceptable in hot climates because of the dangers of cold lap at lower temperatures.

FIGURE 15.14
Third generation pipe lay barge. (Courtesy of Exxon.)
The biggest jump in pipe-laying progress has come with the introduction of automatic welding of one type or another. Dual-torch automatic welding equipment, riding on a self-propelled carriage, can complete quality welds at a high rate, even in rough seas. The operation is fully computer controlled.

Second-generation lay barges are limited by the sea state. When the significant wave height exceeds about 8 ft. (2.54 m), operations must shut down. The specific limit, of course, depends on the relative direction and the period of the waves, as well as the barge length and width. The limiting item is usually control of surge and the interaction between stinger, pipeline, and barge. The working limits can be increased by using a wider and longer barge, by using more powerful tensioners, and by using a fixed cantilever stinger.

When seas reach 10–12 ft. ($H_s = 3–3.5 \text{ m}$), other constraints arise. Anchor-handling boats can no longer pick up the anchor buoys, although this limit has been extended by clever arrangements enabling the boat to run past the buoy and snag it rather than having to back down for the deckhand to make fast to the pendant. Pipe transfer from a barge alongside is no longer practicable with an $H_s$ of 2–2.5 m, but a supply boat can be used to extend this operation to the 3- to 4-m range.

The barge motions in roll and long-period sway (snapback) become too severe in higher sea states, especially with a beam or quartering sea, and the welders are unable to produce quality welds. The pipe starts to jump out of the stinger, and there is danger of buckling the pipe. Even with dynamic positioning, the long-period surge causes severe variations in the pipeline tension and profile.

At this stage, a decision must be made whether to hold on or to initiate abandonment procedures. The major factor here is the weather prediction. If improvement is forecast within the next few hours, it may be practicable to hang on, maintaining tension. Another factor is whether or not the anchors will hold in the seafloor soils or are likely to drag; a dragging anchor will almost always lead to a buckle.

When abandonment is decided, a bull plug (cap) is welded onto the pipe. A line from the constant tension winch is attached. A buoy and pendant are also attached to the bull plug. It is a good precaution also to attach an acoustic pinger to the bull plug. The barge then moves ahead, paying out on the line, until the pipe is fully lying on the seafloor. The end of the constant-tension line is buoyed and run off. The barge can now pick up its anchors to move to a sheltered location or decide to ride the storm out at sea, on its anchors, but turned now to head into the sea.

When the storm ends, the barge moves back to location and resets anchors. While one hopes to find the buoys, it is not unusual for them to have been torn away by the storm. That is when the acoustic pinger is needed.

The constant-tension line is now pulled on-board and the tension applied. The barge slowly moves astern, bringing the pipeline back up onto the stinger. A line from the crane may have to be hooked on (by diver) to help guide the line back onto the rolls of the stinger without fouling. Now the pipe is pulled on board, through the tensioner, until the bull plug reaches the lineup station; the bull plug is cut off, the pipe end re-beveled, and the laying operation recommences.

An important consideration is that abandonment procedures are almost always carried out under extreme conditions, at or above working limits, whereas recovery operations will normally be carried out in good sea conditions.

Earlier, it was stated that the most serious problem in pipe laying is a wet buckle. In the case of a dry buckle—that is, where the line does not take on water—the pipe can be just pulled back up on board. In the case of a wet buckle, however, the pipeline has been flooded and cannot be brought back on board without leading to progressive buckling. For this reason, at start-up, at least one pig was placed in a pig chamber at the start-up end, along with air fittings. If a wet buckle occurs, compressed air lines are connected and the
pig run along the pipe to the point of buckle. This empties the line so that it can be recovered.

Actually, there is one even more serious case, known as a propagating buckle. This is the case where the ovaling of the pipe at the point of initial buckle reduces the collapse strength below the resistance to the external hydrostatic pressure so that the buckle travels back along the pipe. While this case is usually within the province of the designer, the constructor must make sure that this cannot occur; else the entire line could be lost. Where calculations show this to be possible, buckle arrestors in the form of thicker pipe or reinforced pipe are installed at intervals of 1000 m or so. For example, wraparound plates may have been pre-installed. Sleeve-type buckle arrestors may be installed by fusion welding to the ends of a 12 m length of pipe or a thicker walled pipe segment used.

Occasionally, a line may be damaged after it has been successfully laid down. Often, this is due to an anchor dragging into the pipeline. It may even be an anchor from your own spread, that is, the barge or boats, or it may be from another contractor working on the same platform. The line must be repaired. One method is to use a hyperbaric chamber (a “habitat”) lowered down over the line and centered on the junction or repair point. Compressed gas is used to expel the water, and divers descend to make the weld in the gas atmosphere. The selection of the appropriate gas mixture is critical in order to ensure the proper weld quality. Such a repair in 100 m of water, for example, may require several days. It may be tended by the lay barge, but if the sea state permits, a smaller support vessel may be used.

The repair procedure consists of accurately cutting the lines and beveling their ends. A template is made to ensure an exact fit of a “pup” (a short, specially cut pipe section), which is fabricated on board and lowered down for welding. After the welds are completed, the joint is coated for corrosion protection. X-ray is usually not practicable, and reliance must then be placed on visual inspection and magnetic-particle or other NDT techniques to verify the quality of the weld.

Wet-welding techniques have been under development for many years; the problem, of course, is ensuring a weld that will be reliable under its working pressures, which typically are 10 MPa or so. At the present time, there is not universal confidence in the quality obtainable by wet-welding techniques, but development continues. Wet-connector devices are now commercially available, permitting some repairs to be made underwater mechanically.

In shallow water, the damaged section can be brought to the surface for a dry weld. The line should be empty, if possible, and a long length brought up so as not to exceed curvature limits in the pipe. For this reason, many shallow water lay barges are fitted with davits along one side, enabling lifting from the entire length of the barge. The derrick crane may also pick from the stern while the pipe transfer crane picks from the bow. Where this curvature is still too great, floats or buoys may be attached to give positive buoyancy along appropriate lengths of pipeline.

As the line is brought up, there are, of course, length-compatibility problems in all but very shallow water. It is sometimes necessary to cut the line, thus flooding the pipe. Once brought to deck level, the ends are beveled, a pup fabricated and installed, and the line laid back. Now the new line is longer than required, so it must be laid back to lie in a horizontal curve on the seafloor. The pig is now run to empty the pipe.

Installation of risers at platforms is another special operation requiring careful pre-planning of each stage. There are a number of methods which have been used successfully (see Figure 15.15):

1. The riser is pre-attached to the side of the platform. The end of the line, pre-laid on the seafloor but still empty, is pulled over to that same side of the platform by
means of a line rigged to maintain axial tension. Then, divers make a template of the intervening space and a pup is prefabricated and installed using a hyperbaric chamber lowered over the joint so that welds can be made.

Alternatively, with large-diameter pipe (e.g., 42 in. or greater), flanged connections may be used. The line is cleared of water, using a pig if necessary, and a welder descends in the riser to weld the joint from the inside.

Hydrotech has developed a two-piece diagonally flanged coupling which can be sleeved over the two pipe ends and then rotated to accommodate a difference in angle. A three-piece coupling can accommodate up to $15^\circ$ misalignment. After the joints are bolted up, they are seal-welded, using a dry chamber filled with inert gas.

Vickers has developed an explosive-welding method which is especially suitable for tie-ins between pipelines and risers. The explosion is initiated inside the pipe, forcing it out against the sleeve to give a solid intermolecular bond. The reliability of this method has not yet been fully accepted.

Advanced “pull-in and latch” connectors have been developed for deep-water connections.

2. In shallow water, the line is picked up by the davits along the starboard side. The derrick picks the riser so that it hangs just off vertical, at the proper angle to the pipe. The welded joint is made. The riser and line are then lowered back down to the seafloor, the riser coming into position along the jacket to which it is now
clamped. In moderately deep water, it may be necessary to add on to the riser from time to time, the so-called “stovepipe” operation. As the riser and pipeline are being lowered, the riser is stopped off from the position and a new length of riser added.

3. For smaller lines, such as flow lines, J-tube risers are built into the platform. The laying is started from the platform; the pipe is pulled off the lay barge and up into the riser tube by a line from the pipe and to a winch on the platform deck. The J-tube bends the pipeline in a permanent but controlled deformation around the 90° bend and then straightens the line with a small reverse bend.

4. For deeper lines, risers are pre-installed on the platform. Alongside is a riser pull-in tube. In some cases, a line may be led out through the riser. This line is then run to the lay barge. As the laying starts, the pipe end is pulled off the platform and to the mating joint, using a winch on the platform to pull in the line. Initial connection is made by bolted flange, followed by internal or external welding as described earlier.

For lines to be run ashore, there are also several alternatives:

1. A line may be separately pulled out from the shore through the surf zone. The lay barge now moves in just seaward of the end of the pulled line. With a line from the barge exerting axial tension, the shore line is pulled on board into the tensioner and the new pipe sections welded on. Now the standard laying can commence.

2. The lay barge moves into as shallow water as is safe. A wire line is run ashore to a winch on shore. As the lay barge makes up pipe, the winch on shore pulls the end to the shore. Then, the lay barge proceeds with its standard pipe-laying procedure.

3. The lay barge lays from the platform toward the shore. When it reaches shallow water, it lays the end of the pipeline down, then turns itself around and resets anchors. It now pulls a line out from shore. Using the davits, it picks up the end of the previous line, joins the two ends by welding, and relays the line on the seafloor in a horizontal curve to accommodate the slightly excess length.

Third-generation and later lay barges are indeed highly sophisticated systems, enabling pipelines to be laid in more severe sea states, up to $H_s$ of 5–6 m, and in deep water, up to 600 m and potentially more. Among the most advanced are the SAIPEM Castoro Sei, which successfully laid the lines from Tunis to Sicily, and the SEAMAC, now renamed the Bar 420, which laid the 36-in. FLAGS lines in the North Sea in record time (see Figure 15.16 and Figure 15.17).

Third-generation lay barges are more advanced:

1. A stable platform is provided, generally being a semisubmersible but in a few cases, a very long (over 200-m) ship-shape vessel.

2. The stinger is now fixed to the stern of the barge and cantilevered out behind in a long curve.

3. The pipeline is laid down the centerline, not down the side.

4. Higher tension is provided.

5. Advanced welding systems are employed to speed the welding process.

6. Dynamic positioning, using computer controls and GPS, is now utilized to control lateral positioning.
Fourth-generation lay barges incorporate the above improvements and in addition, lay in a near-vertical attitude. This is the J-lay method. The pipe lengths are double-or-tripled-jointed on board, then hoisted into a set of leads inclined to about 75° from the horizontal. The pipe is then
lowered to contact at deck level with the previously laid line and the weld is performed by an automatic welder. The line is then lowered through a tensioner into a moon-pool until it reaches near the seafloor where it deflects to the horizontal in a long sag bend (see Section 15.9). Dynamic positioning is employed, thus eliminating the problems of anchor relocation in deep water and the dynamic surge effects of energy stored in the mooring lines.

### 15.3 Bottom-Pull Method

The bottom-pull method has been developed and extensively used to install pipelines through the coastal zone, to extend out to loading terminals in deep water. It has been further developed in recent years as a means of installing relatively long lines in deep offshore areas.

Initial discussion will be directed to those lines that extend from shore out a distance of several thousand meters. The program is as follows:

1. The pipeline is assembled on shore in parallel segments of 200–300 m in length.
2. A launching ramp with roller supports is constructed, leading out through the inner surf zone.
3. The inner surf zone may be protected by a sheet pile cofferdam so that a trench will stay open.
4. The first 200- to 300-m length of pipe is made up on the launching ramp, with joints welded and coated (see Figure 15.18). Since the ramp is sloped to seaward, the pipe is restrained from longitudinal movement by a holdback winch at the landward end (see Figure 15.19). The seaward end is fitted with a nose section, consisting of pig storage for one or two pigs, a positively buoyant nose, and a swivel. A sheave may be attached seaward of the swivel, with supports or a buoyant tank to keep the sheave from flipping over during the pull (see Figure 15.20).
5. A pulling barge is anchored offshore, on line, at a distance of 1000 m or so.
6. On board, a very large winch is installed, one or two drums, having high pulling capacity, for example, 1350 kN (300,000-lb) line pull on a full drum (see Figure 15.21). This winch is connected by wire lines around equalizing

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**FIGURE 15.18**
Pipeline made up and joined on loading ramp. Note rail cars to reduce friction while pulling out. (Courtesy of H.V. Anderson Engineers.)
sheaves to two bow anchor lines, with large anchors set well out to sea (see Figure 15.22). If the deck of the barge is utilized for this transfer of reaction force, it may have to be reinforced or struts installed.

7. The winch line is now run ashore and connected to the nose of the pipeline. If two parts of line are to be used, the line is run around the sheave and back to the barge. Proper fairlead guides are used where the line runs off the edge of the barge in order to prevent chafing and wear.

8. When all is ready and the weather forecast is favorable, the first section of line is pulled out through the surf zone (see Figure 15.23). When its landward end reaches the shoreline, pulling stops and the pipeline is stopped off. The next
200- to 300-m length of pipeline is rolled sideways onto the launching ramp and the joint welded and coated. The next pull is made.

9. Now the barge itself must move seaward. Its anchors are reset. A third section is placed on the ramp, welded, and pulled. The pulling force is that needed to overcome friction.

Friction on the launching ramp can be reduced by the use of rollers or small railcars to support the pipe. The pipe here is in the air, thus having its full weight exerted on the ramp. Movement seaward can be helped by the use of side-boom cats or by an assisting caterpillar-tread tensioner being used in reverse to push the pipe out. As noted earlier, initial sections of pipe may require restraint by use of a holdback winch.
Once underwater, the empty line has only its buoyant weight. This must be slightly negative. This results in friction on the seafloor. It is this friction which the pulling barge must overcome.

Friction coefficients have been measured in the range of 0.3–0.5 for the dynamic, moving condition, but rise to 0.6–0.8 when the pull is stopped to weld on a new section. Conservative values up to 1.0 are often used in planning since if the line cannot be moved, it will be a total loss.

The pipeline needs enough net weight to be stable on the seafloor and not move laterally. The amount depends on the surf, current, and seafloor conditions, but typical values for coastal lines range from 0.20 – 0.66 kN/m (15–50 lb/ft.). For bottom-pull installations on the seafloor that do not have to have stability in shallow water, net weight can be significantly reduced. It is the total friction force developed when the line is fully laid that limits the length that can be pulled by this method. If we assume a net weight of 0.3 kN/m, a friction factor of 1.0, and a winch having 1500 kN of pull on full drum, then the maximum length that can be pulled with a single line is 4500 m (15,000 ft.). This can be slightly extended by making short pulls at the end to keep the winch drum half-full, since the winch can apply more force under this condition.

By using two parts of pulling line and a sheave at the nose, the potential overall length of line can be doubled. However, the risk of jamming of the line in the sheave makes this solution acceptable only if the required force cannot reasonably be provided with a single line.

The bottom-pull method is extremely sensitive to weight and displacement tolerances, since the net weight, a small value, is the difference between two large numbers. Therefore, great care has to be taken to control and monitor the actual values.
The principal potential variances are

1. Steel pipe wall thickness (often 3%–5% over);
2. Steel pipe outside diameter (O.D.);
3. Concrete weight coating thickness;
4. Unit weight of concrete;
5. Water absorption into concrete during pull, often 2%–3%.

The weight coating is often applied in such a way that the ends are much thicker than the midsection. This needs to be accounted for. In some cases it can be compensated by an under-tolerance in applying the field coating over the joint itself.

The effect of these tolerances will be illustrated using the example in the following table.

<table>
<thead>
<tr>
<th>Nominal</th>
<th>Actual</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air weight</td>
<td>16.5 kN/m</td>
</tr>
<tr>
<td>Displaced water weight</td>
<td>16.0 kN/m</td>
</tr>
<tr>
<td>Net weight</td>
<td>0.5 kN/m</td>
</tr>
<tr>
<td>Total force for 4000 m assuming a moving friction of 0.6</td>
<td>1200 kN</td>
</tr>
</tbody>
</table>

If the single line capacity of the pulling winch is 1350 kN, this means that if the tolerance is shown actually realized, it may be inadequate. A double line around a sheave will be required. If due to sanding in, the friction rises to a factor of 0.8, then the total force available of about 2700 kN will be just barely enough.

In order to measure and check tolerances, the following procedure has been found effective. Three random pipe sections of 40-ft. nominal length are selected for weighing. They are placed in seawater for twenty-four hours and then lifted out and accurately weighed. Their steel pipe wall thickness is calipered and the diameter measured. The circumference of the coated sections is also measured at three points along the length. Then all subsequent pipe sections are measured for steel pipe wall thickness and for diameter and measured with a tape for circumference of the coated section. The above will enable net weights to be calculated within 2%–5%, if the pipes are relatively uniform.

Once the pipeline has been pulled, it is flooded for stability. A test plug is fitted on the inner end to permit hydrostatic testing. After testing, one pig is then activated by compressed air to empty the line. The second pig is there for potential problems such as buckling. Buckling of a pulled pipe does not occur in the vertical plane, as it does when laying from a lay barge, but in the horizontal plane, usually due to long-shore currents.

Out-of-roundness was found on steel pipeline sections being assembled for pulling a long line in Singapore. The line had to cross a deep channel enroute. To prevent buckling under hydrostatic pressure, one atmosphere of air pressure was maintained in the line by installing a steel plate closure at the pulling nose and a pig in the end of the first string. This section was pressurized. When the second string was welded on, the pig was progressively pushed by increased air pressure to a location shoreward of the deep trench.

When even longer lengths of pipeline are to be pulled, three options are available:

1. Increase the winch capacity. Conventional winches have upper limits, so a linear cable jack with spooling drum may be used, increasing single-line pulling force.
to 4500 kN (1,000,000 lb). Wire rope of this capacity working strength would be excessively large and moreover might have excessive bottom friction itself. For a bottom-pull pipe project across Spencer Gulf in Australia, the contractor used high-strength, 10-in. pipe, empty, as a pulling line, and a linear jack, in this case fitted with pipe grips, as the pulling winch.

2. Pull one line out its maximum distance. Pull a second line out beyond it, so that the inner end of the second is at the outer end of the first. Make a connection by flanges or by lifting up the two lines above surface for welding. This procedure was employed for an offshore terminal off Antigua. The ends of the two lines were brought as close together as possible, a “pup” section fabricated from template measurements, and flanged connections made since flanges were adequate for the pressure.

3. Decrease net weight and apply very careful monitoring. On a long pull across the Bay of Trieste, Yugoslavia, each length of pre-saturated pipe was weighed in water in a special tank. This enabled the net weight on bottom to be decreased to 0.1 kN/m (7 lb/ft.).

The net weight can also be reduced, and hence the required pulling force lowered, if floats are attached to the line. Oil drums have often been used in the past but prove rather crude and unreliable. Polyurethane floats can be accurately designed and attached by straps. The reduction in buoyancy in deep water must be considered. This increases the risk of problems during installation, since the floats add significantly to the drag force from waves and current. On occasion, they have been torn loose; if numerous floats are torn off, the line may become too heavy to move, and thus end up as a catastrophic loss. This occurred on an early line offshore Libya.

Assuming satisfactory installation, the floats must later be cut off. While divers were used in the past, mechanical equipment has been designed to travel along the completed pipeline, severing the straps. ROVs, equipped with cutters, have also been used. Despite the potential problems, floats are a viable and accepted solution for heavy pipelines.

Gas lines are much more susceptible to hydrodynamic forces due to their buoyancy in service. Thus they require thicker coatings, which in turn require increased reinforcement, so as to prevent loss of coating. During installation, they will have an increased net buoyant weight, which may require attachment of floats.

The reason a swivel is installed at the nose of a pulled line is to prevent the natural twisting of the wire line under tension from imparting twist to the pipeline. The nose is made buoyant and sometimes shaped like a sled to prevent it from digging in as it is pulled. A pendant and buoy is often fitted to the nose to enable its progress to be observed visually and to facilitate recovery in the event of problems. Often a flanged elbow is incorporated in the nose piece to facilitate later connection to a riser or hose.

The highest pulling force occurs when the pull has been stopped temporarily, for example, to weld on another string. Dynamic friction values are usually in the range of 0.3–0.4 but static (break-out) friction can be much greater than that. Because of the high potential loss if a pulled line cannot be pulled to its design length, the pulling gear and anchor system is often based on a factor of 1.0.

A pulled pipeline normally will follow the path of the pulling force, so that it is usually possible to pull around a long radius curve. However, on a hard sand bottom this is not always true, and in such a case the line may drag sideways. One solution is to make the line heavier, that is, increase the net weight to give it more stability. In other cases, lines to anchors have been rigged so that periodically the curve is pulled back to position. Solutions such as this, or trying to pull around a pile, often result in buckling in the
horizontal plane. A better solution may be to spread crushed rock on the seafloor at the zone where the bend must take place in order to get more lateral stability (i.e., higher local friction). Even better is to pre-trench.

Another solution is to secure several shots of chain inside the pipe, held at the location of the bend or in the heavy surf zone by a line running back to the holdback winch’s second drum. This way, the extra weight of the chain stays at the critical location while the line is pulled past.

In one unfortunate project, the owner furnished coated steel line, which was almost in equilibrium as to buoyancy, having only a few pounds of negative net weight. The contractor, faced with an oncoming storm, decided to go ahead with the pull and try to get the line in place and flooded before the storm hit. As indicated in Chapter 2, long-period swells run out ahead of a storm. Therefore, as the pull was in progress, the swells came in at about a 45° angle. While they refracted around to the normal in shallow water, there was still a net volume of water to be displaced to the south, resulting in a strong wave-induced longshore current. This bowed the pipeline out until it buckled. The contractor aggravated the situation by attaching a line at the buckle leading to a tractor on shore; this attempt to pull sidewise broke the pipe, and the entire line had to be abandoned. On the next try, the contractor used an ingenious trick. He filled the line with rock salt to give it weight, pulled the line out properly, and then washed the salt out.

For pulling around a curve, saw cuts have been made in the concrete coating to reduce the stiffness in that zone. This is not recommended as the coating may come off.

Another tale of disaster will be told to illustrate the interaction of the hydrodynamic weight, buoyancy, and structural aspects. This line was in the Bay of Fundy, with 10-m tides twice a day. The concrete coating was reinforced only with a very light mesh resembling chicken wire. The launching ramp terminated at high tide; the line was to be pulled across the long tidal flats at high tide and out to an offloading buoy. As the pulling operation commenced, the offshore anchors of the barge slipped. By the time these were reset, the tide was falling, exposing the line on the mud flat. Now as they pulled, they had the increased friction of the pipe’s air weight burying the line in the mud flat and developing excessive friction. They then held on until the tide came in and released the pipe from the mud, but now the winds and sea were kicking up and the line bowed laterally. This caused the concrete weight coating to crack, the light wire mesh to break, and the line to float. Eventually, the line broke and ended up on the beach, where it had to be abandoned due to multiple kinks and buckles.

Unfortunately, variations on this theme have occurred elsewhere in the world; for example, one of the first submarine lines to Kharg Island, Iran, also reportedly ended up as “spaghetti” on the beach. Recently, a number of cases of “float-up” of pipelines have occurred in the North Sea, apparently due to breaking off of large segments of concrete coating due to flexing of the line under vortex-shedding movements and subsequent wave-generated pore pressures within cracks and delaminations.

A gas line pulled across the Strait of Magellan became exposed as it crossed the beach, due to longshore currents and storm waves. Trenching was impracticable in the cobbles and gravel. The pipe was eventually covered with large riprap. Use of heavy-weight aggregate was another solution that was considered.

Pipelines crossing sandy and/or silty beaches in such widespread locations as Bass Straits, Australia, and the landfalls from the North Sea have become uncovered due to the pore pressures generated in the underlying sands combined with the uplift as the top of the pipe became exposed. These wave-generated pressures can reach 3.5 kg/m².

The lessons are clear. To all the recommendations regarding weight and buoyancy control must be added the need to ensure adequate reinforcement in the concrete
weight coating, to backfill over the pipe in areas of strong current, and to special protection in shallow water and the beach zone.

The bottom-pull method has been successfully extended to the installation of relatively short deep-water installations such as interconnecting lines between platforms and flow lines. The pulling force is usually that of a large tug and hence is limited to the bollard pull which the tug can exert, with the maximum force being in the range 80–150 tn. Being laid in deeper water, out of the surf zone, the net weight on the bottom can be reduced to a bare minimum, say 0.2 kN/m.

In 1983, a 4-km (2.4-mile) long bundle consisting of a 12-in. (300-mm) diameter oil line and a 4-in. (100-mm) diameter fuel gas line was pulled off from Ninety-Mile Beach in Bass Straits, Australia, and towed 100 km to connect Fortesque and Halibut platforms. The launch from the beach, which included the jointing of sections, took twenty-one hours, the bottom tow thirty-three hours. To reduce friction force and to prevent digging in, 500-m (1600-ft.) long sections were buoyed at each end with pontoons to raise them above the seabed with slight positive buoyancy. This enabled the new bundle to be pulled over an existing line. As the tow approached the platforms, the end sections were flexed laterally, using winches on the platforms, until mating fittings on the ends of the pipeline were mated with receiving fittings on risers from the pipeline. ROVs were then used to disconnect the 3-in. (75 mm) tow cable and all eighty-eight pontoons.

A similar method was used to install the 36-in. (900-mm) connection line, 2200 m long, between the Statfjord A and B platforms in the North Sea, laying it in a trench that had been previously dug with a plow.

Care has to be exercised with this method to make course changes very gradually and to avoid rock outcrop areas, since if the coating is abraded or spalled, the delicate weight-buoyancy balance can be upset, with disastrous results. One of the earlier attempts to use this method involved a relatively long bottom tow with severe course changes to avoid known minefields in the North Sea. The progressive damage to the coating from the sharp bends led to eventual loss of the line.

Another unfortunate catastrophe occurred in the first deep-water installation in the Gulf of Mexico. Seafloor surveys, obviously inadequate in hindsight, had failed to disclose outcropping reefs. The line hit these and was badly damaged through much of its length.

Thus, the importance of a thorough bathymetric and, in many cases, side-scan sonar survey is emphasized.

15.4 Reel Barge

A significant innovation, originally directed to the installation of small-diameter flow lines, but subsequently extended to pipelines of 300 mm (12 in.) and 400 mm (16 in.), is the concept of spooling a long length of pipe on a huge reel and then laying it in a manner similar to an underwater cable.

The first reel barges had a horizontal reel on which the line was spooled. This meant that the line was laid off one side of the barge, making it difficult to move the barge ahead on line. A subsequent “second-generation” reel barge, the Apache, has a large, vertically mounted reel leading astern at the centerline (see Figure 15.24).

A line designed for laying by reel barge can have no concrete weight coating but must have thick enough pipe walls to give negative buoyancy even when empty. This, of course, is relatively economical for smaller-diameter pipe such as flow lines. The steel quality must be such that it can undergo bending beyond yield during winding, and again during unwinding and straightening. The coating must also be able to be bent without cracking.
or loss of adhesion; epoxy coatings have been developed which will undergo this bending without damage.

The basic procedure is as follows. The line is made up in long lengths at a shore base. The reel barge moors at the dock and pulls the line onto the reel through a spiral J-tube, which bends the pipe beyond yield to the proper curvature. The tube and the spiral are designed so that the pipe bends without significant ovaling and without buckling.

Then the reel barge goes out to location. Start-up generally occurs at the platform, where the end of the pipeline is pulled off the reel, through a straightener and tensioner, over a short ramp or stinger, down to mate with a J-tube riser at the base of the platform, then up to the deck.

The reel barge then lays away from the platform. The straightener is a shallow S-curved pipe sleeve with an overcorrecting bulge that brings the pipe back to a straight configuration. This develops significant frictional resistance. Additional tension can be supplied by the powered reel or by a conventional tracked tensioner.

The reel barge now lays out the entire line, letting the end down onto the seafloor by means of a line from a constant-tension winch. The end is buoyed to facilitate recovery for welding to the next reel length. By having suitable onshore spooling facilities, one reel can be wound up at the shore base while another reel is being laid. In many cases, the reel has enough capacity to lay a full-length flow line. As the diameter of line increases, the storage length, of course, decreases. The number of turns that can be placed on a drum is a function of pipe diameter, wall thickness, and tension, to prevent crushing of the pipe. The Apache has the following capacities:

<table>
<thead>
<tr>
<th>Pipe Diameter</th>
<th>Length on One Reel</th>
</tr>
</thead>
<tbody>
<tr>
<td>8.725 in. (220 mm)</td>
<td>360,000 ft. (110,000 m)</td>
</tr>
<tr>
<td>12.75 in. (325 mm)</td>
<td>140,000 ft. (43,000 m)</td>
</tr>
<tr>
<td>16.00 in. (400 mm)</td>
<td>92,000 ft. (30,000 m)</td>
</tr>
<tr>
<td>24.00 in. (600 mm)</td>
<td>24,000 ft. (7300 m)</td>
</tr>
</tbody>
</table>
The Apache was used to lay a 10 in. (250 mm) gas line across the Strait of Georgia, which separates British Columbia from Vancouver Island. Depths ranged up to 500 m. Elsewhere, the reel barge has been used for depths up to 1000 m and more.

15.5 Surface Float

The idea of moving long lengths of pipeline while floating and then progressively sinking the line to the seafloor at the site has attracted many contractors over the years. It appears relatively simple to provide the line with the desired positive buoyancy by attachment of floats, which will later be cut free. To keep the pipeline in line and prevent buckling due to waves, wind, and so on, one boat tows while a line to shore, or a sea anchor, or a second boat astern acts as a drag. This keeps the line under tension.

Unfortunately, this method of flotation has a number of serious drawbacks, which can only be overcome by thorough engineering; even then there may be excessive risk. The first problem is that of waves acting on the floating line, causing it to “snake” in response to the short-crested waves. This may damage the coating and cause it to fall off; in turn, the weight balance and stability in service are affected. Keeping the line under tension minimizes the dynamic bending. Even with the line in tension, the lateral and vertical forces will alternate over many thousands of cycles and can eventually lead to coating damage. Such a line must obviously be towed out in calm weather. It is very susceptible to even small storms such as squalls. A number of offshore lines have broken up and been lost in this way.

The second problem has to do with the attachment of temporary floats. For a moderately long line, there will be hundreds of these. Under the wave action, some attachments may fatigue and fail, thus leading to local areas where the line takes on an increasing sag.

The third and most serious problem to be overcome is that of ballasting down to the seafloor. If floats are cut loose at one end, that end will bend downward sharply and may buckle. The same or worse can happen if attempts are made to introduce water ballast into the line. It will run to one end or a low point; this will cause the rest of the ballast to run to that location and the line will take a sharp bend and buckle.

Successful installations of relatively short lines in shallow water have been made by the flotation method, although most of these were in protected or semiprotected waters. In shallow water, such as a river or estuary crossing, the line may be lowered from a series of barges, with multiple control points. Attempts to carry out the surface float method in the open ocean, even in relatively calm seas, have usually failed, an example being an oil import line off Dakaar, West Africa.

The essential point is that the entire sequence must be thoroughly engineered to ensure success. Adequate redundancy must be provided to ensure that the loss of one or a few buoys does not lead to progressive failure.

Floats pulled underwater near the bend may collapse progressively. The French have developed and tested a well-engineered system of air-filled rubber (neoprene) bags, which intentionally collapse progressively with depth. This “S-curve” method is described in Section 15.10.

To facilitate connections at the platforms, as the line nears its final location, a line from a J-tube on the platform is affixed to the pipeline end. The buoys at that end are progressively released, while a winch on the platform pulls the end down, either to mate with the J-tube or run on up into the J-tube to deck level.
15.6 Controlled Underwater Flotation (Controlled Subsurface Float)

The controlled underwater flotation method has been developed to overcome some of the deficiencies of the surface flotation method described in Section 15.5. In this method, the pipeline, having slight net negative buoyancy, is towed at a depth of 5 m or so below the surface, where it is much less affected by local waves and not at all by wind.

Support for the line is by hinged or articulated spar buoys attached at frequent intervals. These provide a relatively constant upward force, giving a “soft” response, that is, not very responsive to the changes in sea level due to short waves. With their small waterline plane, they do not respond significantly to wind-driven waves, and the frequency of response of the system becomes very long (over one minute). This system, therefore, virtually eliminates the first major problem of flotation.

The line is kept under tension, with one boat towing, another acting as a stern drag. Upon arrival at the site, the line must be lowered to the seafloor. This is done by cutting off every second spar, by a diver or ROV, while still keeping the line under tension. Of course, when the line is on the seafloor, the remaining spars are also removed.

This method of controlled subsurface float has been successfully used for flow lines and platform interconnection lines in the North Sea.

15.7 Controlled Above-Bottom Pull

Continued efforts to develop a reliable method for transport and installation of lines have led to the development of a number of ingenious methods, many of them developed by R. J. Brown. One of these is the “controlled above-bottom pull” method in which the line itself is designed for slight positive buoyancy. Short lengths of chain are attached at frequent intervals to give the overall combination negative buoyancy. Thus it is the end of the chain that drags on the seafloor, not the pipe.

The chains automatically control the net underwater weight of the combined system. If the pipeline tends to rise, it lifts more chain off the bottom; if the pipeline tends to sag down, more chain rides on the bottom, reducing the downward pull on the line.

The friction force is now determined by the weight of the “tails” of the chains, which drag on the seafloor. The length of tail is in turn determined by the variations in bathymetry over a short distance and the safety required to offset tolerances in weight and buoyancy. While these can be calculated ahead of time, once the pipeline has been launched in relatively shallow water it can be inspected by divers and adjustments made in chain length made before pulling out to deep water.

The attachments of the chain to the pipeline must be properly detailed to prevent chafing and abrasion. A weak link may be installed to ensure that should a chain snag on an underwater obstruction, it will break free before buckling or crimping the pipe.

The controlled bottom-pull method has proved cost-effective in installations in the North Sea and offshore California, especially for lines of limited length, of the order of 3000 m. During tow, at 3–4 knots, the pipeline may “fly” at a depth of 30–40 m below the surface. As it approaches location and the tow is slowed, it gradually lowers to just above the seafloor, with the chains dragging the bottom. Then it is pulled into final position and ballasted down onto the seafloor.

A larger-diameter pipeline may be employed as a carrier line for several smaller flow lines and cables bundled inside. Obviously, it is essential that the carrier pipe maintain its watertight integrity during the tow. Internal pressurization has been utilized to overcome
any leakage. Unfortunately, in at least two recent cases, the combined line has prematurely flooded and sunk, damaging the flow lines being carried inside the carrier pipe. This would indicate that consideration needs to be given to methods of “damage control” of in-leakage due to possible overstress during tow. Appropriate steps might include use of foam, compressed air, multiple pipes, or subdivision.

The controlled subsurface-pull and controlled above-bottom-pull methods have been combined by C. G. Doris for bundled lines to constitute what they have named as the “guide rope method” for placing flow line bundles. The bundle assembly includes both floats and chains. When the pipeline is empty, it floats 30 m below the surface; when filled, it floats 10 m above the bottom. Thus, it can “fly” over obstacles, rock outcrops, escarpments, and other pipelines. Filling produces significant bending in the line. This is best controlled by flooding one line in a bundle at a time.

One such bundle of 4- and 2-in. pipes was towed 13 miles just below the surface, and then sunk to the above-bottom mode and the ends pulled into subsea manifold connections, using a guide funnel and pull-in lines through sheaves. Cutting the floats allowed the line to sink to the seafloor.

For installing pipelines between the underwater manifold and the Cormorant A platform in the North Sea, an 8-in. oil line plus 2- to 3-in. TFL well test service lines were made up inside insulated sleeves which in turn were placed within two carrier pipes, one 26-in. line and one 24-in. line. The bundle was then towed in two 3.3-km lengths, kept at mid-depth by the chains for a distance of 490 km using one tug of 75-tn. maximum bollard pull pulling and another of 35-tn. maximum bollard pull restraining, that is, keeping the line in tension. The average pulling forces were 50-tn. pull, and 12-tn. restraint, and the average speed 5.5 knots. Depth below surface was 30–100 m. Slowing down and reducing the tension allowed the line to submerge to near bottom. When in position and mated, the carrier pipe was flooded.

The carrier pipes were pressurized with nitrogen gas to 15 atm to prevent water in-leakage. A full contingency plan was developed to cope with possible accidents or difficulties, such as the snagging of a chain on an obstruction. The position of the pipes as they approached the field installations was monitored by acoustic transponders and side-scan sonar.

Figure 15.25 illustrates four different versions of pulled lines.

**FIGURE 15.25**
Tow installation methods for installation of flow lines.
15.8 J-Tube Method from Platform

Curved J-tubes with a “straightener” curve at the exit can be pre-installed on a jacket. After the platform is in place, a messenger line (also pre-installed in the J-tube and temporarily run up to stop off at the deck) is connected to a long pulling line from shore or a barge. The pipeline is made up vertically on the platform, using steel quality and coating similar to that used for reel barge operations (see Section 15.4). This practice of successive vertical jointing is called stove piping.

The barge or shore winches now pull the end of the line down the J-tube, around the bend, and out over the seafloor as a bottom pull. Thus, the length of line which can be pulled is limited by the friction in the bend and straightener plus the bottom friction.

15.9 J-Lay from Barge

This is the fourth-generation barge, especially designed for deep water. See Chapter 22 for full description of this method. The pipe departs from the pipe-laying vessel almost vertically, and hence has no overbend. This method utilizes a hinged ramp, inclined only slightly from vertical on which a triple- or even quadruple-jointed pipe segment is placed. The joining of the segments to the previously laid pipe takes place at a single station just above deck level. To make acceptable progress, advanced methods for fast automatic welding are employed. These include electron-beam welding, high-frequency induction welding, friction welding, flash-butt welding, high-speed electrical resistance forge welding (HPW), and laser welding. Mechanical connections have been proposed. The aim is to complete the jointing process in two to three minutes, followed by magnetic particle testing (see Figure 15.26).

The axial tension is largely determined by the weight of the pipe hanging below the lay barge, which reduces the forward-leading tension requirements to where this thrust can now be applied by dynamic thrusters, and all mooring lines can be eliminated. This in turn eliminates the slow-drift accelerations, so that work can proceed in more severe sea states, the limiting factor being that of pipe transfer.

FIGURE 15.26
Catenary or “J-curve” method of pipeline installation. (Courtesy of Exxon Exploration & Production.)
15.10 S-Curve with Collapsible Floats

This system employs inflated bags of neoprene or rubber which exert a buoyant effect on the line. As bags are pulled below water, they partially (and eventually, fully) collapse, thus reducing their uplift force.

This method was proved by a test installation of a small-diameter steel line in water 2500 m deep in the Mediterranean. The short length of line was towed to the workboat and fed up over the bow to the deck where the bags were attached and then out over the stern. The sinking was initiated by pulling the end under water; from then on the line automatically took its S-shape and so went to the seafloor without buckling. It was later successfully retrieved by lifting up on the end, after which the bags progressively expanded and brought the pipe to the surface in a gradual curve. Using this method, a gas line was successfully laid across the Strait of Gibraltar, at a depth of over 300 m, despite strong bottom currents.

15.11 Bundled Pipes

The simultaneous installation of two or more pipes in a bundle is feasible by many of the above methods. The usual reason is to handle several products. The main requirement is to ensure that the attachments are sufficiently rugged to take the stresses imposed during laying without failure and without damaging protective coatings. The use of two or more lines in a bundle enlarges the opportunities for construction engineers to control weights and buoyancies to suit their needs. For example, if an oil line and gas line are pulled together, the oil line, in service, may provide the net negative weight to stabilize the system, even though the gas line may be near neutral buoyancy. Similarly, inclusion of a second or third line in a bundle may reduce the net buoyant weight during installation yet increase stability in place after it is flooded. In this case, the additional line becomes an expensive but effective means of stabilization of the system on the seafloor (see also Section 15.7).

15.12 Directional Drilling (Horizontal Drilling)

Directional drilling is frequently employed as a means of installing cables and pipes under the surf zone and adjacent beach. The slant drill rig is set up on the shore and drills and cases an initial length to a depth where stability can be maintained. A drilling fluid is used. Polymer slurries are preferred because they are biodegradable and do not contaminate the water. This method has been successfully used on a number of important river crossings and coast line crossings.

Using directional drilling techniques, the drill drives on a downward angle to the depth required, pulling the drill string behind it. The drill is then steered to near horizontal and eventually slightly upward to exit on the seafloor. The pipeline has been previously pulled out on the seafloor with its shoreward end near the exit. The drilling bit is now changed to a hole-opener, slightly larger than the permanent pipeline to be installed. It is attached by a swivel to the permanent pipeline and then drill string, hole-opener, and pipeline are
pulled back to shore. Variations on this procedure enable the pipe to be pushed from shore into the slurry-filled hole, following an oversize bit.

The critical zone for collapse is the seafloor exit, where there is increasingly shallow cover. Hence, the endeavor is to select a point for exit that is in stable material.

A somewhat similar result can be attained by jacking of a pipe tunnel. Usually concrete pipe sections are used. The initial thrust is from a jacking pit on shore. The line is laid dry, like a tunnel, with a cutter head, essentially a small Tunnel Boring Machine (TBM) at the face. Polymer slurry may be injected into the annulus at intervals to reduce friction. When the initial jacking force is not sufficient, an intermediate jacking station is established to jack a further length. The line may be steered into a pre-set seaward terminal box, which is essentially a small box caisson, sunk to design grade below the sea. Pipelines are then pulled through the concrete pipe tunnel.

15.13 Laying Under Ice

To install pipelines below the ice, several variations on the bottom-pull method have been developed. These have assumed that the work would be done in winter and that the ice would be “fast ice,” with little movement over the period involved in the pipe-laying operations. Initially it is necessary to run a messenger line. Holes can be cut in the ice at intervals along the line and acoustic transponders installed at each. An ROV can then be lowered through one hole, and programmed to lay out a messenger line to each hole in succession.

The messenger line is then used to pull a wire rope line (the pull line). The pipe is then made up on a launching ways and pulled into place by the conventional bottom-pull method.

Prior installation of a larger-diameter pipe under the shoreline through which the principal pipeline is to be pulled may be required for permafrost insulation. This casing can also be used as a means of reducing friction and separating the near-shore excavation and construction from the main pull.

Installation of pipelines in the Arctic is described in more detail in Section 23.16.

15.14 Protection of Pipelines: Burial and Covering with Rock

The burial of pipelines is often required in order to provide protection to the pipeline against repetitive pounding under wave action, the impact of dropped anchors, snagging by trawl boards, and to prevent loss of fishing gear by bottom fishermen. Burial of the pipe also permits the pipe to be designed with less net weight (less coating) which in turn reduces the bending stresses during pipe laying.

The “pounding” referred to above is especially serious in the surf zone, as well as in shallow water where vortex shedding by wave-induced currents can cause alternate raising and lowering of sections of the line, leading to fatigue. Concrete coating can be ruptured and break off, allowing the line to rise. The same phenomenon can occur due to high currents alone, in locations such as Cook Inlet, Alaska. In the inner portion of the surf zone, the damage may be aggravated by direct wave impact and by abrasion from moving sand and gravel.
Burial can be accomplished by laying the line in a predredged trench or by subsequent trenching after the line is laid. A similar protection may be given to a surface-laid line by covering it with rock.

Where underwater sand dunes are migrating, as in the southern portion of the English Channel, then predredging by a trailer suction hopper dredge has proved practicable. The line is predredged to a stable elevation, and then the pipeline is laid.

Through the surf zone, a variety of solutions are employed. At beaches where the surf and longshore currents are relatively mild, a hydraulic dredge may be employed to overdredge a channel through the beach. The line can then be pulled ashore from the lay barge, allowing the sands to naturally backfill the trench. However, where the beach is subjected to heavy pounding from storm surf, over a period of time, the iterative raising of the pore pressures in the sand may jack the pipe up and out to exposure. Therefore, the pipe must be sufficiently heavy in this zone so that in service it remains stable. This may require extra jacketing, the use of the double-pipe concept, pipeline anchors, or high-density backfill over filter fabric. Instances of such raising and exposure are reported from such widespread areas as Cook Inlet, Alaska, Ninety-Mile Beach on Bass Strait, Australia, and the Strait of Magellan.

Another method, of course, is the use of a sheet-pile cofferdam through the surf zone, which keeps the trench open while the line is pulled through it. Finally, a tunnel or tube can be preconstructed through the surf zone. This can be concrete or steel pipe prelaid in a cofferdam, a directionally drilled hole with a casing of larger-diameter pipe, or a precast concrete tube jacked in.

A large, precast concrete submerged tunnel or tube was constructed at Cove Point, Maryland, through which an LNG line was run. Similar precast concrete tube segments were installed on the west coast of Norway, on a very exposed rocky coast. The Statpipe Gas Line was then pulled through the tunnel.

For burial of pipelines in deeper water, trenching has most often been carried out by a jet sled, designed to be guided by the pipe and to excavate the soil beneath it so that the line will sink below the seafloor. The jet sled may be designed to run on the pipe, using rubber wheels. The machine must be designed to ensure that its tires cannot damage the coating (see Figure 15.27). In one case in southern California, repeated running of the jet sled over the line broke up the coating to the extent that the line had to be replaced. Other jet sleds are designed to skid, crawl, or run on the adjoining seabed, being centered and guided by the pipe but not supported by it. A problem here arises, of course, if the trench side slopes become too flat due to encountering loose sediments.

Excavation under the pipe may be accomplished by a combination of jetting, airlift, or eductor removal, or mechanical cutting (see Figure 15.28). The emphasis is on powerful equipment (see Figure 15.28 through Figure 15.30). It should be able to cut to the required depth in one pass. Multiple passes not only are costly, almost in proportion to the number required, but may become less effective due to the increasing depth and progressive infill of the trench.

A steel pipeline has significant bending rigidity and strength. Hence, it will not move down into a dredged trench unless the dredged length is sufficient to cause it to deflect to the bottom. Therefore, the trench when cut must stay open long enough to enable the line to feed itself to the bottom of the trench. Fortunately, this is usually not a problem in most deep-water pipeline installations, since bottom currents and sediment infill are usually limited over a short period of time in the relatively calm seas in which the operation will be carried out.

Power requirements for jet sleds and trenching machines are high. As much as 32,000 HP has been used to power the jets and eductors of a large pipeline burial system used to trench boulder clay in the North Sea. For the pipeline bury barge Creek, eight engines
drive jet pumps to produce 76 m$^3$/s at 17 MPa (2500 psi) pressure. Other jet trenchers use 21 MPa (3000 psi) pressure. Eductors are more efficient than airlifts in the removal of material.

In most cases, once pipelines have been trenched and lowered to their designed elevation, natural sediment transport has often been counted on to backfill the trench. If a pipeline is to be backfilled by dumping or placing sand, care has to be taken that the flowing sand, which is temporarily a high-density fluid, does not raise the line out of the trench. This has occurred on both small and large pipelines, to the great embarrassment of all concerned. Another method of pipe burial involves the principle of liquefaction. By introducing water and air under the pipeline along a length, the sand is “fluidized,” allowing the pipeline to sink of its own weight. Obviously, this works best in easily liquefied materials such as fine sands and silts. Vibration applied to the pipe—as, for example, from inside— aids the process. This method has so far been used, to the author’s knowledge, only for relatively short lengths of line (e.g., through a beach zone).

Ever more sophisticated trenching and burial equipment has been developed, such as mechanical trenching machines. Like the jet sleds, these are guided by the prelaid pipeline, but they take their support from sleds on tracks at the sides. Rotating trenchers excavate beneath the pipe and throw the material to the side.

A recently developed form of trenching is that of plowing. A monstrous plow is pulled along the seafloor, stabilized against tipping by widespread outrigger sleds. The plow digs the trench, with the shares forcing the excavated material up on the sides.
This development was pioneered by R. J. Brown and has proved very successful in the firm clays of the North Sea. The plows have been designed for the soils expected to be encountered, heavy in North Sea clays, lighter in recent sediments in the Beaufort Sea. In the Bass Strait, Australia, an 80-tn. plow was used to post-trench the line, with the plow designed to ride along the pipeline. This pipe dug a furrow up to 1.2 m deep in sand and partially cemented cap rock ledges.

Towing forces generally are one to two times the weight of the plow. Traction is provided by a large, dynamically positioned towboat for relatively light plows or by an offshore derrick barge for heavy plows.

One of the most spectacular uses of the plow to date was on the Northwest Shelf of Australia, where an enlarged version of the plow weighing 380 tn. trenched a 1- to 2.3-m-deep trench for 118 km of 46-in. (1150 mm) O.D. line in only one month (see Figure 15.31 and Figure 15.32). The plow had to dig through limestone and caprock, requiring up to 460 tn. pull, whereas in softer materials, sand plus silt and clay, 250-tn. pulling force was sufficient. Plowing rates reported were 15–45 m/min in sand, 10–20 m/min in sand over rock, and 5–10 m/min in limestone. Difficulties arose principally in soft material, where the plow dug itself in too deeply.

The plow was pulled by a large offshore pipe-laying barge, using a chain-pulling line and developing its reaction force from the barge’s anchor lines. The sequence of start-up was as follows. The two mating (positioning) cones were lowered over the pipeline, being spaced apart 40 m by a strut. Divers guided them to seat over the pipe on the seafloor. The plow was now floated to position over the pipe and ballasted down. Removable female sleeves fitted over the pre-placed mating cones. With the plow now accurately in place, the pipe was pulled up into roller guides at each end. The plowshares were then lowered.
hydraulically to meet underneath the pipe, where they were clamped together. The forward part of the plow rode on two outrigger crawlers, which were Caterpillar D-9 tractor underbodies. The derrick barge had hydraulic controls, which enabled it to raise or lower the plow in relation to the crawlers, thus regulating the depth of cut.

The plow concept uses a long spread between the Cat tractors to automatically even out irregularities on the seafloor. R. J. Brown has suggested that use of computerized controls, reacting to leading sensors, will be developed in the future to handle even rough seafloor profiles. It is believed that a similar system could be employed to scrape the spoil piles back into the trench, should early backfill be required.

Plowing appears especially attractive in Arctic soils where lines will have to be trenched deeply (up to 3 m) in order to protect them from the scour of sea ice pressure ridge keels. For the connection line between the Gullfaks A and Statfjord C platforms, the hard boulder-clay required several passes of the plow. Hydraulically operated grader blades were designed to push the spoil banks aside, leaving a flat level surface for the following passes of the plow. On the Heimdal pipeline in the North Sea, the 115-km pipeline was post-trenched by plow in only 11.5 days. The plow weighed 145 tn. It was deployed onto the pipeline in 150-m water depth in 19 h. Recovery after completion required 13 h.
The most recently developed plows have small shares at the leading end, which ride the previously installed pipe under sensor control, to clear the pipe for the principal plowing action of the larger, deeper plow behind.

When caprock or rock outcroppings must be trenched, it is normal first to break them up with explosives. These can be shaped charges laid on the seafloor or drilled in, using high-pressure jet drills or percussion drills. With caprock it is important not to drill through the hard overlying layers, since then the explosion will take place under the caprock, resulting in it being broken into large slabs only, which are extremely difficult to excavate. For overconsolidated silts and in permafrost, high-pressure jet drilling has generally been found more effective than rotary or pneumatic drilling for the placement of explosives.
Rock breakers (huge chisels repeatedly raised and dropped, or driven with an impact hammer) have been used effectively for caprock in the Arabian Gulf, breaking it downward into the softer soils below.

Covering of pipelines laid on the seafloor with rock has been carried out very effectively by Dutch engineers, using a converted trailer suction hopper dredge, dynamically positioned, fitted with an inclined ladder and conveyor belts, discharging the rock down the ladder to encapsulate the exposed line. Use of the ladder ensured accurate deposition and minimized the impact of falling rock. More recently, this same contractor has used a flexible tremie tube, of steel and polypropylene, hanging vertically under the rock dumping vessel, capable of controlling the deposition of rock. Electronic position indicators are installed at the tip of the tremie.

Sarmac of Italy has developed flexible mattresses of rock-filled fabric which can be placed over submarine pipelines to protect them. They were utilized by Snam-Progetti to cover the gas pipelines from Algeria to Sicily, at depths of 500–600 m. They were lowered to the seafloor, using a structural steel frame that was automatically released once the mattress had been placed on the line. These mattresses are also being used to protect pipelines at locations where they are crossed by another line.

Flexible (articulated) mats of concrete blocks were used to cover portions of the gas pipeline off the Northwest Shelf of Australia, where it was laid on a bare rock seafloor (see Figure 15.33 and Figure 15.34).

Pipeline anchors have been used to hold down the pipe at beach crossings and in areas of high bottom currents, especially when the line lies on a hard, bare seafloor. These are
usually screw anchors, which are drilled into the soil to secure an inverted U-clamp over
the pipe. While these anchors can be installed by divers, this is slow and expensive.
Systems have therefore been developed for installing them from a barge directly, using
a frame lowered over the pipeline.

For crossing beach areas where high currents and waves have created a deep layer
of cobbles, the protection of the pipeline poses significant difficulties. The use of riprap has
been previously described. Heavy-density rock such as iron ore is a possible solution, as well
as double-jacketing with concrete pipe. Horizontal drilling should be considered.

15.15 Support of Pipelines

When laying pipelines across an uneven seafloor of hard material, such as an area of rock
outcrops, it may become necessary to provide supports to prevent excessive sag moments
in the pipeline span. In shallow water, sandbags and grout-filled bags have been stacked in
by divers. Burlap bags, half filled with fresh concrete mix of low slump, are best, because
the grout exuding through the burlap mesh will knit the adjoining bags together. In deeper
and more exposed waters, neoprene and flexible fabric bags can be placed by divers and
pumped full of grout.
The 520-mile Statpipe Ormen-Lange gas-gathering system, crossing the Norwegian Trench, in depths up to 1000 m with steep rock escarpments, resulted in free spans up to 100 m. In addition to grout bags, steel support frames were designed to give intermediate support to the pipe. An underwater bridge was used to support the pipe in waters of moderate depth. To excavate a trench, bottom-crawling “spiders” were used. These were controlled by computer systems utilizing 3D terrain models. These employed small buckets to dig the trench and sidepost the spoil.

15.16 Cryogenic Pipelines for LNG and LPG

For submarine pipelines to transport LNG and LPG, current technology uses INVAR (36% nickel steel) and low-pressure or vacuum systems for insulation. Recently, a new system has been developed using 9% nickel steel product line and high efficiency micro-porous or nano-porous insulating materials, contained within a carbon steel outer jacket and separated by non-metallic bulkheads. This system was used for butane and propane lines to a marine terminal at Pisco, Peru.

Eternal Father, strong to save
Whose hand doth still the mighty wave
Who bids the restless ocean deep
Its own appointed limits keep;
O hear us when we cry to Thee
For those in peril on the Sea.

William Whiting, Hymn of the U.S. Navy