Introduction to Horizontal Directional Drilling

1.1 History

The immense task of maintaining and expanding the utility infrastructure around the world is a challenging one. The traditional methods of replacement and repair primarily revolved around open trench construction. These traditional methods often prove to be costly and troublesome, especially with today’s congested and buried infrastructure. The high cost of open trench construction is often driven by necessary restoration of roadways, sidewalks, driveways, and landscaping. Other problems often stem from the disruption of traffic and the danger to workers in high traffic areas. To overcome the drawbacks of open trench construction, the government, utility, and construction industries started looking for alternative methods for replacing and repairing the underground infrastructure.

One of the alternative construction methods, and perhaps the fastest-growing technology in the trenchless industry, is horizontal directional drilling (HDD). HDD has experienced rapid growth in the construction industry over the past few decades. The horizontal-directional-drilling process represents a significant improvement over traditional cut-and-cover methods for installing pipelines beneath obstructions, such as roadways, driveways, historical areas, landscaped areas, rivers, streams, and shorelines, which warrant specialized construction attention. To efficiently and properly utilize the many benefits offered by HDD construction, design engineers should have a working knowledge of the HDD process. This knowledge will assist them in developing constructible designs that can be
executed in the field while meeting the requirements of the utility company. This book is written for the designers, engineers, and utility company personnel who are involved or interested in HDD construction.

The tools and techniques used in the HDD process are an outgrowth of the oil-well-drilling industry. The first use of directional wells in oil fields was motivated by economics. The oil fields off the California coast were the spawning grounds for directional drilling practices and equipment. Later oil and gas discoveries in the Gulf of Mexico and other countries promoted the expansion of directional drilling technology and practices. The horizontal drilling rigs used for utility and pipeline construction are similar to the oil-well-drilling rigs with the major exception that a horizontal drilling rig is equipped with an inclined ramp as opposed to a vertical mast.

1.2 Applications

HDD is a multi-billion-dollar annual industry with hundreds of contractors and thousands of drilling rigs operating on five continents. HDD in North America has grown from 12 operational units in 1984 to thousands of units today. This rapid growth is attributed at least partially to:

1. The increasing traffic-control and restoration costs involved in the installation of utility conduits and pipes in congested urban areas and the need to dig around existing utilities.
2. The increased awareness of social costs such as traffic delays, disruption of business activities, and disruption to residential neighborhoods.
3. The increasing environmental regulations for the placement of pipelines across rivers, wetlands, and other environmentally sensitive areas.

Excavation requirements in HDD are minimal. As a result, in crowded urban areas, HDD is increasingly viewed as the preferred technology. It minimizes the negative impact on residents and businesses and eliminates the need for the removal and repositioning of expensive restoration and landscaping. In open areas, HDD provides an efficient method for crossing obstacles such as rivers, highways, rail tracks, or airfield runways. The HDD method also eliminates the cost and time associated with installing dewatering facilities for operations carried out below the groundwater table level.

The market for horizontal directional drilling is experiencing a continuous growth worldwide. The installation of pipe and utility conduits in urban areas and across rivers and highways is the mainstay of the HDD industry. It is common practice to use HDD for the installation of new power, natural-gas, and telecommunications networks. Recent advancements in equipment and tracking systems make the use of HDD cost-efficient for projects that involve larger diameter products and
strict placement tolerances, as is the case in many municipal applications. Chart 1-1 lists the distribution by industry of HDD applications.

As a result of the growth of HDD, the marketplace is providing a wide range of HDD units and support equipment. HDD rigs range from mini-rigs that are usually used for the installation of smaller pipe and conduits (2 inches) to maxi-rigs that are capable of installing 48-inch pipelines. The length of pipe that can be installed by HDD is determined by many factors, such as rig size, soil conditions, and carrier pipe diameter. Installations over 6000 feet have been successfully completed. Current HDD equipment can operate in a wide range of soil conditions, from extremely soft soils to full-face rock formations with unconfined compressive strengths of 40,000 psi.

An industry survey was conducted in order to gain a better understanding of this multi-billion dollar business, which is relatively unfamiliar to many in the construction sector (see Appendix D). According to the survey there are 17 manufacturers of HDD rigs and accessories and several hundred dedicated horizontal directional drilling contractors in North America. The survey results indicated that 60 percent of the contractors surveyed were relatively small companies with annual revenues of up to seven million dollars. Nearly 90 percent of the contractors surveyed stated that they were involved in the utility industry, with 74 percent in the municipal market and 63 percent in the pipeline industry. Environmental applications of directional drilling include:

CHART 1-1 HDD Applications

- Electric: 14%
- Telecommunications: 46%
- Sewer and Water: 19%
- Gas: 17%
- Environmental Wells: 4%
drilling are relatively new, as only 28 percent of the contractors indicated that they had experience with the installation of horizontal wells and 17 percent in projects involving horizontal sampling. Most HDD contractors can be described as non-specialty contractors, with 41 percent involved in both the utility market and the pipeline industry and 35 percent involved in three or more different applications. Forty-nine contractors responded to the survey. They owned a total of 185 HDD rigs, with 38 percent classified as mini-size rigs, 33 percent as mid-size rigs, and 29 percent as maxi-size rigs. Seventy-three percent of the mini and mid-size rigs were manufactured by three companies, Vermeer Manufacturing Company, Charles Machine Works, Inc. (“Ditch Witch”), and American Augers, Inc. In the maxi-size category 47 percent were custom-built, 40 percent produced by American Augers, Inc., and the balance manufactured by others.

The survey\(^2\) also revealed that during the 1995-96 construction season, 72 percent of all the products installed had an outside diameter (O.D.) of 4 inches or smaller. Products with O.D. between 6 and 12 inches made up 16 percent of the products installed, and those above 12 inches constituted 12 percent. In terms of pipe material, high-density polyethylene (HDPE) was the most common product, accounting for 62 percent of all pipes installed. In addition, HDPE accounted for 75 percent of all pipes installed with 4-inch or smaller diameter. Steel was the most common material used in the installation of 12 inches and larger products, accounting for 92 percent of all pipes in this category. Polyvinyl-chloride (PVC) pipes are mainly used in the small diameter range (up to 4 inches).

The survey\(^2\) also indicated that HDD projects are normally of short duration and relatively low dollar values. Fifty-one percent of all projects reported in the survey reported durations of 14 days or less, and 47 percent of the projects reported a monetary value less than $70,000. The most common type of contract used in the HDD industry is unit rate; however, all types of contracts ranging from lump sum to target price are also utilized, depending on the project complexity. Appendix 1 contains the full survey report.

**Pipeline**

The oil, gas, and petrochemical industries are an important market for the HDD industry. During the 1970s and early 1980s, HDD had been used primarily in the oil and gas industries, either for exploration, production, or pipeline installation. This sector of the HDD industry mainly consists of 6-inch and larger diameter pipelines. Because of the HDD lengths and pipeline diameters normally associated with pipeline HDD applications, larger HDD rigs are often required. Figure 1-1 is a picture of a typical HDD rig used in a pipeline HDD application.
For pipeline construction, major water crossings, swamps, and environmentally sensitive areas pose significant challenges and permitting issues. Even though there has been widespread historical use of open trenching as a means of crossing these obstacles, today’s stringent environmental regulations pose one of the most significant challenges facing the pipeline industry. Environmental regulations, especially in North America, require a thorough assessment of alternate methods of crossing environmentally sensitive areas. In many cases, HDD is specified as the preferred method of crossing these obstacles. In order to cross these environmentally sensitive obstacles with other methods, the engineer has to prove that HDD is not a viable method of construction. Moreover, most of these environmental regulations do not consider increased construction cost as a reason for not using HDD as the preferred crossing method.

Largely due to the popularity of HDD construction, there has been an increase in the number of qualified and experienced HDD contractors and improvements in HDD equipment and technology. In many instances this has significantly lowered the cost of HDD construction. For “routine” HDD crossings of water bodies and environmentally sensitive areas, it is not uncommon for the HDD construction cost to be lower than traditional open trenching costs. This has resulted in an increase
in HDD construction in the pipeline industry. Table 1-1 lists the percentage of contractors involved in pipeline HDD according to a survey. For pipeline construction HDD has the following advantages over traditional open trench methods:

1. Water bodies, wetlands, and their sensitive environments are not damaged.  
2. Since there is no excavation in the sensitive areas, there is no silt buildup or erosion. It is also not necessary to take special measures to protect marine and plant life.  
3. The workspace is much smaller, resulting in the removal of much less earth material than would be excavated using normal open-cut methods.  
4. The crossing can be performed at almost any time without needing to take into account such factors as as fish spawning seasons or high water flows.  

Table 1-2 lists some of the key factors for pipeline HDD construction.

Utilities

The installation of utility products in urban areas and across rivers and highways has become the largest sector of the HDD industry. Utility companies now use HDD extensively for the installation of power, natural gas, water, sewer, and telecommunications. Municipal applications are still underutilized; however, they are the most promising future market for HDD applications. Recent advancements in equipment and tracking systems make the use of HDD cost-efficient for projects that involve larger products and stricter placement tolerances, as is the case in many municipal applications. As an increasing number of municipal engineers become aware of the technology and its advantages, this market is expected to grow rapidly over the next five years. Figure 1-2 is a typical HDD layout in a municipal environment, and Figure 1-3 is a typical HDD rig used in a utility application.
Another factor in the increased popularity of HDD for municipal applications is the acceptance of HDPE pipe for water and sewer projects. During the 1970s and 1980s municipal gas utilities drove the demand for HDPE pipe. While HDPE pipe has been in use since the early 1950s, it was only during the last several years that the potable water and sewer industries were attracted to the benefits for their applications. In 1978, the American Water Works Association (AWWA) approved
HDPE pipe for water service; at that time the maximum diameter tubing was just 3 inches. In June 1990, AWWA developed the first edition of AWWA Standard C906-90 for 4-inch through 63-inch HDPE pipe and fittings designed for water distribution. The new standard opened the way for innovative applications, and water suppliers began to realize the economic and performance advantages of HDPE.

HDD construction is more suitable for utility applications than any other trenchless procedure. The HDD equipment available today is capable of installing pipe in the sizes that the majority of water and sanitary sewer systems use. As a result, HDD is responsible for a growing percentage of public works construction. HDD equipment developed specifically for utility work was introduced in the late 1980s. Compared to today’s models, they had limited capabilities. In the mid-1990s HDD equipment came into wide use, attracting the most attention for its role in telecommunications construction. Today HDD is being used on water projects using both force-main and gravity-flow sewer systems.

Several factors make directional drilling more appropriate for public works construction than in the past:

1. Current HDD equipment can install pipe in large diameters.
2. Directional drills are perfectly suited for installing the types of pipe used in water and sewer systems. HDD crews are experienced in the installation of fused lengths of HDPE pipe. Restrained-joint PVC pipe products are ideally suited for installation by HDD equipment; couplings quickly lock sections of
pipe together, holding them firmly while pipe is pulled into place by a directional drilling unit.

3. Today’s HDD equipment can operate effectively in most soil conditions, including loose and solid rock.

4. Directional drilling often requires less support equipment than other methods.

HDD is a viable construction alternative that has become very competitive cost-wise in areas where there is limited access and in high-traffic locations, where it eliminates most surface repairs. HDD allows engineers to accomplish work in a more environmentally friendly way. HDD also offers the same benefits for sewer projects, but the need to install pipe on grade for gravity-flow systems has made its acceptance slower. HDD contractors have successfully installed gravity-flow and force-main sewer lines with HDD equipment. New guidance electronics, developed specifically for the sewer market, makes to-grade installations easier to accomplish. HDD is not just for sewers where open-cut construction is not convenient. Many in the municipal market believe that HDD will soon be the primary method of construction and will be used even when project owners do not require it. It will be used because it is the best construction option available.

1.3 The HDD Process

The basic components of a horizontal directional drilling system include:

- Drill unit
- Guidance system
- Drilling fluid system
- Drill pipe and downhole tools, including bits and back reamers
- Drilling fluid mixing or recycling system

The HDD rig is connected to the cutting bit by the drill string, which is made up individual joints of pipe. Back reamers are used to increase the diameter of the pilot hole to the required size to accommodate the diameter of the pipe to be installed. The drilling fluid, commonly known as mud, plays an essential role in drilling, back reaming, and product pullback. The fluid mixing system is separate from the drilling rig. Fluid recirculating systems often are employed on long bores to install large-diameter pipe.

After offloading the HDD rig, it is positioned over the bore path centerline at an adequate distance from the drill entry point to allow the drill bit to enter the ground at the desired location and angle. The HDD rig is often tied down using the powered rotating screws located on the front of the drill rig. The project area, including the
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HDD entry and exit points, should well marked in accordance with the project plans and specifications. Ensure that all the equipment and material required for the HDD project are on hand and in good condition. This includes ensuring that appropriate types and quantities of drilling fluids and additives are on hand.

HDD systems are defined by:

- Thrust and pullback force, stated in pounds
- Spindle torque, stated in foot pounds
- Maximum volume of drilling fluid a machine can pump per minute, and spindle revolutions per minute

A typical HDD rig is illustrated in Figure 1-4.

The HDD drill rig is used to drill and ream the pilot hole and pull the product pipe back through the hole. HDD drill rigs provide torque, thrust, and pullback to the drill string. The drill drive assembly resides on a carriage that travels under hydraulic power along the frame of the drill rig. The thrust mechanism for the carriage can be a cable, chain, screw, or rack-and-pinion system. Table 1-3 lists the three general categories of drilling rigs used in the industry.

Mini rigs are mounted on a trailer, truck, or self-propelled track vehicle. The self-propelled units are self-contained, with the engine, hydraulic power, and drilling fluid pump all part of the unit. The lower end of this class of drill rigs (less than 20,000 pounds thrust/pullback) is designed for drilling in relatively soft semiconsolidated formations and is used primarily for the installation of utility conduits and small-diameter pipelines in congested urban areas. They are not suitable for drilling gravel, cobble, or other formations where bore-hole stability is difficult to maintain. The higher end of this class of drill rigs is suitable for drilling in gravel and cobbles as long as the bore lengths are not excessive.

Medium-sized drilling rigs are used to install larger conduits and pipelines, normally up to 16-inches in diameter, with drill lengths ranging up to 2000 feet. They are particularly suitable for the installation of municipal pipelines, as they are sufficiently compacted to be used in urban areas while at the same time they have the capacity to install large-diameter products beneath highways, subdivisions, and

![FIGURE 1-4 Typical HDD Rig](image)
rivers. Bores can be installed in unconsolidated to consolidated sediments. Many of the drill rigs in this class are self-contained units.

Maxi rigs typically involve a large operation with multiple trailer-mounted support equipment and substantial mobilization and demobilization periods. High operating costs make their use somewhat prohibitive in the utility installation market, and they are employed primarily in the pipeline industry. These large units may be used in the installation of large diameter pipes (16 to 48-inches) and/or exceptionally long bores.

In addition to the drilling rig, a variety of support equipment may be required. Depending on the HDD project, a drilling fluid or mud cleaning and recirculation unit, drill-pipe trailer, water truck, and pump and hoses may be required. An excavator is needed to dig the entry, exit, and recirculation pits. In urban or environmentally sensitive areas a vacuum truck may be required to handle the fluid in the return pits or inadvertent returns.

The physical size of the HDD equipment is also important because the available setup space at many project locations is often limited. HDD units come in a wide range of sizes, with the units most often employed for utility work yielding between 5,000 and 90,000 pounds of pullback. Models with half a million pounds of pullback and more are available. The smallest models are designed to make installations up to 150 feet in length. Units in the 70,000- to 90,000-pound range can

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<th>TABLE 1-3 Typical Characteristics of HDD Rigs</th>
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<td>Mini Rigs</td>
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<td>Drill Rig Area Required (width x length)</td>
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<td>Recommended Work Area Requirements (width x length)</td>
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make pilot bores and pull in pipe to distances of 6,000 feet and more, depending on soil conditions.

Pipe Installation

Installation of a pipe by HDD is usually accomplished in three stages. The first stage involves directionally drilling a small-diameter pilot hole along a designed directional path. The second stage consists of enlarging (reaming) the pilot hole to a diameter that will support the pipeline, and the third stage consists of pulling the pipeline back into the enlarged hole.

Pilot Hole

The first step in a HDD installation is to drill a carefully guided pilot hole that delivers the drill bit and bore head to the surface at the specified exit point. The bore is launched from the surface, and the pilot bore proceeds downward at an angle until the necessary depth is reached. A small-diameter drill string penetrates the ground at a prescribed entry point and the design entry angle, normally between 8 and 16 degrees. To help prevent the drill rod from deflecting upward or to the side, the pilot hole is usually started with the slanted drill head at the 6 o’clock position. At a prescribed depth or point the drill pipe is bent to follow the proposed drill path and the designed bending radius. Then the path of the bore is gradually brought to the horizontal, followed by another bend before the bore head is steered to the designated exit point, where it is brought to the surface. When planning the pilot hole path the designer should include as few bends in the path as possible. This both prolongs the life of the drill string pipe and reduces the installation stress on the product pipe. Choosing the proper drill pipe is a key element in the HDD process. The outer diameter and the wall thickness of the drill pipe have limitations that influence the bend radius of the bore. Larger-diameter drill pipe cannot bend in short distances and cannot be used on short bores. Smaller drill pipes are more flexible and suited for short bores in the right soil conditions.

During the drilling process the bore path is traced by interpreting electronic signals sent by a monitoring device located near the head of the drilling string. At any stage along the drilling path the operator receives information regarding the position, depth, and orientation of the drilling tool, allowing him or her to navigate the drill head to its target. The drill path may also be tracked with a wire line or a wireless non-walk-over system. Regardless of the tracking system used, the objective is to locate the actual position of the drill head as it progresses along the pilot bore path. After the pilot string breaks the surface at the exit location, the bit is removed from the drill string and replaced with a back reamer. The bore path is made up of
straight tangents and long radius arcs. A schematic of the HDD pilot hole is shown in Figure 1-5.

While drilling the pilot hole, the contractor may choose to install a larger diameter wash pipe that will encase the pilot drill string. The wash pipe acts as a conductor casing, providing rigidity to the smaller-diameter pilot drill string and also saving the drilled hole should it be necessary to retract the pilot string for bit changes.

Reaming

Once the pilot hole is successfully drilled, the hole is often enlarged to a suitable diameter for the product pipeline. For instance, if the pipeline to be installed is 8 inches in diameter, the hole may be enlarged to 12 inches or more. This is accomplished by reaming the hole to successively larger diameters. Generally the reamer is attached to the drill string on the bank opposite the drilling rig, rotated, and pulled (pushed in some instances) back through the pilot hole. Joints of drill pipe are added as the reamer makes its way back to the drilling rig. Large quantities of slurry are pumped into the hole to maintain its integrity and to flush out cuttings. While soil conditions do have an impact, the required number of reaming runs is mainly dependent on the diameter of the product pipe and the diameter of the pilot hole. It may vary from no reaming runs to several for large-diameter product pipes.

One method, typically called a continuous bore hole, involves enlarging the pilot hole to the desired diameter while simultaneously pulling back the line product behind the reamer. In some situations with small-diameter product pipe or conduit, the pipe can be pulled straight into the pilot hole after the drill is completed. However, in most HDD operations the bore hole has to be reamed to enlarge the hole to accommodate pulling in the product pipe. Generally the bore hole is reamed to 1½ times the outside diameter of the product pipe. This provides an annular void between the product pipe and the drill hole for the drilling fluids and spoils and for the bending radius of the product pipe.

Sometimes it is necessary to ream the bore hole without pulling back the pipe. After the drill hole is reamed, the product pipe or conduit is pulled back through the hole filled with the drilling fluids. It is best to fabricate the product pipe on the exit side in one section so it can be tested and pulled in one continuous pullback.
The drill pipe is connected to the product pipe or conduit using a pull head or swivel. The swivel is used to prevent rotational torque from spinning the product pipe. A reamer is placed between the pull head and the drill string to keep the drill hole open. A schematic of the HDD reaming process is shown in Figure 1-6.

**Pullback**

Once the drilled hole is enlarged, the product pipeline can be pulled through it. The pipeline is prefabricated and usually tested on the bank opposite the drilling rig. A reamer is attached to the drill string and then connected to the pipeline pull head via a swivel. The swivel prevents any translation of the reamer’s rotation into the pipeline string, allowing for a smooth pull into the drilled hole. The product pipe has to be supported for the pullback operation. This is usually accomplished on rollers or with some type of crane or backhoe. Caution has to be exercised during the pullback to ensure that the product pipe or its coating is not damaged. Often breakaway links that fail before pullback loads exceed the safe limits of the product pipe are utilized. The drilling rig then begins the pullback operation, rotating and pulling on the drill string and once again circulating high volumes of drilling slurry. The pullback continues until the reamer and pipeline break ground at the drilling rig. If possible, there should be enough work space on the pull side so that the product pipe can be assembled in one continuous length. This reduces the chance that the pipe may get stuck during the pullback operation. A schematic of the HDD pullback process is shown in Figure 1-7.

**Drilling and Steering**

Drilling curved and horizontal bore holes requires specialized drilling equipment. This equipment is contained in a bottom-hole assembly (BHA) that consists of a
drilling tool, a bent subassembly, and a steering/tracking tool. Pilot-hole directional control is achieved by using a nonrotating drill string with an asymmetrical leading edge. The asymmetry of the leading edge results in a steering bias. When a change of direction is required, the drill string is rotated so that the direction of the bias is the same as the desired change of direction. The drill string may also be continuously rotated when directional control is not required. Normally, the leading edge will have an angular offset created by a bent subassembly or motor housing. The most common types of down-hole drilling/steering tools used in the HDD industry are compaction tools and down-hole mud motors.

Compaction heads consists of a wedge-shaped drilling bit, which is used for cutting and displacing the soil as well as for steering. To bore a straight hole, the drill string is rotated and pushed simultaneously. When a correction in direction is required, rotation stops and the drilling head is preferentially oriented in the bore hole. Then the drill rig pushes the entire drill string forward. As the slant on the face of the wedge is pushed against the soil, the entire assembly is deflected in the desired direction. After the steering correction is completed, rotation is resumed until another correction is needed. Compaction-type drilling tools are most often used in mini and mid-size drill rigs to drill through soft to medium consolidated soils as well as loose and dense sands. When gravel or hard clay is encountered, compaction heads tend to wear rapidly. They are not suitable for drilling in rock formations.

When drilling with compaction heads, steering difficulties are often encountered in very soft soils. This is caused when the resistance to the deflector plate is not sufficient to offset the tendency of the drill string to drop vertically under its own weight. To solve this problem, use a larger deflector plate. Steering can be improved by increasing the flexibility at the head of the drill string. A common method is to add a length of a smaller-diameter, more flexible drill rod behind the drill bit.

Mud (down-hole) motors are used in ground conditions ranging from hard soil to rock. Mud motors convert hydraulic energy from the drilling mud being pumped from the surface to mechanical energy at the drill bit. This allows for the bit to rotate without drill string rotation. Positive-displacement motors are typically used in HDD operations. These motors generate torque and rotation at the drill bit from the flow output of the mud pump. Directional control is obtained by a small bend in the drill string just behind the cutting head. As with compaction heads, once the correction is made, the complete drill string is rotated to continue boring straight in the new direction. This method costs more than compaction heads and is less common in the utility industry.

The advantage of mud motors is that they cut the formation, reducing drill string rotation requirements and making it possible to drill long bore holes to substantial depths. The main disadvantage of mud motors is that they are more expensive in comparison to compaction heads and require hundreds of gallons of drilling fluids per minute.
Tracking

In HDD applications tracking is the ability to locate the position, depth, and orientation of the drilling head during the drilling process. The ability to accurately track the drill is essential to the completion of a successful bore. The drill path is tracked by taking periodic readings of the inclination and azimuth of the leading edge of the drill string. Readings are recorded with a probe that is inserted in the drill collar as close as possible to the drill bit. The three most common type of tracking tools are electronic beacon systems (walkover), combination magnetometer-accelerometer systems, and inertial navigation systems.

A walkover system consists of a transmitter, receiver, and remote monitor. A battery-powered transmitter is located in the bottom hole assembly near the front of the drill string; it emits a continuous magnetic signal. The receiver is a portable, handheld unit that measures the strength of the signal sent by the transmitter. This information is used to determine the drill head’s position, depth, and orientation. The remote monitor is a display unit installed at the drilling rig in front of the operator. It receives and displays the information provided by the receiver. This information is used to navigate the drilling head below the surface. The data is recorded to provide the as-built profile of the bore path.

When access to a location directly above the bore-hole alignment is not possible or when the depth of the bore exceeds 100 feet, other types of navigation systems should be used. Two systems commonly employed are the magnetometer-accelerometer system and the inertial navigation system. The magnetometer-accelerometer system uses three magnetometers to measure the position (azimuth) of the tool in the earth’s magnetic field and three accelerometers to measure the position (inclination) of the tool in the earth’s gravitational field. The steering tool sends information via a wire line to a computer at the surface, where the azimuth, inclination, and tool-face orientation are calculated. This steering tool does not impose any limitation on the rig’s operating range from the drilling rig. Disadvantages of this system include susceptibility to magnetic inferences from buried metal objects and power lines. Some magnetic-accelerometer systems use a secondary survey system to account for local magnetic influences on the down-hole probe. The secondary survey system induces a known magnetic field at the ground surface through a copper-wire surface grid. A computer program connected to both the surface magnetic field and the steering tool compares the magnetic field measured by the steering tool and the theoretical magnetic field induced by the system in order to compensate for local magnetic interference.

The inertial navigation system uses a system of three gyroscopes and three accelerometers to measure the azimuth and the inclination, respectively, of the steering tool. The gyroscopes are aligned to true north at the ground surface before the survey is made. Any deviation from true north during the survey is detected by the
gyroscopes and relayed to the surface, where the azimuth, inclination, and drilling-tool orientation are calculated by a computer. Because of the cost and sensitivity of these systems, they are used mainly for calibration purposes.

Drilling Fluids

Drilling fluids are commonly called drilling mud or slurry. Drilling mud is mixed on the surface and pumped down the drill string. The mud comes out at the drill bit and is either left in the annulus of the bore hole or circulated back to the surface. Drilling mud is a mixture of water, premium bentonite, and, if needed, small amounts of polymer. Bentonite is a nonhazardous material.

Drilling fluids have many uses or functions. The main purposes of HDD drilling fluids are:

1. To establish and maintain the bore hole integrity.
2. To transport drill cuttings to the surface by suspending and carrying them in the fluid stream that flows in the annulus between the well bore and the drill rod.
3. To clean the buildup on the drill bits or reamer cutters by directing high-velocity fluid streams at the cutters. This also cools the bits and electronic equipment.
4. To reduce the friction between the drill string and the bore-hole wall aided by the lubricating properties of the drilling fluid.
5. To stabilize the bore hole, especially in unconsolidated soils, by building a low permeability filter or mud-cake lining and exerting a positive hydrostatic pressure against the bore-hole wall, preventing collapse as well as preventing formation fluids from flowing into or drilling fluids from exiting the bore hole into the formation (loss of circulation).
6. To provide hydraulic power to downhole mud motors if used.

A drilling fluid is composed of a carrier fluid and solids (clay or polymer). The carrier fluid carries the solids down the bore hole, where they block off the pore spaces on the hole wall. The blockage is referred to as a filter or mud cake. The ideal mud cake will form quickly during construction of the well bore and prevent intrusion of drilling fluid into the formation. At times additives such as detergents are added to the drilling fluids to counteract some of the formation characteristics such as swelling and stickiness.

Drilling fluids that are not properly contained on the surface can cause problems. A drilling plan should include the procedures for handling the drilling fluids as they return to the surface. Pre-dug pits and trenches or a vacuum truck should be a part
of the bore planning. In addition, a drilling-fluid-disposal plan is a requirement for any HDD project. After all the federal, state, and local regulations are met, spreading the used bentonite slurry on pastures and fields or pipeline rights of way with the landowner’s permission can benefit the contractor and the landowner.

Chapter 1 Footnotes

2 A Survey of Current Horizontal Directional Drilling Practices In Canada and the United States, prepared by Ezez N. Allouche, Ph.D., Samuel T. Ariaratnam, Ph.D., and Jason S. Lueke, E.I.T.
A HDD project can be a major event, such as a significant water crossing, or a relatively minor one, such as a driveway or road crossing. Regardless of the nature of the HDD project, potential risks and problems should be identified early in the process. Many projects require extensive surface and subsurface investigations by qualified engineers to determine the feasibility and to assist the owner in preparation, planning, and design. The level of design-engineering effort for a HDD project is affected by many site factors including soil formations, terrain, existing utilities, and equipment setup restraints. Regardless of the upfront engineering effort, it is not unusual for the final bore path to change from the original design because of actual drilling conditions encountered.

When first considering a HDD crossing, there are many factors to evaluate before deciding if HDD is the best installation method for a pipeline or utility conduit. Economics or cost is always a primary factor. A HDD crossing is economically feasible if the project cost is less than or comparable to the cost of alternative construction methods. In many instances HDD provides the most economical choice, and in others it does not. While cost is important, determining if the potential application is technically feasible is usually the key factor when deciding if HDD is appropriate. A HDD project is considered technically feasible if it can be performed with existing equipment, tools, and techniques regardless of uncertainties surrounding the cost of installation. With the capabilities of today’s HDD equipment and drill pipe, there are limitations on the length of a HDD bore and the diameter of the product pipe or conduit. The equipment in use today thrusts the drill pipe from the surface to drill a pilot hole. There are limitations on the amount of
thrust that can be applied to the drill pipe. In addition, control of the drill path diminishes over long lengths, and HDD rigs have limitations on the pullback loads they can handle.

In many instances the above feasibility considerations can be answered quickly by someone experienced with HDD applications. Based on knowledge of the project, project area, HDD equipment, HDD technology, HDD practices, and HDD contracts, the feasibility of a project can often be determined quickly, avoiding wasted time and money. However, in many cases the answers to the feasibility questions require extensive work and research to accurately assess the technical and economical aspects of the project. In these instances, detailed planning, research, and coordination are required to identify the possible problems or challenges for a HDD project. Based on the potential problems and challenges identified, all involved parties—owners, engineers, and contractor—can be aware of the issues and how they could affect the design and construction of the HDD project.

2.1 Technical Feasibility

The technical feasibility of a HDD crossing is usually the first issue to consider. There are many factors to consider when evaluating the technical feasibility of a HDD project. Conducting a site survey, usually the first step, is important for all HDD projects and is a significant part of the HDD site characterization. The site survey should include both surface and some level of subsurface investigations. Based on the information from the site survey, plan and profile drawings are developed. The drawings are used for contract documents and to make a working profile that will be used for navigation of the bore and developing as-built drawings.

Site Evaluation

Selection of HDD for use on a particular crossing should be predicated on a thorough understanding of the site’s characteristics. If HDD is the selected construction method, the design, permitting, and execution of the crossing should be governed by the conditions at the site. Existing features, both natural and man-made, should dictate the manner in which an HDD crossing is configured. Examples of key characteristics are the earth material types, stratification, and groundwater conditions. Also included are the various aspects of the site’s surface such as the topographic/hydrographic relief and the presence of human activities. For a site evaluation, the primary considerations are geological factors, topographic and hydrographic details, and geotechnical aspects.
Surface Conditions

The surface conditions often have a significant impact on the feasibility of HDD construction. The primary consideration is the project area’s suitability for the layout of the required HDD equipment and the product pipe. The main site layout factors that impact the feasibility of HDD are the drill-rig layout area, product cable or pipe layout area, required temporary and/or permanent easements, existing utilities, existing infrastructure such as railroads or highways, adjacent property and use restrictions, and future developments in the area. The surface impact associated with construction of a pipeline crossing by HDD is significantly less than the impact associated with construction by open-cut excavation. However, HDD construction is not without some surface impact. On many projects the working areas for the entry and exit points must be cleared and graded to allow for the HDD equipment and pipe pulling. When the work areas are limited, before declaring that a HDD project is not technically feasible, alternate scenarios for performing the HDD should be considered.

Work-Area Conditions

The area required for the HDD rig must be sufficient for the rig and its ancillary equipment. In general, the size of the required area will depend upon the size of the HDD crossing, including length of bore and diameter of the pipe to be installed. The length of the crossing and diameter of the product pipe will dictate the size of the drill rig and the drilling equipment to be used. See Table 1-3 for the recommended workspace requirements for different classes of drill rigs. Preferably each HDD site would allow an area at least 25 by 50 feet for the entry side (drill rig) and adequate space on the exit side (pipe side) to pull the pipe as one continuous length. In urban areas this is often not possible. Because of restrictions such as lane closures for roads or the need to work in alleyways,
sidewalks, landscaped areas, or utility corridors, HDD equipment must often be configured in a linear arrangement. Other workspace considerations are the presence of overhead utilities and the possibility of restricted work hours due to peak travel times on roadways.

A typical large (maxi) rig may require several tractor-trailer loads to transport all the equipment to the HDD site. A workspace of approximately 150 by 250 feet is normally adequate for most large HDD operations. If necessary, a rig may be installed in a workspace of 50 by 100 feet. However, a workspace this small restricts the size and capability of the drilling rig. A typical HDD site plan is shown in Figure 2-3.

For smaller-diameter products the product pipe can be on a reel, which greatly reduces the workspace requirements on the pull side. This is usually the case in
many municipal projects for communication cables and service gas and water lines. However, when the product pipe is too large a diameter to be supplied on a reel (usually larger than 6 inches), sufficient space is needed at the side opposite the HDD rig, where the pilot bore will exit and the pipe is to be inserted, to accommodate a continuous straight length of prefabricated pipe. The space for the straight length should begin approximately 25 feet from the anticipated pilot-bore exit and extend at a width of 35 to 50 feet, depending upon the pipe diameter. In the immediate vicinity of the pilot bore exit (pipe entry), a work area of typically 25 by 50 feet is desired.

Drilling-Fluid Considerations

For many HDD crossings, facilities for mixing, storing, and pumping drilling fluid may require significant space. When possible it is standard practice to draw fresh water found at the location for mixing the drilling fluid. However, alternate water supplies may be required to obtain proper drilling-fluid characteristics. It may also be necessary to provide access for trucks to transport water or to provide for the installation of a relatively long surface pipe or hose connecting to a remote hydrant.

Proper disposal of the drilling-fluid wastes must also be considered. The volume of drilling fluid used will depend upon the soil characteristics but is typically on the order of one to three times the volume of removed soil. Most drilling fluids use bentonite or polymer additives, which are not generally considered to be hazardous.
However, local regulations should be followed regarding disposal. Drilling-fluid re-
circulation is often used to reduce overall material and disposal costs. If drilling
fluid recirculation is contemplated, a means must be considered for transporting any
fluid exhausted from the opposite (bore exit) side during the pullback operation to
the rig side. This may be accomplished by truck, barge, or a temporary recirculation
pipe line. The recirculation line must be adequate to prevent accidental discharge.

**Topographic and Hydrographic Considerations**

The site topography is another key factor to consider for HDD projects. The key in-
formation is the site’s surface configuration. It allows definition of the obstacle to be
crossed and provides a basis for decisions concerning the arrangement of construc-
tion operations. The items of interest include the land and water conditions of the site
or obstacle as well as any man-made features. A survey is often performed to estab-
lish a reference for the hydrographic and geotechnical data and develop profiles of
the anticipated bore-path centerline. The survey information should be related to topo-
graphical features in the vicinity of the proposed crossing. Existing topographical
information may be available from the U.S. Geological Survey, or federal, state, or
county publications. Aerial photographs also may be useful, especially for crossing

![FIGURE 2-5  HDD Site](image)
land-based obstacles in urban areas, since they may indicate the presence of demol-ished buildings and the possibility of old foundations. It is also necessary to check available utility records to help identify the location of existing below-ground facilities in the vicinity, including electric power, natural gas, petroleum, water, sewer, or telecommunications lines. The presence of existing pipelines or support pilings containing significant steel mass should be noted, since they may cause interference with magnetically sensitive equipment guidance or location instrumentation. One key factor of topographic relief occurs when the surface-pipe entry and exit elevations are substantially different. This can cause problems with maintaining circulation in the bore hole and keeping the hole full of drilling fluid.

Geological Considerations

In assessing the suitability of HDD for a specific location, an understanding of the site’s origin is fundamental. This is important not only to the site’s effects on HDD but also to plan an effective site characterization study. Understanding the mechanism by which the site was developed, whether by aeolian (airborne), colluvial (gravity), alluvial (river), lacustrine (lake), glacial, or marine (saltwater sea) depositional processes, will forecast the types of materials to be expected as well as the potential for anomalous impediments (boulders, cobble fields, buried logs, stumps, etc.) that influence the HDD construction process. The geological evaluation provides the background for assessing the obstacle to be crossed.

Subsurface Conditions and Considerations

The decision to use the HDD method for a crossing should be based on an understanding of the HDD process and the crossing site’s characteristics. The natural and man-made features in the area will dictate the design for the HDD crossing. After determining if the surface conditions are suitable for HDD construction, the next item to consider is the subsurface conditions. A vital element of many HDD design projects is a comprehensive geotechnical survey to identify soil formations at the potential HDD site.

The purpose of the geotechnical investigation is to determine if directional drilling is feasible and if so the most efficient way to accomplish it. The technical feasibility of a HDD project significantly depends on the subsurface conditions that the bore path must penetrate. In many HDD projects an accurate and thorough geotechnical investigation should be performed by a qualified engineer, including review of existing information and site-specific studies for the proposed location. This information is used to develop design drawings (including final bore route, pipe design, and bore design), construction specifications, and permit applications. The contractors also use this information to help them select the appropriate tools and methods for the actual construction.
Site characterization information should do more than just define soil conditions along the bore path; it should also include a forecast of future conditions and anticipate the effect of the HDD project on site conditions. The subsurface investigation usually begins with a review of the existing data that may be obtained from published soil reports (for example, Soil Conservation Service reports, U.S. Geological Survey reports, or U.S. Army Corps of Engineers reports) or records from previous construction projects. In particular, data from nearby pipe or cable crossings or bridge foundation construction should be examined. The results of this study should be used to define the initially recommended bore-path profile.

To successfully complete a HDD project, an open hole must be cut into the subsurface material so that the product pipe can be installed or the soil properties must be modified to allow the product pipe to be pulled through it. The feasibility of achieving either of these conditions depends largely on the subsurface soil conditions. In the open-hole condition a cylindrical hole is cut in the subsurface and the drilling fluid flows to the surface in the annulus between the pipe and the hole wall while transporting the drilled spoil to the surface. The open-hole condition generally applies to rock and cohesive soils, but it can also apply to some sandy or silty soils depending on the density of the material, the specific makeup of the soil coarse, and the binding of the fine fraction. Loose, cohesionless soils will usually not support an open hole over a long HDD length. However, this type of soil condition does not necessarily make HDD unfeasible. The combination of the mechanical action of the reaming tool and the injection of the drilling fluid will result in a decrease in the shear strength of the soil. If the shear strength reaches the desired limits, the soil will behave in a fluid manner, allowing a pipe to be pulled through it. Both the above conditions are acceptable for HDD applications. If they can be achieved and the stresses on the product pipe and HDD equipment are within allowable limits, the HDD installation is technically feasible from this point.

While length, diameter, and subsurface soil material work in combination to limit the technical feasibility of a HDD installation, feasibility is primarily limited by subsurface soil material. The material characteristics that prevent the successful establishment of either an open hole or fluid condition are large grain content (i.e., gravel, cobbles) and excessive rock strength and hardness. Soils that consist of mainly coarse-grained material present a serious restriction on the feasibility of HDD because they cannot be easily fluidized by the drilling fluid. This condition makes it difficult to cut and remove the material in a drilling fluid through the open hole. A boulder or cluster of cobbles will remain in the drilled path and present an obstruction to a bit, reamer, or pipeline. They must be mechanically displaced during hole enlargement. Displacement may be radially outward into voids formed by the entrainment of finer-grained (sand and smaller size) material. However, naturally dense, high-gravel-percentage soils contain little entrainable material and insufficient voids may be developed to permit passage by larger-diameter reamers or pipe. Coarse material may also migrate to low spots on the drilled path, forming impenetrable blocks.
Exceptionally strong and hard rock will hamper all phases of an HDD project. Experience has shown that competent rock with unconfined compressive strengths exceeding 40,000 psi can be negotiated with today’s technology. However, this type of HDD crossing is costly, and the entry of such materials at depth is usually difficult because the directional drilling string often deflects rather than penetrates. Poor-quality (extensively fractured or jointed) rock can present the same problems as coarse granular deposits. General guidelines for assessing the feasibility of prospective HDD installations based on earth material type and gravel percent by weight are presented in Table 2-1. Engineering judgment based on practical experience must be applied when using the guidelines presented in Table 2-1.

### TABLE 2-1 HDD Feasibility Guidelines

<table>
<thead>
<tr>
<th>Earth Material</th>
<th>Gravel % by Weight</th>
<th>HDD Feasibility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very soft to hard strength, possibly slickensided clay</td>
<td>NA</td>
<td>Good to Excellent. Penetration of strong clay surrounded by looser soils may result in the bit skipping at the interface. Bit steering may be difficult when passing through soft soil layers.</td>
</tr>
<tr>
<td>Very loose to very dense sand with or without gravel traces.</td>
<td>0 to 30</td>
<td>Good to Excellent. Gravel may cause steering problems.</td>
</tr>
<tr>
<td>Very loose to very dense gravelly sand.</td>
<td>30 to 50</td>
<td>Marginal. In these conditions drilling fluid characteristics are critical to success. Bit steering may be inaccurate.</td>
</tr>
<tr>
<td>Very loose to very dense sandy gravel.</td>
<td>50 to 85</td>
<td>Questionable. Horizontal penetration for any appreciable distance will be extremely difficult. Bit steering will be inaccurate.</td>
</tr>
<tr>
<td>Very loose to very dense gravel.</td>
<td>85 to 100</td>
<td>Unacceptable. With current technology horizontal penetration is almost impossible. This type of material must be avoided or penetrated at a steep angle.</td>
</tr>
<tr>
<td>Rock</td>
<td>NA</td>
<td>Excellent to Unacceptable. Softer or weathered materials offer good HDD characteristics. Penetrating solid rock after passing through soil may be difficult due to the bit’s tendency to skip on the lower hard surface. Rock in the rounded cobble form is almost impossible to drill.</td>
</tr>
</tbody>
</table>
Geotechnical Investigation

The information from the geotechnical survey is used to select the crossing route, drilling tools, procedures, and the drill-path design. The level of effort required for the geotechnical investigation depends on several factors, such as the pipe diameter, bore length, and the nature of the HDD crossing. For many HDD projects, especially in municipal areas, the subsurface investigation consists primarily of research of existing geotechnical data. Due to the costs and the congested nature of many urban municipal areas, test holes are not performed. This is especially true for shorter drill lengths and smaller-diameter pipe or cable. This is another area where the experience of the design and geotechnical engineers is important. In many instances, the technical feasibility of the project can be reasonably determined without the cost and disruption of test holes. However, when planning HDD crossings without test-hole data of the proposed crossing, the risk element is always higher.

When test holes are required, it is important that they are conducted by qualified personnel and that the needed data is obtained from the investigation. During the survey, the geotechnical consultant will identify a number of relevant items including the following:

- Soil identification to locate rock, rock inclusions, gravelly soils, loose deposits, discontinuities, and hardpan
- Soil strength and stability characteristics
- Groundwater

The length of the drill and the complexity of the strata determine the number of exploration holes required for the geotechnical survey. For drill paths shorter than 1000 feet, two soil-test borings (one on each end of the bore) may be adequate. If the data from these test borings indicate that the conditions are likely to be homogeneous on both sides of the bore, it may not be necessary to conduct any more test borings. If the test data indicate anomalies in the soil conditions or items such as large concentration of gravel, further tests should be conducted. For drill paths longer than 1000 feet, soil-test borings are typically taken at 500- to 700-foot intervals. The soil-test bores should be near the drill path to provide accurate soil data but far enough from the drill-path bore hole to avoid pressurized mud from rupturing to the ground surface through the soil-test bore hole. A general rule is to take soil-test bores at least 25 feet from either side of the drill path. Soil-test bores for geotechnical surveys are usually drilled 20 feet deeper that the pipe drill path. The following are a few suggested guidelines concerning soil-test bores to consider during the HDD planning stage:

1. Get accurate locations and elevations for each exploration bore hole.
2. Do not locate exploration bore holes directly over the proposed HDD path—offset each 25 to 30 feet laterally.
3. Request complete lithologic and geotechnic descriptions for all geologic strata encountered.
4. Require descriptions of boring techniques and all equipment used.
5. Test bores depths should go at least 20 feet below the lowest anticipated elevation of the horizontal directional bore hole.
6. Standard penetration tests (SPT) should be taken at 5-foot intervals for all strata (cohesive and noncohesive units).
7. Grain-size analyses are helpful—either good field estimates or laboratory sieve tests.
8. It is important to get representative unconfined compression (UC) tests for all “harder” rock units that fail SPT tests (generally at auger refusal). Record rock-quality designations (RQD) and retain cores for visual inspection.
9. Have the driller or geologist record free water levels in the borings and note all significant observations during the actual drilling process. These notes should become part of the final log.
10. Have all bore holes thoroughly plugged and/or grouted upon completion of the exploration program.

Geotechnical Aspects

The earth material and subsurface stratification at the HDD crossing are the geotechnical classifications of interest. Earth material is the type and condition of the soil material at the site. Subsurface stratification defines how the earth material is distributed throughout the site. For HDD projects soil and rock are the broad categories for earth material. Soil particles vary in size. They may contain water or air in the interstitial spaces and may be excavated without drilling or blasting. Rock is a hard, consolidated material that may require drilling or blasting. The subsurface investigation is used to determine as accurately as possible the subsurface conditions along the bore path and whether the conditions are suitable for HDD construction. The dividing line between soil and rock, however, is not definite.

Unified Classification System for Soil Type

The type of soil at a crossing site should be classified using a standard classification system. The purpose of a soil-classification system is to provide the engineer with a method to predict the behavior of the soil for engineering projects. For a soil-classification system to be effective in the HDD industry, it must be widely used, simple, inexpensive, and based on parameters that impact the HDD process. The unified soil-classification system (USCS) satisfies these standards. It is described in detail in ASTM Standard D 2487. The standard bases classification on laboratory tests performed on the portion of a soil sample passing a 3-inch (75 mm) sieve.
The USCS separates soils into two main groups: coarse-grained and fine-grained. The basis of the USCS is that the behavior of coarse-grained soil is related to its grain-size distribution and the behavior of fine-grained soil is related to its plasticity characteristics.

**Distribution of Particle Sizes**

The distribution of particle sizes larger than 0.075 mm (No. 200 sieve) is determined by sieving, while the distribution of smaller particle sizes is determined by a sedimentation process. For the USCS, rock fragments or soil particles are defined as follows:

1. Boulders: particles of rock that will not pass a 12-inch-square opening.
2. Cobbles: particles of rock that will pass a 12-inch-square opening and be retained on a 3-inch U.S. standard sieve.
3. Gravel: particles of rock that will pass a 3-inch sieve and be retained on a No. 4 U.S. standard sieve. There are two subdivisions: coarse will pass a 3-inch sieve and be retained on a 3/4-inch sieve, and fine will pass a 3/4-inch sieve and be retained on a No. 4 sieve.
4. Sand: particles of rock that will pass a No. 4 sieve and be retained on a No. 200 U.S. standard sieve. There are three subdivisions: coarse will pass a No. 4 sieve and be retained on a No. 10 sieve; medium will pass a No. 10 sieve and be retained on a No. 40 sieve; and fine will pass a No. 40 sieve and be retained on a No. 200 sieve.
5. Silt: particles that will pass a No. 200 U.S. standard sieve that is non-plastic or slightly plastic and that exhibits little or no strength when air-dry.
6. Clay: particles that will pass a No. 200 U.S. standard sieve that can be made to exhibit plasticity (puttylike properties) within a range of water contents and that exhibits considerable strength when air-dry.

It is important to distinguish between the size of a soil particle and the classification of the soil. For example, a soil could have a fraction of particles that are “clay size.” The same soil could also be classified as “clay.” However, the classification of “clay” does not necessarily mean that the majority of the soil particles are of the clay size (smaller than a No. 200 sieve). In reality, it is not unusual for a soil to be classified as “clay” and have a larger mass of silt-sized particles than clay-sized particles. When reference is given to a particle size, the term “clay-size particles” or “silt-size particles” should be used. When reference is given to a particular soil, then the terms such as silt or clay should be used.
To classify the different soil types, all soils are classified into fifteen groups, each group being designated by two letters. The first letter indicates:

- G: gravel
- S: sand
- M: silt
- C: clay
- O: organic

The second letter indicates:

- W: well graded, which indicates that a coarse-grained soil has particles of all sizes
- P: poorly graded, which indicates that a coarse-grained soil has particles of the same size
- M: a coarse-grained soil that has silt-sized particles
- C: a coarse-grained soil that has clay-sized particles
- L: a fine-grained soil of low plasticity
- H: a fine-grained soil of high plasticity
- PT: peat, humus, or swamp soils

Table 2-2 (adapted from ASTM D 2487-93, 1998) presents a summary of the USCS.

GW and SW groups comprise well-graded gravelly and sandy soils that contain less than 5 percent nonplastic fines passing the No. 200 sieve. Fines that are present must not noticeably change the strength characteristics of the coarse-grained fraction and must not interfere with its free-draining characteristic.

GP and SP groups are poorly graded gravels and sands containing less than 5 percent nonplastic fines. They may consist of uniform gravels, uniform sands, or nonuniform mixtures of very coarse material and very fine sand with intermediate sizes missing. Materials of this latter type are sometimes referred to as skip-graded, gap-graded, or step-graded.

GM and SM groups include gravels or sands that contain more than 12 percent fines with little or no plasticity. Gradation is not important, and both well-graded and poorly graded materials are included. Some sands and gravels in these groups may have a binder composed of natural cementing agents, so proportioned that the mixture shows negligible swelling or shrinkage. Thus the dry strength is provided by a small amount of soil binder or by cementation of calcareous materials or iron oxide. The fine fraction of noncemented materials may
## TABLE 2-2  Unified Soil Classification System (USCS)

<table>
<thead>
<tr>
<th>Major Divisions (1)</th>
<th>Subdivisions (2)</th>
<th>USCS Symbol (3)</th>
<th>Typical Names (4)</th>
<th>Laboratory Classification (5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse-grained soils (more than 50% retained on a No. 200 sieve)</td>
<td>Gravels (more than 50% of coarse fraction retained on No. 4 sieve)</td>
<td>GW</td>
<td>Well-graded gravels or gravel-sand mixtures, little or no fines.</td>
<td>Less than 5% fines*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GP</td>
<td>Poorly graded gravels or gravelly sands, little or no fines.</td>
<td>Less than 5% fines*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GM</td>
<td>Silty gravels, gravel-sand-silt mixtures.</td>
<td>More than 12% fines*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GC</td>
<td>Clayey gravels, gravel-sand-clay mixtures.</td>
<td>More than 12% fines*</td>
</tr>
<tr>
<td>Sands (50% or more of coarse fraction passes No. 4 sieve)</td>
<td>SW</td>
<td>Well-graded sands or gravelly sands, little or no fines.</td>
<td>Less than 5% fines*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SP</td>
<td>Poorly graded sands or gravelly sands, little or no fines.</td>
<td>Less than 5% fines*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SM</td>
<td>Silty sands, sand-silt mixtures.</td>
<td>More than 12% fines*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SC</td>
<td>Clayey sands, sand-clay mixtures.</td>
<td>More than 12% fines*</td>
<td></td>
</tr>
</tbody>
</table>
### TABLE 2-2 (continued)

<table>
<thead>
<tr>
<th>Major Divisions (1)</th>
<th>Subdivisions (2)</th>
<th>USCS Symbol (3)</th>
<th>Typical Names (4)</th>
<th>Laboratory Classification (5)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine-grained soils</td>
<td>Silts and clays</td>
<td>ML</td>
<td>Inorganic silts, rock flour, silts of low plasticity.</td>
<td>Inorganic soil</td>
</tr>
<tr>
<td></td>
<td>(50% or more</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>passes the No. 200</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>sieve)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Silts and clays</td>
<td>CL</td>
<td>Inorganic clays of low plasticity, gravelly clays, sandy clays, etc.</td>
<td>Inorganic soil</td>
</tr>
<tr>
<td></td>
<td>(liquid limit</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>less than 50)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Silts and clays</td>
<td>OL</td>
<td>Organic silts and organic clays of low plasticity.</td>
<td>Organic soil</td>
</tr>
<tr>
<td></td>
<td>(liquid limit</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>more than 50)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Peat</td>
<td>MH</td>
<td>Inorganic silts, micaceous silts, silts of high plasticity.</td>
<td>Inorganic soil</td>
</tr>
<tr>
<td></td>
<td>Highly organic</td>
<td>CH</td>
<td>Inorganic highly plastic clays, fat clays, silty clays, etc.</td>
<td>Inorganic soil</td>
</tr>
<tr>
<td></td>
<td></td>
<td>OH</td>
<td>Organic silts and organic clays of high plasticity.</td>
<td>Organic soil</td>
</tr>
</tbody>
</table>

* Fines are those soil particles that pass a No. 200 sieve. For gravels and sands with between 5 and 12% fines, use of dual symbols is required.
be composed of silts or rock-flour types with little or no plasticity, and the mixture will exhibit no dry strength.

GC and SC groups comprise gravelly or sandy soils with more than 12 percent fines that exhibit either low or high plasticity. Gradation of these materials is not important. The plasticity of the binder fraction has more influence on the behavior of the soils than does variation in gradation. The fine fraction is generally composed of clays.

ML and MH groups include the predominantly silty materials and micaceous or diatomaceous soils. Soils in these groups are sandy silts, clayey silts, or inorganic silts with relatively low plasticity. Also included are loessial soils and rock flours. Micaceous and diatomaceous soils generally fall within the MH group but may extend into the ML group. The same is true for certain types of kaolin clays and some illite clays with relatively low plasticity.

CL and CH groups embrace clays with low and high liquid limits, respectively. They are primarily inorganic clays. Low-plasticity clays are classified as CL and are usually lean clays, sandy clays, or silty clays. Medium- and high-plasticity clays are classified as CH. These include fat clays, gumbo clays, certain volcanic clays, and bentonite. The glacial clays of the northern United States cover a wide band in the CL and CH groups.

OL and OH groups are characterized by the presence of organic matter, including organic silts and clays. They have a plasticity range that corresponds with the ML and MH groups.

The PT group consists of highly organic soils that are very compressible and have undesirable construction characteristics. Peat, humus, and swamp soils with a highly organic texture are typical of the group. Particles of leaves, grass, branches of bushes, or other fibrous vegetable matter are common components of these soils.

Soils in the GW, SW, GP, and SP groups are nonplastic materials in which less than 5 percent of particles pass the No. 200 sieve, while GM, SM, GC, and SC soils have more than 12 percent of particles passing the No. 200 sieve. When these coarse-grained materials contain between 5 and 12 percent of fines, they are classified as borderline and are designated by a dual symbol, such as GW-GM. Similarly, coarse-grained soils that have less than 5 percent of particles passing the No. 200 sieve but that are not free draining or in which the fine fraction exhibits plasticity are also classed as borderline and given a dual symbol.

**Soil Conditions**

Factors that are used to determine a soil’s condition and aid in its classification vary depending on the type of soil. For clay soils, the unit weight, moisture content, and Atterberg limits should be determined. For granular soils, the in situ density (SPT blow counts) and grain-size distribution should be determined. Standard procedures for measuring these characteristics are:
• Unit weight EM1110-2-1906
• Moisture content ASTM D-2216
• Atterberg limits ASTM D-4318
• Standard penetration test ASTM D-1586
• Sieve analysis ASTM D-422

Rock Conditions

Factors that are used to determine the condition of rock are measurements of unit weight, hardness, and in situ conditions. Rock hardness has been correlated with the unconfined compressive strength of rock specimens. Table 2-3 lists the hardness of rock as a function of the unconfined compressive strength.

Because the unconfined compressive strength is performed on small rock specimens, it often does not represent the actual condition of in situ rock. This is caused by the presence of joints, fractures, fissures, and planes of weakness in the actual rock.

### TABLE 2-3 Hardness of Rock / Unconfined Compressive Strength

<table>
<thead>
<tr>
<th>Hardness (1)</th>
<th>Unconfined Compressive Strength (tsf) (2)</th>
<th>Rock Description (3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very soft</td>
<td>10 to 250 tsf</td>
<td>The rock can be readily indented, grooved, or gouged with the fingernail, or carved with a knife. Breaks with light manual pressure.</td>
</tr>
<tr>
<td>Soft</td>
<td>250 to 500 tsf</td>
<td>The rock can be grooved or gouged easily with a knife or sharp pick with light pressure. Can be scratched with a fingernail. Breaks with light to moderate manual pressure.</td>
</tr>
<tr>
<td>Hard</td>
<td>500 to 1,000 tsf</td>
<td>The rock can be scratched with a knife or sharp pick with great difficulty (heavy pressure). A heavy hammer blow is required to break the rock.</td>
</tr>
<tr>
<td>Very Hard</td>
<td>1,000 to 2,000 tsf</td>
<td>The rock cannot be scratched with a knife or sharp pick. The rock can be broken with several solid blows of a geologic hammer.</td>
</tr>
<tr>
<td>Extremely Hard</td>
<td>&gt;2,000 tsf</td>
<td>The rock cannot be scratched with a knife or sharp pick. The rock can only be chipped with repeated heavy hammer blows.</td>
</tr>
</tbody>
</table>

* 1 tsf is approximately equal to 14 psi.
The in situ rock quality is indicated by a modified core recovery ratio known as the rock quality designation (RQD). The RQD is determined by adding the lengths of all pieces of the core that are equal to or longer than 4 inches and dividing by the total length of the core run. The percentage ratio between the total length of such core recovered and the length of core drilled on a given run is the RQD. The diameter of the core should not be less than 2\(\frac{1}{8}\) inches. The mass rock quality is defined as follows:

- RQD = 0 to 25 percent: very poor rock quality
- RQD = 25 to 50 percent: poor rock quality
- RQD = 50 to 75 percent: fair rock quality
- RQD = 75 to 90 percent: good rock quality
- RQD = 90 to 100 percent: excellent rock quality

When calculating the RQD only count the natural fractures. Fresh fractures due to the sampling process should be ignored. RQD measurements provide valuable data on the quality of the in situ rock mass and can be used to locate zones of fractured or weathered rock.

**Groundwater**

For HDD projects, the installation and in-service operation of the product pipe are often dependent on location of the free water surface. To analyze the effects of the water surface, the potential for fluctuation in the groundwater table should be determined. The potential for a perched water table should also be assessed, because the possible unchecked bore-hole flow could jeopardize the successful completion of a HDD project. Regulatory bodies are also beginning to question the effects of HDD on groundwater quality. To satisfy the regulatory questions, study efforts from cursory to extensive are often required. To be able to satisfy these considerations, earth material permeability is a parameter which should also be assessed.

**Subsurface Stratification**

After defining the geotechnical conditions a profile of the subsurface conditions can be developed. The profile is used to identify how the geotechnical conditions are dispersed throughout the project site. It is generally accepted that the earth materials form material and conditional interfaces. A material interface is the separation between two different classifications (e.g., clay and sand, rock and gravel), while a conditional interface is the separation within a particular earth material type (e.g., loose and dense sand, soft and hard clay). Another element of the stratification assessment is the determination of possible natural and man-made obstacles to HDD operations.
Examples of such natural obstacles include buried logs, stumps, gravel pockets, cobble fields, and boulders. Examples of man-made impediments are existing pipelines, sunken barges, and bulkhead/bridge pier piling.

**Site Characterization Study**

The purpose of the site characterization study is to determine and report the site conditions as they impact the selection, design, and execution of the HDD project. To accomplish this goal, the site characterization study utilizes raw data from direct measurements, processed data from tests and calculations conducted on the raw data, and evaluated data such as plans, drawings, specifications, bid documents, and permit applications. This process develops the required information used to produce detailed construction plans and specifications necessary to execute an HDD installation.

Largely due to the emerging-technology nature of HDD, construction contractors have often been charged with the development and evaluation of site characterization details. However, the site characterization evaluation may impact the HDD project from beginning to completion. Because of this impact on the project, the owner is usually best served if he or she assumes responsibility for the study and evaluation, as it may affect many key decisions throughout the project. The owner will lose the benefits of the site characterization study done prior to the construction-method selection, design, and permitting processes if it is done by the contractor. The permitting process, an increasingly involved and intricate phase of any constructed facility, is placed on a critical path in terms of project accomplishment rather than running parallel with contractor selection. Responsibility for the development and evaluation of the site characterization study can be most efficiently performed by the owner.

**2.2 Economic Feasibility**

Once the technical feasibility of a prospective HDD installation has been established, its economic feasibility can be assessed. This assessment includes estimating the economics (or costs) of the HDD project as well as considering how the technical aspects of the project may impact project bids and contracts. This assessment can be accomplished by comparing it to the costs of past similar installations or by getting estimates or preliminary bids from qualified HDD contractors. HDD crossings that are close to the current technical limits in length, product pipe diameter, or soil conditions may be considered by contractors as too risky to undertake for a fixed lump-sum price. In the current competitive HDD climate, most HDD projects that are technically feasible will receive bids, usually on a
lump-sum basis. However, for HDD projects that reach the technical feasibility limits, the lump-sum bids can be expected to be very high. Contractual considerations are discussed in Chapter 8.

There are many things to consider when assessing the economic feasibility of a HDD project. The most obvious is to compare the estimated cost of the HDD with that of an alternate installation method. If the HDD estimate is less, it is economically feasible. While this is basically true, the challenge comes from ensuring an accurate comparison of all costs associated with the alternate construction methods. It is also valid to consider the benefits that may be involved in HDD, such as increased depth and more lenient permitting requirements. The costs associated with restoration for open trench construction and the environmental impacts for each method considered must be considered for an accurate comparison.

Cost Estimating

As mentioned in the preceding section, historical data can be used for the economic feasibility assessment. Another method of estimating costs for the economic assessment is to do a cost estimate of the HDD project. To accurately estimate the cost of the HDD, the contractor’s direct job costs need to be estimated. The contractor’s direct job costs consist of daily costs and non-daily costs. Daily costs depend on the estimated number of days it will take the contractor to complete the HDD crossing. The estimated working days are based on typical production rates based on historical data. Table 2-4 contains typical production rates for various classes of HDD projects

Non-daily costs do not depend on the duration of HDD operations; they include the equipment transportation involved with mobilization and demobilization.

**TABLE 2-4 Typical HDD Production Rates**

<table>
<thead>
<tr>
<th>Task</th>
<th>Mini Rigs</th>
<th>Midi Rigs</th>
<th>Maxi Rigs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Mobilization and Set Up</td>
<td>&lt;6 hours</td>
<td>1–3 days</td>
<td>3–10 days</td>
</tr>
<tr>
<td>2. Pilot Hole Drilling</td>
<td>100–400 ft/hr</td>
<td>60–300 ft/hr</td>
<td>20–180 ft/hr</td>
</tr>
<tr>
<td>3. Prereaming/Reaming (Per Pass)</td>
<td>100–300 ft/hr</td>
<td>60–240 ft/hr</td>
<td>20–180 ft/hr</td>
</tr>
<tr>
<td>4. Product Pullback (Without Reaming)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>a. Cable</td>
<td>200–600 ft/hr</td>
<td>200–600 ft/hr</td>
<td>N/A</td>
</tr>
<tr>
<td>b. HDPE</td>
<td>200–600 ft/hr</td>
<td>200–600 ft/hr</td>
<td>150–450 ft/hr</td>
</tr>
<tr>
<td>c. Steel</td>
<td>200–600 ft/hr</td>
<td>200–600 ft/hr</td>
<td>150–450 ft/hr</td>
</tr>
<tr>
<td>5. Layout, Fabrication, and Testing</td>
<td>Function of material, diameter, length of sections, crew size and skill, and testing requirements.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6. Cleanup and Demobilization</td>
<td>2–4 hours</td>
<td>4 hrs to 2 days</td>
<td>2–7 days</td>
</tr>
</tbody>
</table>
Usually non-daily costs are added as a markup to the contractor’s direct costs. This markup covers the contractor’s overhead, contingencies, and profit.

The typical production rates provided in Table 2-2 are dependent on product pipe size and soil conditions. Table 2-5 provides production rates for various pipe sizes and soil conditions.

The pilot-hole production rate is based on productivity rather than penetration rate. It includes the time for surveying and adding pipe and is dependent upon the subsurface conditions. The pilot-hole duration is determined by dividing the production rate into the HDD length to determine total hours required for the pilot-hole production. The prereaming penetration rate also depends on the soil conditions and the diameter of the reamer. The number of required prereaming passes depends on the subsurface conditions and the product pipe diameter. When estimating the HDD economics, it is typically assumed that all HDD projects will be rereamed at least once. For product pipe diameters larger than 30 inches a second prereaming pass should be assumed. For product pipe diameters greater than...
Installation and Feasibility Considerations

FIGURE 2-6  Tasks Associated With HDD Projects
42 inches three prereaming passes can be anticipated. HDD crossings in soft or hard rock normally require at least two additional passes. The prereaming duration can be determined by dividing the length of the HDD crossing by the penetration rate to establish the actual reaming time, then adding two minutes per drill pipe joint for retooling. This gives the duration for a single prereaming pass, which is multiplied by the number of passes to give a total duration for the prereaming operation. The pull-back penetration rate is the speed at which the pipe is being pulled into the reamed hole. It is dependent primarily on pipe diameter but can also be affected by the quality of the reamed hole. Pull-back duration is determined by dividing the length by the penetration rate to establish the actual pull-back time in minutes, then adding two minutes per drill pipe joint for retooling.

When determining HDD economic feasibility, all the tasks associated with the project should be considered in estimating the total costs of the HDD project. For the typical tasks associated with many HDD projects, see Figure 2-6.

Chapter 2 Footnotes

2 Horizontal Directional Drilling, Good Practices Guidelines, HDD Consortium, May 2001
Installation and Feasibility Considerations
3.1 HDD Rigs

A basic horizontal-directional drill-rig is illustrated in Figure 3-1. Horizontal directional drilling is accomplished using a drill rig. It services a bottom-hole assembly (BHA) that is responsible for creating a curved bore hole. The BHA consists of a drilling tool that is capable of creating a curved bore hole and a guidance system that locates the bore hole and directs changes in the trajectory. There is a variety of HDD rigs currently in use. Table 1-3 lists the three general categories of drill rigs typically used in the HDD industry. Directional drill rigs currently used in HDD typically consist of a carriage that slides on a frame and holds the drill rods at an angle of 0 to 25 degrees. In most cases, hydraulic power is used to energize a motor on the carriage that rotates the drill rods. A chain drive or rack-and-pinion drive is used to push or pull the carriage to advance or retract the drill string.

Drill rigs are available in a range of sizes and are distinguished chiefly by the torque and push/pull force they provide. Despite the range in sizes and details offered by particular manufacturers, the rigs share some common features. The drill rig provides thrust to the drilling tool and pullback to the drill string. When drilling a vertical bore hole, the downward force on the drill bit is provided by the weight of the drill motor and the drill string. While drilling a directional bore hole, the drill string is rarely in a vertical position and therefore the “weight on bit” or thrust on the drill string must be provided by the drill rig. The force on the bit is provided (through the drill pipe) by a chain or rack-and-pinion system on the rig. The rig
must be anchored to provide a reaction against which the mechanical system can operate. Anchoring is typically done by driving stakes through openings at the front of the rig, attaching the rig to a buried weight, or simply attaching the rig to a large, heavy piece of equipment on the surface. The drill rig must provide sufficient thrust (and the drill pipe sufficient strength) to advance the drill string the full length of the proposed bore hole and sufficient pulling force to retract casing into the completed hole. The relationship between thrust and drilling distance also depends on the formation type and use of drilling fluids.

The drill rig must also provide torque to the drill string. Most drilling methods require that the drill string be rotated while it is advanced into the bore hole in order to reduce drag friction on the string. The drill rig must have sufficient capacity to overcome bore-hole friction and supply the necessary torque to the drill string throughout the proposed length of the hole. The drill rig must provide a means to deliver drilling fluid to the drill string. Typically this is accomplished using a pump, capable of handling the drill slurries, to inject fluid through the drill rods and out nozzles in the bit. Most HDD contractors have several directional drill rigs of varying sizes to accommodate various drilling conditions and project demands.

Small (Mini) Rigs

The mini-rig category typically includes drill rigs rated at less than 40,000 pounds of thrust and pullback, less than 4,000 foot-pounds of torque, and a drilling-fluid pump system of less than 75 gallons per minute. Mini drill rigs are usually mounted on a trailer, truck, or a self-propelled track. The self-propelled versions are self-contained units with engine, hydraulic power, and the drilling-fluid pump on the
vehicle. Drill units that have auxiliary power and off-board drilling-fluid pump systems are called umbilical units. Drill rigs that are rated below 20,000 pounds of thrust and pullback are used mainly for utility cable and small-diameter product pipes in congested areas. Some of the higher-end models in this category can be used to drill in gravel, cobble, and other formations where the bore-hole stability is hard to maintain. For small drill rigs specialty drilling systems and down-hole tools are now available for drilling through rock of medium hardness as well as cobbles.

Medium (Midi) Rigs

The midi-rig category typically includes drill rigs rated at 40,000 to 100,000 pounds of thrust and pullback, 4,000 to 20,000 foot-pounds of torque, and a drilling-fluid
pump system of 50 to 200 gallons per minute. Most of the drill rigs in this category are self-contained units. Midi rigs are typically used for installing products up to 16 inches in diameter at distances up to 2,000 feet. This category of drill unit is the primary type used for the installation of municipal pipeline products. These units are compact and can be readily used in urban areas, while offering the capacity to install relatively large-diameter water, gas, and sewer force mains. These units can handle soft to hard soils and soft rock formations. When utilizing down-hole mud motors and specialty reamers, these units can perform drills in hard-rock formations.

**Large (Maxi) Rigs**

Maxi HDD rigs typically are used in large operations with multiple trailer-mounted support equipment and substantial mobilization periods. These units have higher
operating costs and require large workspace areas. This usually restricts their use in the urban utility HDD market. Maxi drill rigs are typically used for large-diameter pipelines (16 to 48 inches) or exceptionally long drills up to 6,000 feet. This category of drill rigs is rated at greater than 100,000 pounds of thrust and pullback, more than 20,000 pounds of torque, and with a drill-fluid pump system greater than 200 gallons per minute.
3.2 HDD Down-Hole Equipment

Unglamorous as down-hole equipment may be, these tools perform their vital functions underground and out of sight, and no drill rig can function without them. Bits and reamers, transmitter housings, swivels and pulling heads—all are down-hole tools necessary to make HDD possible. Bits cut through soil to make pilot holes. The slant-face bits still used by most drillers making utility installations provide the steering ability that makes the HDD rigs directional. Reamers enlarge pilot holes to sizes sufficient to accept the product to be installed.

Down-hole housings protect the radio transmitters that provide bit location and information needed to steer the drill head. Pulling assemblies and heads connect pipe or other product to the drill string so that they can be pulled through the bore hole. Even though drill pipe isn’t actually a tool, it is the link between the drill rig and down-hole tools. Power developed by the drill unit is transferred down the drill string to bit and reamer, and drilling fluid flows through pipe in the drill string to bit, transmitter housing, and reamer.

Dramatic improvements have been made in HDD technology in a relatively short period of time, and the continuing development and improvement of down-hole tool products has played an important part in the growth of the directional-drilling industry. Down-hole tools are made and sold by HDD drill-rig manufacturers and several specialist companies, and drillers have many tool options to meet a wide range of drilling requirements. As directional drilling has become more

![FIGURE 3-8 Typical Down-hole Equipment Diagram]
competitive, drillers are always looking for new down-hole tool designs to increase their production and decrease their downtime. Performance of down-hole tools directly affects productivity. And selecting the best tools for the machine on which they will be used and the soil conditions often makes the difference between success and failure of a directional-drilling installation.

With the choices of down-hole tools available, a driller’s objective is to match the tool to the job conditions. The tricky part of the selection process is that conditions change and the driller may encounter several different sets of conditions during a HDD project. As good as the equipment is now, no one tool is available to handle the variety of conditions found on most projects. Manufacturers have focused on developing tools that have specific applications. Jobs with rocks and several types of soils may require tripping out of the hole to exchange tools. Several so-called universal bits are on the market, but there is no product that is equally effective in all types of conditions. Down-hole tool makers have recognized the unique requirements of HDD applications, and products today are markedly superior to those of only two or three years ago. Down-hole tools are being made with materials that last longer. Carbide is being used more extensively to make tools more effective in tougher conditions and increase wear life.

Drill Bits

The latest bit designs are for specific types of soils, including rock, cobble, and other difficult conditions. Carbide makes today’s bits more productive and last longer. Bits are designed to run smoother in difficult conditions, with less vibration transmitted to the drill unit. A truly universal bit that is effective in all soils has yet to be developed, but some of the latest bits can be productive in a much wider range of soils. For much of today’s short- to medium-range utility applications, slant-face bits also make it possible to change the direction of the path of the pilot bore. Many new bit products are for rock work, and drilling and steering through hard rock remain a challenge for both tool and drill-rig designers.

Some drill bits are used for steering and to excavate the soil or rock at the face of the bore. The types of drill bits commonly used in HDD applications are traditional slanted-face bits, slanted-face rock bits, and hard rock or mud motor bits. Table 3-1 provides some application guidelines for the various types of drill bits.

Slanted-Face Bits

Slanted-face bits, also called spades and modified spades, are typically used in soft to medium clays and loose to dense sands. These bits may be flat or have the more popular bent construction that provides more aggressive steering. When drilling a straight hole, the drill string is rotated and pushed at the same time. When steering
with these bits, rotation is stopped, the slanted face of the drill head is oriented in
the bore hole, and the drill rig pushes the drill string forward. As the slanted face
of the drill bit is pushed against the soil, the entire drill string is deflected in the de-
sired direction. After completing the steering correction, rotation is resumed until
another correction is required. Various slanted-face bits are shown in Figures 3-9,
3-10, and 3-11.

If steering is unresponsive when using slanted-face bits, one procedure is to re-
duce the fluid flow rate and push without rotating. However, reducing flow rate
may cause loss of circulation, which can lead to stuck drill pipe and other serious
problems. If steering remains unresponsive, another option is to trip out of the hole
and change to a wider or longer bent bit. For shallow bores, a backhoe may be used

### TABLE 3-1 Drill Bit Types and Application Guidelines (Courtesy of DCCA)

<table>
<thead>
<tr>
<th>Drill Bit Type</th>
<th>Applications</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Slant-Face Bits</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flat Spade</td>
<td>Clay, Sand, and Organic soils</td>
<td>Increase width, length, and/or angle for more aggressive steering</td>
</tr>
<tr>
<td>Bent Spade</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modified Spade</td>
<td>Hard ground conditions</td>
<td>May be modified by adding teeth, tapers, etc. to match conditions</td>
</tr>
<tr>
<td>Rock Bits</td>
<td>Rock and Hard Pan</td>
<td>Small surface steering area; abrasion and impact resistant cutters</td>
</tr>
<tr>
<td><strong>Mud Motor Rock Bits</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Roller-cone (Mill tooth)</td>
<td>Soft rock</td>
<td>Refer to International Association of Drilling Contractors for numbering schemes</td>
</tr>
<tr>
<td>Sealed Bearing Roller-cone (Tungsten Carbide Inserts)</td>
<td>Medium rock</td>
<td>Refer to International Association of Drilling Contractors for numbering schemes</td>
</tr>
<tr>
<td>Sealed Bearing Roller-cone / Drag Bit</td>
<td>Hard rock</td>
<td>No moving parts</td>
</tr>
<tr>
<td>Polycrystal Diamond Compact (PDC) Drag Bit</td>
<td>Hard rock formations</td>
<td>Generally too expensive and fragile for HDD applications</td>
</tr>
</tbody>
</table>

Soft rock: <5,000-psi, Medium rock: 5,000 to 10,000-psi, Hard rock: >10,000-psi
to excavate down to the bit and apply upward or downward pressure to redirect the bit. If not done carefully, this action can result in excessive stresses on the drill string and overcorrection of steering. In stiff soils, it may be helpful to reduce advance rates while maintaining the flow rate to facilitate cutting of the intended path. However, steering usually is not a problem in hard soils.

FIGURE 3-9 Slanted Face Drill Bits
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FIGURE 3-10  Modified Slanted Face Drill Bits

Shark Tooth Blade  Carbide Tipped Blade
Stepped Carbide Blade  Chevron Blades

Durabit  (Courtesy of Charles Machine Works)
Barracuda Bit  (Courtesy of Charles Machine Works)
Angled Teeth  Steep Taper Tuff Bit  (Courtesy of Charles Machine Works)

FIGURE 3-11  Modified Slanted Face Drill Bits
Slanted-Face Rock Bits

Slanted-face rock bits are used in harder ground conditions and soft rock (less than 3,500 psi) that cannot easily be penetrated with thrust alone. The face of the tool usually has one or more nozzles emitting pressurized drilling fluid. In harder ground conditions, steering is accomplished by techniques such as partial rotation and release, wiggling the bit clockwise/counterclockwise (“fishtailing”) while thrusting at the desired steering orientation, or by a broader arc of clockwise/counterclockwise rotation “oscillation” on either side of the desired steering direction. Various rock drill bits are shown in Figures 3-12 and 3-13.

FIGURE 3-12  Rock Drill Bits

Slanted-Face Rock Bits

Slanted-face rock bits are used in harder ground conditions and soft rock (less than 3,500 psi) that cannot easily be penetrated with thrust alone. The face of the tool usually has one or more nozzles emitting pressurized drilling fluid. In harder ground conditions, steering is accomplished by techniques such as partial rotation and release, wiggling the bit clockwise/counterclockwise (“fishtailing”) while thrusting at the desired steering orientation, or by a broader arc of clockwise/counterclockwise rotation “oscillation” on either side of the desired steering direction. Various rock drill bits are shown in Figures 3-12 and 3-13.
Hard-Rock/Mud Motor Bit

Hard-rock bits are used in ground conditions ranging from hard soil to hard rock with compressive strengths up to 40,000 psi or higher. When drilling in rock or hard soils, the drill bit cannot be pushed without rotation. In these soil conditions aggressive cutting bits and mud motors are used. Hard-rock or mud motor bits are classified as tri-cone bits with mill-tooth and tungsten-carbide inserts, drag bits, and polycrystal-diamond-compact (PDC) drag bits. For rock drilling positive-displacement mud motors that are powered by the flow output of a mud pump generate the torque and rotation of the bit box without rotating the drill string. The bit is threaded into the bit box, which is located at the downstream end of the motor. When drilling with mud motors, directional control is through a small bend (or bent sub) in the motor or drill housing just behind the cutting head. This basically performs the same function as the slant on the face of a slanted-face bit. Successful drilling in rock with mud motors is dependent on proper bit selection. A bit that is too large will have a negative impact on the steering response. A bit that is too small will not create a sufficient annulus for removal of cuttings. The bit should be 0.75 inches to 1.25 inches larger than the diameter of the mud motor housing. The bit must also be matched to the hardness of the rock formation to be drilled. Gauge protection, provided on some tri-cone bits, reduces premature wear of the bit body. PDC drag bits typically are not used in the HDD industry due to high costs and high potential for damage from impact loading in boulders, cobbles, and highly fractured rock. Sealed roller-cone bearings are desired for longer bearing life. Various rock drill bits are shown in Figure 3-14.
Down-Hole Tools

Down-hole tools include mud motors, mechanically driven assemblies, percussive drilling assemblies, reamers, hole openers, and specialized tools such as fishing tools, stabilizers, non-magnetic collars, bent subs, washover pipe, and washover shoes.

Down-Hole Mud Motors

With high-capacity pumps and HDD rigs with higher drilling-fluid-flow capacities, the down-hole mud motor has become the tool of choice for directionally drilling in rock. The drilling-fluid requirements to power mud motors are much higher than for mixing and transporting cuttings; however, the majority of the fluid can be recycled and reused. The important factors in classifying mud motors for HDD applications are the output torque, fluid volume requirements, and length. Length is important because the tracking equipment is located in the drill string,
which may be as much as 26 feet behind the drill bit and thus difficult to track with the desired accuracy.

Mud motors achieve directional control by using a maximum 3-degree bend located approximately 5 feet behind the bit. The drill operator can obtain more aggressive steering if the distance from the bit to the bend is shortened and a greater bend angle is used. The bend is oriented in the desired direction, and the entire assembly is pushed to attain the steering corrections while only the bit rotates. The drill string and bit are rotated and pushed for drilling straight. One significant difference in drilling with a mud motor is that the drill string should rotate at less than 50 rpm because the assembly oscillates in the bore when rotated and may be severely damaged or prematurely worn if rotated at excessive speeds. The rotation should start slowly and carefully after steering. This allows the assessment of restrictions that may prevent the bent assembly from freely rotating in the bore and prevent expensive damage to the mud motor.

To successfully drill very hard rock, minimum requirements are:

- 50,000-pound-thrust rig
- 2 7/8-inch-diameter drill pipe
- 4 3/4-inch pilot bore, using tri-cone roller bit
- 3 3/8-inch diameter mud motor
- 135-gpm pump

When drilling in formations with strengths exceeding 40,000 psi, the penetration rates will be slow and costs will be high. Hard-rock formations are routinely successfully drilled with today’s technology and experienced HDD contractors. Proper site evaluation and project planning are important for successful drilling in

FIGURE 3-15 Typical Mud Motors
hard rock. If hard rock is expected and properly tested, proper selection of equipment can be done before construction begins. Rock may become an obstruction when it is unexpected and tooling has been selected for soils or if the rock encountered is much harder than anticipated. In these cases, the bit may be changed to one capable of cutting the harder rock. Higher-capacity mud motors and pumps may also be required. These modifications can be time-consuming and expensive.

A mud motor is no more effective than the volume of fluid, which generates power, that is pumped through it. If the mud flow is on the low side of specifications, the mud motor will have low bit speed and a slower penetration rate. As the pumping rate increases toward the maximum of the flow specification, the motor is more powerful and efficient. This is why it is essential to match the mud motor with the available deliverable mud flow from the pump. Most mud pumps used in the directional boring industry run at higher speeds to operate mud motors. However, mud pumps lose operating efficiency as the mud viscosity increases and the effect of entrained air in the mud increases. The pump does not completely fill during the suction phase, resulting in a drop in the volume of fluid being pumped.

Most pressure-fed piston or plunger pumps generally have a 96 to 97 percent volumetric efficiency. The loss in efficiency largely results from the valves not opening and closing instantly. The efficiency goes down as mud viscosity increases and drops significantly if air is in the mud. Air in the mud can reduce pump efficiency to 50 percent or less. The main cause of entrained air is the design of the mud-cleaning system. Mud is cleaned by agitation, which mixes air into it. Higher-viscosity mud results in more air entrapment. The cleaning system must provide enough time for the mud to expel this air before it enters the suction manifold of the pressure pump. In addition, small internal diameters of piping and hoses cause pressure losses as pumping rates increase. This reduces the pressure available for the motor, causing a decrease in motor torque and slower boring.
Small inside-diameter drill pipe also tends to require a higher surface mud-system pressure to offset piping losses. Mud-flow rates provided by manufacturers are usually a calculated volume based on pumping water at 100-percent efficiency. Air in the mud, the size of the restricted passages, mud viscosity, and the length of the various restrictions reduce the true working efficiency of the pumps.

**Mechanically Driven Assembly**

A specialty drill rig, with dual top drives for a dual-member drill string, mechanically powers the steerable down-hole rotary-drilling assembly. The down-hole assembly is much like that of a mud motor but without its fluid-driven power section. The rotary bit (usually a tri-cone bit) is continuously rotated by the inner member of the dual-member drill string. The outer drill-string member is used to control steering by orienting the bent housing (also the bearing support for the rotating bit and home for the tracking transmitter) in the proper direction. Straight drilling is accomplished, much as with a mud motor, by slowly rotating the outer pipe. The tracking transmitter is closely positioned behind the bit, providing more timely indication of steering response than possible with most mud motors. The inner drive, however, prohibits use of non-walkover tracking systems.

The inefficiencies of drilling-fluid pumps and down-hole mud motors are not factors with this mechanically driven system. Greater torque can be applied to the bit than with comparable-size mud motors. Only the drilling-fluid flow rate needed to clear cuttings from the hole is pumped. Thus, fluid requirements are substantially lower, and the cleaning system can be much smaller or possibly replaced with a vacuum system. The mechanically driven system is effective for short bores in soft to medium-hard rock, where limited work space may preclude use of a large rig and the pump needed for driving a mud motor. The mechanically driven down-hole system is not as efficient as a mud motor system for large-diameter, long bores in hard rock.

**Percussive Drilling**

One of the most common misconceptions about a percussive hammer is that it is not a proven method for rock drilling. Percussive hammers have been around for decades in the vertical industry. There are three basic categories: rotary, percussive drifter, and down-the-hole percussive hammer. Rotary drill equipment was covered in the previous sections.

Drifter percussive drills do not rely on high thrust or high torque for the cutting action; they operate on the percussive energy that comes from a hammering action from the carriage that is then transmitted through the drill string to a button carbide bit that in turn is engaged in the rock. They almost always pass low-pressure air through the drill string to evacuate the cuttings. This method of drilling rock is
good for short holes 100 feet or less because the deeper the hole, the further the percussive energy must travel to engage the bit. These drills are used in the mining industry, mostly where vibration from blasting material has to be kept at a minimum due to the smaller holes drilled. Drifter percussive drilling is very cost-effective but limited by the depth and the size of the hole.

The third category of drilling is the down-the-hole (DTH) percussive hammer. Unlike the drifter drill, the hammering action passes through the drill string. The DTH hammering action takes place at the end of the bit only, with little loss of energy. These tools are unique in that the more air pressure they can hold, the faster they will cut. It does not require high rotational torque or much thrust, as with the rotary bit, to penetrate the rock. As the high-pressure air passes through the hammer with the button bit engaged in the face of the rock, the piston will hit the back of the bit, forcing the bit into the rock at a rate of 2000 blows per minute. The air then passes through the end of the bit, removing the rock cuttings through the bore hole back to atmospheric air pressure. This is called up-hole velocity and is measured in feet per minute. Down-the-hole percussive hammers are very cost-effective for drilling hard rock. They are used for water-well drilling, blast-hole drilling, surface mining, and exploration for gas and were introduced to the directional rock-drilling industry about three years ago. This method is gaining popularity especially in the southeastern United States for directional rock drilling due to the extremely hard abrasive granite and gneiss rock in this region. The system can be adapted to most directional machines. It can drill at speeds never seen until now while eliminating most of the mud mixing and cleanup, which is perfect for environmentally sensitive jobs. The hammering action that takes place at the end of the drill string only requires around 600 pounds of thrust.

Several down-hole percussive-drilling systems are available. Most are compressed air-powered systems adapted from vertical down-hole hammer-drilling technology. Minor modification of a conventional drill rig will adapt it to an air compressor instead of one that pumps drilling fluid. However, the conversion requires a rig with properly sized drilling-fluid-circuit and drill-string tool-joint inside diameters as the starting point. Otherwise, flow-path restrictions to high-volume compressed air will create pressure losses that degrade penetration rates. The thrust requirements are low, as percussion and rotation fracture the rock. Excessive thrust actually may decrease penetration rates and increase transmission of impact shock up the drill string. Steering of percussive down-hole systems is accomplished with an eccentric, flat-faced bit with tungsten-carbide inserts. The bit has a high spot that is preferentially oriented to follow the desired path as it penetrates without rotation. Straight drilling is accomplished by slowly rotating under moderate thrust.

As rock hardness increases, the penetration rate of percussive drilling surpasses that of rotary drilling. Thus, these systems may have an advantage over mud motors in harder rock. However, they may not be suited to completing a bore in as
wide a range of geological formations. The cuttings and dust must be contained and controlled at the surface. The high-pressure air may erode the drilled hole or follow a crack or fissure and blow out to the surface in noncompetent formations. Small flow rates (1 to 3 gpm) of water or water and drilling foam mixture generally must be injected along with the air to cool the transmitter. This fluid also aids in cleaning the hole of cuttings (which can be substantially larger than those from rotary drilling) and suppresses dust “fines” in the spoil returns to the entry pit.

Reamers and Hole Openers

New reamers offer drillers more choices than ever for the right tool for varying soil conditions, and reamers are available in more sizes than in the past. Low-torque tools require less force to cut through soils and mix fluid slurry. New reamer designs also have increased fluid-mixing efficiency.

Reamers are used to enlarge the bore sufficiently to facilitate installation of the product. The reamer must be capable of displacing the native material or reducing it to manageable cuttings, mixing those cuttings with the drilling fluid, and preparing the bore for installation. Reamers generally are classified as barrel or compaction reamers and as mixing and all-purpose. Within each category there exist several reamer types. Proper selection is based on soil conditions, hole size, and pump capacity. Recommended practice is to select a reamer that is the smaller of 1.5 times the outside diameter or 12 inches larger than the diameter of the product pipe to allow for an annular void for the return of drilling fluids and cuttings in order to reduce frictional pullback forces and to allow for the bend radius of the pipe. Often the reamed diameter is less than 1.5 times the diameter of the product in collapsing soil formations and may need to be increased if substantial swelling of the soil is expected to occur. The larger the hole, the more important it is to mix the cuttings into a slurry with the drilling fluid before and during product installation. This ensures that cuttings remaining in the bore will not restrict displacement of the slurry by the product pipe. The slurry must be displaced from the hole in a quantity equivalent to the product-pipe outer volume to prevent stalling the pullback operation or creating surface heave.

When formations cannot be penetrated with reamers or if stalling or overtorque of the reamer occurs, hole openers should be used. Hole openers that utilize rolling cutters are used primarily for reaming or prereaming the bore hole in rock formations and come in many sizes and configurations. Most hole openers provide excellent flow characteristics, cutting capability, and low torque due to rolling cutters.

Percussive reamers can also be used for enlarging holes in rock. These systems use a special carbide-button-faced bit powered by a down-hole air hammer. Some are configured for conventional pullback reaming, where air is supplied through the drill string and reaming bit to a reverse-circulation hammer or through a hose trailing from the exit side to a conventional down-hole hammer driving the reaming bit.
TABLE 3-2  Reamers/Hole Openers Application Guidelines (Courtesy of DCCA)

<table>
<thead>
<tr>
<th>Category</th>
<th>Type</th>
<th>Application</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compaction Barrel</td>
<td>Spiral</td>
<td>Clays</td>
<td>minimal flow characteristics</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Silts</td>
<td>some cutting capability</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sands</td>
<td>minimal mixing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cobbles</td>
<td>must have overcuts to maximize circulation</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>caution due to higher potential for ground heaving</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>best application after pre-ream is completed</td>
</tr>
<tr>
<td>Mixing Blade</td>
<td>Wheel</td>
<td>Clays</td>
<td>excellent flow characteristics</td>
</tr>
<tr>
<td></td>
<td>Sands</td>
<td></td>
<td>good cutting capability</td>
</tr>
<tr>
<td></td>
<td>Combination</td>
<td></td>
<td>facilitates suspension of cuttings in drilling fluids</td>
</tr>
<tr>
<td></td>
<td>Off-set Bar</td>
<td></td>
<td>minimal compaction</td>
</tr>
<tr>
<td></td>
<td>Wing</td>
<td></td>
<td>best used on pre-ream because can cut bottom of hole on subsequent reams</td>
</tr>
<tr>
<td>All-purpose</td>
<td>Fluted</td>
<td>Varied soil conditions</td>
<td>moderate flow characteristics</td>
</tr>
<tr>
<td></td>
<td>Modified</td>
<td></td>
<td>moderate cutting capability</td>
</tr>
<tr>
<td></td>
<td>Compaction</td>
<td></td>
<td>substantial compaction</td>
</tr>
<tr>
<td>Hole-Opener</td>
<td></td>
<td>For hard soil and</td>
<td>excellent flow characteristics</td>
</tr>
<tr>
<td></td>
<td></td>
<td>rock formations. Hole</td>
<td>excellent cutting capability</td>
</tr>
<tr>
<td></td>
<td></td>
<td>openers should be selected</td>
<td>low torque due to rolling cutters</td>
</tr>
<tr>
<td></td>
<td></td>
<td>using the same criteria as</td>
<td>used for reaming and pre-reaming hole</td>
</tr>
<tr>
<td></td>
<td></td>
<td>that shown in Table 3-1 for</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>mud motor rock tricone bits.</td>
<td></td>
</tr>
</tbody>
</table>

Cable and Pipe-Pulling Devices

Cable grips are used for pulling cables and small-diameter pipe, usually 4 inches or less. Cable grips are attached to the outside of the pipe and can be taped or tied with clamps at the end to prevent them from pulling off. When using cable grips for pulling pipe, the normal practice is to use a solid insert that is at least twice as long as the inside diameter of the pipe in order to help prevent the pipe from collapsing.

Duct pullers are also a very important part of pullback operation. The most common attachment used to be a setup with a couple of holes through the end of the...
duct and nuts and bolts passed through a pull chain. This put the entire load of the pull on the holes drilled through the duct and was for that reason quite ineffective. Today, every duct manufacturer recommends the use of a puller that distributes the load around the entire circumference of the duct. The most common type of puller has a set of wedge-shaped teeth on a conical mandrel that is inserted inside the end of the duct. As the mandrel is pulled forward, it forces the teeth outward, causing them to grip the inside wall of the duct. Duct pullers are placed inside plastic pipes to assist with pulling during HDD installation. Duct pullers are available in one-piece units that are screwed into the end of the product pipe and multiple-piece units that expand in the pipe. Figure 3-21 illustrates typical pullers, and Figure 3-22 illustrates typical cable grips.

Swivels connect pulling tools to the drill string, and the pipe or other product to be installed is attached to pulling tools. Performance of pulling components is critical to every HDD installation. A failure can abruptly stop a project short of
completion, resulting in time-consuming and costly delays. Today’s pulling tools are stronger and more trouble-free. One of the most recent advances in pulling equipment is to install bundles of conduit on long-haul telecommunications projects. Swivels are placed between the reamer and the duct puller or pulling head to prevent the product pipe from rotating during pullback. For large-diameter pipes
Carrot Duct Puller

Duct Puller

Multiple Duct Puller

Duct Puller

FIGURE 3-21  Typical Duct Pullers

FIGURE 3-22  Typical Cable Grips
a flexible link between the swivel and pulling head is sometimes used to reduce the pipe’s buoyancy effect, which may exert upward bending forces on the reamer. Breakaway swivels, which break or give way when a certain pullback force is exceeded, are often used for plastic product pipes. These products are designed to protect pipe from overload during HDD installation and are used between the pullback swivel and the duct puller or pulling head. The connectors are usually a three-part product, held together by a group of pins. The pins are designed to break at a specific load. The assembly of the connector is completed by using one or more of the breakaway pins. The sum of the values of the pins is the value at which the connector will come apart. If a single 1,000-pound pin is used, the connector will come apart at 1,000 pounds. If three 1,000-pound pins are used, the connector would come apart at 3,000 pounds. Different pin values can be mixed and matched to create a number of different values, all in the same connector. Figure 3-23 illustrates typical swivels.

FIGURE 3-23 Typical Swivels
Quick-connect couplers simplify the task of connecting and disconnecting down-hole tools, speeding the process and reducing the risk of accidents during tool change. Drill pipe links the drill rig to down-hole tools, transmitting engine horsepower to them for thrust, pullback, and rotational torque. Drilling fluid is delivered to down-hole tools through the string of the drill pipe; guidance-system components are attached to the drill string behind the drill bit. When the pilot hole is finished, the pipe pulls reamer and product through the hole to complete the installation. HDD pipe must withstand tremendous forces generated during the drilling and pullback. Each length of pipe must be flexible enough to be steered effectively, yet have enough rigidity not to break or become permanently bent. Connections must be durable to resist wear from repeated makeup and breakout.

**Transmitter Housings**

Bit location and data needed to guide the drill path are relayed to the drilling crew by a radio transmitter located behind the drill bit. While the transmitter itself isn’t classified as a down-hole tool, the housing it’s in is one of the most important down-hole components, protecting the tool from the stresses of drilling and allowing cooling fluid to flow around the transmitter. The newest radio-transmitter housings are made of more durable materials to resist cracking, and their designs provide improved flow of drilling fluids to better protect transmitters from the intense heat generated during drilling. Side-load models make access to transmitters more convenient. Some regulatory agencies and project owners have begun requiring that reamers be tracked, and transmitter housings now are available for this purpose, placed in the drill string adjacent to the reaming tool. Figures 3-24 and 3-25 illustrate typical transmitter housings.

**FIGURE 3-24  Typical Transmitter Housings**
Drill pipe is arguably the most overlooked and taken-for-granted component in directional drilling. The drill string consists of separate joints of pipe that are the link between the drill unit and the down-hole components. The success or failure of every HDD project depends on drill-pipe performance. Drill pipe is used to transmit power by rotary motion and thrust from the drill rig to the down-hole equipment and to convey drilling fluid to the down-hole tools while flushing media to the cutting face of the tool. With the exception of specialty tools, it is probable that no other part of the drill stem is subjected to the complex stresses that drill pipe must withstand. Drill pipe is an important and expensive part of the total rig with a relatively short life span. The cost of the drill pipe makes it a capital investment and not a strictly expendable item. A recommended practice, followed by many contractors, is to identify each joint upon purchase. In turn a recording should be made, along with its length, when it is placed in the string. By this means, and with some effort in the field and through office accounting, the following is made possible:

1. Useful life of the joint may be determined.
2. Type of service and/or stresses to which it is subjected may be recorded.
3. Switching within the string can be done to obtain optimum use.
4. Causes of failures can be determined with greater accuracy.
5. Down-hole failures can be prevented or minimized.
Specialized HDD drill pipe is much more than a hollow length of steel with threaded fittings at each end. For directional drilling, pipe must withstand tremendous forces generated during the drilling and pullback. Each length of pipe must be flexible enough to be steered effectively, yet have sufficient rigidity not to break or become permanently bent. Connections must be durable to resist wear from repeated use. Forces on pipe used for directional drilling are different than those encountered in vertical drilling operations. HDD pipe must be more flexible than pipe used by vertical drills because it must bend in ways that are not required in vertical drilling. Pipe for horizontal directional drilling is subject to more wear because it is supported by the bore wall during drilling and reaming, and it also encounters greater pullback and rotational forces than vertical pipe.

A length of horizontal boring drill pipe is a steel tube with a pin (male fitting) on one end and a box (female fitting) on the other. Types of steel used and methods of manufacturing distinguish the basic types of HDD pipe:

1. Forged pipe is made from a single piece of steel. During manufacturing, pressure is used to upset each end, thickening shaft walls to create the pin and box.
2. Welded construction pipe is made of three pieces of steel with separate pin and box components welded to the tube.
3. Composite pipe is made of three separate pieces of steel, with machined tool ends pressed into the ends of the tube and welded.

There are many manufacturers of drill pipe, and each should be contacted for specific information concerning their products. The following paragraphs provide information about three of the most popular drill-rod manufacturers.

Ditch Witch drill pipe is designed and manufactured by the company, and all pipe is designed as a part of a system to match the power of the drill unit. Tool joints are manufactured from 4140 steel. Ditch Witch drill pipe contains patented Fluid Miser II lining which reduces the amount of time it takes to pressure up fluid in the drill string.

TorqueLock manufactures one-piece forged pipe with the proprietary TorqueLock thread in pipe sizes from 1.66 to 4 inches. It is tube forged to S-135 specifications from controlled-yield, flexible steel. TorqueLock connection benefits include elimination of thread jump out and cross threading, largest inside diameter in relation to outside diameter, extended wear life, high fluid volume yields, and improved bending radius. Pipe can be manufactured for all drill-rig brands.

Vermeer offers a one-piece forged drill stem made with enhanced chemistry designed specifically for horizontal directional drilling applications. Available are original Firestick drill pipe and new Firestick II for drill rigs with higher torque and drilling-fluid flow capabilities with the same bend radius and same approximate weight as original Firestick pipe. Firestick II has a lower thread profile and slightly
larger outside diameter through tube upset to provide significantly larger flow capability. This feature is designed to increase mud-motor capabilities of small and mid-size HDD models.

Regardless of the drill pipe used, directional-drilling pipe is a costly part of the HDD system. The following lists some basic care procedures that will extend pipe life and reduce the risk of pipe failure:

1. Inspect pipe for signs of wear and damaged threads.
2. On the tube look for signs of cracks, cuts, gouges, and excessive wear. Bent or bowed pipe should be straightened or replaced.
3. Look for broken, cracked, or flared joints and damage to threads. Keep joints clean using zinc- or copper-based tool compound, not petroleum-based grease. Replace protective caps.
4. During drilling operations, rotate the sequence of pipe sections going in the drill string. (Use pipe lengths that were at the beginning and end of the drill string on the last job somewhere in the middle of the string on the next job.)
5. Make up pipe in accordance with recommended torque.

Drill-pipe manufacturers have different specifications. The Drilling Handbook (Gabolde and Nguyen, 1999) and the IADC Drilling Manual (International Association of Drilling Contractors, 2000) provide information associated with drill pipe. To ensure that drill pipe has an effective life and to reduce the risk of down-hole failure, sound operational practices must be followed during HDD operations.

A primary consideration for the proper use of drill pipe is not to have any bends tighter than the allowable bend radius of the drill pipe. This is accomplished by proper bore-profile planning, including entry and exit angles, bend radius, and setback distances. The bend radius may also be exceeded by oversteering or not following the intended bore path. An important action to reduce drill-pipe wear and achieve maximum drill-string life is to move the lead drill pipe to the end of the string or use other pipe rotation methods. When drill pipe shows evidence of being bent or damaged, it should be taken out of service immediately.

Drill pipe can also be bent by overthrusting with too much exposed drill pipe in the drill rig or above ground in front of the rig. To avoid these effects, at least half of each added drill pipe should be rotated into the ground before attempting any steering and the distance from the leading edge of the drill rig and where the drill pipe enters the ground should be as short as possible. During the drilling operation the thrusting and pulling forces often loosen the drill-rig anchoring system so that the rig moves out of alignment with the bore hole. This may also result in bending.

The bore should always begin with a straight drill segment of at least one length of the drill pipe. This will help in maintaining proper tool joint alignment. During drilling the drill head must not be allowed to deflect as it enters the ground. The
best procedure for controlling this is to excavate a small pit at the entry point. For slant-faced drilling bits it is good practice to:

- Start at the 6 o’clock steering position
- Use a slow and controlled entry without rotation for at least 2 to 3 feet
- Prevent entry misalignment by holding the drill head, up or down, with a backhoe.

During drilling avoid stalling the pipe rotation to minimize stress damage from shock loading. Stalling often causes the drill pipe to corkscrew or the tool joints to overtorque. Drill bits and reamers that are in poor condition or not suited for the soil formations may also cause stalling. For example, a bit that is too large for the drill pipe and ground conditions may result in excessive steering bends and stresses or buckling of the drill pipe. A reamer that is too large may result in excessive torque and pullback loads. It is often more productive to use multiple reaming passes to obtain the final bore-hole size.
Drilling Fluid Systems

Most HDD projects require fluid-mixing systems. They mix the drilling-fluid additives with the water to make a drilling-fluid mixture that is required by the local geological conditions. Typical mixing systems include a gas- or diesel-powered engine, centrifugal pumps, a hopper for mixing and adding the materials, delivery hoses, and tanks. Most fluid-mixing-system tanks are 300 gallons or larger. Many of the most popular fluid-mixing systems feature venturi/hopper-mixing systems to provide the initial mixing of drilling-fluid additives. Figures 3-26 and 3-27 illustrate some mixing systems.

Modular mixing systems provide fast mixing of high volumes of drilling fluid for larger-diameter and longer-distance HDD applications, including projects requiring mud motors.

These systems can support multiple mixing tanks, and the fluid system has typical capacities to mix and deliver from 125 to 350 gpm to the drill. Figures 3-28, 3-29, 3-30, and 3-31 illustrate some modular mixing systems.
Modular mixing systems provide fast mixing of high volumes of drilling fluid for larger-diameter and longer-distance HDD applications, including projects requiring mud motors.

FIGURE 3-28 Modular Fluid Mixing Systems

FIGURE 3-29 Modular Fluid Mixing Systems
3.2 HDD Down-hole Equipment

FIGURE 3-30 Modular Fluid Mixing Systems

MX250 Modular Drilling Fluid System

FIGURE 3-31 Modular Fluid Mixing Systems

MX125

MX350 Modular Drilling Fluid System
Chapter 3 Footnotes

4.1 HDD Design Basics

The planning, design, and construction of HDD projects requires a specialized knowledge of pipeline construction methods and HDD equipment and technology. While Chapter 3 provides information about HDD equipment, this chapter discusses HDD design and installation. The planning and design of a HDD crossing should focus on meeting the requirements of the owner while keeping the project costs as low as possible. Many factors have an impact on HDD costs, but the most important is the crossing length. During the planning and design of the HDD crossing every effort should be made to keep the length as short as possible while meeting all of the project requirements such as depth and entry/exit pit locations.

The HDD design process needs to be thorough. At a minimum, the design process should include the following tasks prior to preparing final plans and specifications:

1. Prepare or obtain a scaled mapping for the planned installation including all existing surface facilities and improvements and any indication of underground facilities or improvements.
2. Collect existing underground utility information including the horizontal location and depth of all known substructures whenever possible.
3. Obtain right-of-way information through survey records or other sources.
4. Obtain general and/or specific geotechnical information including USDA Soil Conservation Service data for the project area and possibly site-specific geotechnical sampling and analysis.
5. Prepare construction plans using the information noted above including the location of any planned improvements, existing underground utility information, and right-of-way limits and property ownership.

In addition to the design requirements listed above consider the following items to help determine the most appropriate HDD design:

1. Consider the minimum horizontal and vertical clearance requirements when determining the HDD alignment, including road setbacks, existing surface features, and existing underground utilities.
2. Consider product pipe and reamer diameter requirements. For pipes smaller than 8 inches use a reamer 4 inches larger than the pipe diameter; for pipes 8 to 24 inches use a reamer 1.5 times the product pipe diameter; and for pipe larger than 24 inches use a reamer 12 inches larger than the pipe diameter.
3. Consider the bore geometry for the ground profile. The bore geometry is influenced by the bore length and depth requirements, and the bending radius for the product pipe.
4. Consider HDD equipment requirements for the geotechnical conditions such as geometry, final product diameter, thrust and pullback ratings, and tracking systems.
5. Consider the required equipment and material handling requirements such as drilling fluid, drilling-fluid containment, HDD rig operation, and final product staging.
6. Consider material strengths, capabilities, and joining methods.

Defining the obstacle to be crossed is a key factor in the HDD design process. For a river crossing the water’s width and depth should be considered, as well as the potential for future bank migration and scour. For a highway crossing in a built-up area, other underground utilities and future roadwork or development should be considered. Consideration should always be given to the site as it exists and also the anticipated future conditions of the site. The design should account for flexibility in locating the pipeline to be installed by HDD in both the horizontal and vertical plane.

HDD Project Design Considerations

Planning

Often the overall project requirements have a significant impact on the HDD design. The project requirements dictate choices such as the diameter and material of the product pipe, the length and depth of the crossing, and the HDD methods and equipment to be used. Thorough and organized planning is the key to a successful
HDD project. The bore path design should take into account all the important factors relating to the HDD crossing. Many of the factors that impact the HDD crossing can be identified easily with experience, common sense, and tools such as a tape measure, camera, and magnetic locator. Items that could adversely impact the crossing include fences, bridge abutments, buildings, guardrails, and rock outcrops. These types of items should be identified early in the planning and design phase so alternate bore paths (if appropriate) may be considered. This level of planning reduces risks and problems during the execution of the HDD crossing by identifying them well in advance.

Preplanning and mapping HDD projects have been common practices for many engineers and contractors. New technology has made this task much easier. While some systems only provide bore-path-mapping capabilities, others provide mapping, planning, and design support features. As experience with HDD construction and planning tools continues to evolve, the benefits of pre-planning with special computer software has expanded outside the original use of cost efficiency and time savings. Now, safety and damage prevention are also key factors.

HDD planning systems and tools are provided by a number of manufacturers. Planning systems such as the Vermeer ATLAS BORE PLANNER provide graphic visualization of the HDD project during both the planning phase and also as the bore is completed. Many of these systems link to locating systems so the actual bore path is recorded during the project. The software for many of these systems plots the most efficient path while taking several factors into account and produces a suggested bore path that uses the fewest possible drill rods, minimizes wear on the drill rig and drill rod, and remains consistent with desired depths and necessary distances from existing utilities. Many of the planning tools allow users to calculate the setback distance, point-to-point bore paths, estimated pullback time, and hole volumes and configure outside diameter and orientation of multiple-sized ducts for the HDD bore path. These systems can provide the HDD crew with the necessary information to set up a job site for the best possible bore.

There are certainly efficiencies to be gained by proper planning. Safety and damage prevention are also emerging as critical features, especially as HDD construction is increasingly scrutinized. HDD projects should emphasize the advantages of technology-aided planning and mapping.

Permitting and Easements

As in traditional pipeline or utility construction projects, there are numerous federal, state, and local agencies that may be involved in HDD crossings. Large projects or projects on federal land typically require a lead agency to coordinate the permit-application process and to monitor construction compliance with the applicable permits. The U.S. Bureau of Land Management, U.S. Forest Service, U.S. Fish and Wildlife, U.S. Army Corps of Engineers, and the Federal Energy
Regulatory Commission may act as lead agencies. HDD projects on private or state property are often regulated by the state’s Public Utility Commission, Department of Transportation, Department of Fish and Wildlife, and Department of Forestry. They usually enforce state regulations and may report to the federal agencies. The majority of the regulatory requirements are either environmentally driven or deal with right-of-way and encroachment issues.

While all construction projects are subject to environmental concerns, pipeline projects typically are subject to the greatest amount of regulation. The environmental issues that typically concern HDD include:

- Access restrictions due to wetlands, streams, endangered plant or animal life, endangered habitat, and potential erosion
- Oil and fuel spills from construction equipment
- Drilling-fluid surface spills that endanger animal and plant life
- Drilling fluid returns in water bodies
- Groundwater contamination from drilling-fluid additives
- Drilling-fluid disposal locations (The contractor must obtain approval to dispose of the drilling fluid at an approved disposal location. Bentonite is a good product for sealing drainage ditches, irrigation reservoirs, and livestock ponds. However, approval must be obtained from the proper regulatory agency.)

In contrast to the above, many utility projects do not have significant environmental issues, but they often locate the product pipe or cable within the local or state right of ways. Right-of-way and easement issues typically involve getting permission from the appropriate agency or individual to place the HDD product pipe in the easement or right of way. The owner or developer provides the appropriate agency with proposed HDD project information such as:

- Facility information and details such as project type (communication, water, gas, etc.)
- System capacities, pressures, etc.
- Construction plans based on scalable mapping in accordance with the submission requirements
- Pipeline alignment (dimensioned)
- Existing utility information
- Depths of cover and clearances, including all above- and below-grade structures
- Specific installation requirements or typical installation parameters indicating the design bending radius and diameter(s)
- Assumed subsurface geotechnical conditions based on experience, USDA Soil Survey data, or site-specific soils reports
- Traffic-control plans in accordance with the appropriate agency requirements
- Stormwater-pollution prevention plans as required by the appropriate agency

Many projects require that various environmental permits be obtained from the appropriate agency before construction begins. For environmentally sensitive (or potentially sensitive) HDD crossings an environmental permitting plan should be prepared. The plan is used to identify all the permitting requirements and provide a list of the required permits (for example, USAE NWP-12 for utility-line crossings), the time needed to prepare them, and an estimated date of issuance. Items that are typically considered in an environmental plan are solid and hazardous materials and waste management, wetlands, burial grounds, land use, air pollution, noise, water supply and discharge, traffic control, and river and railroad transportation.

The U.S. Army Corps of Engineers (USAE) regulates activities involving interstate bodies of water, including marshes and tributaries, as well as intrastate waters that can affect interstate or foreign commerce. The organization is responsible for work affecting such waterways, including the headwaters of freshwater streams, wetlands, swamps, and lakes. The Regional District Engineer of the USAE will advise applicants about the types of permits required for proposed projects. In addition, state and/or local agency environmental review and permitting may be required. For railroad crossings, the engineering representative of the railroad should be consulted about the approved methods of crossing the line.

All HDD construction activities should be performed in accordance with the National Pollution Discharge Elimination System (NPDES) as regulated by the Environmental Protection Agency (EPA), as well as state and local requirements. The contractor should implement best management practices to ensure that any stormwater runoff is not contaminated by the sediment caused by land disturbances associated with the construction activities. The following seven goals are primary functions of effective stormwater-pollution prevention planning:

1. Ensure that sediment controls are in place prior to disturbance.
2. Maintain sediment controls throughout the construction and restoration processes.
3. Minimize the overall disturbance whenever possible.
4. Protect disturbed areas throughout the construction process.
5. Prevent stormwater runoff from entering disturbed areas.
6. Never intentionally discharge construction contaminants directly into creeks, rivers, ditches, or storm systems.
7. Complete permanent restoration as soon as possible.
In addition to the overall goals stated above, the contractor should, at a minimum, implement the following specific practices:

1. Provide temporary erosion protection whenever possible.
   a. Mulch, seed, or gravel may be applied even if a disturbed area may and/or will be disturbed again or other permanent measures of stabilization are to follow.
   b. Cover spoil piles with a tarp or contain with a sediment barrier.
2. Contain disturbed sediment on site.
   a. Use sediment barriers such as silt fencing, sandbags, straw bales, rock checks, and/or traps to contain sediment on the construction site.
   b. Existing vegetation may be used as a sediment filter where minimal grades and sheet flow runoff will occur.
   c. Ensure that all sediment barriers are installed and functioning properly.
3. Avoid causing flooding in roadways and adjacent rights-of-way.
   a. Do not block existing culverts and storm inlets except as a last resort.
   b. Ensure that sediment is removed from sediment traps and filters after all storms.

Access to the project area is another factor that should be considered early in the planning phase. Many HDD crossings are in remote areas without immediate access to the project site. The cost of temporary and/or construction access easements can be costly. Usually the HDD equipment is required on both sides of the crossing. One way to minimize cost is to look for crossing locations with access to both sides from an improved road. Another option is to use the pipeline right-of-way for access to the HDD crossing. For most HDD project all required access agreements are provided by the owner.

**Identification of Risks**

An important part of the planning and design phase of a HDD project is to identify and avoid or at least reduce possible risks. If potential risks cannot be avoided or reduced, the crossing alternative should be closely evaluated and other alternatives considered. A decision has to be made as to whether to accept the risks or select another crossing option.

Even with the best planning and design efforts unexpected risks can occur. Experienced and qualified contractors are well equipped to solve many of these problems as they occur. The problem-solving process can be assisted during the planning phase by developing contingency plans for any anticipated risks. Listed below are some of the risks that are often of concern with HDD projects:

- Failure to complete the bore
- Damage to environmental, natural, historical, and cultural resources
• Surface collapse of heave
• Hydrofracture or inadvertent drilling fluid returns
• Damaging other utilities

Drill-Path Design

The information gathered during the planning phase is used to develop the best possible design for the drill path. The designed drill path should meet all the location and depth control points while keeping the drill length as short as possible. All designed drill paths are made up of a series of straight lines, called tangents, and curves, which are typically sag bends, over bends, or side bends depending on their axial plane. It is not uncommon for HDD drill paths to have compound bends even though they are generally avoided if possible. The location and configuration of a drilled profile are defined by its entry and exit points, entry and exit angles, radius of curvature, and points of curvature and tangency. The relationship among these parameters is shown in Figure 4-1. The values of these parameters should be called out in the contract plan and profile drawings. Often the design drawings will call out maximum or minimum parameter limits and allow the contractor to vary the bore path as long as he or she meets the limits and maintains all the design control points, such as depth at a particular location.

As previously described, the entry and exit points are the end points of the drilled profile. Confusion often arises concerning the location of the points. It is important to understand the terminology and identify the point correctly, because it has an impact on the pull load and stress calculations. The drilling rig is positioned at the entry point. The pilot hole is drilled from the entry point to the exit point, and the pipeline is pulled into the ground at the exit point and then pulled back to the entry point.

FIGURE 4-1 Drill Path Definition
point. When designing the drill path, keep the number of bends to the minimum required. This reduces pullback loads and extends drill-rod life. The best bore path starts with a straight tangent section at the prescribed entry angle to gain the depth required for steering control and the depth of cover. At the required depth the drill head is steered upward with a curve, then transitions to a horizontal segment, and again turns upward with another curve before transitioning to another straight tangent section at the desire exit angle.

**Entry and Exit Angles**

Generally the entry angles should be held between 8 and 16 degrees from horizontal, although entry angles up to 24 degrees have been used on some projects. These boundaries are due chiefly to equipment limitations. The preferred drill path is made up of straight tangent sections before the introduction of any curves. The radius of the curve is determined by the bending characteristic of the product pipeline or in some cases the drill-rod pipe. The curve usually brings the drill-path profile to the elevation that meets the design depth requirements for crossing the obstacle. Long horizontal runs can be made at this elevation before curving up towards the exit point. Exit angles should be designed to allow easy break-over support. The exit angle should not be so steep that the pull section must be severely elevated in order to guide it into the drilled hole. Usually the exit point angles are between 5 and 10 degrees.

**Length**

As a general rule, the drill length should be kept as short as possible to reduce the HDD project costs. However, depending on the estimated costs for alternate construction methods, this may not hold true. In the current market, it is common for HDD to be used as the primary method of construction on many projects.

To date the longest HDD project has been a little over 6,000 feet. The maximum length of a bore is usually controlled by the drill-rig fluid requirements, pullback and torque capabilities, and subsurface ground conditions. When planning HDD projects, ensure that the drill design is within the capabilities of the anticipated drill equipment.

**Depth of Cover**

The depth of cover is governed by the definition of the obstacle and the intended function of the product pipe, such as a gravity sewer. Other factors such as subsurface conditions, site features, existing utilities, and environmental concerns can have a major impact on the depth requirements. When crossing a major water body, other factors include flow characteristics of the river, the depth of scour.
from periodic flooding, and future channel widening or deepening. Ground character-
istics such as gravel, cobbles, and boulders can cause the drill path to be deeper to avoid the poor conditions.

Adequate cover should be provided to maintain the required HDD crossing depth over its design life. A minimum depth of cover of 10 feet is recommended for most drilled profiles. This aids in reducing inadvertent returns, provides a margin for error in existing grade elevation, and allows for future changes in grade. For water crossings, it is normally recommended that the minimum depth of cover be 20 feet under the lowest section of the crossing.

**Design Radius of Curvature**

Determining the entry and exit points, the depths that must be achieved, and direction changes for the drill path are all major parts of the planning process. One of the keys to these calculations is the bend radius of the drill rod and/or the product pipe. Bend radius is often misunderstood. It is often confused with the number of feet needed to make a 90-degree turn. Bend radius is defined as the forward distance required for a drill string to make a 90-degree turn (see Figure 4-2).

Understanding bend radius and how to use it is very important to the success of a HDD crossing and of the utmost importance to the engineer and driller. HDD
contractors often only think of radius as it applies to the drill rod, and owners/engineers often think of it as it applies to the product pipe. Both must be considered during the HDD design, as well as the allowable bend radius of mud motors and wireline systems.

**Drill Rod.** Bend radius is a key factor in any HDD design because it is an indication of how much bending the drill rod can handle without significant and possibly harmful stresses. Exceeding the allowable bend radius can result in significant damage to the pipe or drill rod. While drill-rod manufacturers may use different methods to establish the bend-radius rating for their pipe, SAE standard J2022 provides a voluntary guideline for evaluating drill rods using the same baseline. It is necessary to know what method of calculation is being used by a manufacturer when comparing the bend radius of drill rods from different manufacturers.

Regardless of the design, drill-rod wear and ultimate failure will happen. However, effective designs with proper bend-radius ranges will help extend the useful life of the drill rod. Drill-rig manuals provide data concerning the bend radius for the drill rod and recommendations and allowable steering changes for each section of the rod. The recommended allowable steering changes provided apply to both up or down pitch changes as well as left or right corrections. Allowable bend-radius information is used to determine the setback distance required by the drill unit at the entry point. Shallower bore depths require smaller entry angles and greater setback distances, while deeper bore depths allow for steeper entry angles. Any changes and corrections that are made during the drill should not exceed the recommended bend radius of the drill rod. When the bend radius is exceeded, the useful life of the drill rod decreases dramatically. The damage that is done to the drill rod is subtle and most likely will not be noticed immediately. The failure of the drill rod usually occurs several jobs after the damage is done.

**Product Pipe or Conduit.** Steel product pipe usually has a much larger bend radius than the drill rod. The largest bend radius of either the drill rod or product pipe is the number that must be used for planning and completing the bore. A common industry standard for determining the design radius of curvature for bends used in HDD installations is to multiply the nominal diameter of the pipe in inches by 100 to determine the allowable radius in feet. This relationship has been developed over the years in the HDD industry and is based on experience, not theoretical analysis. Bending radius and stress calculations are important for HDD installations. Methods for calculating bending stresses in steel pipe have been presented in many publications and are covered in this chapter and in Chapter 5 of this book.

In general the bending radius ratings for plastic, generally PVC or PE, pipe will not exceed that of the drill rod. The exception may be the larger diameters of these types of pipe, where the integrity of the pipe and the joints becomes a concern if
they are pulled through severe bends. Bending stresses and bend radius are usually not critical factors for PVC, PE, and ductile-iron products; however, they should be calculated and compared to the manufacturer’s specifications for allowable bending radius. There is much data from the Plastics Pipe Institute and pipe manufacturers on this subject. The general equations for calculating bending stresses are similar for steel, PE, and other materials, but the material properties and behavior are different and must be accounted for during any calculations.

Exceeding the recommended bend radius of the product pipe has consequences that may be apparent during installation or not show up for years, reducing the life of the product pipe. The main result during installation is a harder than expected pullback. The product pipe must go through tight bends and curves, and there is a much greater chance of getting stuck in the hole. If the drill path is smooth and gradual, the pullback loads are smaller and the pull will be much easier and quicker.

An area of concern, often overlooked, when considering the allowable bend radius involves the use of mud motors and wireline systems. The mud motor is a very stiff section, and depending upon the length, it generally has a bend radius greater than the drill rod. The stainless-steel monel section that houses the steering tool is also very stiff and more brittle than the drill rod. The suppliers of the mud motor and steering tools can provide information and recommendations concerning the allowable bend radius of their products. When using these tools, the designer should always factor their limits into the bore plan.

Pipe Stress Criteria

Typical products installed by HDD construction are composed of steel, polyethylene (HDPE and PE), polyvinyl chloride (PVC), and ductile iron, as well as direct buried cables. During installation the pipeline products experience a combination of tensile, bending, and compressive stresses. The magnitude of these stresses is a function of the approach angle, bending radius, product diameter, length of the borehole, and the soil properties at the site. Proper selection of the radius of curvature and type of product will ensure that these stresses do not exceed the product capacity during the installation. The HDD design should require the minimum number of product-pipe joints. Flush-type joints, such as butt fusion or welding, are preferable to glued or threaded joints, which tend to increase the drag on the product in the bore hole. Other considerations include minimum cover, minimum separation from existing utilities, tolerances for deviation in the vertical and horizontal profiles, and maximum true depth.

During the design, the stresses imposed on the HDD product pipe during construction and operation must be calculated and checked to be within allowable
limits for the material being used. The stresses at each stage must be considered both individually and in combination. Stresses come from the spanning between rollers prior to pullback, the hydrostatic testing pressures, pulling forces during installation, radius of curvature as the pipe enters the ground, the drilling profile curvature, external pressures in the drilled hole, and the working pressure. The load and stress analysis for a HDD pipeline is different from similar analyses of conventionally buried pipelines because of the high-tension loads, occasional severe bending, and external fluid pressures endured by the pipeline during the installation process. In some cases the installation loads may be higher than the design service loads. Pipeline properties, such as wall thickness and material grade, and pilot-hole bore path must be selected so the pipeline can be installed and operated without risk of damage.

During design the preinstallation, installation, and operating stresses of the product pipe must be considered and analyzed. Chapters 5 and 6 of this book cover the methods for estimating these stresses. The principal stresses of concern during the preinstallation stage are the hoop and longitudinal stresses caused by hydrostatic testing and the stress caused by the spanning distance between support rollers for the pipe. The distance between the support rollers is the free-spanning distance; it is used to calculate the maximum bending moments and the allowable span distance. If you are hydrostatic-testing the pipeline, the pipe will be full of water and the additional weight must be included in the bending stress calculations.

**Preinstallation**

The principal stresses of concern during the preinstallation stage are the hoop and longitudinal stresses caused by hydrostatic testing and the stress caused by the spanning distance between support rollers for the pipe. The distance between the support rollers is the free-spanning distance; it is used to calculate the maximum bending moments and the allowable span distance. If you are hydrostatic-testing the pipeline, the pipe will be full of water and the additional weight must be included in the bending stress calculations.

**Installation**

During installation the spanning stresses mentioned above must also be considered. In addition, the theoretical pulling force on the product pipe must be determined to calculate the stresses that the pipe will experience during installation. A down-hole friction factor (usually 1.0 is recommended for conservative results) is used to include the effect of the pipeline being pulled around a curve. The maximum predicted pulling force is then be used in calculating the resulting longitudinal stress. It is normal to allow for a 10-percent drilling tolerance, which leads to a radius of curvature that is 90 percent the design radius when calculating the longitudinal curvature stresses. The external pressure on the product pipe from static head in the drilled hole and/or overburden pressures must also be considered. It is often recommended that the static head resulting from the maximum drilling-fluid density should be used with a factor of safety of 1.5 to provide conservative estimations of resulting hoop and longitudinal stresses.
Operating Stresses

The operating stresses of concern include a combination of the longitudinal curvature stresses, external pressure stresses, and hoop and longitudinal stresses mentioned above. For operating stresses, the maximum working pressure of the pipeline is used to calculate the longitudinal and hoop stresses that will be imposed during service.

After determining the individual and combined stresses, they are compared with the allowable stress limits for the product pipe. For example, ASME B31.8 provides the following limits for natural-gas pipelines:

- Maximum allowable longitudinal stress: 80 percent of SMYS (specified minimum yield strength of the pipe material)
- Maximum allowable hoop stress: 72 percent of SMYS
- Maximum allowable combined stress: 90 percent of SMYS

There are many industry standards that address allowable stresses for various product-pipe materials. Manufacturers of HDD product pipe and conduits also provide data concerning the allowable stresses for their products and materials. In many cases regulatory agencies impose additional stress limits that must be considered. During the design phase identify all applicable allowable stresses and any further constraints that may apply and ensure the adequacy of the design for HDD construction.

Directional Accuracy and Tolerances

The instruments typically used for HDD down-hole surveys are magnetic and are subject to some inaccuracy. In addition, the actual pilot bore-hole path may also deviate from the designed drilled path due to soil reaction. Because of these factors it is common practice to allow HDD contractors a tolerance between the final bore path and the designed pilot bore-hole path. For magnetic instruments, an error in alignment of 1 percent of the drilled length is not unusual. Error can be reduced by using a surface monitoring system or redrilling the pilot hole, but this will increase the cost of the installation. It is good practice to establish tolerance limits for various applications that are acceptable from the design point of view and at the same time achievable using current tracking and steering capabilities of HDD equipment. During the planning phase, the engineers and owners should consider and establish allowable tolerances for locating the HDD segment, paying special consideration to bore paths near existing facilities and when purchasing easements. The tolerance values are application-dependent.

When a product pipeline is installed in a crowded right-of-way, the safe minimum separation distances are important. Many utilities companies have regulations for
minimum separation distances between various utilities. These distances often have to be adjusted because of possible minor deviations when a pipeline is installed using HDD. There are many different rules and guidelines in the various industries that use HDD concerning what is the minimum separation. One often-used criterion is to allow normal HDD construction practices if the separation between the proposed product pipe and the existing utility line is 15 feet or more. For product-pipe separation less that 5 feet special measures, such as observation bore holes, are required. This criterion is subject to engineering judgment and the potential impact if a foreign utility is damaged by the HDD construction. For example, a natural-gas pipeline is usually treated more cautiously than a stormwater drainage line. In all cases, the bore path and the product pipe should be installed to the alignment and elevations that are shown on the project plans within the specified tolerances.

Product-Pipe Considerations

During the design process an evaluation of the product to be installed by HDD is critical. The design should evaluate the product pipe’s suitability for the installation loads, corrosion conditions, pull-in installation, and intended function. In general, the pipe to be installed must be capable of being joined together continuously while maintaining sufficient strength to resist the high tensile stresses imposed during the pullback operation. The primary criterion governing the specification of product pipe to be installed by HDD is its intended service. However, stresses and loads imposed by the installation should be reviewed and, where prudent, analyzed in combination with operating stresses to ensure that acceptable limits are not exceeded. Usually the wall thickness and specified minimum yield strength are determined from applicable codes and regulations. The types of product pipes being installed by HDD have increased over the last several years. Originally steel and polyethylene products were the primary products used for HDD; however, improved joining methods for ductile iron and PVC products have made their use in HDD applications more common.

The primary loads include tensile pullback forces and bending and buckling stresses. The main load concerns for HDD crossings are usually product-pipe buckling with deep crossings and bending with shallow crossings. There are industry-accepted safety factors that should be used during the design. The appropriate safety factor depends on your confidence in the subsurface conditions, the material being used, and the level of risk acceptance. These safety factors are usually applied to all loads to account for shock loads, increased loads after any pullback delays, high frictional pullback loads, and unexpected surcharge or traffic loads. The minimal safety factor is typically 1.5 to 2.

When installing cable by HDD, the cable manufacturer’s specifications should be used to determine allowable loads and stresses. The bend radius for these bores...
is determined by the steel drill rods. When installing cables directly, the buckling and bending stresses are not a concern; however, when installing the cable in a conduit, the bore path should be evaluated as a pipe installation with all loads and stresses considered.

Steel Product Pipe

Steel-pipeline properties such as wall thickness and material grade, as well as the bore path profiles, must be specified so the pipeline can be installed and operated without risk of damage. During HDD installation the pipeline is subjected to tension required to pull the pipe into the pilot hole and around curved sections. The tension comes from the drag due to the friction between pipe and bore hole and the fluid drag caused by pulling the pipe through the viscous drilling mud trapped in the annulus. In addition, tension results from the unbalanced gravity effects of pulling the pipe into and out of the bore hole at different elevations. The bending loads are caused as the pipe is forced through the curves in the bore hole, and the external loads result from the pressure exerted by the drilling mud in the annulus around the pipe (unless the pipe is flooded with a fluid at a similar pressure). The stresses and loads resulting from the HDD installation method should be reviewed and analyzed in combination with the operating stresses to ensure that acceptable limits are not exceeded. Methods for analyzing the loads and stresses imposed on a steel pipeline installed by HDD are discussed in Chapter 5. Table 4-1 is an example of a steel product-pipe specification for a gas pipeline.

Steel products have a high pulling load capability and can handle considerable pullback loads. The allowable pulling loads for steel pipe are a function of the steel material grade, pipe diameter and wall thickness, and safety or code load factors. Equation 4-1 is a commonly used formula for determining the allowable pulling forces for steel products.

\[
F = \left( \left( \frac{SMYS \cdot fl}{fs} \right) - \left( \frac{E \cdot D}{24 \cdot R} \right) \right) \cdot A \quad \text{Equation 4-1}
\]

where:
- \( F \) = maximum allowable pull force, pounds
- \( R \) = design radius of curvature, feet
- \( E \) = modulus of elasticity, psi
- \( A \) = cross-sectional pipe area, inches\(^2\)
- \( D \) = pipe outside diameter, inches
- \( SMYS \) = specified minimum yield strength of the steel, psi
- \( fl \) = maximum load factor
- \( fs \) = safety factor
The allowable bend radius for steel products is typically large and can often be the main factor in the layout of the bore path. It depends on many factors such as the pipe diameter and wall thickness, the steel grade, and any code safety factors. Below are two commonly used equations for calculating the allowable bending radius for steel pipe.

\[
R = \frac{3 \times E \times I}{2 \times Z \times Sa}
\]  
\[
R = \frac{3 \times E \times r}{2 \times Sa}
\]

where:
- \( R \) = maximum radius of curvature, inches
- \( E \) = modulus of elasticity, psi

**TABLE 4-1 Typical Steel Pipe Specification for HDD**

<table>
<thead>
<tr>
<th>Description</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel pipe shall conform to API 5L X52 specifications.</td>
<td>The pipe shall be seamless or electric resistance welded (ERW) steel pipe as specified in ASME B31.8. Butt-weld fittings shall be in accordance with ASME B16.9. All steel pipes shall be plain end and beveled for welding.</td>
</tr>
<tr>
<td>Steel pipe shall be plant coated with Fusion Bonded Epoxy External Line Pipe Coating.</td>
<td>Approved products are 3M #206N FBE Coating and NAP-GARD #2500 FBE Coating. Uniform cured film thickness shall be 12 mils +/- 2 mils. Pipe for Horizontal Directional Drills will be coated additionally with Powercrete or 20 mils +/- 2 mils of Lilly 20/40.</td>
</tr>
<tr>
<td>The minimum steel pipe properties are as follows:</td>
<td></td>
</tr>
<tr>
<td>8-inch, API 5L, X-52, 0.250-inch wall thickness</td>
<td></td>
</tr>
<tr>
<td>Steel Making Process: basic oxygen or electric arc furnace, fully killed; fine grained practice</td>
<td></td>
</tr>
<tr>
<td>Pipe Making Process: seamless or ERW</td>
<td></td>
</tr>
<tr>
<td>Material Chemistry, percent by weight: CE &lt; 0.42%; S &lt; 0.01%</td>
<td></td>
</tr>
<tr>
<td>Tensile Properties: excess strength &lt;20 ksi</td>
<td></td>
</tr>
<tr>
<td>Fracture Toughness: per API 5L</td>
<td></td>
</tr>
<tr>
<td>Mill Test Pressure: 100% SMYS</td>
<td></td>
</tr>
<tr>
<td>Nondestructive Examination: Entire weld seam and plate, calibrated to mill speed</td>
<td></td>
</tr>
<tr>
<td>Coating: Fusion Bonded Epoxy; 12-mils +/- 2 mils</td>
<td></td>
</tr>
<tr>
<td>Loading and Transport: per API RP5L1</td>
<td></td>
</tr>
</tbody>
</table>
The stresses in the steel pipe due to bending are another key factor to consider during the design of a HDD crossing. The allowable bending stress for steel pipe depends on many factors such as the pipe diameter and wall thickness, the steel grade, and any code safety factors. Below are some commonly used equations for calculating the bending stress and the allowable bending stress for steel pipe.

\[
bending_{stress} = \frac{E \cdot D}{24 \cdot R}
\]

Equation 4-4

\[
bending_{allow} = \left(0.75 \cdot SMYS\right) \left(\text{if } \frac{D}{t} \leq \frac{1500000 \text{ psi}}{SMYS}\right)
\]

Equation 4-5a

\[
bending_{allow} = \left(0.84 - \frac{1.74 \cdot SMYS \cdot D}{E \cdot t}\right) \cdot SMYS \left(\text{if } \frac{1500000 \text{ psi}}{SMYS} < \frac{D}{t} \leq \frac{3000000 \text{ psi}}{SMYS}\right)
\]

Equation 4-5b

\[
bending_{allow} = \left(0.72 - \frac{58 \cdot SMYS \cdot D}{E \cdot t}\right) \cdot SMYS \left(\text{otherwise}\right)
\]

Equation 4-5c

where:
- \(R\) = design maximum radius of curvature, feet
- \(E\) = modulus of elasticity, psi
- \(D\) = pipe outside diameter, inches
- \(t\) = pipe wall thickness, inches
- \(SMYS\) = specified minimum yield strength of the steel, psi

For projects that utilize plastic pipe such as PE or PVC, it is common to have to transition to steel pipe for crossing railroads and sometimes highways. If a project application requires the use of plastic pipe and the HDD stresses exceed the allowable limits, transitioning to steel pipe is the usual approach for overcoming the plastic limitations. Manufacturers produce steel-to-plastic transition fittings for this purpose.
**External Pipe Coating.** Corrosion control is a key area of concern when using steel pipe in HDD applications. Pipe coatings are typically applied to provide a corrosion barrier for the pipe and an abrasion barrier to protect the coating during installation. HDD crossings generally encounter varying materials and often can be exposed to extra abrasion during the pullback. An outer abrasion-resistant overcoat is often required. To facilitate the pullback of the pipeline, the coating should bond well to the pipe to resist soil stresses and have a smooth, hard surface to reduce friction and maintain the corrosion barrier. As in any pipeline construction, the recommended external coating system should be compatible with any specifications for the field joint coating or any internal coating. The pipe coating most often used is mill-applied fusion-bonded epoxy (FBE) with a recommended minimum thickness of 20 mils.

The coating application of the weld area is critical for field operations to maintain a smooth, abrasion-resistant pipe string. The most frequent method of field repair is to coat the girth weld with FBE powder, utilizing an induction heating coil and powder application machine to a minimum dry-film thickness of 25 mils. Another method is a two-component catalyzed liquid epoxy, applied to the girth weld area to a minimum dry-film thickness of 25 mils with a paintbrush or roller. Tape should never be used for joint coating on the pullback portion of a directional crossing. Small coating-damaged areas can be repaired with a polymeric melt-stick patching material. Holidays larger than 1 inch in diameter should be repaired utilizing the two-component catalyzed liquid epoxy.

As an extra abrasion-resistant barrier for crossings through stones, boulders or solid rock it is recommended that the FBE-coated pipeline be overcoated with an epoxy-based polymer concrete. The material should be applied at a mill or with a portable yard coating machine to a minimum thickness of 20 mils. Girth-weld and coating-damaged areas should be field-coated using an epoxy-based polymer concrete compatible with the overcoat material. The patch material should be applied so the material tapers uniformly and feathers into the original coating. Stability of the pipeline in drilled crossings is not normally a concern, so a Portland-cement-type concrete coating is not recommended.

**Plastic Product Pipe**

Over the last thirty years, the underground piping market in North America has seen tremendous growth in the use of thermoplastic materials. Benefits such as corrosion resistance, improved hydraulics, and reduced installation costs have been paying large dividends for owners of natural gas, water, and sanitary and storm sewer systems. The most widely used of this group of non-metallic polymers is polyvinyl chloride, also known as PVC. The second most prominent thermoplastic used in the underground pipe market is polyethylene (PE). This material was primarily used for gas piping and drainage tubing before its recent introduction into
the water and sewage force-main markets. Understanding the similarities and differences of PVC and PE is essential to the proper selection and specification of these two thermoplastic products for pressure service. In-depth pipe-design considerations for both materials are beyond the scope of this book but are provided by many organizations such as the Plastic Pipe Institute.

While PVC pipe has been widely used for years, its use in the HDD construction industry is relatively new. The predominant plastic material of choice for HDD applications has been PE. PE, due to its fused joints, is ideal for pulling through bores. PE has been used in the gas industry for many years. Because of the advantages of trenchless installations PE pipe has found new markets in the water and sewer fields, mainly for trenchless projects. Fusible PVC pipe has recently been developed and is expected to compete directly against butt-fused PE pipe for the water and sewer trenchless construction market.

Underground Solutions introduced Fusible C900™/C905™ PVC pipe to the HDD market. A first of its kind, this product uses a fusion process to join lengths of AWWA C900 and C905 pipe, ranging in diameters of 4 to 48 inches, in a continuous, jointless chain, similar to the way in which PE pipe is assembled. With the ability of PVC pipe to be fused in this manner, the product could potentially increase the use of PVC pipes installed by HDD construction methods. Overall, PVC has not been used as widely as other materials for HDD construction. Technological developments within the PVC pipe industry have resulted in the design and manufacture of some restrained joint products to enable trenchless installation of PVC water and sewer pipe via processes such as HDD.

Currently there are two types of PVC pressure-pipe products that are designed to withstand the pulling forces involved in HDD. The gasket joints in both products have been modified to provide the restraint necessary to hold the joints together during the pullback action.

Manufactured by IPEX, Inc., Terra Brute™ trenchless restraining joint pipe is AWWA C900 pressure pipe with a newly developed joint for pull-in-place installation of pipe in pressure piping systems. The modification made to a regular piece of AWWA C900 pipe consists of a set of small-diameter stainless-steel pins that are inserted through an external ring and the bell of the pipe into an internal steel ring placed in a groove cut into the spigot section. This bell-and-spigot joint modification increases the tensile-load capacity of the pipe joint by a factor of 36 to 60, depending on the diameter and the wall thickness of the pipe. The tensile capacity of the joint can be optimized by controlling the number of pins, pin diameter, depth of groove in the spigot, and wall thickness of the internal ring. Several successful installations of various lengths of Terra Brute™ have been completed with HDD. The design approach of the joint is universal and can be adapted to PVC pressure pipes of 4- through 42-inch diameters.

Certa-Lok C900/RJTM PVC restrained joint pipe, manufactured by Certain Teed Corporation, is another product conforming to AWWA C900 pipe, but again
with a proprietary joint type that makes the product ideal for HDD installation. The Certa-Lok C900/RJ is used in new construction of water distribution/transmission lines or sewer force mains or for new gravity-sewer-main installation. The Certa-Lok™ C900/RJ restrained joint pipe has a groove machined in the pipe and in the coupling to allow the insertion of a flexible thermoplastic spline that provides a full 360-degree restrained joint with evenly distributed loading. Although the wall thickness of the pipe is locally reduced at the groove area, positive reinforcement and stress control are provided at this location by the installed Certa-Lok coupling and spline. Finite-element structural analysis has verified that under internal pressure tensile hoop stress in the pipe groove area does not increase above the nominal predicted levels away from the groove. Available diameters currently include 4 inches through 12 inches in both 150 psi and 200 psi pressure classes.

When designing any pressurized piping system, consideration must be given to the stress created in the pipe wall due to the internal operating pressure. Metallic materials used in pressure pipes are elastic—i.e., the relations between stress and strain are linear and independent of loading time. However, plastics are different. Their strain is not proportional to stress or independent of loading time. Even though plastics (such as PVC and PE) do not behave elastically, most of the design equations that have been derived on the assumption of elastic behavior can still be used, provided the strength values used are appropriately established. The use of elastic equations requires the selection of strength values that account for long-term loading response. For PVC and PE pipe materials such values are determined from long-term pressure tests conducted on pipe specimens made from the material under evaluation. Pipe testing is performed in accordance with ASTM D1598, Time to Failure of Plastic Pipe Under Constant Internal Pressure. Sufficient pressures versus time-to-failure points are obtained to plot a line on log stress versus log time-to-failure coordinates. In order for a thermoplastic material to qualify for pressure piping, the data must plot along a nearly straight line. That straight line is defined mathematically and extrapolated to the 100,000-hour intercept. This extrapolation procedure is detailed in ASTM D2837, Obtaining Hydrostatic Design Basis for Thermoplastic Pipe Materials. The resulting long-term (extrapolated 100,000-hour) tensile strength values are categorized into hydrostatic design basis (HDB) values. The HDB values are appropriate for use in the elastic design equations for determining either the pipe wall thickness or selecting the pipe pressure rating/class needed.

**External Load Considerations.** Plastic pipe has been installed for gas, water, and sewer mains; electrical conduits; and a variety of chemical lines. These projects involved river crossings, highway crossings, right-of-ways through developed driveways, and business entrances. As mentioned in Chapter 2, the condition of the bore hole is an important factor in determining the loads on the product pipe. The primary area of concern is whether the bore hole stays open or collapses. The types of
ground, drilling techniques, and the presence of drilling mud all influence the bore-hole condition. If the bore hole remains intact after drilling and reaming, the earth loads arch around the hole, resulting in little soil pressure being transmitted to the pipe. For intact bore holes the pipe experiences pressure from the hydrostatic forces caused by the drilling slurry or any groundwater present. If the bore hole does not remain intact and collapses, the earth pressure will be experienced on the pipe. Earth pressure resulting from a bore-hole collapse could exceed the slurry pressure unless considerable tunnel arching occurs above the hole. If tunnel arching does not occur, the external pressure is a combination of the earth, groundwater, and live-load pressure. Arching is not usually experienced during river crossings because of the unconsolidated and saturated soil conditions. In this case the pressure on the pipe likely equals the geostatic stress or prism load. Arching may occur in consolidated soils. Under this condition the applied pressure is often less than the prism load.

The net external pressure is the difference between the inside and outside pressure acting on the pipe. The external pressure operating on the pipe may be reduced or eliminated by the internal pressure. Product pipes operating under an internal vacuum will experience an increase in the external pressure because of the absence of atmospheric pressure inside the pipe. For a collapsed or deformed bore hole Equation 4-6 calculates the net external pressure. For an intact or open bore hole Equation 4-7 calculates the net external pressure.

\[ \text{Pressure}_{\text{net}} = P_{\text{ext}} + P_{\text{water}} + P_{\text{live}} - P_{\text{int}} \]  

Equation 4-6

\[ \text{Pressure}_{\text{net}} = P_{\text{slurry}} - P_{\text{int}} \]  

Equation 4-7

where:

- \( P_{\text{ext}} \) = External pressure due to earth pressure, psi
- \( P_{\text{water}} \) = Groundwater pressure (including the height of river water), psi
- \( P_{\text{live}} \) = Live loads, psi
- \( P_{\text{int}} \) = Internal pressure, psi (negative in the event of vacuum)
- \( P_{\text{slurry}} \) = Hydrostatic pressure of slurry or groundwater pressure, psi

Earth loads may be experienced on the pipe when the bore hole contacts the pipe. When bore-hole deformation places the soil above the hole in a plastic state, arching may result. Under these conditions the deformation of the bore hole is limited and may result in no soil actually making contact with the pipe. If the soil does not contact the pipe, it will not experience any earth load. However, the bore hole may deform enough to allow earth loads to be transmitted to the pipe. Under these conditions it is a challenge to determine the earth loading experienced by the pipe. The
reader should refer to materials published by plastic-pipe manufacturers and the Plastic Pipe Institute for detailed coverage of this type of earth loading. If arching in the soil above the pipe does break down, the pipe may experience considerable earth loading. Under this condition the earth load is the weight of the soil above the pipe. This type of prism load is more common in shallow HDD bore paths that experience live loads and in unconsolidated sediments such as river crossings. Equation 4-8 is used to calculate the external earth pressure load under this condition.

\[ P_{\text{earth}} = \gamma_{\text{soil}} \times H_{\text{soil}} \]  
Equation 4-8

where:
\( \gamma_{\text{soil}} \) = effective weight of the soil, pounds/feet\(^3\)
\( H_{\text{soil}} \) = soil height above the pipe, feet

Groundwater loads will be experienced on the pipe regardless of the bore-hole condition. The primary concern is determining whether the slurry head or groundwater head is higher and whether they will control the design requirements for external loading. If present in the soil conditions, the external pressure caused by groundwater must be taken into account during the design. Equation 4-9 calculates external pressure due to the slurry head, and Equation 4-10 calculates the external pressure due to the ground or surface water head.

\[ \rho_{\text{slurry}} = g_{\text{slurry}} \times H_{\text{borehole}} \]  
Equation 4-9

\[ \rho_{\text{water}} = g_{\text{water}} \times H_{\text{water}} \]  
Equation 4-10

where:
\( \rho_{\text{slurry}} \) = unit weight of the slurry and soil cuttings
\( g_{\text{water}} \) = unit weight of the water
\( H_{\text{borehole}} \) = elevation difference between the lowest part of the bore hole and the entry or exit point
\( H_{\text{water}} \) = height of the water above the pipe

**Plastic-Pipe Resistance to Loads.** A key factor in the design of a HDD crossing using plastic pipe is to select a pipe that can withstand the external loads without incurring damage that can affect the operation or life of the pipe. Most product pipelines experience several operational cycles during their life. The different operational cycles result in various net external pressures that have to be considered during the design phase. In addition to determining the various loads for the operational cycles, consideration must be given to the duration of each load. Most plastic-pipe products react to loads with time-dependent properties. For example, a
plastic conduit resists constant groundwater and soil pressure with its long-term stiffness. A plastic-pipe force main may be subjected to pressure surges resulting in cavitation. During cavitation the net external pressure is the sum of the external pressure plus the vacuum. Cavitation is instantaneous, so it is resisted by the pipe’s short-term stiffness, which can be four times higher than the long-term stiffness.

The tensile-strength limits for plastic pipes may have a significant impact on HDD designs. Tensile properties are time-dependent, and the pipe’s resistance to a newly applied load decreases with time. This causes a higher resistance to short-term than to long-term loading. The HDD design should take into account the duration and frequency of each load so the performance limit can be calculated using the appropriate pipe-material properties. Under HDD pullback operations the pipe’s tensile yield strength decreases with pulling time. As a result, the allowable pulling stress is a function of time. In addition, for viscoelastic materials, the ratio of the applied stress to strain is called the apparent modulus of elasticity, because the ratio varies with the load rate. See Table 4-2 for typical values for HDPE and PE pipe.

**Deflection and Bending-Load Considerations.** The design process consists of calculating the loads applied to the product pipe, selecting a preliminary pipe dimension ratio (DR)—the outside diameter divided by the wall thickness—and then calculating the safety factor for that DR. If the safety factor is adequate, the design is complete. If not, a lower DR is used and the process repeated. Safety factors are established for the various performance limits of the pipe. Safety factors are the ratio of the pipe’s ultimate strength or resistance applied to the load. During HDD construction plastic pipes are typically installed in a bore hole with a diameter that is approximately 1.5 times larger than the product pipe. The drilling mud and hole cuttings fill the annular space. This material is similar to very soft clay and does not provide soil support for the pipe. Due to these conditions, the design normally does not account for any support from the annular-space mixture. A pipe should be selected that has adequate ring stiffness to resist the net external pressure without the support of the surrounding soil. External pressure applied to the plastic pipe

<table>
<thead>
<tr>
<th>Duration</th>
<th>HDPE</th>
<th>MDPE</th>
<th>Duration</th>
<th>HDPE</th>
<th>MDPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short term</td>
<td>110,000 psi</td>
<td>87,000 psi</td>
<td>30 min</td>
<td>1300 psi</td>
<td>1000 psi</td>
</tr>
<tr>
<td>10 hours</td>
<td>57,500 psi</td>
<td>43,500 psi</td>
<td>60 min</td>
<td>1200 psi</td>
<td>900 psi</td>
</tr>
<tr>
<td>100 hours</td>
<td>51,200 psi</td>
<td>36,200 psi</td>
<td>12 hours</td>
<td>1150 psi</td>
<td>850 psi</td>
</tr>
<tr>
<td>50 years</td>
<td>28,200 psi</td>
<td>21,700 psi</td>
<td>24 hours</td>
<td>1100 psi</td>
<td>800 psi</td>
</tr>
</tbody>
</table>
produces a compressive ring thrust in the pipe wall and may cause ring bending deflection. Ring buckling or collapse is the performance limit for plastic pipes that are subjected to compressive thrust, and ring deflection is the performance limit related to ring bending.

Deflection reduces the pipe’s resistance to external loads. HDD installation may produce ring deflection from earth loads, bending loads, and buoyancy forces. Allowable deflection limits for pipes depend on many factors. Diametrical deflection is limited by geometric stability and by the bending strain induced in the pipe wall due to deflection. Geometric stability (collapse) will be covered next. The maximum deflection a pipe can handle before becoming unstable depends on a number of factors, but typically instability occurs above 20-percent deflection in ground above the water table and above 15-percent deflection in ground below the water table. Normally a safety factor is applied. ASTM F-894 gives long-term deflection for pressurized pipes between 7.5 and 3 percent depending on the pipe DR (See Table 4-3). Pipes operating under internal pressure are also subjected to additional strain due to internal pressure attempting to reround the pipe. Because of this it is typical to limit the deflection for pipes under internal pressure. Table 4-3 provides some design deflection limits for PE pipes.

To calculate the ring deflections, use the larger of the deflections resulting from soil loads assuming no side support or from buoyant deflection due to mud weight. The first equation is for ring bending deflection; the second, for buoyancy deformation:

\[
\frac{0.0125 \times P_{net} \times 100}{E \times 12 \times (DR - 1)^3}
\]

\[\text{Equation 4-11}\]

<table>
<thead>
<tr>
<th>SDR</th>
<th>Deflection Limit Non-pressure Pipe (% diameter)</th>
<th>Deflection Limit Pressure Pipe (% diameter)1</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>7.5</td>
<td>7.5</td>
</tr>
<tr>
<td>17</td>
<td>7.5</td>
<td>6.0</td>
</tr>
<tr>
<td>15.5</td>
<td>7.5</td>
<td>6.0</td>
</tr>
<tr>
<td>13.5</td>
<td>7.5</td>
<td>6.0</td>
</tr>
<tr>
<td>11</td>
<td>7.5</td>
<td>5.0</td>
</tr>
<tr>
<td>9</td>
<td>7.5</td>
<td>4.0</td>
</tr>
<tr>
<td>7.3</td>
<td>7.5</td>
<td>3.0</td>
</tr>
</tbody>
</table>

1 Deflection limits for pressure pipe applications are equal to 1.5 times the short-term deflection limits given in ASTM F-714.
where:
\[
\% \Delta D = \text{percent of ring deformation}
\]
\[
P_{net} = \text{earth pressure, psi}
\]
\[
DR = \text{pipe dimension ratio}
\]
\[
E = \text{modulus of elasticity (usually long-term), psi}
\]

\[
\% \Delta D_b = \frac{.088 \times \text{mud weight}}{E \times DR} \times (DR - 1)^4 \times 100
\]
Equation 4-12

where:
\[
\% \Delta D_b = \text{percent of ring deflection}
\]
\[
\text{mud weight} = \text{weight of fluid in borehole, foot-pounds/inches}^3
\]
\[
D = \text{pipe outside diameter, inches}
\]
\[
DR = \text{pipe dimension ratio}
\]
\[
E = \text{modulus of elasticity (usually long-term), psi}
\]

Uniform external pressure results in ring compressive forces around the circumference of the pipe. This force causes compressive stresses in the pipe wall that could cause the pipe to collapse. As mentioned above, for HDD applications the pipe is considered to have no side support from the soil. Equation 4-13, known as Levy’s equation, is often used to determine the allowable net external collapse pressure for HDD installed pipe.

\[
P_{\text{collapse}} = \frac{2 \times E}{(1 - u^2)} \times \left(\frac{1}{SDR - 1}\right)^3 \times \frac{f_o}{N}
\]
Equation 4-13

where:
\[
E = \text{apparent modulus for the specified pipe}
\]
\[
u = \text{Poisson’s ratio (long-term loading 0.45; short-term loading 0.35)}
\]
\[
DR = \text{pipe dimension ratio}
\]
\[
f_o = \text{ovality compensation factor}
\]
\[
N = \text{safety factor (usually 2.0 or higher)}
\]

The ovality compensation factor is provided in Figure 4-4. The above equations are suitable to use for pullback calculations after applying a further reduction factor due to the pulling force applied to the product pipe. Chapter 7 covers the pullback forces in detail.

The critical loading concern for deep HDD crossings of PE and PVC pipe products is usually buckling loads caused by the pressure of the drilling fluid in the annulus around the product pipe. PVC offers a higher buckling pressure than PE, but
both are considerably lower than steel. Tables 4-4 and 4-5 show the critical buckling (collapse) pressure typically used for PE and PVC pipe.

PE and PVC products have a much smaller bending radius than steel, and the bending radius of the drill rod will usually control the allowable bending radius of the bore path. The bending radius should be sufficiently large to allow for minimal bending strain and stress. The recommended minimum bending radius can be provided by the pipe manufacturer. Tables 4-6 and 4-7 show the allowable bend radius typically used for HDPE/PE and PVC pipe.

Pullback Load Considerations. HDD installation can exert significant pull forces on the product pipe. While Chapter 7 of this book covers HDD pulling loads in detail, a brief discussion of the topic is provided here. Determining what percentage of the total pullback force will be transmitted to the product pipeline is a challenge at best. The pulling force, which overcomes the combined frictional drag, capstan effect, and hydrokinetic drag, is applied to the pull head and first joint of product pipe, and the axial tensile stress grows in intensity over the length of the pull. The tensile forces on the pipe are caused by the fractional drag forces due to the weight or buoyancy forces as it is pulled into and through the bore hole.

<table>
<thead>
<tr>
<th>TABLE 4-4</th>
<th>Typical HDPE Critical Buckling Pressure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Critical Buckling (collapse) Pressure, PE; psi</td>
<td></td>
</tr>
<tr>
<td>SDR</td>
<td>7.3</td>
</tr>
<tr>
<td>Short Term</td>
<td>1,003</td>
</tr>
<tr>
<td>100-hours</td>
<td>488</td>
</tr>
<tr>
<td>50-years</td>
<td>283</td>
</tr>
</tbody>
</table>
### TABLE 4-5  Typical PVC Critical Buckling Pressure

<table>
<thead>
<tr>
<th>Dimension Ratio</th>
<th>Pressure (psi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>14</td>
<td>426</td>
</tr>
<tr>
<td>18</td>
<td>190</td>
</tr>
<tr>
<td>25</td>
<td>67</td>
</tr>
<tr>
<td>32.5</td>
<td>27</td>
</tr>
<tr>
<td>41</td>
<td>14.6</td>
</tr>
<tr>
<td>51</td>
<td>7.4</td>
</tr>
</tbody>
</table>

### TABLE 4-6  Typical Minimum Bend Radius for PE Fusion Joined Pipes; Bend radius is based on the pipe outside diameter.

<table>
<thead>
<tr>
<th>SDR</th>
<th>Allowable Bend Radius</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;= 13.5</td>
<td>R = 20 times pipe outside diameter</td>
</tr>
<tr>
<td>&gt; 13.5 to 21</td>
<td>R = 25 times pipe outside diameter</td>
</tr>
<tr>
<td>&gt; 21</td>
<td>R = 30 times pipe outside diameter</td>
</tr>
<tr>
<td>Pipe with fittings or flanges in the bend</td>
<td>R = 100 times pipe outside diameter</td>
</tr>
</tbody>
</table>

### TABLE 4-7  Typical Minimum Bend Radius for PVC Fusion Joined Pipes; Bend radius is based on the pipe outside diameter.

<table>
<thead>
<tr>
<th>Nominal Pipe Size (inches)</th>
<th>Minimum Allowable Bend Radius (feet)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>100</td>
</tr>
<tr>
<td>6</td>
<td>144</td>
</tr>
<tr>
<td>8</td>
<td>188</td>
</tr>
<tr>
<td>10</td>
<td>232</td>
</tr>
<tr>
<td>12</td>
<td>275</td>
</tr>
<tr>
<td>14</td>
<td>319</td>
</tr>
<tr>
<td>16</td>
<td>363</td>
</tr>
<tr>
<td>18</td>
<td>406</td>
</tr>
<tr>
<td>20</td>
<td>450</td>
</tr>
<tr>
<td>24</td>
<td>538</td>
</tr>
<tr>
<td>30</td>
<td>667</td>
</tr>
<tr>
<td>36</td>
<td>798</td>
</tr>
<tr>
<td>42</td>
<td>927</td>
</tr>
<tr>
<td>48</td>
<td>1058</td>
</tr>
</tbody>
</table>
The force is amplified by pulling the pipe through the curves and to the resistance due to the pipe stiffness. The required tensile force at the leading end of the product pipe will vary during the pullback. The amount of time that the pipe experiences the pulling stress is longest at the pull nose. The tail end of the pipe segment has zero applied tensile stress for zero time. The tensile stress should not exceed the allowable tensile stress for the pipe. Increasing the pipe wall thickness will allow for a greater total pull force, but the thicker wall also increases the weight per foot of the pipe in direct proportion. Selecting a thicker wall pipe may not necessarily reduce stresses but rather only increase the absolute value of the pull force.

A common practice to control this loading and to reduce the pullback loads is to fill the product pipe with water during the installation. The water will counteract the external buckling pressures and help provide neutral buoyancy for the product pipe. The critical load for shallow HDD crossings with PE and PVC products is usually the pullback load. Engineering judgment should be used in selecting the standard DR of the product pipe to resist the pullback load. Smaller values of DR will result in stiffer PE/PVC pipe. During the design the first step is normally to select the DR by determining the DR requirement for the internal pressure (or other hydraulic requirements). This DR is used in the preliminary calculations to determine if it is capable of withstanding the earth, live, and groundwater service loads. The next step is usually to check the DR against the installation (pullback) forces that are anticipated. Based on these steps, a DR is selected that will satisfy all three requirements. It is common to have some pipe wall stresses generated by the combination of internal pressure and wall bending. However, the internal pressure and external service-load stresses are usually treated independently. This is acceptable because plastic pipe is a ductile material and failure is usually caused by average stress rather than local maximums. The estimated pulling loads should not exceed the manufacturer’s recommended maximum. Tables 4-8 and 4-9 provide typical maximum pulling loads for PE and PVC pipe.

Pipe resistance to pullback in the bore hole depends primarily on the frictional force created between the pipe and the hole or the pipe and the ground surface in the entry area, the frictional drag between pipe and drilling slurry, the capstan effect at bends, and the weight of the pipe. As mentioned previously, the buoyant force pushing the empty pipe to the bore-hole crown will cause the pipe to rub the crown. During pullback, the moving drill mud lubricates the contact zone. If the drilling stops or if the pipe or the mud flow stops, the pipe, slightly ring-deflected by the buoyant force, can push up and squeeze out the lubricating mud. The resultant startup friction is measurably increased. The pulling load to loosen the PE pipe from the mud can be very high. This situation is best avoided by using higher-ring-stiffness pipes, inserting full rather than empty pipe, and continuing nonstop drilling.

The maximum outer-fiber tensile stress should not exceed the safe pull stress. The maximum outer-fiber tensile stress is obtained by taking the sum of the tensile stress.
stress in the pipe due to the pullback force, the hydrokinetic pulling force, and the
tensile bending stress due to pipe curvature. During pullback it is advisable to mon-
itor the pulling force and to use a weak link (such as a pipe of higher DR) or other
failsafe method to prevent overstressing the pipe. The axial tensile stress due to the
pulling forces should not exceed the safe pull load. Allowable safe pullback values
for gas pipe are given in ASTM F-1804-97, Determining Allowable Tensile Load
for Polyethylene (PE) Gas Pipe during Pull-In Installation. After pullback, pipe
may take several hours (typically equal to the duration of the pull) to recover from
the axial strain. When pulled from the reamed bore hole, the pull nose should be
pulled out about 3 percent beyond the total length of the pull. The elastic strain will
recover immediately, and the viscoelastic stretch will remember its original length
and recover overnight. After the pull the pipe should be inspected. Significantly
ovaled or flattened pipe is an indicator of collapse and that the pipe was over-
stressed during the pull. Deep scratches or gouges can reduce the pressure rating of
the pipe and increase stress. A common rule of thumb requires that pipes with
scratches or gouges deeper than 10 percent of the pipe wall thickness should be re-
placed. In some instances this may be restrictive, and other engineering judgments
may be necessary.

Ductile-Iron Product Pipe

As can be seen in the preceding section, in many ways plastic pipe and HDD seem
to be made for one another. As HDD became commonplace in the underground

TABLE 4-8  Typical PE Safe Pulling Loads

<table>
<thead>
<tr>
<th>Pipe</th>
<th>Safe Pull Load @ 24 hours; lbs</th>
</tr>
</thead>
<tbody>
<tr>
<td>2-inch SDR 11</td>
<td>PE 1,525 HDPE 1,875</td>
</tr>
<tr>
<td>4-inch SDR 11</td>
<td>PE 5,470 HDPE 6,732</td>
</tr>
<tr>
<td>6-inch SDR 11</td>
<td>PE 11,855 HDPE 14,590</td>
</tr>
<tr>
<td>8-inch SDR 11</td>
<td>PE 20,093 HDPE 24,729</td>
</tr>
<tr>
<td>8-inch SDR 13.5</td>
<td>PE 16,675 HDPE 20,524</td>
</tr>
<tr>
<td>10-inch SDR 11</td>
<td>PE 31,213 HDPE 38,416</td>
</tr>
<tr>
<td>12-inch SDR 11</td>
<td>PE 43,908 HDPE 54,040</td>
</tr>
<tr>
<td>12-inch SDR 13.5</td>
<td>PE 36,440 HDPE 44,848</td>
</tr>
<tr>
<td>24-inch SDR 11</td>
<td>PE 155,577 HDPE 191,480</td>
</tr>
<tr>
<td>24-inch SDR 17</td>
<td>PE 104,220 HDPE 128,271</td>
</tr>
<tr>
<td>36-inch SDR 11</td>
<td>PE 350,048 HDPE 430,829</td>
</tr>
<tr>
<td>36-inch SDR 17</td>
<td>PE 234,496 HDPE 288,610</td>
</tr>
</tbody>
</table>
### Table 4-9  Typical PVC Safe Pulling Loads

<table>
<thead>
<tr>
<th>Nominal Pipe Size (inches)</th>
<th>DR</th>
<th>Safe Pulling Force (pounds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>14</td>
<td>13,460</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>10,600</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>7700</td>
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<td>6</td>
<td>14</td>
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<tr>
<td></td>
<td>18</td>
<td>21,900</td>
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<td>8</td>
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<td>37,800</td>
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<td>10</td>
<td>14</td>
<td>71,800</td>
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<td>56,500</td>
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<td></td>
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<td></td>
<td>25</td>
<td>79,000</td>
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<tr>
<td>16</td>
<td>14</td>
<td>175,000</td>
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<td></td>
<td>18</td>
<td>139,000</td>
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<td>25</td>
<td>102,000</td>
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<td>175,000</td>
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<td>20</td>
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<td>210,000</td>
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<td></td>
<td>25</td>
<td>155,000</td>
</tr>
<tr>
<td>24</td>
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<td></td>
<td>25</td>
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<tr>
<td></td>
<td>32.5</td>
<td>215,000</td>
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<td>32.5</td>
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<tr>
<td>42</td>
<td>32.5</td>
<td>500,000</td>
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<tr>
<td></td>
<td>41</td>
<td>400,000</td>
</tr>
<tr>
<td></td>
<td>51</td>
<td>320,000</td>
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<tr>
<td>48</td>
<td>41</td>
<td>520,000</td>
</tr>
<tr>
<td></td>
<td>51</td>
<td>420,000</td>
</tr>
</tbody>
</table>
construction market during the 1990s, plastic pipe was the material installed most often. Today, the use of plastic pipe in HDD installation is increasing in segments of the potable water and sanitary and storm sewer systems. However, many water and sewer operators continue to prefer and specify ductile-iron pipe for new construction and replacement projects. The main reason is the inherent strength, toughness, and versatility of ductile-iron pipe.

There are still many engineers and contractors who do not know that ductile-iron pipe can be effectively installed by HDD methods. This is due to the incorrect assumption that pipe joints will pull apart during HDD installation. Flexible restrained joints are available that will effectively hold ductile-iron pipe together during the pull-in process while allowing the joints to deflect as a bore path changes direction. American Ductile Iron Pipe, the Ductile Iron Pipe Association (DIPRA), and other groups are actively promoting ductile-iron pipe’s appropriateness for HDD installation.

As with any product pipe, the HDD bore-path alignment and design for ductile-iron pipe are based on many factors. Some of the key factors are the pipe bell and barrel diameters, the optimum individual pipe length (20 feet is standard), bore-path inside diameter, and maximum deflection capabilities of the joint (see Table 4-10). The alignment for ductile-iron pipe should be designed and prepared with as

### TABLE 4-10  Typical Ductile Iron Pipe Properties for Pressure Class 350

<table>
<thead>
<tr>
<th>Pipe Size, In</th>
<th>Pipe O.D., In</th>
<th>Pipe Bell O.D., In</th>
<th>Unit Weight of Pipe, lb/ft</th>
<th>Density of Empty Pipe, lb/ft³</th>
<th>Net Unit Buoyancy of Empty Pipe in Water, lb/ft</th>
<th>Allowable Pull Load, lb</th>
<th>Allowable Deflection, Deg</th>
<th>Minimum Radius of Curvature, ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>4.8</td>
<td>7.06</td>
<td>13</td>
<td>100</td>
<td>−5</td>
<td>10,000</td>
<td>5.0</td>
<td>230</td>
</tr>
<tr>
<td>6</td>
<td>6.9</td>
<td>9.19</td>
<td>18</td>
<td>69</td>
<td>−2</td>
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<td>230</td>
</tr>
<tr>
<td>8</td>
<td>9.05</td>
<td>11.33</td>
<td>25</td>
<td>55</td>
<td>3</td>
<td>30,000</td>
<td>5.0</td>
<td>230</td>
</tr>
<tr>
<td>10</td>
<td>11.1</td>
<td>13.56</td>
<td>31</td>
<td>46</td>
<td>11</td>
<td>45,000</td>
<td>5.0</td>
<td>230</td>
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<tr>
<td>12</td>
<td>13.2</td>
<td>15.74</td>
<td>40</td>
<td>42</td>
<td>19</td>
<td>60,000</td>
<td>5.0</td>
<td>230</td>
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<tr>
<td>14</td>
<td>15.3</td>
<td>19.31</td>
<td>53</td>
<td>41</td>
<td>27</td>
<td>75,000</td>
<td>4.0</td>
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<tr>
<td>16</td>
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<td>305</td>
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<td>18</td>
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<td>52</td>
<td>120,000</td>
<td>3.75</td>
<td>305</td>
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<td>20</td>
<td>21.6</td>
<td>25.82</td>
<td>90</td>
<td>35</td>
<td>69</td>
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<td>3.5</td>
<td>327</td>
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<td>24</td>
<td>25.8</td>
<td>29.88</td>
<td>122</td>
<td>34</td>
<td>104</td>
<td>210,000</td>
<td>3.0</td>
<td>380</td>
</tr>
<tr>
<td>30</td>
<td>32.0</td>
<td>36.34</td>
<td>173</td>
<td>31</td>
<td>175</td>
<td>220,000</td>
<td>2.5</td>
<td>458</td>
</tr>
<tr>
<td>36</td>
<td>38.3</td>
<td>42.86</td>
<td>233</td>
<td>29</td>
<td>266</td>
<td>310,000</td>
<td>2.0</td>
<td>570</td>
</tr>
<tr>
<td>42</td>
<td>44.5</td>
<td>49.92</td>
<td>315</td>
<td>29</td>
<td>359</td>
<td>390,000</td>
<td>2.0</td>
<td>570</td>
</tr>
</tbody>
</table>
gradual curvatures as possible in any direction, so the pipe can be smoothly and safely installed with proper support. The exit angle is selected so that when the flexible-restrained-joint ductile-iron pipe is pulled back in the bore hole, any transition from the surface to the hole is within the manufacturer’s allowable joint deflection. In cases where the bore-path alignment is at an extreme depth or at high pumping pressures, particularly for larger sizes of pipe, the buckling strength of the pipe may need to be evaluated.

Ductile-iron pipe used for HDD installation is restrained with boltless flexible joints. Joints with bulky glands or flanges that may prevent the smooth flow of the drilling slurry over the joint may not be acceptable. Unlike lighter pipes, empty ductile-iron pipe, even in smaller-diameter sizes, results in very low buoyancy numbers. Net unit buoyancy is one factor that can influence pulling loads on pipe strings because of its effects on normal bearing force in pulling friction calculations. As a result of the buoyancy, the pulling loads for ductile-iron HDD installations are often less than plastic pipe. The weight of the pipe offsets the buoyancy effects after the pipe enters a slurry-filled bore path. The minimum curve radius for ductile-iron pipe is typically tighter than industry rules-of-thumb for welded pipes. Based on 20-foot nominal laying lengths and Equation 4-14:

\[
R = \frac{L}{2 \cdot \tan \left( \frac{Y}{2} \right)}
\]

where:
- \( R \) = minimum radius, feet
- \( L \) = laying length, feet
- \( Y \) = maximum joint deflection angle, degrees

Based on the material properties and common available thicknesses, ductile-iron pipe offers greater long-term buckling strength than many other piping materials. However, when non-pressurized ductile-iron pipe is subjected to very high external pressures or depth of cover, as with deep bore paths or high fluid pumping pressures, the buckling capability of the pipe should be checked. Evaluations should be made in accordance with the DIPRA Technical Report Critical Buckling Pressure for Ductile Iron Pipe. The properties of pipe shown in Table 4-10 are for pressure class (PC) 350 ductile-iron pipe with standard cement-mortar lining. Consult with manufacturers for information regarding applications with lower grades in 14- to 42-inch sizes. In no case shall the specified nominal thickness of pipe be less than PC 350 for 4- to 12-inch sizes, PC 250 for 14- to 24-inch sizes, PC 200 for 24 inches, and PC 150 for 30- to 42-inch sizes.

The use of restrained-flexible-joint ductile-iron pipe currently has two HDD installation techniques, the cartridge and assembled-line methods. The cartridge
method involves the assembly of individual sections of flexible-restrained-joint ductile-iron pipe in a secured entry and assembly pit. The pipe sections are assembled individually and then progressively pulled into the bore path for a distance equivalent to a single pipe section.

This assembly-pull process is repeated for each pipe length until the entire line is pulled through the bore path to the exit point. The cartridge method involves excavating a safe entry or assembly pit and then connecting the joints during the pulling installation one at a time in this entry pit. Generally, the invert of the entry/assembly pit is excavated to allow for the pipe to be assembled in a straight alignment prior to entering the bore path. This method is preferred in locations where there is insufficient right-of-way or easements to use the assembled-line method. The cartridge method also usually has only minimal risk to polyethylene encasement, as it is not necessary to pull significant lengths of pipe along the ground or over rollers.

The assembled-line method involves the preassembly of multiple pieces of flexible-restrained-joint ductile-iron pipe. The pull length is then pulled into the bore
path as a long pipe string. This method requires an entry ramp or pipe fabrication space the length of the drill for the pipe’s entrance into the bore path. The ramp needs to provide adequate length and grade so that any one pipe joint does not exceed the allowable joint deflection at any point prior to the pipe string entering the bore hole. This method requires significantly greater length of right-of-way and access. Special precautions are required with this method to prevent damage to any polyethylene encasement. The pipe entry angle has to be carefully controlled to keep any joint deflection within the allowable deflection limits of the pipe joints.

With both HDD installation methods, pipe sections are pulled into the bore hole with spigots ahead, allowing the drilling fluid and slurry of excavated material to flow over the smooth contour of the bells. Joints used in HDD should be boltless, flexible, and restrained. Joints with bulky glands or flanges may prevent the smooth flow of the drilling fluid over the joint and are not normally used for HDD crossings.

A commonly used joint for ductile-iron HDD applications is the Flex-Ring joint developed by American Ductile Iron Pipe in the early 1980s for purposes unrelated
to HDD. The joints are used in buried piping systems where axial thrust restraint is required for restraining bends and other fitting configurations.

Multiple Pipe Installations

Multiple product lines are frequently installed in a single drilled hole by joining them to a common pulling head for pullback. The lines should not be tied together but rather follow the pull head freely as they are pulled into the drilled hole. Installation of multiple pipelines in a single hole in this manner is fairly common. There are several manufacturers of pulling heads and duct pullers that support multiple pipe installation. Chapter 3 provides information about this type of equipment. If the installed products require separation for cathodic protection purposes, rubber spacers or thick, resilient coatings are often used. When multiple pipes are simultaneously pulled into the bore hole, higher overall loads will result due to the greater weight or buoyancy of the combination as well as an effectively amplified coefficient of friction within the hole. The amount of increase depends upon the product pipe and bore-hole diameters and can be minimized with a greater clearance within the hole.
Machine Size Selection

During the design phase of a HDD project, the preliminary selection of the type and size of drilling equipment is an important factor due to its impact on site selection and workspace requirements. Table 1-3 provides guidelines and information relating to drilling equipment. The drill-rig capabilities or specifications that are usually of importance are pullback, torque/RPM, fluid capacity, and required workspace.

Pullback Considerations

Based on the designed bore path and product-pipe characteristics, the estimated pull loads for the HDD are calculated. These estimated pull loads are used to assist in the selection of an appropriate drill rig. The pullback rating of the drill rig must be adequate for installation of the product pipe. HDD experience and engineering judgment should be used to determine how much pulling capacity is preferred for the estimated pulling loads. An often-used rule is to select a drill rig that has a pull capacity at least twice the weight of the product pipe. Knowledge of the subsurface conditions, bore-path profile, product-pipe characteristics, drilling fluids, and installation procedures (continuous or interrupted pullback) all affect the decision on how much to oversize the drill rig. The pullback and thrust capabilities of the drill rig are also limited by the anchoring and stake-down system that will resist the pullback forces.

Torque and RPM Considerations

Torque and drill-pipe rotational speed (RPM) are the drill-rig characteristics that determine possible production rates. Torque and rotational speed are a measure of the drive-spindle horsepower, delivered through the drill string, available at the drill bit or reamer. This is not the case when auxiliary power is used, such as a down-hole mud motor. The basic equation for horsepower is:

\[
HP = \frac{(T \times RPM)}{5252}
\]

where:

- \( HP = \) spindle horsepower
- \( T = \) spindle torque, foot-pounds
- \( RPM = \) spindle speed

As can be seen in the above equation, torque and RPM have equal importance. Table 1-3 has typical torque and spindle-rotation speeds for different sizes of drill
rigs. Selecting the appropriate RPM for the drill rig is influenced by the style of bit or reamer being used and the geological formation being drilled. Spindle drives are available with selectable range gear reducers or variable displacement motors. For the range gear reducers the horsepower must be calculated for one gear range. For the variable displacement motors the horsepower is calculated at one displacement string. Using the drill rig’s maximum torque at maximum RPM would significantly overestimate the rig’s capability. The correct numbers to utilize come from the drill rig’s specification sheets or are obtained from the manufacturer.

Fluid Capacity
Selecting a drill rig with an adequate fluid capacity is a key factor for supporting the production rate and avoiding stuck drill-pipe conditions. It is also important to properly match the fluid mixing and cleaning equipment with the drill-rig fluid capacity. If the mixing and cleaning equipment is undersized, the drill rig cannot reach optimum production rates because the drilled solids cannot be pumped out of the bore hole and cleaned as fast as the drill is capable of advancing. Likewise, a smaller drill rig can be used for rock drilling with a down-hole motor if an auxiliary pump and recycling system is used to enhance the fluid handling capability.

Required Workspace
While selecting a larger class of drill rig may seem appropriate, you need to consider the available workspace as well as operating costs. The proper method is to balance the required power, pullback, torque, and fluid handling capacity with the drill rig that can do the HDD crossing reliably. The rig should be capable of doing most of the anticipated jobs without reaching the limits of the drill system’s capabilities. The best drill system will perform the job while staying well within its limits. When selecting a drill system that is pushing its capabilities, mechanical problems are often encountered, and frequently the equipment will fail to complete the HDD. There are significant overlaps between the machine size categories. Mid-size rigs may be used for small-diameter product pipes and short bore lengths if the workspace is adequate. Many experienced contractors can use a mid-size rig to bore large-diameter pipes for longer lengths instead of stepping up to a large rig. In these cases the production rate may be slower, but the lower operating costs could very well offset it.

Other Considerations
There are many other potential site-specific considerations that may need to be taken into account during the design phase. State and local regulations, the local
environment, local residents, and local regulatory officials all may have a significant impact on the HDD project.

**Noise**

Noise is often an area of concern in congested urban areas. Many local areas do not have noise ordinances that establish limits such as maximum decibel levels. In fact, there does not seem to be any consensus on what level of noise is a problem. If the regulatory agency has noise-control provisions, the contractor may use the manufacturer’s specifications for the equipment and/or measure noise levels at various distances. Based on the data, noise-abatement equipment can be used as necessary to meet the restrictions.

**Water Sources**

Drilling fluids are a critical part of the HDD process and are dependent on a reliable and suitable water source. Clean, potable water is preferred. However, if poor-quality water has to be used, it should be treated to reduce any levels of objectionable materials. Low or high pH, salt water, and hard water are all generally unsuited for HDD operations unless properly treated. Drilling-fluid additives are available to help reduce the problems associated with poor water quality.

**Drilling-Fluid Cleanup**

It should be expected that some drilling fluid and slurry will escape from the drill pits, and inadvertent returns are also common. These types of spills are normally small and can be easily managed with proper planning. There are a variety of materials and methods available for containing and cleanup of these spills. Hay bales, silt fences, and earth berms are typically used to contain spills. They can be cleaned up by hand or with vacuum trucks. The need for vacuum trucks depends on the environmental sensitivity and the size of the bore.

**Historical, Cultural, and Habitat Issues**

The National Historic Preservation Act defines the criteria used to identify historical and cultural resources. Any site on the National Register of Historic Places can have no negative impact from construction activities. For many HDD projects, especially in rural areas, it is a good idea to check the Register to determine if any such resources are in the project area. If any are identified, the property can be
modified in the early stages to avoid any conflicts. However, if such features are identified after the project has started, all work must stop and the authorities notified. Fish and wildlife habitats are sensitive in all states. The use of HDD technology favors these areas because of less surface disruption. However, HDD projects can be adversely impacted if sensitive habitat issues are not identified before construction activities begin.

Chapter 4 Footnotes

HDD Design
5.1 Installation Basics

All HDD installation work should be performed according to the design documents and in accordance with any permit agency requirements. Before beginning construction activities the HDD contractor should become familiar with the work area and the technical requirements of the project plans. The project limits and controls should be identified by marking or staking prior to any construction to indicate the HDD entry and exit locations and the proposed HDD alignment, using no greater than 50-foot intervals. The desired location for the entry and exit points should be established after the geotechnical and topographical surveys. When choosing the relative locations of the entry and exit points, it is important to note that steering precision and drilling effectiveness are greater close to the drilling rig. Where possible, the entry point should be located close to anticipated adverse subsurface conditions.

Regardless of the planning effort, sometimes it is not possible to fit all the required HDD drilling and support equipment at the drill rig launch area. This limitation can be overcome by locating nonessential tools, parts, equipment, and supplies offsite and delivering them to the work area as needed. While this approach is frequently used, it usually results in reduced project efficiency, which means higher project costs. It is important for a HDD project’s success that the planners try to provide adequate workspace. It is also important that the bidder or contractor confirm that the workspace is acceptable for the plans and the equipment they are intending to use. If not, alternatives need to be developed to provide the required workspace.
The owner, engineer, and contractor share the responsibility to confirm that the HDD project can be successfully completed in the approved time frame. Schedule constraints in the contract documents, such as work days and work hours allowed, must be reasonable and allow sufficient time to meet the project timeline. The driller must schedule the HDD operation to be compatible with the constraints and meet the project timeline. While drilling scheduling is often thought of as an obvious function, more than one HDD project has run into difficulties due to poor scheduling. Often a pullback operation is interrupted only to find the pipe stuck the next morning. The chance of this type of problem increases with larger diameter pipes and longer HDD distances. There are two good rules to follow: do not start the pullback unless it can be completed without interruption, and once the pullback has started, do not stop until it is completed.

5.2 Work Plan

Establishing a work plan is an important function of a HDD project. The work plan should identify:

- What is to be done
- When it is to be done
- The cost
- Who will do it

Table 5-1 is an example of a project management format that is often used in setting up a simple HDD project, and Table 5-2 is an example for a major HDD project.

The work plan should contain a task outline. A good task outline consists of a brief summary of the scope of work required to complete the project described in the contract. The following can be used to evaluate the suitability of a task outline:

1. Does it contain all the deliverables required by the contract?
2. Can the task outline be used to establish the project schedule?
3. Can the task outline be used to establish the project budget?

<table>
<thead>
<tr>
<th>Task Identification</th>
<th>Responsibility</th>
<th>Budget/Hours</th>
<th>Target Date</th>
<th>Actual Date</th>
</tr>
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</tr>
</tbody>
</table>
4. Does each item meet the criteria for inclusion in the task outline: scope, duration, and level of effort?
5. Will the task require revision only if the contract is modified?

The following is a sample task outline:

- Research/walkdown
- Preliminary design
- Preliminary plans
- Permit preparation
- ROW work
- Preparation of technical specifications
- Bid plans and specifications
- Final design
- Final plans
- Project management

Based on the task outline, prepare a milestone chart and a schedule for the project.
5.3 Drilling Fluid System

For HDD construction the primary impact on the environment revolves around the use of drilling fluids. Many regulatory problems result from a misunderstanding of the effects of drilling fluids. Informing the regulatory agencies about the purpose and composition of HDD drilling fluids is important for many successful HDD projects.

For many HDD projects the drilling fluid system comprises a substantial portion of the HDD equipment and cost. The system is composed of both the equipment and the drilling fluids. The proper selection of the equipment and fluids can be a major factor in the project’s success. Drilling-fluid systems may consist of mixing systems, holding tanks, and cleaning systems. Mixing systems are used to mix the drilling-fluid additives with water to make a mixture that is suitable for the specific HDD conditions. Generally the drill rig should have holding tanks with enough volume to provide at least 15 minutes of full pumping capacity. The longer the bore, the higher the fluid requirements and the larger the storage should be. The hopper allows for faster mixing and hydration of the additives. Separate tanks for

![FIGURE 5-1 HDD Drilling Fluid System](image-url)
mixing and storage are necessary to avoid delays in mixing water and hydrating additives. Cleaning systems are used to remove the cuttings and recycle the drilling fluids. In urban and environmentally sensitive areas a vacuum truck is required to contain the drilling fluids.

An effective drilling-fluid system saves on water, additives, and disposal costs. It also reduces costs on drills that use mud motors. When cleaning drilling fluid for reuse, a mud balance is required to measure the density of the fluid. If the fine solids in the fluid exceed the ability of the fluid to suspend cuttings in the bore hole, the fluid must either be disposed of and replaced with a new fluid or cleaned to reduce the weight. The drilling fluid weight should be kept below 9 pounds per gallon for small to medium-size systems.

If neutral pH water is not available at the HDD site, a water truck will be required to deliver water to the site. Soda ash can also be used to adjust the pH of the water before filling the mixing tanks. The water truck should not be used for any other fluid or additives. The presence of solids in the water may cause problems with the mud pump and can plug the downhole water source.
A pit pump is an essential item if a cleaner is used. To increase the pump life, the pump should be suspended above the bottom of the recovery pit to minimize the solids being pumped. A second smaller pit can be excavated beside the entry or exit pit to allow most of the solids returning from the bore hole to settle in the first pit, with the overflow going to the second pit.

Drilling Fluids

There is much mystery surrounding the topic of drilling fluids. Drilling fluids perform the primary functions of enhancing the bit cutting, suspending the cuttings, removing the cuttings from the bore hole, stabilizing the hole, preventing loss of the drilling fluid, cooling the bit, reamer, and tracking sonde, reducing pipe to borehole friction, and providing lateral support for the pipe.
Drilling fluids also perform the secondary functions of preventing soil swelling, controlling the formation pressure, and minimizing wear and corrosion of the drill equipment. The key point to remember is that the essential function of all drilling fluids is to aid in the drilling process.

The main component of any drilling fluid is water. In some soils, water can be the only component. However, in many instances the water by itself does not do the required job. In order for water to perform the functions previously listed, it is often necessary to modify its properties by adding a viscosifier. The viscosifier almost exclusively used for HDD applications is naturally occurring clay in the form of bentonite. The water is treated with drilling-fluid additives such as bentonite, polymers, surfactants, wetting agents, or a combination. There is no one universal or ideal drilling fluid that meets all the possible requirements for HDD applications. The best drilling fluid for the application depends on many factors, such as soil type and conditions, composition of the water, site conditions, drilling application, and drill equipment. Deciding which additive to use involves matching the additive or additives to these factors. Tables 5-3 and 5-4 provide some application guidelines for drilling fluids.

**Additives**

*Bentonite.* Bentonite is a natural clay mineral mined in Wyoming. It swells and forms a mud when mixed with water. It provides high lubrication and low viscosity and is environmentally safe. Bentonite is usually mixed with water in a proportion of 2 to 4 percent per volume. It suspends the cuttings in the bore hole and creates a low permeability zone around the edge of the bore (the filter cake).

**Polymers**

Polymers are often used in drilling fluids to improve the properties of the bentonite. This improvement typically involves increasing the yield. The polymers reduce the amount of dry bentonite required to produce a given amount of drilling fluid. When used in drilling fluids, Wyoming bentonite yields in excess of 85 barrels per ton of material. The addition of polymers to produce high-yield bentonite can increase the yield to 200 barrels per ton of material. Polymers are long-chain molecules consisting of many simple molecules linked together. They offer a clay-free drilling fluid that is nontoxic. There are a variety of polymer types that are often used in water-well drilling. Polymers are added to achieve specific functions such as water swelling and gel strength.

**Surfactants**

Surfactants, or soaps, are wetting agents that are used to break clay water bonds and disperse clay particles to stop or break up clumps. Surfactants are usually used in sticky clays.
### TABLE 5-3  
**Applications of Bentonite-Based Drilling Fluids** *(Courtesy of DCCA)*

<table>
<thead>
<tr>
<th>BAROID DRILLING FLUIDS</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore Gel</td>
<td>Specially blended system using high yielding Wyoming sodium bentonite. When mixed with fresh water, develops an easy to pump slurry with desirable properties for HDD drilling.</td>
</tr>
<tr>
<td>Quick-Gel</td>
<td>Viscosifier and gallant. Easy to mix in fresh water, premium grade, exceptional high yielding Wyoming sodium bentonite. Provides excellent rheological properties.</td>
</tr>
<tr>
<td>Hydraul-EZ</td>
<td>Can stabilize bore and return cuttings. It is easy on pumps and easy to mix.</td>
</tr>
</tbody>
</table>

**CETCO**

<table>
<thead>
<tr>
<th>CROSS TECH</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross-Gel</td>
<td>API 90 bbl yield sodium bentonite for freshwater drilling. Increases viscosity and controls filtration water base fluids.</td>
</tr>
<tr>
<td>Cross-Thick</td>
<td>Extra high yield 220 bbl sodium bentonite for freshwater drilling. Provides maximum borehold integrity in unstable geologic formations.</td>
</tr>
<tr>
<td>Hydraul-EZ</td>
<td>High yield 220-mesh sodium bentonite clay with a special dry polymer additive. It is designed to maintain borehold integrity in unstable geologic formations.</td>
</tr>
</tbody>
</table>

**FEDERAL SUMMIT DRILLING FLUIDS**

| MAX GEL | A 220+ barrel yield bentonite with extremely low sand content. Its finer grind allows it to mix easier and yield quicker than most other bentonites. |
| Smooth Bore | A multi-purpose, one sack HDD system. Five components are blended together to provide for a wide range of drilling conditions. |

**KEM-TRON**

| Poly Kem EZT | Liquid polymer and drilling fluid additive for use in HDD applications along with bentonite or as a substitute. Excellent for clear water drilling, for water well drilling, and exploration bores. Has excellent borehold stabilization properties and prevents clay from swelling. Improves cutting transport in air foam injection. |
| Poly Kem D   | Dry polymer drilling fluids additive. Excellent borehold properties and can be used to enhance or substitute bentonite properties. |
| Poly Seal    | Water absorbing polymer sealant for preventing loss of drilling fluids to porous unconsolidated formations or through cracks/crevices. Polymer when pumped down to area of loss circulation quickly settles and seals formation due to its swelling properties. Swells times its volume |

The following is a list of some commonly used drilling fluid terms:

1. **Viscosity** is the fluid resistance to flow. While the viscosity measurements are important in HDD, they are not as important as gel strength and filtration. However, high viscosity may be a byproduct of these properties. Viscosity is
### 5.3 Drilling Fluid System

**TABLE 5-3** (Continued)

<table>
<thead>
<tr>
<th>Product</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kem X</td>
<td>Dry biopolymer drilling fluid additive to generate high viscosity. Excellent bentonite substitute. Super properties for hole cleaning and suspension, excellent for sand, cobble, and rock drilling.</td>
</tr>
<tr>
<td>Kem Det</td>
<td>Drilling detergent with inhibiting properties to reduce torque when drilling in swelling clays. Keeping the drill bit clean aids in preventing bit balling.</td>
</tr>
<tr>
<td>Ken Thin Super</td>
<td>Liquid thinner used to control viscosity of drilling fluids in high solids and viscosity fluids</td>
</tr>
<tr>
<td>Kem Pak ULV</td>
<td>Modified polymer imparts viscosity and controls water loss properties of drilling fluid, increased borehole stability, and tighter filter cake.</td>
</tr>
</tbody>
</table>

**PARCHEM**

<table>
<thead>
<tr>
<th>Product</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bore Flow</td>
<td>A one-sack system of premium Wyoming bentonite with additives for reducing fluid loss control. NSF approved.</td>
</tr>
<tr>
<td>Pargel 220</td>
<td>A high yield 220bbl/ton NSF approved Wyoming bentonite used for HDD.</td>
</tr>
<tr>
<td>Salt Gel</td>
<td>An attapulgite clay used where chlorides exceed the limitations of sodium bentonite performance ranges.</td>
</tr>
</tbody>
</table>

**POLYMER DRILLING SYSTEMS**

<table>
<thead>
<tr>
<th>Product</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>High Yield</td>
<td>Specially modified for water-well drilling or wherever a minimum 220 bbl yield is required. Mixes rapidly for quick hydration and carries cuttings in mud with lower soil content.</td>
</tr>
<tr>
<td>Extra High Yield</td>
<td>High performance Wyoming bentonite for fresh water fluids. Offers fast mixing, low solids, consistent performance in all boring operations. NFS Certified and environmentally safe.</td>
</tr>
<tr>
<td>SW-101</td>
<td>Unique modified Wyoming bentonite that will not fall apart in brackish or seawater conditions. SW-101 is the only sodium bentonite drilling fluid, which can be mixed with seawater. Imparts excellent fluid loss control and hole cleaning ability.</td>
</tr>
<tr>
<td>Tru-Bore</td>
<td>High performance one-bag mix for building viscosity, controlling fluid loss, and increasing rig performance. Uniquely, yields in excess of 240 barrels. Environmentally safe and NSF Certified</td>
</tr>
</tbody>
</table>

defined as resistance to flow; it creates pipe friction. In HDD applications the objective is to maintain the fluid flow. This is why it is more important to obtain gel strength, yield, and filtration control rather than simply to raise the viscosity by adding bentonite.

2. Gel strength is a measure of the electrical attractive forces within the drilling fluid under static conditions. The weak static forces that produce gel strength are related to the yield point. However, gel strength is destroyed once drilling-fluid flow is started. As gel strength increases, the potential for progressive gel exists. Progressive gel has a direct impact on the ability to break circulation once the drilling fluid or slurry has set for a period of time. This
TABLE 5-4 Applications of Polymer-Based Drilling Fluids (Courtesy of DCCA)

<table>
<thead>
<tr>
<th>BAROID DRILLING FLUIDS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bio-Bore</strong></td>
<td>A polymer-based system that provides a clay-free biodegradable drilling fluid in situations where the use of clay-based fluids are restricted.</td>
</tr>
<tr>
<td><strong>Diamond Seal</strong></td>
<td>A water-swellable, not water-soluble, 100 percent crystalline synthetic polymer. Absorbs hundred of times its weight in water. It is used primarily as a loss circulation material in HDD.</td>
</tr>
<tr>
<td><strong>EZ-Mud Plus</strong></td>
<td>A liquid polymer emulsion used as a borehole-stabilizing agent to prevent active shale and clay from swelling and sloughing. May be added to bentonite slurries to improve cuttings carrying capacity and to air foam injection mixtures to upgrade all properties, including foam stability and cuttings carrying capacity.</td>
</tr>
<tr>
<td><strong>No-Sag</strong></td>
<td>A free flowing biopolymer when added to a bentonite-based drilling fluid provides increased gel strength, resulting in superior suspension of coarse drill cuttings, sand, and gravel. Can be used with fresh or brackish water slurries.</td>
</tr>
<tr>
<td><strong>Poly-Bore</strong></td>
<td>Soluble fresh water, easy mixing, 100 percent dry granular polymer. Provides a clear, solids-free, viscous, clay-free, borehole-stabilizing fluid.</td>
</tr>
<tr>
<td><strong>Quik-Trol</strong></td>
<td>A modified natural cellulose polymer. Provides filtration controlled clay stability in bentonite-based fresh water drilling and boring fluids.</td>
</tr>
<tr>
<td><strong>PureGold</strong></td>
<td>For drilling operations where clay-based drilling fluids are restricted and a biodegradable drilling fluid is recommended</td>
</tr>
<tr>
<td><strong>Clean Drill</strong></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CETCO</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Cross-Lube</strong></td>
<td>Used to reduce bit-balling, clay sticking to drill pipe and downhole tools. Reduced torque and drag to improve temperature stability.</td>
</tr>
<tr>
<td><strong>Cross-Vis</strong></td>
<td>Multi-functional, non-fermenting polymer for improved viscosity, fluid loss control, bit lubrication, and shale stabilization/inhibition.</td>
</tr>
<tr>
<td><strong>Rel-Pac Dry Polymer</strong></td>
<td>Designed for building low solids drilling fluid with increased borehole stability and assisting in forming a thinner, less permeable filter cake.</td>
</tr>
<tr>
<td><strong>Super Pac</strong></td>
<td>Designed to be added to drilling fluids for increasing viscosity for better cuttings transport and suspension, minimizing fluid loss to the formation.</td>
</tr>
<tr>
<td><strong>Liquid Polymer</strong></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>FEDERAL SUMMIT DRILLING FLUIDS</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Enviro-Bore</strong></td>
<td>A starch-based product that provides excellent viscosity and hole cleaning, but breaks down quickly to allow for permeable formations.</td>
</tr>
<tr>
<td><strong>FSF 1500 &amp; 1800</strong></td>
<td>Polymers that boost viscosity, lubricity, and improve general rheology of the drilling slurry. Formulated to resist settling out in a pail</td>
</tr>
<tr>
<td><strong>FSF Liquid PAC Plus</strong></td>
<td>An additive that provides water-loss control, clay swelling inhibition, and boosts overall fluid viscosity and performance.</td>
</tr>
<tr>
<td><strong>FSF Super VIS</strong></td>
<td>An additive that dramatically improves the suspension and hole cleaning performance of your drilling slurry. Especially effective in sand, cobble, gravel, rock.</td>
</tr>
</tbody>
</table>
### TABLE 5-4 (Continued)

<table>
<thead>
<tr>
<th>Product</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Super PAC</td>
<td>An additive that provides water loss control, clay swelling inhibitions and boosts overall fluid viscosity and performance.</td>
</tr>
<tr>
<td><strong>PARCHEM</strong></td>
<td></td>
</tr>
<tr>
<td>Enviromud</td>
<td>A clay-free polymer-base biodegradable system primarily used in environmental remediation installations or where bentonite-based fluids are restricted.</td>
</tr>
<tr>
<td>Mud Up</td>
<td>A phpa polymer viscosifier for addition to a bentonite system offering improved viscosity and lubrication qualities. Mud Up can be used as a viscosifier in a clear water system, is biodegradable or can be rapidly broken back</td>
</tr>
<tr>
<td>Mud Up</td>
<td>An easy mixing dry granular polymer. Provides a clear solid free, viscous, clay free, borehole stabilizing fluid for use in HDD applications. Can also be used in bentonite slurry like the regular liquid Mud Up.</td>
</tr>
<tr>
<td>Xanvis</td>
<td>A biopolymer when added to a bentonite-based drilling fluid provides high gel strength, resulting in vastly improved suspension of large drill cuttings, sand and gravel. Xanvis is effective with or brackish make-up water.</td>
</tr>
<tr>
<td>Envis</td>
<td>When added to bentonite slurry, produces high fragile gels for superior suspension and carrying capacity of sand, gravel, and rock cuttings from the borehole. Easy to pump, improves hole stability, and reduces the chances of loss circulation.</td>
</tr>
<tr>
<td>Staflo</td>
<td>A polyanionic cellulose polymer or pac material used for reducing fluid loss and improving the filter cake and overall quality of a bentonite system.</td>
</tr>
<tr>
<td><strong>POLYMER DRILLING SYSTEMS</strong></td>
<td></td>
</tr>
<tr>
<td>Super Mud</td>
<td>Liquid polymer emulsion primarily used as viscosifying agent and as a soil stablizer to prevent sloughing and/or collapse of a borehole.</td>
</tr>
<tr>
<td><strong>WYO-BEN, INC</strong></td>
<td></td>
</tr>
<tr>
<td>Borzan</td>
<td>True biopolymer developed for environmental or other specialized applications where bentonite-based drilling fluids may be undesirable. Its highly concentrated formula allows for significantly lower application rates and lower cost per gallon of fluids.</td>
</tr>
<tr>
<td>Kwik-Vis “D”</td>
<td>A highly concentrated dry polymer viscosifier for use in all types of boring and trenching applications. It disperses quickly and builds viscosity rapidly. Kwik-Vis “D” promotes excellent gel-strengths and provides superior lubricity.</td>
</tr>
<tr>
<td>Uni-Drill</td>
<td>Advanced polymer for conducting drilling fluids to control fluid loss, shield troublesome clays, and maintain hole control. It mixes rapidly and promotes a thin tough filter cake, which reduces rotational torque and pullback pressures. Non-toxic and environmentally compatible. Extended shelf life and pourable in sub-zero temperatures.</td>
</tr>
<tr>
<td>Wyo-Vis</td>
<td>A PHPA polymer for building viscosity fast, Wyo-Vis also shield clays and promotes lubricity. Can be mixed with bentonite-based drilling fluids or used as a standalone polymer drilling fluid.</td>
</tr>
</tbody>
</table>
increase in gel strength requires higher initial pressure to move the fluid or slurry. If this pressure is high enough, loss of circulation or frac-out may occur. Adequate gel strength must be maintained to suspend the drilled particles when the fluid is not flowing.

3. Fluid loss is the measurement of the free water (filtrate) passing from the drilling fluid into the formation. It should not be confused with whole mud loss to the formation (loss circulation).

4. Fluid density is the weight of a gallon of drilling fluid. A typical mud weight for a clean bentonite-polymer HDD drilling fluid is approximately 8.5 pounds per gallon, or 3 percent solids by weight. Any additional weight is due to active or inactive solids from the bore hole.

5. Filter cake is extremely important in sand because it acts as a sealant and helps maintain the integrity of the bore hole. A good filter cake cannot be obtained without an acceptable water loss. The filter cake smears the clays on the bore-hole wall to prevent fluid loss into the formation. The suspended particles in the drilling fluid are deposited on the bore-hole walls. This deposit, called filter cake, is an indicator of bore-hole integrity.

6. Lubricity is the relative measure of the fluid lubrication. It is the capacity of the fluid for reducing friction.

7. Sand content is the percent of sand particles in the drilling fluid.

Soil Conditions

For HDD purposes there are two broad soil types: nonreactive, which consists of sand, silt, and gravel; and reactive, which consists of clay and shale. For nonreactive soils and rock the best drilling fluid to use is bentonite (clay)-based. The bentonite will assist with filtration control, cutting suspension and removal of the slurry, and supporting the bore hole. For reactive soils and rock, use polymer-based drilling fluids. This will slow down swelling, clean the drill bit, and help with the soil suspension and removal.

In drilling sand and gravel, the fluid should do two things. First, it should be able to stay in the hole. Water by itself will not perform that function, because it flows through sand. However, bentonite, when thoroughly mixed in water, breaks down into small particles called platelets. These flat platelike particles are quite small. If you mix 1 cubic inch of high-quality sodium bentonite until it is broken down to its smallest dimension (the platelet), you have enough surface area to cover 66 football fields. Clearly you can see why quality mixing equipment is so necessary. When pumping bentonite fluid into the hole under pressure, the fluid, just like water, wants to flow through the sand or gravel. However, in this case the bentonite platelets start to plaster or shingle off the wall of the bore hole and form a filter cake that cuts off the flow of fluid into the surrounding sand or gravel. The water phase
of the fluid that does filter through this filter cake is referred to as filtrate. The filter-cake quality can be improved while reducing the amount of filtrate going into the surrounding soil by one of two methods. One is to add more bentonite; the other is to use certain polymers in conjunction with the bentonite to “tighten” the filter cake. It is usually more desirable to use a bentonite/polymer system because the end result is a fluid that is easier to pump. In this case the polymer enhances the performance of the bentonite. This is not a polymer system; polymer by itself does not have the necessary beneficial solids to form a filter cake.

The second important function that the drilling fluid performs in sand or gravel is to provide suspension characteristics or gel strengths. The bit or reamer are cutting or drilling tools. However, these tools serve an important secondary function; they are also responsible for mixing the soils they are cutting with the fluid into flowable slurry. The fluid has to be able to support, suspend, and carry these drilled spoils (cuttings). If the fluid does not have the ability to suspend the drilled material, the material is going to quickly pack off around the drill rods or, more dangerously, around the product line. Bentonite provides the carrying capacity (gel strength) required to support this material. The term “viscosity” is often used to describe the thickness of a drilling fluid. The viscosity is the number of seconds that it takes for 1 quart of fluid to flow through a Marsh viscosity funnel. The problem is that viscosity only indicates the thickness of a fluid. You can have a thick fluid (high viscosity) that has low carrying capacity (gel strength). In this case gel strength becomes much more important than viscosity. Water by itself has low viscosity and no gel strength. Polymers by themselves can give rather high viscosity but low gel strength. Bentonite, on the other hand, can give both viscosity and gel strength.

Usually at least 30 to 35 pounds of high-quality bentonite per 100 gallons of water is required before any margin of safety is achieved in sand or gravel. Sometimes as much as 50 pounds per 100 gallons will be needed. Sands and gravels can pose significant problems. There should be enough margin of safety to be successful.

After ensuring that the fluid will stay in the bore hole (filter cake and filtrate) and have good carrying capacity (gel strength), circulation is the next question to be addressed. When the slurry spoils are flowing out of the bore hole either from the exit or entry side, there is an open bore path. When you have an open bore path, the product pipe should not get stuck. While having a good fluid flow can create a mess, it is better than getting stuck a good part of the time. Having good slurry flow on both the bore and the ream is highly recommended.

**Quantity Estimating Calculations**

Calculating drilling-fluid quantity estimates that will be used during a HDD installation are important in determining the impact of drilling activities. Calculation of quantities consumed is performed by considering each phase of the HDD while
making certain assumptions. Equations for calculating estimated drilling fluid/slurry quantities are provided below.

Pilot Hole Drilling

The total volume, \( V_{\text{pilot hole}} \), in barrels of drilling fluid consumed (not available for recirculation) during pilot-hole drilling can be found using the relation:

\[
V_{\text{pilot hole}} = Q \left( \frac{L}{P_{\text{rate}}} \right) \cdot f_{\text{pump}} \cdot f_{\text{cir}} \quad \text{Equation 5-1}
\]

where:

- \( Q \) = drilling fluid flow rate, barrels per minute
- \( L \) = drilled length, feet
- \( P_{\text{rate}} \) = pilot hole production rate, feet per hour
- \( f_{\text{pump}} \) = pumping factor, minutes per hour (the actual time that the mud pump is pumping down hole)
- \( f_{\text{cir}} \) = pilot hole circulation loss factor

Reaming

The total volume, \( V_{\text{ream}} \), in barrels of drilling fluid consumed (not available for recirculation) during a single reaming pass is given by the following equation (in the event that multiple reaming passes are to be executed, \( V_{\text{ream}} \) should either be calculated for each pass or multiplied by the number of passes, depending on the accuracy required for the quantity estimate):

\[
V_{\text{ream}} = Q \left( \frac{L}{R_{\text{rate}}} \right) \cdot f_{\text{cir}} \quad \text{Equation 5-2}
\]

where:

- \( Q \) = drilling fluid flow rate, barrels per minute
- \( L \) = drilled length, feet
- \( R_{\text{rate}} \) = reaming penetration rate, feet per minute
- \( f_{\text{cir}} \) = reaming circulation loss factor
Pulling Back

The total volume, $V_{pull}$, in barrels of drilling fluid consumed (not available for re-circulation) during pull back (pipe installation) is given by:

$$V_{pull} = Q \left( \frac{L}{Pull_{rate}} \right) * f_{cir}$$  \hspace{1cm} \text{Equation 5-3}

where:
- $Q$ = drilling fluid flow rate, barrels per minute
- $L$ = drilled length, feet
- $Pull_{rate}$ = estimated pullback penetration rate, feet per minute
- $f_{cir}$ = pullback circulation loss factor

Using the above equations, the total estimated volume of drilling fluid consumed ($V_{consumed}$) is the sum of $V_{pilothole}$, $V_{ream}$, $V_{pull}$, and the fluid system line fill. The fluid system line fill is the volume of fluid remaining in the surface piping, storage tanks, and the reamed bore-hole annulus at the completion of pullback. This estimate does not consider the drilling fluids that have been discharged at the surface.

5.4 Project Contract Documents, Plans, and Specifications

The contract is important for all HDD projects. It is important that HDD contractors understand the project contract documents and technical specifications before starting any work. This will help reduce unexpected risks and delays in the project. It is very difficult to identify all the potential risks during the planning and design phase of any HDD project. The contract documents should address the risks of a failed bore due to unforeseen problems, and a shared-risk contingency plan should be developed.

The contract documents typically include the project plans, specifications, and geotechnical reports if available. These documents usually provide the scope of work, performance requirements, design criteria, quality-control procedures, measurement and payment procedures, acceptance procedures, and time schedules/constraints. The contract documents should provide guidance for the resolution of any disputes and procedures for reacting to any unplanned events once the project has started. All the parties involved in the HDD project should be familiar with the contract documents and the project.
In addition to the HDD technical specification, the contract documents should contain a plan and profile drawing of the HDD. The drawing should complement the technical specification by providing a clear presentation of the crossing design as well as the results of topographic, hydrographic, and geotechnical surveys. This drawing will be used by the contractor to produce a working profile upon which he or she must rely for downhole navigation; therefore, accurate measurements are essential. A sample plan and profile drawing for a HDD installation is presented in Figures 9-1 and 9-2.

The following sections utilize much of the previous material to provide an easy-to-follow list of many common practices, which are summarized and categorized chronologically beginning at the prequalification stage and ending with postconstruction evaluation.

Risk Mitigation

Sharing risk with the contractor can significantly reduce the average bid price on a project. This is particularly true in underground construction. Factors that should be addressed in contracts involving HDD work may include provisions for ground or water conditions that are different from what is expected for the project and a walk-away provision.

Adequate geotechnical information is invaluable in underground construction and can help to reduce the contractor’s risk. However, even with good geotechnical data, unexpected ground conditions may be encountered. These conditions can make it difficult or even impossible to complete the crossing using the HDD method. The contract should include provisions for unexpected ground conditions. Walk away provisions in the contract entitle the contractor to stop working and walkaway from the job without penalty, provided that the contractor demonstrated a diligent effort to complete the project.

Turbid water and inadvertent returns are difficult to predict and may lead to work stoppage and loss of equipment. The contract should offer a mechanism to mutually address and mitigate these problems if and when they arise. For example, contingency plans for containment and disposal of inadvertent returns can be priced as a separate bid price and agreed prior to construction.

Contractor Proposal/Bid

As part of the bid, each HDD contractor should provide the following items: construction plan, site layout plan, project schedule, communication plan, safety manual/procedures, emergency procedures, company experience record, list of subcontractors on the project, and drilling-fluid management plan.
Construction Plan

The following information should be submitted with respect to the construction plan:

- Access requirements to the site
- Type and capacity of drilling rig to be used on the project including thrust and rotary torque (The size of the drilling equipment should be adequate for the job. An industry rule of thumb is that the drilling rig’s pull/push capacity should be at least equal to twice the weight of the product to be pulled or the weight of the drilling rod in the hole, which ever is greater. It should be noted that the range of a particular rig for a particular product type can vary significantly depending on soil conditions, drill path profile [i.e., radius of curvature], and crew experience.
- Type and capacity of the mud mixing system (This is of particular importance if at least part of the bore path is suspected to consist of solid rock or the final ream has a diameter of 14 inches or greater.)
- A listing of any specialized support equipment required
- Project schedule indicating the various tasks and their expected duration
- Drawing of work site indicating the location and footprints of all equipment, location of entry and exit pits, and location of slurry containment pits
- Construction method, including diameter of pilot hole; number and size of pre-reams; use of rollers, baskets, and side booms to suspend and direct pipe during pullback; and number of sections in which product is to be installed
- Type, operating range, and degree of accuracy of tracking equipment

Drilling-Fluids Management Plan

The following information should be provided as part of the drilling-fluid management plan:

- Source of fresh water for mixing the drilling mud (Necessary approvals and permits are required for sources such as streams, rivers, ponds, or fire hydrants.)
- Method of slurry containment
- Method of recycling drilling fluid and spoils
- Method of transporting drilling fluids and spoils off the site
- Approved disposal site for drilling mud and spoils

Previous Experience

The bidder should provide the following information:

- A list of similar projects completed by the company, including name of owner, location, project environment (e.g., urban work, river crossing), product diameter, length of installation, and contact name and telephone number
• A list of key personnel assigned to the project including title, experience record, and personal references

Safety
Each bidder should submit a copy of the company safety manual, including:

• Operating procedures that comply with applicable regulations, including shoring of pits and excavations when required
• Emergency procedures that comply with applicable regulations for inadvertently boring into natural gas lines, live power cables, water mains, sewer lines, or fiberoptic cables
• Emergency evacuation plan in case of an injury

The drilling unit must be equipped with an electrical strike safety package. The package must include warning sound alarm, grounding mats, and protective gear.

Contingency Plans
The bid should include contingency plans for the following:

• A plan in case of spill (e.g., drilling fluids, hydraulic fluids), including measures to contain and clean the affected area
• A plan for the cleanup of surface seepage of drilling fluids and spoils
• Specific action(s) required to be taken in the event that the installed pipe fails the post-installation leak test

Communication Plan
The communication plan should address the following items:

• The form and frequency of communication with the owner or representative on the site
• Identification of key person(s) who will be responsible for the communication plan
• Issues to be communicated including safety, progress, and unexpected technical difficulties

Traffic Control
When required, the contractor at his or her cost shall be responsible for supplying and placing warning signing, barricades, safety lights, and flags or flag operators
as required for the protection of pedestrians and vehicle traffic. Obstruction of the roadway should be limited to off-peak hours on major roads.

**List of Subcontractors**

Subcontractors and their designated tasks should be identified. Possible tasks to performed by subcontractors include:

- Utility location
- Hydro-excavation
- Pipe suppliers
- Leak testing
- Fusion or welding
- Tie-ins to services and/or mains.
- Mud-mix disposal
- Excavation of entry/exit pits
- Surface restoration including pavement, sidewalks and lawns

**Other Considerations**

Other requirements to be addressed in the bid include permit requirements:

- Business operation or license
- Street opening (cut) permits
- Use of hydrants for water
- Permits for storage, piling, and disposal of material
- Permits for water/bentonite disposal
- Any other permits required to carry out the work

**Site Evaluation**

The HDD location should be inspected prior to commencing the project. The following should be addressed:

1. Establish whether or not there is sufficient room at the site for entrance and exit pits; HDD equipment and its safe, unimpeded operation; support vehicles; fusion machines; and single, continuous pipe pullback.
2. Establish suitability of soil conditions for HDD operations. The HDD method is ideally suited for soft subsoils such as clays and compacted sands. Subsurface soils consisting of large-grain materials like gravel, cobble, and boulders make HDD difficult to use and may damage the pipe.
3. Check the site for evidence of substructures such as manhole covers, valve box covers, meter boxes, electrical transformers, conduits or drop lines from utility poles, and pavement patches. HDD may be a suitable method in areas where the substructure density is relatively high.

Preconstruction

The following steps should be undertaken by the contractor in order to ensure a safe and efficient construction site with minimum interruption to normal everyday activities:

1. Notify owners of subsurface utilities along and on either side of the proposed drill path of the impending work through the One-Call program. All utilities along and on either side of the proposed drill path are to be located.
2. Obtain all necessary permits or authorizations to carry out construction activities near or across all such buried obstructions.
3. All utility crossings shall be exposed using a hydro-excavation, hand excavation, or another approved method to confirm depth.
4. Construction schedules should be arranged to minimize disruption.
5. The proposed drill path should be determined and documented, including its horizontal and vertical alignments, location of buried utilities, and substructures along the path.
6. Size of excavation for entrance and exit pits are to be large enough to avoid a sudden radius change of the pipe and consequent excessive deformation at these locations. Sizing the pits is a function of the pipe depth, diameter, and material. All pits must be shored as required by the relevant regulations.

Drilling Operations

The following list provides general rules of thumb related to the directional boring method as well as specific details regarding various stages along the installation process:

1. Only trained staff should be permitted to operate the drilling equipment. They should always follow the manufacturer’s operating instructions and safety practices.
2. Drilling mud pressure in the bore hole should not exceed the amount that can be supported by the overburden to prevent heaving or a hydraulic fracturing of the soil (frac-out). Always allow for a sufficient cover depth.
3. The drill-path alignment should be as straight as possible to minimize the fractional resistance during pullback and maximize the length of the pipe that can be installed during a single pull.
4. It is preferable to drill straight tangent sections before introducing a long radius curve. Under all circumstances, a minimum of one complete length of drill rod should be utilized before starting to level out the bore hole path.

5. The radius of curvature is determined by the bending characteristics of the product line.

6. The entrance angle of the drill string should be between 8 and 20 degrees, with 12 degrees considered optimal. Shallow angles may reduce the penetrating capabilities of the drilling rig, while steeper angles may result in steering difficulties, particularly in soft soils. A recommended value for the exit angle of the drill string is in the range of 5 to 10 degrees.

7. Whenever possible, HDD installation should be planned so that back reaming and pulling can be completed on the same day. It is permissible to drill the pilot hole and pre-ream, if necessary, on one day and to complete both the final ream and the pullback on the next day.

8. If a drill hole beneath a road must be abandoned, the hole should be filled with grout or bentonite to prevent future subsidence.

9. Pipe installation should be performed in a manner that minimizes overstressing and straining of the pipe. This is of particular importance in the case of polyethylene pipe.

**Equipment Setup and Site Layout**

The following are guidelines for setting up equipment on the site:

1. Sufficient space is required on the rig side to safely set up and operate the equipment. The workspace required depends on the type of rig used. A working space of similar dimensions to that on the rig side should be allocated on the pipe side, in case you need to move the rig and attempt drilling from this end of the crossing.

2. If at all possible the crossing should be planned to ensure that drilling proceeds downhill, allowing the drilling mud to remain in the hole and minimizing inadvertent return.

3. Sufficient space should be allocated to fabricate the product pipeline into one string, thus enabling the pullback to be conducted in a single continuous operation. Tie-ins of successive strings during pullback may considerably increase the risk of unsuccessful installation.

**Drilling and Back Reaming**

The following are basic requirements for this stage of the process:

1. Drilling mud should be used during drilling and back-reaming operations. Using water alone may cause the bore hole to collapse in unconsolidated
soils, while in clays the use of water may cause swelling and subsequent jamming of the product.

2. Heaving may occur when attempting to back-ream too large of a hole. This can be avoided by using several pre-reams to gradually enlarge the hole to the desired diameter.

3. A swivel should be attached to the reamer or drill rod to prevent rotational torque from being transferred to the pipe during pullback.

4. In order to prevent overstressing of the product during pullback, a weak link or breakaway pulling head may be used between the swirl and the leading end of the pipe.

5. The pilot hole must be back-reamed to accommodate free sliding of the product inside the bore hole. A rule of thumb is to have a bore hole 1.5 times the product’s outer diameter.

6. The conduit must be sealed at either end with a cap or plug to prevent water, drilling fluids, and other foreign materials from entering the pipe as it is being pulled back.

7. Pipe rollers, skates, or other protective devices should be used to prevent the edges of the pit from damaging the pipe during pullback, eliminate ground drag, and reduce pulling force and subsequent stress on the product.

8. The drilling mud in the annular region should not be removed after installation; allow it to solidify and provide support for the pipe and neighboring soil.

**Segment Jointing**

There are two requirements for this process, also known as butt fusion or welding:

1. The contractor should perform a leak test on the pipeline prior to pipe pullback.

2. A qualified welder or fusion technician should do all joining in accordance with industry standards or the pipe manufacturer’s specifications.

**Tie-Ins and Connections**

Here are some guidelines for tie-ins:

1. Trenching should be used to join sections of conduits installed by the directional boring method.

2. An additional pipe length, sufficiently long to join to the next segment, should be pulled into the entrance pit. The length of this pipe should not damage or interfere with the subsequent drilling of the next leg. The contractor should leave a minimum of 3 feet of conduit above the ground on both sides of the bore hole.
3. In the case of a PE pipe, tie-ins and connections should only be made after a suitable time period in order to allow the pipe to recover. Ideally, the pipe should be allowed to recover overnight. If this is not possible, the recovery period should be equal to at least twice the pullback time.

**Alignment and Minimum Separation**

In all cases the product should be installed to the alignment and elevations shown on the drawings within prespecified tolerances. However, tolerance values are application-dependent. For example, in a major river crossing a tolerance of 12 feet from the exit location along the drill-path centerline may be an acceptable value. However, this tolerance is not acceptable when installing a product line between manholes. Similarly, grade requirements for water force mains are significantly different than those on a gravity sewer project. It is advisable to establish tolerance limits for various applications that are acceptable from the design point of view and at the same time achievable using current tracking and steering capabilities of HDD equipment.

**Breakaway Pulling Heads**

Recent reports from several natural-gas utility companies reveal concerns regarding failure experiences on HDPE pipes installed by horizontal directional drilling. These failures were attributed to deformation of the pipe due to the use of excessive pulling force during installation. A mitigation measure adopted by some gas companies involves the use of breakaway swivels to limit the amount of force used when pulling PE products. The weak link used can be either a small-diameter pipe (but same DR) or a specially manufactured breakaway link. The latter consists of a breaking pin with a defined tensile strength incorporated in a swivel. When the strength of the pin is exceeded, it will break, causing the swivel to separate. The use of breakaway swivels is warranted particularly when installing small-diameter plastic pipes (up to 4 inches OD). Application of such devices in the installation of larger-diameter products is currently not a common practice. If the drilling equipment rated pulling capacity is less than the safe load, the use of a weak link may not be required. Exceeding the product’s elastic limit can be avoided simply by following good drilling practices, namely: regulating pulling force; regulating pulling speed, proper ream sizing, and appropriate amounts of drilling slurry fluid.

**Drilling Fluid Collection and Disposal**

The collection and handling of drilling fluids and inadvertent returns is perhaps one of the most debated topics in the HDD community in North America. On one side the industry realizes the need to keep drilling fluids out of streams, streets,
and municipal sewer lines. On the other hand, tough new regulations in some states (e.g., California) present HDD contractors with escalating expenses. Owners need to adopt an approach that addresses environmental concerns while at the same time avoiding unnecessary expenses and escalating drilling rates. The following can be used as a guideline for the development of such an approach:

1. Drilling mud and additives to be used on a particular job should be identified in the proposal and their Material Safety Data Sheets (MSDS) provided to the owner.
2. Excess drilling mud slurry should be contained in a lined pit or containment pond at exit and entry points until recycled or removed from the site. Entrance and exit pits should be of sufficient size to contain the expected return of drilling mud and spoils.
3. Methods to be used in the collection, transportation, and disposal of drilling fluids and spoils should be provided as part of the prequalification. Excess drilling fluids should be disposed of in compliance with local ordinances, regulations, and environmentally sound practices in an approved disposal site.
4. In working in an area of contaminated ground, the slurry should be tested for contamination and disposed in a manner that meets government requirements.
5. Precautions should be taken to keep drilling fluids out of streets, manholes, sanitary and storm sewers, and other drainage systems, including streams and rivers.
6. Recycling drilling fluids is an acceptable alternative to disposal.
7. The contractor should make all diligent efforts to minimize the amount of drilling fluids and cuttings spilled during the drilling operation and provide complete clean-up of all drilling-mud overflows or spills.

Site Restoration and Postconstruction Evaluation

After the project has been completed, here are the final tasks to accomplish:

1. If possible it is recommended that the pipe be inspected for damage at every excavation pit as it being pulled back and after the installation is completed.
2. All surfaces affected by the work must be restored to their preconstruction conditions. Performance criteria for restoration work are similar to these employed in traditional open excavation work.
3. Performance specifications should be developed to hold the contractor responsible for settlement/heave damage that may occur along the drill path.
4. It is recommended that an additional length of pipe that is 1 percent of the length or 5 feet, whichever is greater, be pulled through the entrance pit, exposed, and
examined for scratches, scores, cuts, or other forms of damage. If excessive damage is found, a second additional pipe length equal to the first should be pulled through the entrance pit.

5. A final leak test should be performed on the installed pipe.

6. The contractor shall provide a set of as-built drawings including both alignment and profile. Drawings should be constructed from actual field readings. Raw data should be available for submission at any time upon the owner’s request. As part of the as-built document the contractor should specify the tracking equipment used, including methods or confirmatory procedures used to ensure that the data was captured.

### 5.5 HDD Risk Identification

Potential risks that are a part of all HDD projects include a failure to complete the bore, safety of the public and workers, environmental issues, damage to surface structures, and striking other underground structures. Risk reduction is the attempt to identify potential risks during the planning and design phase so that they may be eliminated or reduced. A risk contingency plan is often used by the engineer and/or contractor to help identify the major risks and develop general plans and procedures for resolving them. Unexpected risks often occur. Risk contingency plans are a starting point for determining the best course of action to overcome the problem. The use of experienced contractors is also a benefit when encountering unexpected problems. Their resourcefulness and experience at solving HDD problems will often reduce delays and find alternative methods in order to successfully complete the HDD project.

Failure to complete the bore is often the main concern, as the project would not be attempted if the product pipe could not be installed. The following are some of the frequent problems that can result in a failed bore attempt:

1. The HDD can lose circulation by drilling through voids, highly fractured rock, a collapse of the bore hole fast, improper drilling fluids, or a migration of water. An effective drilling-fluids plan and a suitable drilling rate for the subsurface conditions around the bore are required. These are critical factors for maintaining circulation and bore-hole stability. Circulation can be lost very quickly if voids are encountered and cannot be resumed until the void is filled or the path to the void is sealed.

2. Obstructions can cause a failed bore if the drill bit, reamer, or product pipe cannot be advanced past the object. If identified during planning, the best approach is to avoid the obstacle. If the bore cannot be changed, an appropriate response can be developed before installation begins. Typical obstructions faced during HDD construction are cobbles and boulders, gravel beds, wood, bedrock, and construction debris or foundations.
3. Hydrolock is a condition that may occur when the circulation from the bore hole is lost and the subsurface formation is resistant to fracturing, resulting in a hydraulic cylinder in the bore hole. This problem is common in fine-grained rock, frozen ground, and any formation that is resistant to hydraulic fracturing.

4. Line and grade problems occur due to faulty tracking and steering or subsurface conditions that prevent or hamper the proper steering. The improper matching of the downhole tools to the subsurface conditions can also cause line and grade problems.

5. Bore hole collapse severely impacts the chances of success on any HDD project. Soft or loose soils present a high risk of collapse during HDD operations. When a bore hole collapses, there is an immediate increase in rotary torque and pressure and a decrease or loss of circulation.

6. A failure or damage to the product pipe during HDD installation can occur due to an improper ream bore hole, poor workmanship, and improper HDD design. The best approach to avoid product-pipe failures is to establish conservative design criteria and follow the pipe manufacturer’s guidelines. It is also important to make sure that the products specified in the design are actually the products delivered to the work site. Another key factor in maintaining suitable product pipe is to ensure that all weld or fusion connections are properly performed and tested.

7. Surface heave or humping is a condition that is usually a result of excess pumping of drilling fluids after a loss of circulation. This condition can quickly pressurize the formation and cause a heave at the surface. Heaving can also arise from reaming with a barrel reamer without enough depth, which can result in a displacement of soil towards the surface. Pulling the reamer or product pipe through the bore hole too rapidly can also result in a surface heave.

8. Fortunately large surface collapses are rare. Heaving or humping the surface is a far more common occurrence. Surface collapse is typically a result of a significant overexcavation above the bore hole, which can be caused by large volumes of thin drilling fluid used at high velocities, incomplete filling of the annulus with drilling fluids for a large-diameter bore near the surface, or leaks in high-pressure pipes after installation, which erode the soil above the bore hole.

Experienced and knowledgeable personnel are valuable assets in the successful completion of HDD projects. While unforeseen problems do arise, most problems encountered during HDD installation result from the decisions made during the planning and design phase or from the lack of contractor qualifications for the proposed crossing. Largely due to the rapid increase in HDD construction, the skill and experience of many HDD contractors are questionable. Many contractors are
new to the HDD field and have limited experience. This makes it all the more im-
portant that owners and engineers make an effort to ensure that the contractors are
qualified for the specific HDD project. In most cases a HDD contractor who has
experience installing small-diameter pipe or communications cable is not qualified
for a large-diameter pipeline crossing. The contract documents and technical spec-
fications are an important part of most HDD projects. A key part of the HDD pro-
ject’s success is the contractor’s full understanding of the project requirements.
With proper planning and design and the contractor’s full understanding of the
project, the chances of a successful HDD project are greatly increased.

Chapter 5 Footnotes

6.1 General Information

Determining the loads and stresses that the product pipe will experience as a result of installation by HDD is an important process and a primary concern for the owners and engineers of the pipeline system. HDD contractors, on the other hand, are usually concerned about the loads and stresses on the drilling equipment. It is common for owners and engineers who are unfamiliar with HDD design and construction methods to rely solely on the advice of the contractor as to whether a crossing is feasible. Most HDD contractors will determine that a crossing is feasible if they can successfully bore and ream the hole and pull the product pipe back through within the specified tolerances and will not consider the pipe itself. As a result, in some HDD crossings, the product pipe did not perform as intended. It is not that the HDD contractors intentionally mislead; it is just that they usually look at the crossing from a different perspective. This is the reason why it is important for the owners and/or engineers to ensure that the HDD contractor is provided with a crossing design that is acceptable for the product pipe.

Due to the relatively recent introduction of HDD construction there is not a lot of literature on the subject of product-pipe installation loads and stresses. However, this is changing as the industry grows. A detailed manual was published in 1995 by the Pipeline Research Council International\(^1\). This manual, which will be referred to as the PRCI Manual throughout this chapter, provides detailed information and methods for determining the estimated loads and stresses that a steel product pipeline may experience as a result of HDD installation. This chapter utilizes many of the methods, procedures, and calculations provided in this manual.
The methods provided in the PRCI Manual and this chapter deal with the loads and stresses on the product pipe, not the total forces experienced by the drill rig. The installation loads experienced by the drill string and reamer are not considered because they do not impact the product pipe. Loads from the above-ground portion of the pull section are omitted because they are seldom critical to the success of an installation; if these loads should become critical, the use of pipe side assistance techniques can essentially counteract their impact. The key point is that these methods estimate the tensile force experienced by the product pipe, not the total force exerted by the drill rig. There are many variables associated with the pulling loads that may occur during HDD construction. These variables often depend on site-specific conditions and individual contractor practices. Some of the principal variables are subsurface conditions, drilling-fluid properties, bore-hole diameter and stability, and effectiveness of buoyancy control measures. The methods that follow cannot account for all the possible variables. For this reason the theoretical calculations should be used with caution by someone with some knowledge and experience in HDD design and construction.

6.2 Steel Product-Pipe Stress Analysis

When pipes are installed by HDD, they often experience high tension loads, severe bending, and external fluid pressures. Often these installation loads are more severe than the design service loads. When selecting the appropriate pipe materials for a HDD installation, the designer must consider the pipe properties as well as the bore-hole profile. These two factors should be considered together in order to choose the best material and profile so that the pipeline can be installed and operated without risk of damage. To ensure that the material and bore-hole profile are suitable for the proposed application, the installation, operational, and combined loads and stresses are analyzed.

Installation

When a pipe is installed by HDD construction, it is subjected to tension, bending, and external pressure as it is pulled through the reamed hole. The tension required to pull the product pipe into the bore hole comes from the frictional drag between the pipe and the wall of the hole, the fluidic drag as the pipe is pulled through viscous drilling fluid, and the effective weight of the pipe as it is pulled through elevation changes within the hole. Bending stress results from pulling the rigid pipe through the curved hole. The pipe will experience external pressure from the drilling fluid that may result in external hoop stress. This stress may be reduced or eliminated by filling the product pipe with a fluid of equal or greater density. The stresses and the resulting potential for pipe failure are caused by the combination
of these loads. This book and the PRCI Manual provide a method to estimate the applicable loads and stresses and help the engineer determine if the HDD design and material specifications are suitable for the proposed crossing. The following method assumes that the bore hole has been reamed, that the reamed hole is approximately 12 inches larger than the pipe outside diameter, and that the annulus between the pipe outside diameter and the reamed hole is filled with drilling fluid of a known or estimated density. This method assumes that the bore hole remains intact during installation and that no significant formation loads were exerted on the pipe during the pullback process.

**Product-Pipe Pull Loads**

Product-pipe pull loads are calculated based on an analysis of the designed bore profile or the actual pilot hole. Figure 6-1 is an example of a bore profile plotted in the vertical and horizontal planes with horizontal pipe length along the x-axis and vertical distance from the reference line along the y-axis. The entire bore path is made up of straight and/or curved sections. The bore path should comprise the fewest number of sections possible. However, the design can include as many sections as necessary to define the crossing. There are no upper or lower boundaries on the length of any straight section or the arc length of any curved section. Straight sections are ideally level but may have a very slight curvature. Sections that do not deviate beyond the bore-hole wall, for this method approximately 12 inches larger than the product pipe, can be considered straight sections. Curved sections should have one constant radius for the entire sweep of the section. The junction between a straight and a curved section is considered the start of the curve and is referred to as the point of curvature (PC). The junction where the curve ends and a straight section begins is referred to as a point of tangent (PT). Straight sections should always join curved sections, since there is no reason to divide straight sections.

The estimated pulling load is calculated as a series of straight and curved segments. The forces acting on each segment are calculated sequentially from pipe side to rig side to determine the tensile load at the end of each segment. Normal

---

**FIGURE 6-1  HDD Design Profile**

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practice is to neglect the drag forces from the above-ground portion of the product pipe. This results in the initial tension on the first segment being zero (point 1). The initial tension for each of the following segments is equal to the tension at the end of the previous segment (points 2–6). The total tensile load at the end of the pullback is the sum of the individual forces required to pull the pipe through each of the straight and curved segments in the bore hole. The axial load in the product pipe at the end of the pullback process is distributed along the entire product-pipe length. The total axial load is made up of the combined axial loads occurring in each section of the hole due to the friction between the product pipe and the bore-hole wall plus the dynamic fluid friction needed to make the pipe move through the drilling mud. Because the bore-hole wall and pipe frictional components are caused by the shape of the bore hole, the axial tension in the product pipe at any point in the bore path can be considered to be confined to that location in the bore hole, regardless of which portion of the product pipe is passing that point. This allows for worst-case loads anywhere in the bore hole to be calculated only for the case in which the pipe has just emerged from the hole.

The coefficients used in the calculation of frictional and fluidic drag are usually assumed. When the PRCI method was first developed, values for these coefficients were recommendations based on available field data. These coefficients were intentionally incorporated as variables, allowing them to be modified as better information became available. Since the development of the PRCI method, calculated pulling loads have been compared against actual field pulling loads on numerous HDD installations. In most cases the calculated pull loads compared favorably with recorded rig loads. However, in many cases the loads estimated by the PRCI method exceeded the rig loads as the pullback neared completion. This is actually an expected result due to the conservative nature of the PRCI method. Sometimes it is necessary to refine the input parameters used in the following calculations to more closely match the calculated and actual loads. Jeffrey S. Puckett, P.E., conducted an analysis of the calculated versus actual pulling loads using documentation from completed HDD installations. This analysis focused on a more accurate parameter for the fluid-drag coefficient, the input parameter with the greatest uncertainty. Based on a comparison of the calculated loads and the actual loads it was determined that using a fluid drag coefficient of 0.05 psi produced a substantially greater calculated load than actual load as pullback neared completion. After running several pulling-load calculations using different fluid-drag coefficients, it was determined that a coefficient of 0.025 psi produced closer calculated and actual data. As can be seen from the above comments, using a fluid-drag coefficient between 0.025 and 0.05 psi usually provides accurate results. The normal practice is to use 0.05 psi for most applications, since this will provide accurate yet somewhat conservative results. However, in borderline crossings or crossings where drill-rig selection is crucial, a fluid-drag coefficient of 0.025 psi may provide a more useful result.
Calculating the Pull Loads

The first step in calculating the estimated pulling loads is to develop the input data that will be used in the calculations. This data includes the product-pipe material properties, the drilling-fluid properties, and any code or design factors that are applicable. An example of the input data required for calculating estimated pulling loads is provided in Example 6-1 later in this chapter.

Defining the Bore Path

The next step is to define the bore path for the crossing. Figure 6-1 defines a typical bore path profile. The values are assigned to the variables based on the profile required to successfully cross the obstacle while reaching the required depth. The preliminary attempt at determining the values is based on the definition of the obstacle, the subsurface conditions, and the material properties of the product pipe. Using this data and the equations provided in Chapter 8, the designer can develop a combination of straight lines and curves that will cross the obstacle at the desired depth within the available overall bore length. Figure 6-2 provides an example of a designed bore path where:

\[
\begin{align*}
L_1 &= 91 \text{ feet} \\
L_{arc1} &= 126 \text{ feet} \\
L_S &= 52 \text{ feet} \\
L_{arc2} &= 126 \text{ feet} \\
L_2 &= 177 \text{ feet}
\end{align*}
\]

![FIGURE 6-2  Bore-Path Example](image-url)
In this example the total bore length is the sum of each segment for a bore-path length of 572 feet.

**Straight Sections** After defining the input data and the bore path, the calculations begin with the straight section of pipe, assuming that the pipe is pulled from the left to the right (as viewed in Figure 6-2). The modeling and calculation process must be done from the pipe side to the rig side. As stated earlier, it is usually assumed that the load at point 1 is zero. When using this assumption the first calculated load is at the end of the first straight section, or point 2. Each straight section is modeled with variables as shown in Figure 6-3.

For any straight section the tension at $T_2$ is calculated from the static force balance:

$$T_2 = T_1 + |fric| + DRAG \pm W_S \times L \times \sin \theta$$  \hspace{1cm} \text{Equation 6-1}

where:
- $T_2$ = the tension (or pull load) at the rig side of the straight section required to overcome the drag and friction in pounds
- $T_1$ = the tension (or pull load) at the pipe side of the straight section, usually assumed to be zero, in pounds
- $|fric|$ = the friction between the pipe and soil in pounds

The +/- term is (-) if $T_2$ is downhole, (+) if $T_2$ is uphole, and (0) if the hole is horizontal.

$$|fric| = W_S \times L_1 \times \cos\left(\theta \text{S} \right) \times \mu_{\text{soil}}$$  \hspace{1cm} \text{Equation 6-2}

where:
- $DRAG$ = the fluidic drag between the pipe and the drilling fluid in pounds

$$DRAG = \pi \times D \times L_1 \times \mu_{\text{fluid}}$$  \hspace{1cm} \text{Equation 6-3}
where:

\( W_S \) = the effective (submerged) weight of the pipe plus any internal contents (if filled with water) in foot-pounds

\( L_1 \) = the length of the straight section in feet

\( \pi \) = the angle of the straight section relative to the horizontal plane (zero is horizontal and 90 degrees is vertical)

\( \mu_{soil} \) = the average coefficient of friction between the pipe and soil; the recommended value is 0.21 to 0.30 (Maidla)

\( \mu_{mud} \) = the fluid-drag coefficient for steel pipe pulled through the drilling mud; the recommended value is 0.025 to 0.05

\( D \) = the outside diameter of the pipe in inches

Curved Sections Each curved section is modeled with variables as shown in Figure 6-4.

The variables that are different than those in the straight sections are:

\( R_1 \) = the radius of curvature of the curved section between points 2 and 3 in feet

\( \theta_{c1} \) = the angle of the curved section in degrees

\( \theta_1 \) = the angle from horizontal of \( T_2 \) at the right end of the section in degrees

\( \theta_2 \) = the angle from horizontal of \( T_3 \) at the left end of section in degrees

\( \theta = (\theta_1 + \theta_2)/2 \) in degrees

\( L_{arc1} = R_1 \times \theta_{c1} \) in feet

The values \( N, N_1, \) and \( N_2 \) are the contact forces at the center, right, and left points of the section. The values \( fric, fric_1, \) and \( fric_2 \) are the frictional forces at the center,
right, and left points of the section. The curved sections are modeled as three-point
beams. For the bent pipe to fit in the bore hole it must bend enough to place its cen-
ter at a point that reflects the displacement \( h \):

\[
h = R \left[ 1 - \cos \left( \frac{\theta_{el}}{2} \right) \right]
\]

Equation 6-4

This method is not completely accurate, however, since the objective is to deter-
mine the normal contact forces and then calculate the frictional forces, it is an ac-
ceptable estimation. The vertical component of the distributed weight and the arc
length of the pipe section are used to find \( N \). From Roark’s solution for elastic
beam deflection:

\[
N = \frac{T * h - W_s * \cos \left( \frac{\theta_{el}}{2} \right) * Y}{X}
\]

Equation 6-5

where:

\[
X = 3 * \frac{L_{arc}}{12} - \left( \frac{j}{2} \right) * \tanh \left( \frac{U}{2} \right)
\]

Equation 6-6

\[
Y = 18 * \left( \frac{L_{arc}}{12} \right)^2 - j^2 * \left[ 1 - \frac{1}{\cosh \left( \frac{U}{2} \right)} \right]
\]

Equation 6-7

\[
j = \left( E * \frac{I}{T} \right)^{\frac{1}{2}}
\]

Equation 6-8

\[
I = \pi * (D - t)^3 * \frac{t}{8}
\]

Equation 6-9

\[
U = \frac{L_{arc}}{j}
\]

Equation 6-10
Equations 6-5 and 6-8 both require a value for $T$, which is the average value of $T_2$ and $T_3$. This requires an iterative solution to solve for $T_3$. One method is to change the variable $T$ to an assumed average value and solve the problem until the required accuracy is obtained. The assumed average value of $T$ should be within 10 percent of the actual average of $T_2$ and $T_3$.

where the values:

$$T_{avg} = \frac{T_2 + T_3}{2}$$

and

$$\frac{T_{avg} - T_{avg, assumed}}{T_{avg, assumed}} * 100 \text{ should be with 10 percent. If not within }$$

10 percent use a new assumed value for $T_{avg}$ and solve again. Using computer programs makes this a relatively easy task. For a curved section $f_{ric}$ becomes:

$$f_{ric} = \left| N * \mu_{soil} \right|$$

Equation 6-11

The reactions at the end of the curved section are assumed to be $N/2$, and end friction forces are assumed to be $f_{ric}/2$. For positive values of $N$ (defined as downward-acting as in Figure 6-4) the bending resistance and/or buoyancy of the pipe is sufficient to require a normal force acting against the top of the hole in order for the pipe to displace downward by an amount equal to $h$. Where $N$ is negative, the submerged pipe weight is sufficient to carry the pipe to the bottom of the curved section, where an upward-acting normal force is felt at the point of contact. Regardless of the value of $N$, all friction values are positive, acting in opposition to $T_3$. The estimated forces acting along the curved path of the pipeline are added as if they were acting in a straight line. As a result $T_3$ becomes:

$$\Delta T_3 = 2 * f_{ric} + DRAG \pm W_S * L_{arc} * \sin \left( \frac{\theta_{cl}}{2} \right)$$

Equation 6-12

The load at point 3 then becomes $\Delta T_3 + T_2$ in pounds of force.

**Total Pulling Loads**

The total force (or pulling load) required to pull the pipe through the bore hole is the sum of the required force for all the straight and curved sections in the pipeline. Example 6-1 is an example of the pulling-load calculations for the HDD crossing provided in Figure 6-2.
**Pulling Load Calculation**

**Input Data:**

- $D = 6.625\text{in}$  
  Pipe outside diameter, inches
- $t = .219\text{in}$  
  Pipe wall thickness, inches
- $\text{SMYS} = 42000\text{psi}$  
  Specified yield strength of pipe, psi
- $\text{codelign factor} = 1$
- $\text{SMYS}_{\text{code}} = \text{codelign factor SMYS} = 42000\text{psi}$
- $E = 2.9 \times 10^7\text{psi}$  
  Young's Modulus
- $v = .3$  
  Poisson's ratio
- $\mu_{\text{soil}} = .3$  
  Average coefficient of friction between pipe and soil. Recommended value between .21-.3 (Macla
- $\mu_{\text{mud}} = .05\frac{\text{lbf}}{\text{in}^2}$  
  Fluid drag coefficient for steel tube pulled through bentonite mud
- $\text{mud}_{\text{wt}} = 89.76 \frac{\text{lbf}}{\text{ft}^3}$  
  Mud weight value. 12 ppg = 89.76 lb/ft$^3$
  
  $x = 12 \frac{\text{lbf}}{\text{gal}} = 89.8 \frac{\text{lbf}}{\text{ft}^3}$

$$\text{Displacemud}_{\text{weight}} = \pi \left(\frac{D}{2}\right)^2 \text{mud}_{\text{wt}}$$

$$\text{pipe}_{\text{interior,vol}} = \pi \left(\frac{D}{2} - t\right)^2$$

$$\text{pipe}_{\text{interior,vol}} = 0.2088 \frac{\text{ft}^3}{\text{ft}}$$

$$\text{Displacemud}_{\text{weight}} = 21.5 \frac{\text{lbf}}{\text{ft}}$$

$$\text{pipe}_{\text{weight}} = 10.68 \left(\frac{D}{\text{in}} - \frac{t}{\text{in}}\right) \frac{1}{\text{in}} \frac{\text{lbf}}{\text{ft}}$$

$$\text{pipe}_{\text{weight}} = 15 \frac{\text{lbf}}{\text{ft}}$$

$$W_s = \text{pipe}_{\text{weight}} - \text{Displacemud}_{\text{weight}}$$

$$W_s = -6.5 \frac{\text{lbf}}{\text{ft}}$$

Effective submerged weight per foot of the pipeline plus internal contents, lbs/ft

---

**EXAMPLE 6-1A**  HDD Pull Loads
Define the Borehole Profile:

\[ L_1 = 91\text{ft} \]
Length of straight section 1 (pipe side - exit pit)

\[ \theta_{s1} = 12\text{deg} \]
Angle in degrees from horizontal for straight section 1 (pipe side - exit pit)

\[ \theta_{c1} = 12\text{deg} \]
Angle in degrees from horizontal for curved section 1 (pipe side - exit pit)

\[ R_1 = 600\text{ft} \]
Radius of curvature of curve section 1, pipe side, feet

\[ l_{arc1} = R_1 \theta_{c1} \]
Length of curved section 1 (pipe side - exit pit)

\[ L_s = 52\text{ft} \]
Length of straight section between bends

\[ \theta_s = 0\text{deg} \]
Angle in degrees from horizontal for straight section between bends

\[ \theta_{c2} = 12\text{deg} \]
Angle in degrees from the horizontal for curved section 2 (rig side - entry pit)

\[ R_2 = 600\text{ft} \]
Radius of curvature of curve section 2, rig side, feet

\[ l_{arc2} = R_2 \theta_{c2} \]
Length of curved section 2 (rig side - entry pit)

\[ L_2 = 177\text{ft} \]
Length of straight section 2 (rig side - entry pit)

\[ \theta_{s2} = 12\text{deg} \]
Angle in degrees from horizontal for straight section 2 (rig side - entry pit)

\[ l_{total} = L_1 + l_{arc1} + L_s + l_{arc2} + L_2 \]

\[ l_{total} = 571.3\text{ft} \]

Pulling Loads

Straight Section at point 2

\[ \Delta T_2 = T_2 - T_1 \]

\[ \text{fric}_2 = \text{Ws} \cdot L_1 \cos(\theta_{s1}) \mu_{\text{soil}} \]

\[ \text{DRAG}_2 = \pi \cdot D \cdot L_1 \mu_{\text{mud}} \]

\[ |\text{fric}_2| = 173.7\text{bf} \]

\[ \text{DRAG}_2 = 1136.4\text{bf} \]

\[ \Delta T_2 = |\text{fric}_2| + \text{DRAG}_2 - \text{Ws} \cdot L_1 \sin(\theta_{s1}) \]

\[ \Delta T_2 = 1433.1\text{bf} \]

\[ T_1 = 0\text{bf} \]
Pull back as the pipe enters the drill hole.

\[ T_2 = \Delta T_2 + T_1 \]

\[ T_2 = 1433.1\text{bf} \]
Pull load at point 2

EXAMPLE 6-1B HDD Pull Loads
Curved Section at point 3

\[ T_{\text{avgassumed3}} = 2616 \text{lbf} \]

\[ h_3 = R_1 \left( 1 - \cos \left( \frac{\theta_c l}{2} \right) \right) \]

\[ h_3 = 3.3 \text{ ft} \quad I_3 = \pi (D - t)^2 \frac{t}{8} \quad I_3 = 22.6 \text{in}^4 \]

\[ j_3 = \left( \frac{E}{T_{\text{avgassumed3}}} \right)^{1/2} \]

\[ j_3 = 500.6 \text{in} \quad U_3 = \frac{I_{\text{arc1}}}{j_3} \quad U_3 = 3.0122 \]

\[ X_3 = 3 \left( \frac{L_{\text{arc1}}}{12} \right) - \left( \frac{j_3}{2} \right) \tanh \left( \frac{U_3}{2} \right) \]

\[ X_3 = 150.1 \text{in} \]

\[ Y_3 = 18 \left( \frac{L_{\text{arc1}}}{12} \right)^2 - j_3 \left( 1 - \frac{1}{\cosh \left( \frac{U_3}{2} \right)} \right) \]

\[ Y_3 = 139573.8 \text{in}^2 \]

\[ N_3 = \frac{T_{\text{avgassumed3}} h_3 - W_s \cdot \cos \left( \frac{\theta_c l}{2} \right) Y_3}{X_3} \]

\[ N_3 = 1188.3 \text{lbf} \]

\[ \Delta T_3 = T_3 - T_2 \]

\[ \text{fric}_3 = \left| N_3 \mu_{\text{soil}} \right| \quad \text{fric}_3 = 356.5 \text{lbf} \]

\[ \text{DRAG}_3 = \pi D l_{\text{arc1}} \mu_{\text{mud}} \quad \text{DRAG}_3 = 1569.3 \text{lbf} \]

\[ \Delta T_3 = 2 \left| \text{fric}_3 \right| + \text{DRAG}_3 - W_s l_{\text{arc1}} \sin \left( \frac{\theta_c l}{2} \right) \]

\[ \Delta T_3 = 2367.7 \text{lbf} \]

\[ T_3 = \Delta T_3 + T_2 \quad T_3 = 3800.8 \text{lbf} \quad \text{Pull load at point 3} \]

\[ T_{\text{avg3}} = \frac{T_3 + T_2}{2} \quad T_{\text{avg3}} = 2616.972 \text{lbf} \]
EXAMPLE 6-1D  HDD Pull Loads
HDD Stress Analysis for Steel Product Pipe

\[ N_5 = \frac{T_{\text{avg assumed}} - h_5 - Ws \cdot \cos \left( \frac{\theta_{e2}}{2} \right) \gamma_5}{X_5} \quad N_5 = 1565.4\text{bf} \]

\[ \Delta T_5 = T_5 - T_4 \]

\[ \text{fric}_5 = N_5 \mu_{\text{soil}} \quad \text{fric}_5 = 469.6\text{bf} \]

\[ \text{DRAG}_5 = \pi \cdot D \cdot L_{\text{arc2}} \mu_{\text{mud}} \quad \text{DRAG}_5 = 1569.3\text{bf} \]

\[ \Delta T_5 = 2 \cdot \left| \text{fric}_5 \right| + \text{DRAG}_5 + Ws \cdot L_{\text{arc2}} \sin \left( \frac{\theta_{e2}}{2} \right) \quad \Delta T_5 = 2423.1\text{bf} \]

\[ T_5 = \Delta T_5 + T_4 \quad T_5 = 6974.7\text{bf} \quad \text{Pull load at point 5} \]

\[ T_{\text{avg5}} = \frac{T_5 + T_4}{2} \quad T_{\text{avg5}} = 5763.2\text{bf} \]

\[ \frac{T_{\text{avg5}} - T_{\text{avg assumed5}}}{T_{\text{avg assumed5}}} \cdot 100 = 0 \quad \text{if this does not fall within the 10% limit pick new assume tension.} \]

**Straight Section at point 6**

\[ \Delta T_6 = T_6 - T_5 \]

\[ \text{fric}_6 = Ws \cdot L_2 \cdot \cos \left( \theta_{s2} \right) \mu_{\text{soil}} \quad \left| \text{fric}_6 \right| = 337.8\text{bf} \]

\[ \text{DRAG}_6 = \pi \cdot D \cdot L_2 \mu_{\text{mud}} \quad \text{DRAG}_6 = 2210.3\text{bf} \]

\[ \Delta T_6 = \left| \text{fric}_6 \right| + \text{DRAG}_6 + Ws \cdot L_2 \sin \left( \theta_{s2} \right) \quad \Delta T_6 = 2308.8\text{bf} \]

\[ T_6 = \Delta T_6 + T_5 \quad T_6 = 9283.5\text{bf} \quad \text{Pull load at point 6} \]
EXAMPLE 6-1F  HDD Pull Loads

\[ T_{\text{total}} = \Delta T_2 + \Delta T_3 + \Delta T_4 + \Delta T_5 + \Delta T_6 \]

\[ T_{\text{total}} = 9283.5 \text{lbf} \quad \text{Total pull load of the pipe} \]

Determine Maximum Pull Force, F:

\[ f_l = 0.9 \quad \text{maximum load factor} \]

\[ f_s = 1.2 \quad \text{safety factor} \]

\[ \frac{E \cdot D^2}{24R_1} \quad f_b = 13342 \text{psi} \]

\[ \text{Area} = \frac{\pi}{4} \left( D^2 - ID^2 \right) \quad \text{Area} = 4.4 \text{in}^2 \]

\[ F = \left( \frac{\text{SMYS}_{\text{code}} \cdot f_l}{f_s} \right) \quad \text{Area} \quad F = 80029.2 \text{lbf} \quad \text{maximum pull force} \]

RESULT\text{pull} = \begin{cases} 
\text{"PASS"} & \text{if } T_{\text{total}} < F \\
\text{"FAIL"} & \text{otherwise} 
\end{cases}

RESULT\text{pull} = \text{"PASS"}
Calculating the Installation Stresses

The installation stresses experienced by product pipes are often the worst-case load events that the pipe will experience over its life. As a result, the installation stresses often dictate the material properties of the product pipe. During HDD installation the worst-case stress condition is located where tensile, bending, and hoop stresses occur at the same time. Generally these are areas of tight radius bends; high tension, which is usually closer to the drill rig; and high external pressure, which is usually at the deepest point. The approach used in this book and the PRCI Manual is taken from the API Recommended Practice 2A-WSD. For this approach select a location in the drill-path profile that is suspected of being a critical stress location. The first step is to calculate the individual stresses for the tensile, bending, and hoop stresses and compare the calculated values against allowable levels for these stress states. If all are within allowable limits, the next step is to check the combined stress state. The combined stress state is compared in two interaction equations presented as unity checks. The combined stresses in the interaction equation must be less than 1.0 for the pipe to be safe from bending or hoop collapse in all regimes (plastic, elastic, and transition).

Example 6-2 is an example of the installation stress calculations for the HDD crossing provided in Figure 6-2.

Calculating Operating Loads and Stresses

Except for elastic bending, the operating loads and stresses experienced in a pipe installed by HDD are not different from those experienced by pipes installed by cut-and-cover techniques. The same methods and procedures for calculating and limiting stresses can be applied to HDD installations except for elastic bending. A pipeline installed by HDD will contain elastic bends. The pipe is not bent to fit in the drilled hole as is a pipe installed by cut and cover to fit the ditch. The pipe bending stresses imposed by HDD construction are usually not excessive. However, the bending stresses should be checked in combination with other longitudinal and hoop stresses to ensure that the allowable stress limits are not exceeded. The equations for bending and hoop stress (also provided in Example 6-2) are:

\[
stress_{\text{bending}} = \frac{(E * D)}{(24 * R)} \quad \text{Equation 6-13}
\]

\[
stress_{\text{hoop}} = \frac{(\Delta p * D)}{(2 * t)} \quad \text{Equation 6-14}
\]
6.2 Steel Product-Pipe Stress Analysis

**Pipe Stress**

*Installation Stress Analysis*

**Stress at Point 3**

**Tensile Stress**

\[
\text{stress}_{t3} = \frac{T_3}{\text{Area}} \quad \text{stress}_{t3} = 862.4\text{psi}
\]

**Allowable Tension**

allowstress\(_{t3}\) = \(0.9\cdot\text{SMYS}\)  
allowstress\(_{t3}\) = 3780psi  
Note that stress\(_{t3}\) is less than allowstress\(_{t3}\), so tension is within limits.

RESULT\(_{\text{tensile3}}\) = \[
\begin{cases} 
\text{return "PASS"} & \text{if stress}_{t3} < \text{allowstress}_{t3} \\
\text{return "FAIL"} & \text{otherwise}
\end{cases}
\]

RESULT\(_{\text{tensile3}}\) = "PASS"

**Bending Stress**

\[
\text{stress}_{b3} = \frac{E \cdot D \cdot 12}{24R_1} \quad \text{stress}_{b3} = 13342\text{psi}
\]

**Allowable Bending**

\[
a_1 = 0.75\cdot\text{SMYS}
\]

\[
b_1 = \left(0.84 - \frac{1.74\cdot\text{SMYS}\cdot D}{E\cdot t}\right) \cdot \text{SMYS}
\]

\[
c_1 = \left(0.72 - \frac{58\cdot\text{SMYS}\cdot D}{E\cdot t}\right) \cdot \text{SMYS}
\]

allowstress\(_{b3}\) = \[
\begin{cases} 
\frac{D}{t} \leq \frac{1500000\text{psi}}{\text{SMYS}} & a_1 \\
\frac{1500000\text{psi}}{\text{SMYS}} < \frac{D}{t} \leq \frac{3000000\text{psi}}{\text{SMYS}} & b_1 \\
\text{otherwise} & c_1
\end{cases}
\]

**EXAMPLE 6-2A**  Installation Stress
allowstress \( b_3 = 31500 \text{psi} \)  

Note that stress \( b_3 \) is less than allowstress \( b_3 \), so bending stress is with in limits.

\[
\text{RESULT}_{\text{bending3}} = \begin{cases} 
\text{return "PASS" if stress } b_3 < \text{allowstress } b_3, \\
\text{return "FAIL" otherwise}
\end{cases}
\]

\[
\text{RESULT}_{\text{bending3}} = \text{"PASS"}
\]

**External Hoop Stress**

\[
\text{depth}_3 = \left( \frac{L}{1} \sin \left( \frac{\theta_1}{4} \right) \right) + \left[ R_1 \left( 1 - \cos \left( \frac{\theta_1}{4} \right) \right) \right] \quad \text{depth}_3 = 32 \text{ ft}
\]

\[
\Delta p = x \text{ depth}_3 \quad \Delta p = 20 \text{psi}
\]

\[
\text{stress}_h3 = \frac{\Delta p D}{2t} \quad \text{stress}_h3 = 302 \text{psi}
\]

**Allowable Elastic Hoop Buckling**

\[
a_2 = 0.88E \left( \frac{1}{D} \right)^2 \quad b_2 = 0.45 \text{SMYS} + 0.18a_2
\]

\[
c_2 = \frac{1.31 \text{SMYS}}{1.15 + \left( \frac{\text{SMYS}}{a_2} \right)} \quad d_2 = 6.2 \text{SMYS}
\]

\[
\text{allowstress}_h3 = \begin{cases} 
\text{} a_2 \text{ if } 0.55 \text{SMYS} \geq a_2, \\
\text{} b_2 \text{ if } 0.55 \text{SMYS} < a_2 \leq 1.6 \text{SMYS}, \\
\text{} c_2 \text{ if } 1.6 \text{SMYS} < a_2 \leq 6.2 \text{SMYS}, \\
\text{} d_2 \text{ otherwise}
\end{cases}
\]

\[
\text{allowstress}_h3 = 23919.6 \text{psi}
\]

\[
\frac{\text{allowstress}_h3}{1.5} = 15946.4 \text{psi} \quad \text{Note that stress}_h3 \text{ is less than allowstress}_h3 / 1.5 so external hoop stress is with allowable limits for buckling.}
\]
HDD Stress Analysis for Steel Product Pipe

6.2 Steel Product-Pipe Stress Analysis

EXAMPLE 6-2C  Installation Stress

RESULT_{ hoop3 } = \begin{cases} 
  \text{"PASS"} & \text{if } \text{stress}_{h3} < \frac{\text{allowstress}_{h3}}{1.5} \\
  \text{"FAIL"} & \text{otherwise} 
\end{cases}

RESULT_{ hoop3 } = \text{"PASS"}

Combined load interactions at point 3

Since all individual stress checks are acceptable, check combined loads.

Tensile and Bending

\[
tensile_{bend3} = \frac{\text{stress}_{c3}}{0.9 \cdot \text{SMYS}} + \left( \frac{\text{stress}_{h3}}{\text{allowstress}_{h3}} \right) \\
tensile_{bend3} = 0.446
\]

RESULT_{tb3} = \begin{cases} 
  \text{"PASS"} & \text{if } tensile_{bend3} < 1 \\
  \text{"FAIL"} & \text{otherwise} 
\end{cases}

RESULT_{tb3} = \text{"PASS"}

Tensile, Bending and External Hoop

\[
A^2 + B^2 + 2 \cdot v \cdot |A| \cdot B \leq 1
\]

\[
\Lambda = \left( \text{stress}_{c3} + \text{stress}_{h3} - 0.5 \cdot \text{stress}_{h3} \right) \frac{1.25}{\text{SMYS}} \\
\Lambda = 0.42
\]

\[
B = \frac{1.5 \cdot \text{stress}_{h3}}{\text{allowstress}_{h3}} \\
B = 0.019
\]

\[
tensile_{bend.hoop3} = A^2 + B^2 + 2 \cdot v \cdot |A| \cdot B \\
tensile_{bend.hoop3} = 0.18
\]
EXAMPLE 6-2D  Installation Stress

\[ \text{RESULT}_{\text{tensile.bend.hoop3}} = \begin{cases} \text{"PASS"} & \text{if } \text{tensile.bend.hoop3} < 1 \\ \text{"FAIL"} & \text{otherwise} \end{cases} \]

\[ \text{RESULT}_{\text{tensile.bend.hoop3}} = \text{"PASS"} \]

\textbf{Stress at Point S}

\[ \text{Tensile Stress} \quad \text{stress}_{15} = \frac{T_S}{\text{Area}} \quad \text{stress}_{15} = 1582.5\text{psi} \]

\textbf{Allowable Tension}

\[ \text{allowstress}_{15} = .9 \cdot \text{SMYS} \quad \text{allowstress}_{15} = 37800\text{psi} \quad \text{Note that stress}_{15} \text{ is less than allowstress}_{15}, \text{ so tension is within limits.} \]

\[ \text{RESULT}_{\text{tensile5}} = \begin{cases} \text{"PASS"} & \text{if } \text{stress}_{15} < \text{allowstress}_{15} \\ \text{"FAIL"} & \text{otherwise} \end{cases} \]

\[ \text{RESULT}_{\text{tensile5}} = \text{"PASS"} \]

\textbf{Bending Stress}

\[ \text{stress}_{b5} = \frac{E \cdot D \cdot 12}{24R_1} \quad \text{stress}_{b5} = 13342\text{psi} \]

\textbf{Allowable Bending}

\[ a_3 = .75 \cdot \text{SMYS} \]

\[ b_3 = \left( .84 - \frac{1.74 \cdot \text{SMYS} \cdot D}{E \cdot t} \right) \cdot \text{SMYS} \]

\[ c_3 = \left( .72 - \frac{.58 \cdot \text{SMYS} \cdot D}{E \cdot t} \right) \cdot \text{SMYS} \]
allowstress_{b5} = \begin{cases} 
a_3 \frac{D}{t} & \text{if } 1500000 \text{psi} < \frac{D}{t} \leq \frac{SMYS}{2} \\
b_3 & \text{if } 1500000 \text{psi} < \frac{D}{t} \leq \frac{SMYS}{3} \\
c_3 & \text{otherwise} 
\end{cases}

allowstress_{b5} = 31500 \text{psi}

Note that stress\_b5 is less than allowstress\_b5, so bending stress is within limits.

RESULT\_bending5 = \begin{cases} 
\text{return "PASS"} & \text{if stress\_b5 < allowstress\_b5} \\
\text{return "FAIL"} & \text{otherwise} 
\end{cases}

RESULT\_bending5 = "PASS"

**External Hoop Stress**

\[ \sigma_{\delta} = \left( 1.2 + \sin \theta \right) + \frac{R_2 \left( 1 - \cos \theta \right)}{R_1} \]

\[ \Delta p = 31.1 \text{psi} \]

\[ \delta = 49.9 \text{ft} \]

\[ \Delta p \cdot \delta = 470.6 \text{psi} \]

**Allowable Elastic Hoop Buckling**

\[ a_4 = 0.88 \frac{E}{D} \left( \frac{t}{D} \right)^2 \]

\[ b_4 = 0.45 \text{SMYS} + 0.18a_2 \]

\[ c_4 = \frac{1.31 \text{SMYS}}{1.15 + \left( \frac{\text{SMYS}}{a_2} \right)} \]

\[ d_4 = 6.2 \text{SMYS} \]

**EXAMPLE 6-2E**  Installation Stress
allowstress_{h5} = \begin{cases} 
  a_4 & \text{if } .55 \text{-SMYS} \geq a_4 \\
  b_4 & \text{if } .55 \text{-SMYS} < a_4 \leq 1.6 \text{-SMYS} \\
  c_4 & \text{if } 1.6 \text{-SMYS} < a_4 \leq 6.2 \text{-SMYS} \\
  d_4 & \text{otherwise} 
\end{cases}

allowstress_{h5} = 23919.6 \text{psi}

\frac{allowstress_{h5}}{1.5} = 15946.4 \text{psi} \quad \text{Note that stress}_{h3} \text{ is less than } \frac{allowstress_{h5}}{1.5} \text{ so external hoop stress is with allowable limits for buckling.}

\text{RESULT}_{\text{hoop5}} = \begin{cases} 
  \text{"PASS"} & \text{if stress}_{h5} < \frac{allowstress_{h5}}{1.5} \\
  \text{"FAIL"} & \text{otherwise} 
\end{cases}

\text{RESULT}_{\text{hoop5}} = \text{"PASS"}

Combined load interactions at point 5

Since all individual stress checks are acceptable, check combined loads.

Tensile and Bending

tensile_{bend5} = \frac{stress_{t5}}{.9 \text{ SMYS}} + \left( \frac{stress_{b5}}{allowstress_{b5}} \right) 
	ensile_{bend5} = 0.465

\text{RESULT}_{tb5} = \begin{cases} 
  \text{"PASS"} & \text{if } tensile_{bend5} < 1 \\
  \text{"FAIL"} & \text{otherwise} 
\end{cases}

\text{RESULT}_{tb5} = \text{"PASS"}

Tensile, Bending and External Hoop

A^2 + B^2 + 2 \cdot V \cdot |A| \cdot B \leq 1

\text{EXAMPLE 6-2F} \quad \text{Installation Stress}
HDD Stress Analysis for Steel Product Pipe

6.2 Steel Product-Pipe Stress Analysis

\[ \Delta \sigma = \left( \text{stress}_{\text{t5}} + \text{stress}_{\text{h5}} - 0.5 \cdot \text{stress}_{\text{h5}} \right) \frac{125}{\text{SMYS}} \quad A = 0.44 \]

\[ B = \frac{1.5 \cdot \text{stress}_{\text{h5}}}{\text{allowstress}_{\text{h5}}} \quad B = 0.03 \]

\[
\text{tensile}_{\text{bend.hoop5}} = A^2 + B^2 + 2 \cdot \nu \cdot |A| \cdot B \\
tensile_{\text{bend.hoop5}} = 0.2
\]

\[
\text{RESULT}_{\text{tensile.bend.hoop5}} = \begin{cases} 
\text{"PASS"} & \text{if } \text{tensile}_{\text{bend.hoop5}} < 1 \\
\text{"FAIL"} & \text{otherwise}
\end{cases}
\]

\[ \text{RESULT}_{\text{tensile.bend.hoop5}} = \text{"PASS"} \]

EXAMPLE 6-2G  Installation Stress
The term $\Delta p$ is the difference between the hydrostatic pressure caused by the groundwater acting on the pipe and the internal pressure from the fluid or gas inside the pipe. The thermal stress calculation from ASME/ANSI B31.4 is:

$$stress_{thermal} = (E * k) \cdot (T_1 - T_2)$$  \hspace{1cm} \text{Equation 6-15}

where:
- $k$ = the coefficient of thermal expansion (for steel 0.0000065 inches per inch per degree F)
- $T_1$ = installed temperature in degrees F
- $T_2$ = operating temperature in degrees F

According to ASME/ANSI B31.4 the maximum shear stress in the pipeline should not exceed 45 percent of the SMYS of the pipe. Maximum shear may be calculated using the following equation (Timoshenko and Gere):

$$ shear_{maximum} = \frac{stress_{hoop} - stress_{long}}{2} $$  \hspace{1cm} \text{Equation 6-16}

where:
- $stress_{long} = stress_{bending} + stress_{thermal} + stress_{hoop} \cdot \nu$  \hspace{1cm} \text{Equation 6-17}
- $\nu$ = Poisson’s ration (0.3 for steel)

When performing this analysis all tensile stresses are positive and all compressive stresses are negative. The product pipe will experience the maximum shear stress on the compressive side of the bend at the maximum distance from the bend’s neutral axis. Example 6-3 is an example of the operating-stress calculations for the HDD crossing provided in Figure 6-2.

**Chapter 6 Footnotes**

### 6.2 Steel Product-Pipe Stress Analysis

**Operating loads and Stress Analysis**

**Bending Stress**

\[
\text{stress}_{\text{bending}} = \frac{ED \cdot 12}{24R_t} \quad \text{stress}_{\text{bending}} = 13342 \text{psi}
\]

**External Hoop Stress**

\[
\text{stress}_{\text{hoop, external}} = \frac{\Delta p \cdot D}{2t} \quad \text{stress}_{\text{hoop, external}} = 470.6 \text{ psi}
\]

**Thermal Stress**

\[
\begin{align*}
K &= 0.0000065 \\
T_1 &= 80 \\
T_2 &= 50 \\
\text{stress}_{\text{thermal}} &= (E \cdot k) \cdot \left( \frac{T_1 - T_2}{T_1} \right) \\
\text{stress}_{\text{thermal}} &= 5655 \text{ psi}
\end{align*}
\]

**Combined stress and limitations**

Combined stress is analyzed by calculating the maximum shear stress on a small element in the pipeline. The maximum shear stress should be limited to 45% of the SMYS (ASME/ANSI B31.4). The maximum shear stress at any element is calculated using the following formula:

\[
\Delta p = 31.1 \text{ psi} \quad \text{Internal pressure} = 600 \text{ psi}
\]

\[
\text{stress}_{\text{hoop}} = \frac{(\text{Internal pressure} - \Delta p) \cdot D}{2t} \quad \text{stress}_{\text{hoop}} = 8604.7 \text{ psi}
\]

\[
\text{stress}_{\text{long}} = \text{stress}_{\text{bending}} + \text{stress}_{\text{thermal}} + \text{stress}_{\text{hoop}} \quad \text{stress}_{\text{long}} = 21578.4 \text{ psi}
\]

**Maximum shear stress**

\[
\text{stress}_{\text{shear}} = \frac{\text{stress}_{\text{hoop}} - \text{stress}_{\text{long}}}{2} \quad |\text{stress}_{\text{shear}}| = 6486.9 \text{ psi}
\]

SMYS\(_{45} = 18900\text{ psi} \quad \text{This is within the 45% limit.}

SMYS\(_95 = \text{SMYS}_{45} \quad \text{SMYS}_{95} = 18900 \text{ psi}

RESULT = \text{"PASS" if } \text{SMYS}_{95} > |\text{stress}_{\text{shear}}| \quad \text{return } "FAI" \text{ otherwise}

RESULT = "PASS"

---

**EXAMPLE 6-3  Operating Stress**
HDD Stress Analysis for Steel Product Pipe
7.1 General Information

When planning HDD crossings with plastic pipe, the primary concern for owners is usually whether the product pipe can safely handle the stresses and the required pullback loads. As discussed in Chapter 4, after selecting the required DR for the product pipe the next step is to determine if the DR selected can handle the installation loads. As with steel product pipe, plastic pipe, when installed by HDD, may experience high-tension loads, severe bending, and external fluid pressures. Usually these installation loads are more severe than the design service loads, and they are the primary factor in pipe material selection. It is quite common for the installation forces to be the deciding factor and to require the designer to specify a lower DR (stronger pipe) than would have been required for the other factors.

HDD installation subjects the pipe to axial tensile forces caused by the frictional drag between the pipe and the bore hole or drilling fluid, the frictional drag on the ground surface, the capstan effect around drill-path bends, and hydrokinetic drag. The pipe may also be subjected to external hoop pressures caused by the external fluid head and bending stresses. Estimating of pullback forces involves the assumption of many variables and installation techniques. The equations provided in this chapter are guidelines only, and the pulling loads calculated are estimated values.
7.2 Bore-Path Profile

The procedures for designing the bore path for plastic pipe are basically the same as discussed for steel pipe in Chapter 6. The first step in calculating the estimated pulling loads is to develop the input data, such as pipe properties, DR, drilling-fluid properties, and code design factors, that will be used in the calculations. Examples of typically required input data are provided in the examples in this chapter. The bore path is selected based on the profile required to successfully cross the obstacle while reaching the required depth. The preliminary bore path is based on the definition of the obstacle, the subsurface conditions, and the material properties of the product pipe. Using this data and the equations provided in Chapter 8, the designer can develop a combination of straight lines and curves that will cross the obstacle at the desired depth within the available overall bore length. The bend radius selected must be compatible with both the steel drill rods and the plastic pipe or conduit.

Bore-Path Geometry for Plastic Pipe

In addition to the bore-path-geometry methods discussed for steel pipe in Chapter 6, other methods from ASTM\textsuperscript{1} and plastic pipe organizations\textsuperscript{1} are often used for plastic-pipe crossings. These methods use an average radius of curvature for the pipe section from the entrance of the bore hole to the end of the curve. Figure 7-1 defines a typical bore-path profile used for plastic-pipe crossings. The values are assigned based on the profile required to successfully cross the obstacle while reaching the required depth.

This method can assist the engineer in designing the bore path. The equations that follow are estimates, and the engineer should use judgment and experience in applying them.

![Figure 7-1 Bore Path Example](image-url)
**Average Radius of Curvature**

The average radius of curvature for a pipe segment, such as point 1 to point 2 or point 3 to point 4 in Figure 7-1, may be estimated from the entry and exit angles and the depth of the bore by:

\[
R_{\text{avg}} = \frac{2 * H}{\theta}
\]

Equation 7-1

and the radius of curvature at any point along the bore path may be estimated by:

\[
R = \frac{\Delta S}{\Delta \theta}
\]

Equation 7-2

where:

- \(R_{\text{avg}}\) = average radius of curvature along the bore-path segment in feet
- \(H\) = depth of the bore beneath the surface in feet
- \(\theta\) = bore entry and exit angle to the surface in radians/degrees
- \(R\) = local radius of curvature along the bore path in feet
- \(\Delta S\) = pipe segment length in feet
- \(\Delta \theta\) = angular change in direction in radians/degrees

The corresponding horizontal distance (in feet) required to achieve the depth or rise to the surface may be estimated by:

\[
L = \frac{2 * H}{\theta}
\]

Equation 7-3

The resulting bore-path profile is what determines the stresses that the product pipe will experience during installation and service life.

**7.3 Pullback Loads**

HDD drill rigs can exert extensive pull forces. Most of the force is applied to the cutting face of the reamer. As discussed in Chapter 6, it is a difficult task to estimate what portion of the total pullback force is being transmitted to the product pipeline. The pulling force, which overcomes the combined frictional drag, capstan effect, and hydrokinetic drag, is applied to the first joint of plastic pipe. The axial tensile stress intensifies over the length of the pull. The duration of the pulling load is longest at the first joint of pipe. The end of the pipe segment has zero applied tensile stress for zero time. The incremental time duration of stress intensity along the
length of the pipeline from nose to tail causes a varying degree of recoverable elastic strain and viscoelastic stretch per foot of length along the pipe. The product pipe DR must be selected so that the tensile stress due to the pullback force does not exceed the permitted tensile stress for the pipe. Thicker pipe-wall thickness can withstand larger pulling loads; however, the thicker wall also increases the weight per foot of the pipe in direct proportion. As a result thicker wall pipe may not necessarily reduce the stresses but rather increase the value of the pull force.

Figure 7-1 shows the geometry of a typical bore path including the depth, entry and exit curves, and the straight segment beneath the obstacle to be crossed. The pulling load is normally calculated at the leading end of the product pipe. The tensile forces will vary during the pullback operation and will increase as the pipe is pulled further into the bore hole. The tensile forces result from the fractional drag acting on the sides of the pipe due to the weight or buoyancy forces as it is pulled into and along the bore hole, force amplifications caused by pulling the pipe around the curves, and resistance due to pipe stiffness. The magnitude of the forces depends on whether the pipe is empty or deliberately weighted to reduce the buoyancy.

Frictional Resistance

Pipe resistance to pullback in the bore hole depends primarily on the frictional force created between the pipe and the hole or the pipe and the ground surface in the entry area, the frictional drag between pipe and drilling slurry, the capstan effect at bends, and the weight of the pipe. Equation 7-4 gives the frictional resistance or required pulling force for pipe pulled in straight, level bores or across level ground (Figure 7-2).

\[ F_p = \mu W_B L \]  

where:
- \( F_p \) = pulling force in pounds
- \( \mu \) = coefficient of friction between pipe and slurry (typically 0.3) or between pipe and ground (typically 0.5 or 0.1 when pipe is on rollers)
- \( W_B \) = net downward (or upward) force on pipe in pounds per foot
- \( L \) = length in feet

**FIGURE 7-2** Frictional Resistance
When slurry is present, WB is the upward buoyant force of the pipe and its contents. Filling the pipe with fluid significantly reduces the buoyancy force and thus the pulling force. If the pipe is installed empty using a closed nose-pull head, the pipe will tend to float on the crown of the bore hole leading to the sidewall loading and frictional drag through the buoyancy-per-foot force and the wet soil to pipe coefficient of friction. If the pipe is installed full of water, the net buoyant force is drastically reduced. During pullback, the moving drill mud lubricates the contact zone. If drilling, pipe, or mud flow stops, the pipe can push up and squeeze out the lubricating mud.

For curves in the bore hole, the force can be factored into horizontal and vertical components (Figure 7-3). When drilling with steel pipe there is an additional frictional force that occurs due to the pressure required by the bore hole to keep the steel pipe curved. When drilling with plastic pipe using a radius of curvature similar to that used for steel pipe, these forces are likely insignificant. However, when using tight bends these forces should be taken into consideration. The frictional resistance during a pull is compounded by the capstan effect. Compounding forces caused by the direction of the pulling vectors are created as the pipe is pulled around a curve or bend, creating an angle. The pulling force due to the capstan effect is given in Equation 7-5. This equation and the preceding one are applied recursively to the pipe for each section along the pullback distance. This method is credited to Larry Slavin of Bellcore (Middletown, NJ).

\[ F_c = e^{\mu \phi} (\mu W_B L) \]

where:
- \( e \) = natural logarithm base (\( e = 2.71828 \))
- \( \mu \) = coefficient of friction between the pipe and slurry (typically 0.3)
- \( \phi \) = angle of bend in pipe in radians
- \( W_B \) = weight of pipe or buoyant force on pipe in pounds per foot
- \( L \) = length of pull in feet

FIGURE 7-3 Capstan Effect
Pulling Force

Most HDD crossings are comprised of a combination of straight sections and bends, and Equations 7-4 and 7-5 have to be applied to each straight section and bend in the bore hole. The corresponding loads may be estimated by the following equations. For calculating the estimated peak force on the product pipe the load is calculated at four points, as shown in Figure 7-1. The greatest load will be experienced at point 4. The loads may be estimated by using the following equations:  

\[ T_1 = \exp(v_a \alpha) \left( v_a w_a (L_1 + L_2 + L_3 + L_4) \right) \]  
Equation 7-6

\[ T_2 = \exp(v_b \alpha) \left( T_1 + v_b w_b |L_2 + w_b H - v_a w_a L_2 \exp(v_a \alpha) \right) \]  
Equation 7-7

\[ T_3 = T_2 + v_b w_b |L_3 - \exp(v_b \alpha) \left( v_a w_a L_3 \exp(v_a \alpha) \right) \]  
Equation 7-8

\[ T_4 = \exp(v_b \beta) \left( T_3 + v_b w_b |L_4 - w_b H - \exp(v_a \alpha)(v_a w_a L_4 \exp(v_a \alpha)) \right) \]  
Equation 7-9

where:

- \( T_1 \) = pull force at point 1 in pounds per foot
- \( T_2 \) = pull force at point 2 in pounds per foot
- \( T_3 \) = pull force at point 3 in pounds per foot
- \( T_4 \) = pull force at point 4 in pounds per foot
- \( L_1 \) = additional pipe length required outside of bore hole in feet
- \( L_2 \) = horizontal distance to desired depth in feet
- \( L_3 \) = additional horizontal distance required to transverse at depth in feet
- \( L_4 \) = horizontal distance to rise to surface in feet
- \( H \) = depth of bore in feet
- \( \exp(x) = \) natural logarithm base \((e = 2.71828)\)
- \( v_a \) = coefficient of friction applicable at the surface before the pipe enters the bore hole
- \( v_b \) = coefficient of friction applicable in the bore hole
- \( w_a \) = weight of empty pipe in pounds per foot
- \( w_b \) = net upward buoyant force on the pipe in the bore hole in foot-pounds per foot
- \( \alpha \) = bore-hole angle at pipe entry in radians/degrees
- \( \beta \) = bore-hole angle at pipe exit in radians/degrees
The above equations do not completely account for the resistance caused by the pipe's stiffness as it moves through the curves in the bore hole. This can be greatly reduced by having larger radius bends and sufficient clearance in the bore hole. The exponential factors correspond to the capstan effect, reflecting increased bearing pressure caused by the pipe being pulled against the inside surface of the bend. In addition, the equations above do not account for the resistance resulting from pipe stiffness at the bends along the bore-hole path. This effect can be greatly reduced by using sufficiently large radius bends and maintaining adequate clearance within the bore hole.

The coefficient of friction used in these calculations depends on the characteristics of the surfaces bearing against each other, the presence of any lubrication, and whether there is relative motion between the surfaces. The degree of friction immediately prior to slippage is generally greater than the level during subsequent sliding. Although brief interruptions in the HDD installation process are necessary during the removal of the drill rods during the pullback operation, it is important to attempt to complete the operation without extensive interruptions, which may allow the bore hole to collapse or the pipe to become stuck in the surrounding soil. The value for $v_b$ represents the pipe in the bore hole, surrounded by drilling fluid and mud slurry, and assuming minimal interruptions. It is recommended that the pipe external to the bore hole be supported to provide as low a coefficient of friction $v_a$ as possible. The typically suggested design value for the frictional coefficients between plastic pipe and the wet bore hole ($v_b$) is 0.3 and the value between the plastic pipe and the ground ($v_a$) is 0.5. For pipe supported on rollers, $v_a$ is typically considered equal to 0.1. The friction is highest just before the product pipe starts to move and decreases during movement. When the pipe is stopped, the drilling-fluid viscosity will increase if left undisturbed, which will result in an increase in frictional and drag forces due to the thixotropic nature of the drilling fluid. If multiple pipes or a bundle of small-diameter pipes are pulled simultaneously into the bore hole, higher overall loads will result due to the greater weight or buoyancy of the combination as well as an effectively amplified coefficient of friction within the hole.

The required pulling force depends upon whether the product pipe is empty or filled with water to reduce buoyancy. Buoyant force will push the product pipe against the top of the bore hole, resulting in increased frictional drag. Filling the pipe with water will reduce this effect. The weight of the empty pipe or conduit may be obtained from the manufacturer or calculated by:

$$\text{pipe weight} = \pi * D^2 * \left(\frac{DR - 1}{DR}\right) * \rho_w * \gamma_a$$  

Equation 7-10
Typically assumed average wall thickness equals 1.06, and the minimum wall thickness is:

\[ \text{pipe}_{\text{weight}} = 1.06 \times \text{pipe}_{\text{weight}} \]  
Equation 7-10a

where:
\[ \text{pipe}_{\text{weight}} = \text{weight of empty pipe in foot-pounds per inch} \]
\[ \gamma_a = \text{specific gravity of pipe material (for example, 0.955 for PE)} \]
\[ \rho_w = \text{weight density of water in foot-pounds per inch} \]
\[ D = \text{outside diameter of pipe in inches} \]
\[ DR = \text{pipe-wall dimension ratio} \]

The net upward buoyant force on empty pipe surrounded by mud slurry may be calculated by:

\[ w_b = \frac{\pi \times D^2}{4} \times \rho_w \times \gamma_b - \text{pipe}_{\text{weight}} \]  
Equation 7-11  
(pipe empty)

Or the effective submerged weight per foot of the pipeline plus internal contents, lbs/ft

\[ \text{Displaced}_{\text{mudweight}} = \pi \times \left( \frac{D}{2} \right)^2 \times \gamma_b \]  
Equation 7-12

\[ \text{pipe}_{\text{volume}} = \pi \times \left( \frac{D}{2} - t \right)^2 \]  
Equation 7-13  
\[ \text{water}_{\text{weight}} = 62.4 \frac{\text{lbf}}{\text{ft}^3} \]

and weight of water equals \[ \text{pipe}_{\text{volume}} \times \text{water}_{\text{weight}} \]

\[ w_s = \text{pipe}_{\text{weight}} + \text{water}_{\text{weight}} - \text{Displaced}_{\text{mudweight}} \]  
Equation 7-14

where:
\[ D = \text{outside diameter of pipe in inches} \]
\[ \gamma_b = \text{specific weight of the mud slurry in foot-pounds per foot} \]
\[ t = \text{pipe wall thickness in inches} \]

Hydrokinetic Pressure

During pullback the pipe experiences resistance from the drag of the drilling fluid. This develops a pressure gradient that corresponds to the force required to exhaust the drilling fluid out of the hole towards the pipe entry area. This is called hydrokinetic force, and it is difficult to estimate. The drag force may be estimated by
considering a balance of the forces acting on the fluid annulus in the bore hole due to the hydrokinetic pressure and the lateral shear forces acting on the pipe and walls of the bore hole. Typical values used for hydrokinetic pressure are 5 to 10 psi. An equation frequently used to estimate hydrokinetic force is:

\[ T_{\text{hydrok}} = \frac{\pi}{8} \left( D_{\text{hole}}^2 - D^2 \right) \]  \hspace{1cm} \text{Equation 7-15}

where:
- \( T_{\text{hydrok}} \) = hydrokinetic force in foot-pounds
- \( \text{hydrok}_{\text{pressure}} \) = hydrokinetic pressure in psi
- \( D_{\text{hole}} \) = bore-hole diameter in inches
- \( D \) = product-pipe outside diameter in inches

The hydrokinetic force may be added to the calculated pulling forces to obtain the total pull force at each corresponding point of the installation. For a bundle of pipes \( D^2 \) in Equation 7-15 is replaced by the equivalent sum of the corresponding quantities (diameters squared) for the individual pipes.

**Axial Tensile Stress**

The maximum tensile stress during pullback is the sum of the tensile stress due to the pullback force, including the hydrokinetic force, and the tensile stress resulting from the bending of the pipe. The average axial stress acting on the pipe cross-section at points 1, 2, 3, or 4 is given by:

\[ \sigma_x = \frac{T_x}{\pi D^2} \left( \frac{DR^2}{DR - 1} + \frac{E_{24} D}{2 r} \right) \]  \hspace{1cm} \text{Equation 7-16}

where:
- \( \sigma_x \) = average outer-fiber axial tensile stress at corresponding point in psi
- \( T_x \) = tensile force at corresponding point in foot-pounds
- \( D \) = pipe outside diameter in inches
- \( DR \) = pipe dimension ratio
- \( E_{24} \) = time-dependent modulus of elasticity in psi
- \( r \) = radius of curvature of the pipe in the bore hole in inches

The highest average axial stress will occur at the pulling head. However, depending on the curvature of the bore path, the peak tensile stress may occur in a curve. In the curve, the maximum tensile stress due to bending occurs in the outer fibers of the pipe. For each curve, the maximum tensile stress equals the sum of the
bending stress caused by the curvature and the average axial stress at that point due to pulling. The maximum tensile stress for each curve should be determined and compared with the average axial stress at the pulling head to determine the peak tensile stress occurring in the pipe:

\[
\varepsilon_{\text{axial}} = \frac{D}{2 \cdot r} \quad \text{Equation 7-17}
\]

\[
\sigma_{\text{axial}} = E_a \cdot \varepsilon_{\text{axial}} \quad \text{Equation 7-18}
\]

\[
\sigma_{\text{peakx}} = \sigma_x + \sigma_{\text{axialx}} \quad \text{Equation 7-19}
\]

where:
- \(\varepsilon_{\text{axial}}\) = peak axial strain in inch/inch
- \(D\) = pipe outside diameter in inches
- \(r\) = local radius of curvature in inches
- \(\sigma_{\text{axial}}\) = peak axial stress in psi
- \(E_a\) = modulus of elasticity in psi
- \(\sigma_{\text{peakx}}\) = peak tensile stress at corresponding point in psi
- \(\sigma_x\) = average axial tensile stress at corresponding point in psi
- \(\sigma_{\text{axialx}}\) = peak outer-fiber tensile stress at corresponding point in psi

The peak outer-fiber tensile stress should not exceed the allowable tensile stress for the appropriate time period (see Table 4-2). The term “safe pull strength” can be confusing. It is often incorrectly assumed that the allowable pulling force is a pipe property that is independent of the bore path. Bends in the bore path result in tensile stress in the pipe wall, and as a result they decrease the safe pull strength as shown in Table 7-1.

| TABLE 7-1 | Radius of Curvature and Safe Pull Force for 6.625-inch DR 11 with \(\sigma_{\text{allow}} = 1200\)-psi |
|------------|---------------------------------|---------------------------------|---------------------------------|
| Radius of Curvature (ft) | Bending Stress (psi) | Safe Pull Stress (psi) | Safe Pull Force (lbf) |
| 50 | 308 | 892 | 10,170 |
| 100 | 154 | 1,046 | 11,923 |
| 200 | 77 | 1,123 | 12,799 |
| 400 | 38 | 1,162 | 13,237 |
| 800 | 19 | 1,181 | 13,456 |

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The safe pull stress can be estimated by subtracting the bending stress caused by the curvature from the allowable tensile stress.

\[ \sigma_{\text{safe\,pull}} = \sigma_{\text{allow}} - \frac{E \times D}{2 \times r} \]  

Equation 7-20

where:
- \( \sigma_{\text{safe\,pull}} \) = safe pull stress in psi
- \( \sigma_{\text{allow}} \) = allowable tensile stress in psi (Table 4-2)

The safe pull force can be estimated by the following equation:

\[ \text{Pull\ force} = \pi \times \sigma_{\text{safe\,pull}} \times D^2 \times \left( \frac{1}{DR} - \frac{1}{DR^2} \right) \]  

Equation 7-21

The tensile strength of plastic pipe is load-rate-sensitive. Under continuous loads plastic pipe will experience creep deformation. As a result the safe pull-stress values for plastic pipes are time- and temperature-dependent. The time required to install a pipe by HDD depends on the length of the drill and the rate of pullback of the pipe. Pullback rates can vary greatly depending on the soil conditions and the HDD procedures being used. If the reaming process is expected to be slow and difficult, it is recommended that a separate reaming operation be performed to allow for a subsequent faster pipe pullback and shorter time interval for the product-pipe installation. If necessary, the stress on the product pipe or conduit may be reduced by increasing the pipe wall thickness (lower DR value) or, possibly, by reducing the net buoyant force by filling the pipe with water. Pullback calculations for PE gas pipe are provided in ASTM F-1804, Practice for Determining Allowable Tensile Load for Polyethylene (PE) Gas Pipe during Pull-In Installation. However, the bending stresses should be subtracted from the calculated values in F-1804 to obtain the safe pullback stresses.

After the pullback operation plastic pipe may take several hours (typically equal to the duration of the pull) to recover from the axial strain. When pulled from the reamed bore hole, the nose should be pulled out about 3 percent longer than the total length of the pull. The elastic strain will recover immediately, and the viscoelastic stretch will remember its original length and recover overnight. To be conservative allow about 4 percent extra length (40 feet per 1000 feet) to ensure that the nose remains extended beyond the bore-hole exit.

The torsional stresses can also be eliminated or reduced by the use of a swivel at the leading end of the pipe. A typical value for torsional shear stress is 50 percent of the tensile strength. Divide the transmitted torque by the wall area to get the torsional shear-stress intensity. Swivels are not 100 percent efficient, and some minor amount of torsion will be transmitted to the pipeline.
Resistance to External Collapse Pressure During Pullback Installation

The allowable external buckling-pressure equation, Equation 4-14, with the appropriate time-dependent modulus value can be used to calculate the pipe’s resistance to the external pressure during pullback with proper reductions. The reduction occurs due to ovality and the hoop strain created by the pulling force.

If the pipe is empty, the buoyant force will cause a reduction in the vertical diameter. The deflection fraction due to buoyancy can be calculated using Equation 4-13. This value can be converted to percent ovality by multiplying the deflection fraction by 100. Ovality reduces buckling resistance. The appropriate ovality compensation factor for Equation 4-14 is found in Figure 4-3.

The tensile pulling force reduces the buckling resistance. This can be accounted for by an additional reduction factor. The pulling load in the pipe creates a hoop strain as described by Poisson’s ratio. The hoop strain reduces the buckling resistance. Multiply Equation 4-14 by the reduction factor to obtain the allowable external buckling pressure during pullback:

\[
fr = \sqrt{5.57 - (r + 1.09)^2} - 1.09 \quad \text{Equation 7-22}
\]

where:

\[
r = \frac{\sigma_s}{2 \sigma_{safepull}} \quad \text{Equation 7-23}
\]

\(fr\) = reduction factor caused by axial stress

7.4 Examples

Example 7-1 is an example of the calculations for pullback force, stress, and a safety factor for a HDD crossing with a 14-inch DR 9 PE pipe. All the calculations produced acceptable results.

Example 7-2 is an example of the calculations for an 8.625-inch DR 11 PE pipe. With these calculations the pipe fails to meet acceptable conditions in several areas. One key point to notice is that it fails to provide for allowable pull force and stress.

Example 7-3 has the same conditions as Example 7-2 except that the DR was changed from 11 to 9. Changing the DR produced acceptable results for the pull force and stress. This option provides a satisfactory safety factor of 3.4 against collapse during the pull and a safety factor of 2.3 for the critical unconstrained buckling pressure. One area of concern with this example is the ring deflection of 7.5
percent. The maximum recommended ring deflection for $DR^9$ pressurized pipe is 4 percent. This would require further analysis and possibly design modifications.

Example 7-4 has the same conditions as Example 7-2 except that the product pipe is full of water. This produced acceptable results and substantially lowered the pull force and stress. This example provides a 1.7 safety factor against collapse during the pull and no safety factor for the critical unconstrained buckling pressure. This example also had a high ring deflection of 13.9 percent. This would probably require selecting another $DR$, possibly $DR^9$. Figure 7-4 displays the bore-path profile and the pull and stress loads at points 1 through 4.

Example 7-5 shows a different method for calculating the pullback forces and stress. This method uses similar procedures to the example for steel pipe in Chapter 6. This method uses the exact designed drill path and local radius of curvature for the bends. This example has the same input data and conditions as Example 7-4, with the pipe full of water. Comparing the examples show that the results are close, with Example 7-5 showing higher required pull force and stress in the bends. This is to be expected, since this method uses the local radius, which is smaller than the average method. This produced acceptable results and substantially lowered the pull force and stress. This example also provides a 1.7 safety factor against collapse during the pull and no safety factor for the critical unconstrained buckling pressure. This example also had a high ring deflection of 13.9 percent. This would probably require selecting another $DR$, possibly $DR^9$. Figure 7-5 displays the bore-path profile and the pull and stress loads at points 1 through 6.

Chapter 7 Footnotes

1 Polyethylene Pipe for Horizontal Directional Drilling. Plastics Pipe Institute, Washington, D.C.
Chapter 7  •  HDD Pipe Stress Analysis for Plastic Pipe

EXAMPLE 7-1A  Calculated Force Required to Pull Back PE Pipe and the Safety Factor Against Collapse

Input Data

\[ D = 14\text{in} \quad \text{Pipe nominal OD} \quad E_{\text{long}} = 28200\text{psi} \quad \text{Long term modulus} \]

\[ DR = 9 \quad \text{Pipe dimension ratio} \quad E_{24} = 57500\text{psi} \quad \text{24 hour modulus} \]

\[ t = \frac{D}{DR} \quad t = 1.6\text{in} \quad \text{pipe wall thickness} \quad \text{ID} = D - 2t \quad \text{ID} = 10.9\text{in} \quad \text{pipe inside diameter} \]

\[ \mu = 0.45 \quad \text{Poisson's ratio, long term} \quad \sigma_{\text{sp}} = 1100\text{psi} \quad \text{Safe pull stress 24 hour} \]

Bore Path Profile:

\[ H = 15\text{ft} \quad \text{depth of bore} \]

\[ \theta_{\text{in}} = 10\text{deg} \quad \text{Pipe entry angle} \quad \theta_{\text{ex}} = 12\text{deg} \quad \text{Pipe exit angle} \]

\[ L_4 = 100\text{ft} \quad \text{Pipe drag on surface. This value starts at the total length of the pull. Assume 100 ft remaining at end of pull.} \]

\[ L_{\text{cross}} = 1810\text{ft} \]

Estimated average radius of curvature for path at pipe entry.

\[ R_{\text{avgin}} = \frac{2H}{\theta_{\text{in}}} \quad R_{\text{avgin}} = 984.8\text{ft} \quad R_{\text{avgex}} = \frac{2H}{\theta_{\text{ex}}} \quad R_{\text{avgex}} = 683.9\text{ft} \]

Estimate the horizontal distance required to achieve the depth at the pipe entry.

\[ L_2 = \frac{2H}{\theta_{\text{in}}} \quad L_2 = 171.9\text{ft} \]

Estimate the horizontal distance required to rise to the surface at the pipe exit.

\[ L_4 = \frac{2H}{\theta_{\text{ex}}} \quad L_4 = 143.2\text{ft} \quad \text{where } L_2 \text{ and } L_4 = \text{horizontal transition distance at bore exit and entry pits.} \]
EXAMPLE 7-1B  Calculated Force Required to Pull Back PE Pipe and the Safety Factor Against Collapse

\[
L_1 = 100\text{ft} \quad L_2 = 171.9\text{ft} \quad L_4 = 143.2\text{ft} \quad L_3 = L_{\text{cross}} - L_2 - L_4 \quad L_5 = 1494.9\text{ft}
\]

\[
I_{\text{total}} = L_2 + L_3 + L_4 \quad I_{\text{total}} = 1810\text{ft}
\]

Weight of empty pipe

\[
\rho_w = \frac{3.6 \times 10^2 \text{ lbf in}^3}{\text{in}^3} \quad \rho_w = \frac{3.6 \times 10^2 \text{ lbf in}^3}{\text{in}^3}
\]

[\gamma]_a = 0.95 \quad \gamma_b = 1.5 \quad \gamma_b = 1.5

\[
\text{pipe weight} = \pi D^2 \frac{DR - 1}{D^2} \rho_w \gamma_a \quad \text{pipe weight} = 25 \frac{\text{lbf}}{\text{ft}}
\]

Assume that the average wall thickness equals 1.06 times the minimum wall thickness.

\[
w_a = 1.06 \times \text{pipe weight} \quad w_a = 26.5 \frac{\text{lb}}{\text{ft}} \quad \text{average weight of empty pipe lb/ft}
\]

\[
w_b = \frac{\pi D^2}{4} \rho_w \gamma_b - w_a \quad w_b = 73.3 \frac{\text{lb}}{\text{ft}} \quad \text{net upward buoyant force on empty pipe}
\]

\[
w_b = 73.3 \frac{\text{lb}}{\text{ft}} \quad \text{surrounded by mud slurry.}
\]

Estimate pullback force acting on the pipe:

\[
v_a = 0.1 \quad \text{coefficient of friction applicable at the surface before the pipe enters borehole}
\]

\[
v_b = 0.3 \quad \text{coefficient of friction applicable within the lubricated borehole or after the wet pipe exits}
\]

\[
\text{hydrokinetic pressure} = 5 \text{ psi} \quad \text{hydrokinetic pressure}
\]

\[
D_{\text{bh}} = 1.5D \quad D_{\text{bh}} = 21 \text{ in} \quad \text{borehole diameter, inches}
\]

\[
T_{\text{hk}} = \frac{5}{2} \left( \frac{D_{\text{bh}}^2 - D^2}{\gamma_a} \right) \quad T_{\text{hk}} = 481.1 \text{ lbf} \quad \text{hydrokinetic force, lbf}
\]
EXAMPLE 7-1C  Calculated Force Required to Pull Back PE Pipe and the Safety Factor Against Collapse

\[
\text{Estimate force at point 1:} \\
T_1 = \exp(v_b \theta_{in}) \left[ v_a w_a (L_1 + L_2 + L_3) \right] \\
T_1 = 5142.1\text{lbf}
\]

\[
\text{Estimate force at point 2:} \\
T_2 = \exp(v_b \theta_{in}) \left( T_1 + T_{hk} + v_b \left| w_b \right| L_2 + w_b H - v_a w_a L_2 \exp(v_a \theta_{in}) \right) \\
T_2 = 10579.06\text{lbf}
\]

\[
\text{Estimate force at point 3:} \\
T_3 = T_2 + T_{hk} + v_b \left| w_b \right| L_3 - \exp(v_a \theta_{in}) \left( v_a w_a L_3 \exp(v_a \theta_{in}) \right) \\
T_3 = 39835.2\text{lbf}
\]

\[
\text{Estimate force at point 4:} \\
T_4 = \exp(v_b \theta_{ex}) \left( T_3 + T_{hk} + v_b \left| w_b \right| L_4 - w_b H - \exp(v_b \theta_{in}) \left( v_a w_a L_4 \exp(v_a \theta_{in}) \right) \right) \\
T_4 = 44681.1\text{lbf} \\
\text{Total Pull Force} \\
\text{Total pull} = T_4
\]

Where:

- \( T_1 \) = pull force on pipe at point a, lbf
- \( T_2 \) = pull force on pipe at point b, lbf
- \( T_3 \) = pull force on pipe at point c, lbf
- \( T_4 \) = pull force on pipe at point d, lbf
- \( T_{HK} \) = Hydrokinetic force, lbf
- \( L_1 \) = pipe on surface, feet
- \( L_2 \) = horizontal distance to desired depth, feet
- \( L_3 \) = additional distance traversed at desired depth, feet
- \( L_4 \) = horizontal distance to rise to the surface, feet
- \( H \) = depth of borehole from ground surface, feet
- \( \exp(x) = e^x \), where \( e \) = natural logarithm base (\( e = 2.71828 \))
- \( v_a \) = coefficient of friction applicable at the surface before the pipe enters borehole, typically 0.5
- \( v_b \) = coefficient of friction applicable within the lubricated borehole or after the wet pipe exits, typically 0.3
- \( w_a \) = weight of empty pipe, lbf/ft
- \( w_b \) = net upward buoyant force on the pipe in borehole, lbf/ft
- \( \theta_{en} \) = borehole angle at pipe entry (drill exit angle), degrees/radians
- \( \theta_{ex} \) = borehole angle at pipe exit (drill entry angle), degrees/radians
Approximate Axial Bending Stress:

Radius of curvature should not exceed 40 times the pipe OD to minimize ring kinking.

\[ r = 40D \quad R > r \text{ okay} \]

Bending Strain

\[ \epsilon_{ain} = \frac{D}{2\text{avg}in} \quad \epsilon_{ain} = 0.001 \quad \text{equals pipe entry bending strain in/in.} \]

\[ \epsilon_{aex} = \frac{D}{2\text{avg}ex} \quad \epsilon_{aex} = 0.001 \quad \text{equals pipe exit bending strain in/in.} \]

Bending Stress:

\[ \delta_{ain} = E_{24} \epsilon_{ain} \quad \delta_{ain} = 34.1 \text{psi} \quad \text{equals pipe entry bending stress} \]

\[ \delta_{aex} = E_{24} \epsilon_{aex} \quad \delta_{aex} = 49 \text{psi} \quad \text{equals pipe exit bending stress} \]

\[ \delta_{allow} = \delta_{sp} - \frac{E_{24} D}{2\text{avgex}} \quad \delta_{allow} = 1051 \text{psi} \quad \text{Allowable bending stress} \]

Compare axial tensile stress due to pullback force with allowable tensile stress (1051 psi)

Average estimated axial stress acting on the pipe cross-section at points 1, 2, 3, 4.

\[ \sigma_1 = \frac{T_1}{\pi D^2} \frac{DR^2}{DR - 1} \quad \sigma_1 = 84.6 \text{psi} \]

RESULT$_1 = \begin{cases} 
\text{return "PASS" if } \sigma_1 < \delta_{allow} \\
\text{return "FAIL" otherwise}
\end{cases} \quad \text{RESULT}_1 = "PASS"

\[ \sigma_2 = \frac{T_2}{\pi D^2} \frac{DR^2}{DR - 1} + \frac{E_{24} D}{2\text{avgin}} + \delta_{ain} \quad \sigma_2 = 242.1 \text{psi} \]

RESULT$_2 = \begin{cases} 
\text{return "PASS" if } \sigma_2 < \delta_{allow} \\
\text{return "FAIL" otherwise}
\end{cases} \quad \text{RESULT}_2 = "PASS"

EXAMPLE 7-1D Calculated Force Required to Pull Back PE Pipe and the Safety Factor Against Collapse
HDD Pipe Stress Analysis for Plastic Pipe

Chapter 7  •  HDD Pipe Stress Analysis for Plastic Pipe

EXAMPLE 7-1E  Calculated Force Required to Pull Back PE Pipe and the Safety Factor Against Collapse

\[ \sigma_3 = \frac{T_3}{\pi D^2} \left( DR^2 - 1 \right) \]
\[ \sigma_3 = 655 \text{psi} \]

RESULT_3 = return "PASS" if \( \sigma_3 < \delta_{\text{allow}} \)  
RESULT_3 = "FAIL" otherwise

\[ \sigma_4 = \frac{T_4}{2 \pi D^2} \left( DR^2 - 1 \right) + \frac{E_24 D}{2 \pi D_{\text{avgex}}} + \delta_{\text{ass}} \]
\[ \sigma_4 = 832.8 \text{psi} \]

RESULT_4 = return "PASS" if \( \sigma_4 < \delta_{\text{allow}} \)  
RESULT_4 = "FAIL" otherwise

Breakaway links should be set so that the pull-back force applied to the pipe does not exceed 1051 psi.

\[ F_b = \delta_{\text{pp}} \frac{\pi}{4} \left( D^2 - D_{\text{ass}}^2 \right) \]
\[ F_b = 66896.5 \text{bf} \]

RESULT.pull = return "PASS" if Total.pull < \( F_b \)  
RESULT.pull = "FAIL" otherwise

Estimate safety factor against ring collapse during pullback

External hydraulic load:

\[ p_{\text{ext}} = \rho_w \gamma_b H \]
\[ p_{\text{ext}} = 9.7 \text{psi} \]  
External static head pressure:

Combine static head pressure with hydrokinetic pressure to find the maximum pressure during pullback.

\[ p_{\text{max}} = p_{\text{ext}} + \text{hydro pressure} \]
\[ p_{\text{max}} = 14.7 \text{psi} \]

Find the estimated critical collapse pressure:

Calculate the ring deflection. Use the larger of the deflections resulting from (a) soil loads assuming no side support or from (b) buoyant deflection due to mud weight:

<table>
<thead>
<tr>
<th>Non-Pressure (% of Dia)</th>
<th>21</th>
<th>17</th>
<th>15.5</th>
<th>13.5</th>
<th>11</th>
<th>9</th>
<th>7.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.50%</td>
<td>7.50%</td>
<td>7.50%</td>
<td>7.50%</td>
<td>7.50%</td>
<td>7.50%</td>
<td>7.50%</td>
<td></td>
</tr>
<tr>
<td>Pressure pipe (% of Dia)</td>
<td>7.50%</td>
<td>6.00%</td>
<td>6.00%</td>
<td>6.00%</td>
<td>5.00%</td>
<td>4.00%</td>
<td>3.00%</td>
</tr>
</tbody>
</table>
EXAMPLE 7-1F  Calculated Force Required to Pull Back PE Pipe and the Safety Factor Against Collapse
EXAMPLE 7-1G  Calculated Force Required to Pull Back PE Pipe and the Safety Factor Against Collapse

**Tensile ratio based on assumed 1051 psi pull stress calculation:**

\[ f_r = \frac{\sigma_4}{2 \delta_{allow}} \quad \tau = 0.4 \]

\[ f_r = \sqrt{5.57 - (\tau + 1.09)^2 - 1.09} \quad \xi = 0.7 \quad \text{tensile reduction factor} \]

**Estimated collapse pressure with reduction for tensile pulling force:**

\[ P_{cr} = \frac{2 E_{24}}{1 - \mu^2} \left( \frac{1}{2 \text{DR} - 1} \right)^3 \xi_0 \xi_f \quad P_{cr} = 150.7 \text{psi} \]

**Safety factor against collapse during pull:**

\[ SF = \frac{P_{cr}}{P_{max}} \quad SF = 10.2 \]
### Input Data

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>8.625 in</td>
</tr>
<tr>
<td>DR</td>
<td>11</td>
</tr>
<tr>
<td>$E_{\text{long}}$</td>
<td>28200 psi</td>
</tr>
<tr>
<td>$E_{24}$</td>
<td>57500 psi</td>
</tr>
<tr>
<td>t</td>
<td>0.8 in</td>
</tr>
<tr>
<td>$\mu$</td>
<td>0.45</td>
</tr>
<tr>
<td>$\delta_{\text{sp}}$</td>
<td>1100 psi</td>
</tr>
<tr>
<td>$H$</td>
<td>35 ft</td>
</tr>
<tr>
<td>$\theta_{\text{in}}$</td>
<td>10 deg</td>
</tr>
<tr>
<td>$\theta_{\text{ex}}$</td>
<td>12 deg</td>
</tr>
<tr>
<td>$L_1$</td>
<td>100 ft</td>
</tr>
<tr>
<td>$L_\text{cross}$</td>
<td>2200 ft</td>
</tr>
</tbody>
</table>

**Bore Path Profile:**

- **$H$**: depth of bore
- **$\theta_{\text{in}}$**: Pipe entry angle
- **$\theta_{\text{ex}}$**: Pipe exit angle
- **$L_1$**: Pipe drag on surface. This value starts at the total length of the pull. Assume 100 ft remaining at end of pull.
- **$L_\text{cross}$**: 2200 ft

**Estimated average radius of curvature for path at pipe entry.**

$$R_{\text{avg}} = \frac{2H}{\theta_{\text{in}}^2} \quad R_{\text{avg}} = 2298 \text{ ft} \quad R_{\text{avg}} = \frac{2H}{\theta_{\text{ex}}^2} \quad R_{\text{avg}} = 1595.8 \text{ ft}$$

**Estimate the horizontal distance required to achieve the depth at the pipe entry.**

$$L_2 = \frac{2H}{\theta_{\text{in}}} \quad L_2 = 401.1 \text{ ft}$$

**Estimate the horizontal distance required to rise to the surface at the pipe exit.**

$$L_4 = \frac{2H}{\theta_{\text{ex}}} \quad L_4 = 334.2 \text{ ft} \quad \text{where } L_2 \text{ and } L_4 = \text{horizontal transition distance at bore exit and entry pts.}$$

---

**EXAMPLE 7-2A** Calculated Force Required to Pull Back PE Pipe and the Safety Factor Against Collapse
EXAMPLE 7-2B  Calculated Force Required to Pull Back PE Pipe and the Safety Factor Against Collapse

\[
\begin{align*}
L_1 &= 100\text{ft} & L_2 &= 401.1\text{ft} & L_4 &= 334.2\text{ft} & L_3 &= L_{\text{cross}} - L_2 - L_4 & L_3 &= 1464.7\text{ft} \\
L_{\text{total}} &= L_2 + L_3 + L_4 & L_{\text{total}} &= 2200\text{ft}
\end{align*}
\]

Weight of empty pipe

\[
\rho_w = 3.6 \cdot 10^{-2} \frac{\text{lbf}}{\text{in}^3} \quad \text{density of water, lbf/in}^3 \quad \gamma_a = 0.95 \quad \text{specific gravity of the pipe material}
\]

\[
\gamma_b = 1.5 \quad \text{specific gravity of the mud slurry}
\]

\[
\text{pipe weight} = \pi \cdot D^2 \cdot \frac{DR - 1}{DR^2} \cdot \rho_w \gamma_a \quad \text{pipe weight} = 7.9 \frac{\text{lbf}}{\text{ft}}
\]

Assume that the average wall thickness equals 1.06 time the minimum wall thickness.

\[
w_a = 1.06 \cdot \text{pipe weight} \quad w_a = 8.4 \frac{\text{lbf}}{\text{ft}} \quad \text{weight of empty pipe lbf/ft}
\]

\[
w_b = \pi \cdot \frac{D^2}{4} \cdot \rho_w \gamma_b - w_a \quad w_b = 29.5 \frac{\text{lbf}}{\text{ft}} \quad \text{net upward buoyant force on empty pipe surrounded by mud slurry.}
\]

Estimate pullback force acting on the pipe:

Estimate hydrokinetic pressure:

\[
\nu_a = 0.1 \quad \text{coefficient of friction applicable at the surface before the pipe enters borehole}
\]

\[
\nu_b = 0.3 \quad \text{coefficient of friction applicable within the lubricated borehole or after the wet pipe exits}
\]

\[
\text{hydro pressure} = 5\text{psi} \quad \text{hydrokinetic pressure}
\]

\[
D_{bh} = 1.5D \quad D_{bh} = 12.9\text{in} \quad \text{borehole diameter, inches}
\]

\[
T_{hk} = \text{hydro pressure} \cdot \frac{\pi}{8} \left( D_{bh}^2 - D^2 \right) \quad T_{hk} = 182.6\text{lb} \quad \text{hydrokinetic force, lbs}
\]
Estimate force at point 1:

\[ T_1 = \exp(v_a \theta_{in}) \left[ v_a w_a \left( L_1 + L_2 + L_3 + L_4 \right) \right] \quad T_1 = 1966.5 \text{lb} \]

Estimate force at point 2:

\[ T_2 = \exp(v_b \theta_{in}) \left( T_1 + T_{HK} + v_b w_b \left| L_2 + w_b H - v_a w_a L_2 \exp(v_a \theta_{in}) \right| \right) \quad T_2 = 6724.69 \text{lb} \]

Estimate force at point 3:

\[ T_3 = T_2 + T_{HK} + v_b w_b \left| L_3 - \exp(v_a \theta_{in}) \left( v_a w_a L_3 \exp(v_a \theta_{in}) \right) \right| \quad T_3 = 18577 \text{lb} \]

Estimate force at point 4:

\[ T_4 = \exp(v_b \theta_{in}) \left( T_3 + T_{HK} + v_b w_b \left| L_4 - w_b H - \exp(v_b \theta_{in}) \left( v_a w_a L_4 \exp(v_a \theta_{in}) \right) \right| \right) \]

\[ T_4 = 21702.8 \text{lb} \quad \text{Total Pull Force Required} \quad \text{Total pull} = T_4 \]

Where:

- \( T_1 \) = pull force on pipe at point a, lb
- \( T_2 \) = pull force on pipe at point b, lb
- \( T_3 \) = pull force on pipe at point c, lb
- \( T_4 \) = pull force on pipe at point d, lb
- \( T_{HK} \) = Hydrokinetic force, lb
- \( L_1 \) = pipe on surface, feet
- \( L_2 \) = horizontal distance to desired depth, feet
- \( L_3 \) = additional distance traversed at desired depth, feet
- \( L_4 \) = horizontal distance to rise to the surface, feet
- \( H \) = depth of borehole from ground surface, feet
- \( \exp(x) = e^x \), where \( e \) = natural logarithm base \( (e = 2.71828) \)
- \( v_a \) = coefficient of friction applicable at the surface before the pipe enters borehole, typically 0.5
- \( v_b \) = coefficient of friction applicable within the lubricated borehole or after the wet pipe exits, typically 0.3
- \( w_a \) = weight of empty pipe, lb/ft
- \( w_b \) = net upward buoyant force on the pipe in borehole, lb/ft
- \( \theta_{en} \) = borehole angle at pipe entry (drill exit angle), degrees/radians
- \( \theta_{ex} \) = borehole angle at pipe exit (drill entry angle), degrees/radians

**EXAMPLE 7-2C** Calculated Force Required to Pull Back PE Pipe and the Safety Factor Against Collapse
Approximate Axial Bending Stress:

Radius of curvature should not exceed 40 times the pipe OD to minimize ring kinking.

\[
\tau = 40 \cdot D \quad \tau = 28.8 \text{ft} \quad R > \tau \text{ okay}
\]

Bending Strain

\[
\varepsilon_{\text{ain}} = \frac{D}{2 \cdot R_{\text{avg}, \text{in}}} \quad \varepsilon_{\text{ain}} = 0 \quad \text{equals pipe entry bending strain in/in.}
\]

\[
\varepsilon_{\text{aex}} = \frac{D}{2 \cdot R_{\text{avg}, \text{ex}}} \quad \varepsilon_{\text{aex}} = 0 \quad \text{equals pipe exit bending strain in/in.}
\]

Bending Stress:

\[
\delta_{\text{ain}} = E_{24} \varepsilon_{\text{ain}} \quad \delta_{\text{ain}} = 9 \text{psi} \quad \text{equals pipe entry bending stress}
\]

\[
\delta_{\text{aex}} = E_{24} \varepsilon_{\text{aex}} \quad \delta_{\text{aex}} = 12.9 \text{psi} \quad \text{equals pipe exit bending stress}
\]

\[
\delta_{\text{allow}} = \delta_{\text{up}} - \frac{E_{24} \cdot D}{2 \cdot R_{\text{avg}, \text{ex}}} \quad \delta_{\text{allow}} = 1087.1 \text{psi} \quad \text{Allowable bending stress}
\]

Compare axial tensile stress due to pullback force with allowable tensile stress (1087 psi)

Average estimated axial stress acting on the pipe cross-section at points 1, 2, 3, 4.

\[
\sigma_1 = \frac{T_1 \cdot DR^2}{\pi \cdot D^2 \cdot (DR - 1)} \quad \sigma_1 = 101.8 \text{psi}
\]

RESULT_1 = \begin{cases} 
\text{return "PASS" if } \sigma_1 < \delta_{\text{allow}} \\
\text{return "FAIL" otherwise}
\end{cases}

RESULT_1 = "PASS"

\[
\sigma_2 = \frac{T_2 \cdot DR^2}{\pi \cdot D^2 \cdot (DR - 1)} + \frac{E_{24} \cdot D}{2 \cdot R_{\text{avg}, \text{in}}} + \delta_{\text{ain}} \quad \sigma_2 = 366.2 \text{psi}
\]

RESULT_2 = \begin{cases} 
\text{return "PASS" if } \sigma_2 < \delta_{\text{allow}} \\
\text{return "FAIL" otherwise}
\end{cases}

RESULT_2 = "PASS"

EXAMPLE 7-2D  Calculated Force Required to Pull Back PE Pipe and the Safety Factor Against Collapse
$$\sigma_3 = \frac{T_3}{\pi \cdot D^2} \frac{DR^2}{DR - 1}$$
$$\sigma_3 = 961.8 \text{psi}$$

$$\sigma_4 = \frac{T_4}{\pi \cdot D^2} \frac{DR^2}{DR - 1} + \frac{E_{24} D}{2 \cdot \rho_{avg \cdot x}}$$
$$\sigma_4 = 1149.6 \text{psi}$$

RESULT $T_3$ = 

- return "PASS" if $\sigma_3 < \delta_{allow}$
- return "FAIL" otherwise

RESULT $T_3$ = "PASS"

RESULT $T_4$ = 

- return "PASS" if $\sigma_4 < \delta_{allow}$
- return "FAIL" otherwise

RESULT $T_4$ = "FAIL"

Breakaway links should be set so that the pull-back force applied to the pipe does not exceed 1087 psi.

$$F_b = \delta_{allow} \frac{\pi}{4} \left( D^2 - D_h^2 \right)$$
$$F_b = 20995.8 \text{ lbf}$$

RESULT pull = 

- return "PASS" if Total pull < $F_b$
- return "FAIL" otherwise

RESULT pull = "FAIL"

Estimate safety factor against ring collapse during pullback

External hydraulic load:

$$P_{ext} = \gamma_b H$$
$$P_{ext} = 22.7 \text{ psi}$$

External static head pressure:

Combine static head pressure with hydrokinetic pressure to find the maximum pressure during pullback.

$$P_{max} = P_{ext} + \text{hydro pressure}$$
$$P_{max} = 27.7 \text{ psi}$$

Find the estimated critical collapse pressure:

Calculate the ring deflection. Use the larger of the deflections resulting from (a) soil loads assuming no side support or from (b) buoyant deflection due to mud weight:

<table>
<thead>
<tr>
<th>Pressure pipe (% of Dia)</th>
<th>7.50%</th>
<th>6.00%</th>
<th>6.00%</th>
<th>6.00%</th>
<th>5.00%</th>
<th>4.00%</th>
<th>3.00%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-Pressure (% of Dia)</td>
<td>7.50%</td>
<td>7.50%</td>
<td>7.50%</td>
<td>7.50%</td>
<td>7.50%</td>
<td>7.50%</td>
<td>7.50%</td>
</tr>
</tbody>
</table>

EXAMPLE 7-2E  Calculated Force Required to Pull Back PE Pipe and the Safety Factor Against Collapse
EXAMPLE 7-2F  Calculated Force Required to Pull Back PE Pipe and the Safety Factor Against Collapse
**EXAMPLE 7-2G**  Calculated Force Required to Pull Back PE Pipe and the Safety Factor Against Collapse

**Tensile ratio based on assumed 1087 psi pull stress calculation:**

\[
\lambda = \frac{\sigma}{2 \delta_{\text{allow}}} \quad \tau = 0.5
\]

\[
\lambda_1 = \sqrt{5.57 - (3 + 1.09)^2 - 1.09} \quad \lambda_1 = 0.6 \quad \text{tensile reduction factor}
\]

**Estimated collapse pressure with reduction for tensile pulling force:**

\[
P_{cr} = \frac{2-E24}{1-\mu} \left( \frac{1}{DR - 1} \right)^3 \cdot \lambda_1 f_t \quad P_{cr} = 29.9 \text{psi}
\]

**Safety factor against collapse during pull:**

\[
SF = \frac{P_{cr}}{P_{\text{max}}} \quad SF = 1.079
\]
EXAMPLE 7-3A  Calculated Force Required to Pull Back PE Pipe and the Safety Factor Against Collapse

**Input Data**

- \( D = 8.625 \text{in} \) Pipe nominal OD
- \( E_{\text{ong}} = 28200 \text{psi} \) Long term modulus
- \( DR = 9 \) Pipe dimension ratio
- \( E_{24} = 57500 \text{psi} \) 24 hour modulus
- \( t = \frac{D}{DR} \) Pipe wall thickness
- \( ID = D - 2t \) ID = 6.7in Pipe inside diameter
- \( \mu = 0.45 \) Poisson's ratio, long term
- \( \delta_p = 1100 \text{psi} \) Safe pull stress 24 hour
- \( H_{\text{DL}} = 35 \text{ft} \) depth of bore
- \( \theta_{\text{in}} = 10 \text{deg} \) Pipe entry angle
- \( \theta_{\text{ex}} = 12 \text{deg} \) Pipe exit angle
- \( L_1 = 100 \text{ft} \) Pipe drag on surface. This value starts at the total length of the pull. Assume 100 ft remaining at end of pull.
- \( L_{\text{cross}} = 2200 \text{ft} \)

**Bore Path Profile:**

- Estimated average radius of curvature for path at pipe entry.
  \[ R_{\text{avgin}} = \frac{2H}{\theta_{\text{in}}} \]
  \( R_{\text{avgin}} = 2298 \text{ft} \)
  \[ R_{\text{avgex}} = \frac{2H}{\theta_{\text{ex}}} \]
  \( R_{\text{avgex}} = 1595.8 \text{ft} \)

- Estimate the horizontal distance required to achieve the depth at the pipe entry.
  \[ L_2 = \frac{2H}{\theta_{\text{in}}} \]
  \( L_2 = 401.1 \text{ft} \)

- Estimate the horizontal distance required to rise to the surface at the pipe exit.
  \[ L_4 = \frac{2H}{\theta_{\text{ex}}} \]
  \( L_4 = 334.2 \text{ft} \)
  \( \text{where } L_2 \text{ and } L_4 = \text{horizontal transition distance at bore exit and entry pits.} \)
EXAMPLE 7-3B  Calculated Force Required to Pull Back PE Pipe and the Safety Factor Against Collapse

\[ L_1 = 100\text{ft} \quad L_2 = 401.1\text{ft} \quad L_4 = 334.2\text{ft} \quad L_3 = L_{\text{cross}} - L_2 - L_4 \quad L_3 = 1464.7\text{ft} \]

\[ L_{\text{total}} = L_2 + L_3 + L_4 \quad L_{\text{total}} = 2200\text{ft} \]

**Weight of empty pipe**

\[ \rho_w = 3.6 \times 10^{-2} \frac{\text{lbf}}{\text{in}^3} \quad \text{density of water, lbf/in}^3 \quad \gamma_a = .95 \quad \text{specific gravity of the pipe material} \]

\[ \gamma_b = 1.5 \quad \text{specific gravity of the mud slurry} \]

\[ \text{pipe weight} = \pi D^2 \frac{DR - 1}{DR^2} \rho_w \gamma_a \quad \text{pipe weight} = 9.5 \frac{\text{lbf}}{\text{ft}} \]

Assume that the average wall thickness equals 1.06 time the minimum wall thickness.

\[ w_a = 1.06 \text{pipe weight} \quad w_a = 10 \frac{\text{lbf}}{\text{ft}} \quad \text{weight of empty pipe lbf/ft} \]

\[ w_b = \pi \frac{D^2}{4} \rho_w \gamma_b - w_a \quad w_b = 27.8 \frac{\text{lbf}}{\text{ft}} \quad \text{net upward buoyant force on empty pipe surrounded by mud slurry}. \]

**Estimate pullback force acting on the pipe:**

**Estimate hydrokinetic pressure:**

\[ v_a = .1 \quad \text{coefficient of friction applicable at the surface before the pipe enters borehole} \]

\[ v_b = .3 \quad \text{coefficient of friction applicable within the lubricated borehole or after the wet pipe exits} \]

\[ \text{hydro pressure} = 5\text{psi} \quad \text{hydrokinetic pressure} \]

\[ D_{bh} = 1.5D \quad D_{bh} = 12.9\text{in} \quad \text{borehole diameter, inches} \]

\[ T_{\text{bhk}} = \text{hydro pressure} \frac{\pi}{8} \left( D_{bh}^2 - D^2 \right) \quad T_{\text{bhk}} = 182.6\text{lbf} \quad \text{hydrokinetic force, lbs} \]
EXAMPLE 7-3C Calculated Force Required to Pull Back PE Pipe and the Safety Factor Against Collapse

\[
E_{\text{stimate force at point 1}}:
\]
\[
T_1 = \exp(v_a \theta_{in}) \left[ v_a w_a (L_1 + L_2 + L_3 + L_4) \right] \quad T_1 = 2350.1\text{lbf}
\]

\[
E_{\text{stimate force at point 2}}:
\]
\[
T_2 = \exp(v_b \theta_{in}) \left[ T_1 + T_{HK} + v_b \left[ w_b + w_b H - v_a w_a L_2 \exp(v_a \theta_{in}) \right] \right] \quad T_2 = 6790.17\text{lbf}
\]

\[
E_{\text{stimate force at point 3}}:
\]
\[
T_3 = T_2 + T_{HK} + v_b \left[ w_b \left[ L_3 - \exp(v_a \theta_{in}) \right] \left( v_a w_a L_3 \exp(v_a \theta_{in}) \right) \right] \quad T_3 = 17673.8\text{lbf}
\]

\[
E_{\text{stimate force at point 4}}:
\]
\[
T_4 = \exp(v_b \theta_{ex}) \left[ T_3 + T_{HK} + v_b \left[ w_b \left[ L_4 - w_b H - \exp(v_b \theta_{in}) \right] \left( v_a w_a L_4 \exp(v_a \theta_{in}) \right) \right] \right] \\
T_4 = 20564.5\text{lbf} \quad \text{Total Pull Force Required} \quad \text{Total}_\text{pull} = T_4
\]

Where:

- \( T_1 \) = pull force on pipe at point a, lbf
- \( T_2 \) = pull force on pipe at point b, lbf
- \( T_3 \) = pull force on pipe at point c, lbf
- \( T_4 \) = pull force on pipe at point d, lbf
- \( T_{HK} \) = Hydrokinetic force, lbf
- \( L_1 \) = pipe on surface, feet
- \( L_2 \) = horizontal distance to desired depth, feet
- \( L_3 \) = additional distance traversed at desired depth, feet
- \( L_4 \) = horizontal distance to rise to the surface, feet
- \( H \) = depth of borehole from ground surface, feet
- \( \exp(x) = e^x \), where \( e \) = natural logarithm base (\( e = 2.71828 \))
- \( v_a \) = coefficient of friction applicable at the surface before the pipe enters borehole, typically 0.5
- \( v_b \) = coefficient of friction applicable within the lubricated borehole or after the wet pipe exits, typically 0.3
- \( w_a \) = weight of empty pipe, lbf/ft
- \( w_b \) = net upward buoyant force on the pipe in borehole, lbf/ft
- \( \theta_{en} \) = borehole angle at pipe entry (drill exit angle), degrees/radians
- \( \theta_{ex} \) = borehole angle at pipe exit (drill entry angle), degrees/radians

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Approximate Axial Bending Stress:

Radius of curvature should not exceed 40 times the pipe OD to minimize ring kinking.

\[ r = 40D \quad r = 28.8 \text{ ft} \quad R > r \quad \text{Okay} \]

Bending Strain

\[ \epsilon_{\text{ain}} = \frac{D}{2R_{\text{avg}in}} \quad \epsilon_{\text{ain}} = 0 \quad \text{equals pipe entry bending strain in/in.} \]

\[ \epsilon_{\text{aex}} = \frac{D}{2R_{\text{avg}ex}} \quad \epsilon_{\text{aex}} = 0 \quad \text{equals pipe exit bending strain in/in.} \]

Bending Stress:

\[ \delta_{\text{ain}} = E_{24} \epsilon_{\text{ain}} \quad \delta_{\text{ain}} = 9 \text{ psi} \quad \text{equals pipe entry bending stress} \]

\[ \delta_{\text{aex}} = E_{24} \epsilon_{\text{aex}} \quad \delta_{\text{aex}} = 12.9 \text{ psi} \quad \text{equals pipe exit bending stress} \]

\[ \delta_{\text{allow}} = \delta_{\text{sp}} - \frac{E_{24} D}{2R_{\text{avg}ex}} \quad \delta_{\text{allow}} = 1087.1 \text{ psi} \quad \text{Allowable bending stress} \]

Compare axial tensile stress due to pullback force with allowable tensile stress (1087 psi)

Average estimated axial stress acting on the pipe cross-section at points 1, 2, 3, 4.

\[ \sigma_1 = \frac{T_1}{\pi D^2} \frac{DR^2}{DR - 1} \quad \sigma_1 = 101.8 \text{ psi} \]

RESULT1 = return "PASS" if \( \sigma_1 < \delta_{\text{allow}} \) RESULT1 = "PASS"

return "FAIL" otherwise

\[ \sigma_2 = \frac{T_2}{\pi D^2} \frac{DR^2}{DR - 1} + \frac{E_{24} D}{2R_{\text{avg}in}} + \delta_{\text{ain}} \quad \sigma_2 = 312.2 \text{ psi} \]

RESULT2 = return "PASS" if \( \sigma_2 < \delta_{\text{allow}} \) RESULT2 = "PASS"

return "FAIL" otherwise

EXAMPLE 7-3D Calculated Force Required to Pull Back PE Pipe and the Safety Factor Against Collapse
EXAMPLE 7-3E  Calculated Force Required to Pull Back PE Pipe and the Safety Factor Against Collapse
EXAMPLE 7-3F  Calculated Force Required to Pull Back PE Pipe and the Safety Factor Against Collapse

\[ \% \Delta D = \frac{0.0125 P_{\text{max}}}{F_{\text{long}}} \times \frac{100}{12 \cdot (\text{DR} - 1)^3} \quad \% \Delta D = 7.5 \quad \text{Ring deformation} \]

\[ \text{mud}_{\text{wt}} = 89.76 \frac{\text{lb}}{\text{ft}^3} \quad \text{Mud weight value.} \quad 12 \text{ ppg} = 89.76 \frac{\text{lb}}{\text{ft}^3} \]

\[ x = 12 \frac{\text{lb}}{\text{gal}} \quad x = 89.8 \frac{\text{lb}}{\text{ft}^3} \]

\[ \% \Delta D_b = \frac{0.088 \text{mud}_{\text{wt}} \cdot (\text{DR} - 1)^4}{E_{\text{long}} \cdot \text{DR}} \times \frac{100}{100} \quad \% \Delta D_b = 0.064 \quad \text{Buoyant deformation} \]

Use highest load to determine the safety factor against buckling.

\[ f_0 = 0.47 \quad \text{Ovality compensation factor based on ovality above and table.} \]

\[ \Delta a = 1 \quad \text{Safety Factor} \]

\[ P_{\text{uc}} = \frac{2 \cdot F_{\text{long}}}{1 - \mu} \left( \frac{1}{\text{DR} - 1} \right)^3 \frac{f_0}{N} \quad P_{\text{uc}} = 64.9 \text{psi} \quad \text{Critical unconstrained buckling pressure (safety factor applied)} \]

Safety factor against buckling

\[ \text{SF}_{\text{buckling}} = \frac{P_{\text{uc}}}{P_{\text{max}}} \quad \text{SF}_{\text{buckling}} = 2.345 \]
Chapter 7  •  HDD Pipe Stress Analysis for Plastic Pipe

EXAMPLE 7-3G  Calculated Force Required to Pull Back PE Pipe and the Safety Factor Against Collapse

Tensile ratio based on assumed 1087 psi pull stress calculation:

\[ \frac{\sigma_4}{2 \cdot \delta_{\text{allow}}} = 0.4 \]

\[ f_t = \sqrt{5.57 - (\tau + 1.09)^2} - 1.09 \quad f_t = 0.7 \quad \text{tensile reduction factor} \]

Estimated collapse pressure with reduction for tensile pulling force:

\[ P_{\text{cr}} = \frac{2 \cdot E_2 \cdot \left( \frac{1}{DR - 1} \right)^3 \cdot f_0 \cdot f_t}{1 - \mu} \quad P_{\text{cr}} = 95.6 \text{ psi} \]

Safety factor against collapse during pull:

\[ SF = \frac{P_{\text{cr}}}{P_{\text{max}}} \quad SF = 3.455 \]
EXAMPLE 7-4A  Calculated Force Required to Pull Back PE Pipe and the Safety Factor Against Collapse

Input Data

\[
\begin{align*}
D &= 8.625 \text{ in} & \text{Pipe nominal OD} & E_{\text{long}} &= 28200 \text{ psi} & \text{Long term modulus} \\
\text{DR} &= 11 & \text{Pipe dimension ratio} & E_{24} &= 57500 \text{ psi} & \text{24 hour modulus} \\
\frac{D}{\text{DR}} &= t = 0.8 \text{ in} & \text{pipe wall thickness} & \text{ID} &= D - 2t & \text{ID} = 7.1 \text{ in} & \text{pipe inside diameter} \\
\mu &= 0.45 & \text{Poisson's ratio, long term} & \delta_{\text{sp}} &= 1100 \text{ psi} & \text{Safe pull stress 24 hour} \\
\end{align*}
\]

Bore Path Profile:

\[
\begin{align*}
A &= 35 \text{ ft} & \text{depth of bore} \\
\theta_{\text{in}} &= 10^{\circ} & \text{Pipe entry angle} & \theta_{\text{ex}} &= 12^{\circ} & \text{Pipe exit angle} \\
L_1 &= 100 \text{ ft} & \text{Pipe drag on surface. This value starts at the total length of the pull. Assume 100 ft remaining at end of pull.} \\
L_{\text{cross}} &= 2200 \text{ ft} \\
\end{align*}
\]

Estimated average radius of curvature for path at pipe entry.

\[
\begin{align*}
R_{\text{avgin}} &= \frac{2H}{\theta_{\text{in}}} & R_{\text{avgin}} &= 2298 \text{ ft} & R_{\text{avgex}} &= \frac{2H}{\theta_{\text{ex}}} & R_{\text{avgex}} &= 1595.8 \text{ ft} \\
\end{align*}
\]

Estimate the horizontal distance required to achieve the depth at the pipe entry.

\[
L_2 = \frac{2H}{\theta_{\text{in}}} & L_2 = 401.1 \text{ ft} \\
\]

Estimate the horizontal distance required to rise to the surface at the pipe exit.

\[
L_4 = \frac{2H}{\theta_{\text{ex}}} & L_4 = 334.2 \text{ ft} & \text{where L2 and L4 = horizontal transition distance at bore exit and entry pits.}
\]
EXAMPLE 7-4B  Calculated Force Required to Pull Back PE Pipe and the Safety Factor Against Collapse
EXAMPLE 7-4C  Calculated Force Required to Pull Back PE Pipe and the Safety Factor Against Collapse
EXAMPLE 7-4D  Calculated Force Required to Pull Back PE Pipe and the Safety Factor Against Collapse

Where:

- $T_1$ = pull force on pipe at point a, lbf
- $T_2$ = pull force on pipe at point b, lbf
- $T_3$ = pull force on pipe at point c, lbf
- $T_4$ = pull force on pipe at point d, lbf
- $T_{HK}$ = Hydrokinetic force, lbf
- $L_1$ = pipe on surface, feet
- $L_2$ = horizontal distance to desired depth, feet
- $L_3$ = additional distance traversed at desired depth, feet
- $L_4$ = horizontal distance to rise to the surface, feet
- $H$ = depth of borehole from ground surface, feet
- $\exp(x) = e^x$, where $e$ = natural logarithm base ($e = 2.71828$)
- $\nu_a$ = coefficient of friction applicable at the surface before the pipe enters borehole, typically 0.5
- $\nu_b$ = coefficient of friction applicable within the lubricated borehole or after the wet pipe exits, typically 0.3
- $w_a$ = weight of empty pipe, lbf/ft
- $w_p$ = net upward buoyant force on the pipe in borehole, lbf/ft
- $\theta_{en}$ = borehole angle at pipe entry (drill exit angle), degrees/radians
- $\theta_{ex}$ = borehole angle at pipe exit (drill entry angle), degrees/radians

Approximate Axial Bending Stress:

Radius of curvature should not exceed 40 times the pipe OD to minimize ring kinking.

$\tau = 40\cdot D \quad R > \tau \quad $Okay

Bending Strain

$\varepsilon_{ain} = \frac{D}{2R_{avgin}} \quad \varepsilon_{ain} = 0 \quad $equals pipe entry bending strain in/in.

$\varepsilon_{aex} = \frac{D}{2R_{avgex}} \quad \varepsilon_{aex} = 0 \quad $equals pipe exit bending strain in/in.

Bending Stress:

$\sigma_{ain} = E_{24} \cdot \varepsilon_{ain} \quad \sigma_{ain} = 9\text{ psi} \quad $equals pipe entry bending stress

$\sigma_{aex} = E_{24} \cdot \varepsilon_{aex} \quad \sigma_{aex} = 12.9\text{ psi} \quad $equals pipe exit bending stress

$\delta_{allow} = \frac{E_{24} \cdot D}{2R_{avgex}} \quad \delta_{allow} = 1087.1\text{ psi} \quad $Allowable bending stress
EXAMPLE 7-4E  Calculated Force Required to Pull Back PE Pipe and the Safety Factor Against Collapse

Compare axial tensile stress due to pullback force with allowable tensile stress (1087 psi)

Average estimated axial stress acting on the pipe cross-section at points 1, 2, 3, 4.

\[
\sigma_1 = \frac{T_1}{\pi D^2} \frac{DR^2}{DR - 1} \quad \sigma_1 = 101.8 \text{psi}
\]

RESULT\(_1\) = \begin{cases} 
\text{"PASS"} & \text{if } \sigma_1 < \delta_{\text{allow}} \\
\text{"FAIL"} & \text{otherwise}
\end{cases}
\text{RESULT}_1 = \text{"PASS"}

\[
\sigma_2 = \frac{T_2}{\pi D^2} \frac{DR^2}{DR - 1} + \frac{E_{24}D}{2R_{\text{avg}}^2} + \delta_{\text{min}} \quad \sigma_2 = 201.6 \text{psi}
\]

RESULT\(_2\) = \begin{cases} 
\text{"PASS"} & \text{if } \sigma_2 < \delta_{\text{allow}} \\
\text{"FAIL"} & \text{otherwise}
\end{cases}
\text{RESULT}_2 = \text{"PASS"}

\[
\sigma_3 = \frac{T_3}{\pi D^2} \frac{DR^2}{DR - 1} \quad \sigma_3 = 355.4 \text{psi}
\]

RESULT\(_3\) = \begin{cases} 
\text{"PASS"} & \text{if } \sigma_3 < \delta_{\text{allow}} \\
\text{"FAIL"} & \text{otherwise}
\end{cases}
\text{RESULT}_3 = \text{"PASS"}

\[
\sigma_4 = \frac{T_4}{\pi D^2} \frac{DR^2}{DR - 1} + \frac{E_{24}D}{2R_{\text{avgex}}^2} + \delta_{\text{aux}} \quad \sigma_4 = 433.9 \text{psi}
\]

RESULT\(_4\) = \begin{cases} 
\text{"PASS"} & \text{if } \sigma_4 < \delta_{\text{allow}} \\
\text{"FAIL"} & \text{otherwise}
\end{cases}
\text{RESULT}_4 = \text{"PASS"}
7.4 Examples

### EXAMPLE 7-4F

**Calculated Force Required to Pull Back PE Pipe and the Safety Factor Against Collapse**

Breakaway links should be set so that the pull-back force applied to the pipe does not exceed 1087 psi.

\[
F_b = \delta_{op} \frac{\pi}{4} \left( D^2 - ID^2 \right) \quad F_b = 21245.9 \text{ lbf}
\]

RESULT\text{pull} = \begin{cases} 
\text{"PASS"} & \text{if Total\text{pull} < } F_b \\
\text{"FAIL"} & \text{otherwise}
\end{cases} \quad \text{RESULT\text{pull} = "PASS"}

**External hydraulic load:**

\[ P_{\text{ext}} = \rho \cdot g \cdot H \quad P_{\text{ext}} = 21.2 \text{ psi} \]

**External static head pressure:**

Combine static head pressure with hydrokinetic pressure to find the maximum pressure during pullback.

\[ P_{\text{max}} = P_{\text{ext}} + \text{hydro\text{pressure}} \quad P_{\text{max}} = 26.2 \text{ psi} \]

**Find the estimated critical collapse pressure:**

Calculate the ring deflection. Use the larger of the deflections resulting from (a) soil loads assuming no side support or from (b) buoyant deflection due to mud weight:

<table>
<thead>
<tr>
<th>DR</th>
<th>21</th>
<th>17</th>
<th>15.5</th>
<th>13.5</th>
<th>11</th>
<th>9</th>
<th>7.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-Pressure (% of Dia)</td>
<td>7.50%</td>
<td>7.50%</td>
<td>7.50%</td>
<td>7.50%</td>
<td>7.50%</td>
<td>7.50%</td>
<td>7.50%</td>
</tr>
<tr>
<td>Pressure pipe (% of Dia)</td>
<td>7.50%</td>
<td>6.00%</td>
<td>6.00%</td>
<td>6.00%</td>
<td>5.00%</td>
<td>4.00%</td>
<td>3.00%</td>
</tr>
</tbody>
</table>

\[ \% \Delta D = \frac{0.0125 P_{\text{max}}}{E_{\text{long}} (12 \cdot (DR - 1))^3} \quad \% \Delta D = 13.9 \quad \text{Ring deforation} \]

\[ \text{mud}_{\text{wt}} = 89.76 \frac{\text{lb}}{\text{ft}^3} \quad \text{Mud weight value, } 12 \text{ ppg} = 89.76 \text{ lb/ft}^3 \]

\[ x = 12 \frac{\text{lb}}{\text{gal}} \quad x = 89.8 \frac{\text{lb}}{\text{ft}^3} \]

\[ \% \Delta D_b = \frac{0.888 \text{mud}_{\text{wt}} D^4 (DR - 1)}{E_{\text{long}} DR} \cdot 100 \quad \% \Delta D_b = 0.127 \quad \text{Buoyant deformation} \]
Use highest load to determine the safety factor against buckling.

\[ f_0 = 0.35 \quad \text{Ovality compensation factor based on ovality above and table.} \]

\[ N_s = 1 \quad \text{Safety Factor} \]

\[ P_{uc} = \frac{2E_{long}}{1 - \mu} \left( \frac{1}{DR - 1} \right)^3 \frac{f_0}{N} \quad P_{uc} = 24.8 \text{psi} \quad \text{Critical unconstrained buckling pressure (safety factor applied)} \]

Safety factor against buckling

\[ SF_{buckling} = \frac{P_{uc}}{P_{max}} \quad SF_{buckling} = 0.946 \]

Tensile ratio based on assumed 1051 psi pull stress calculation:

\[ r = 0.2 \]

\[ f_t = \sqrt{5.57 - (r + 1.09)^2} \quad f_t = 0.9 \quad \text{tensile reduction factor} \]

Estimated collapse pressure with reduction for tensile pulling force:

\[ P_{cr} = \frac{2E_{long}}{1 - \mu} \left( \frac{1}{DR - 1} \right)^3 \frac{f_0 f_t}{N} \quad P_{cr} = 44.7 \text{psi} \quad SF = \frac{P_{cr}}{P_{max}} \quad SF = 1.7 \quad \text{Safety factor against collapse during pull} \]

**EXAMPLE 7-4G** Calculated Force Required to Pull Back PE Pipe and the Safety Factor Against Collapse
EXAMPLE 7-5A  Calculated Force Required to Pull Back PE Pipe and the Safety Factor Against Collapse

Input Data:

- **D** = 8.625 in
- **t** = 0.78 in
- **E** sub 24 = 57500 psi
- **δ** sub sp = 1100 psi
- **δ** sub long = 28200 psi
- **Dr** = 11
- **ID** = **D** - 2 * **t**
- **ν** = 0.45
- **μ** sub soil = 0.1
- **ρ** sub w = 62.2 lb/ft³
- **μ** sub mud = 0.1 lb/ft²
- **γ** sub b = 1.4
- **γ** sub a = 0.95
- **γ** sub w = 1.4

### Calculations

**Pipe outside diameter, inches**: D = 8.625 in

**Pipe wall thickness, inches**: t = 0.78 in

**Long Term Modulus, psi**: E sub 24 = 57500 psi

**Safe 24 hour pull stress**: δ sub sp = 1100 psi

**24 hour Modulus, psi**: δ sub long = 28200 psi

**Pipe wall thickness for PE pipe**: t = D / Dr

**Pipe wall thickness for PE pipe**: t = (D - 2 * t) / Dr

**Pipe weight calculation**:

\[ \text{Pipe weight} = \pi \cdot D^2 \cdot \frac{DR - 1}{DR^2} \cdot \rho \cdot \gamma_a \]

\[ \text{Pipe weight} = 7.93 \text{ lb/ft} \]

**Average wall thickness**: w_a = 1.06 * pipe weight

**Average weight of empty pipe**: w_a = 8.4 lb/ft
EXAMPLE 7-5B Calculated Force Required to Pull Back PE Pipe and the Safety Factor Against Collapse

\[
W_s = w_a + \text{water}_{\text{weight}}
\]

\[
|W_s| = 11.07 \text{ lb/ft} \quad \text{Effective submerged weight per foot of the pipeline plus internal contents, lbs/ft}
\]

\[
L_1 = 115\text{ft} \quad \text{Length of straight section 1 (pipe side - exit pit)}
\]

\[
\theta_{s1} = 10\text{deg} \quad \text{Angle in degrees from horizontal for straight section 1 (pipe side - exit pit)}
\]

\[
\theta_{c1} = 10\text{deg} \quad \text{Angle in degrees from horizontal for curved section 1 (pipe side - exit pit)}
\]

\[
R_1 = 1000\text{ft} \quad \text{Radius of curvature of section 1, pipe side, feet}
\]

\[
L_{arc1} = R_1 \theta_{c1} \quad L_{arc1} = 174.5\text{ft} \quad \text{Length of curved section 1 (pipe side - exit pit)}
\]

\[
L_s = 1620\text{ft} \quad \text{Length of straight section between bends}
\]

\[
\theta_s = 0\text{deg} \quad \text{Angle in degrees from horizontal for straight section between bends}
\]

\[
\theta_{c2} = 12\text{deg} \quad \text{Angle in degrees from the horizontal for curved section 2 (rig side - entry pit)}
\]

\[
R_2 = 1000\text{ft} \quad \text{Radius of curvature of section 2, rig side, feet}
\]

\[
L_{arc2} = R_2 \theta_{c2} \quad L_{arc2} = 209.44\text{ft} \quad \text{Length of curved section 2 (rig side - entry pit)}
\]

\[
L_2 = 81\text{ft} \quad \text{Length of straight section 2 (rig side - entry pit)}
\]

\[
\theta_{s2} = 12\text{deg} \quad \text{Angle in degrees from horizontal for straight section 2 (rig side - entry pit)}
\]

\[
L_{total} = L_1 + L_{arc1} + L_s + L_{arc2} + L_2 \quad L_{total} = 2200\text{ft}
\]

Pulling Loads

\[
\text{hydro pressure} = 5\text{psi} \quad \text{hydrokinetic pressure}
\]

\[
D_{bh} = 1.5D \quad D_{bh} = 12.94\text{in} \quad \text{borehole diameter, inches}
\]

\[
T_{hk} = \text{hydro pressure} \pi \left( \frac{D_{bh}^2}{4} - D^2 \right) \quad T_{hk} = 182.58\text{lb} \quad \text{hydrokinetic force, lbs}
\]
Chapter 7  HDD Pipe Stress Analysis for Plastic Pipe

**Straight Section at point 2**

\[ \Delta T_2 = T_2 - T_1 \quad \text{fric} = W_s \cdot L_1 \cdot \cos(\theta_{s1}) \cdot \mu_{soil} \quad \text{DRAG} = \pi \cdot D \cdot L_1 \cdot \mu_{mud} \]

\[ |\text{fric}| = 125.4 \text{ lbf} \quad \text{DRAG} = 373.9 \text{ lbf} \]

\[ \Delta T_2 = |\text{fric}| + \text{DRAG} - W_s \cdot L_1 \cdot \sin(\theta_{s1}) + T_{hk} \]

\[ \Delta T_2 = 902.9 \text{ lbf} \]

\[ T_1 = 0 \text{ lbf} \quad \text{Pull back as the pipe enters the drill hole.} \]

\[ T_2 = \Delta T_2 + T_1 \]

\[ T_2 = 902.9 \text{ lbf} \quad \text{Pull load at point 2} \]

**Curved Section at point 3**

\[ T_{3\text{avgassumed}} = 1478 \text{ lbf} \]

\[ h = R_1 \left(1 - \cos \left(\frac{\theta_{c1}}{2}\right)\right) \quad h = 3.81 \text{ ft} \]

\[ I = \pi \cdot (D - t) \cdot \frac{3}{8} \cdot t \quad I = 148.43 \text{ in}^4 \]

\[ j = \left(\frac{E_24}{T_{3\text{avgassumed}}} \cdot \frac{1}{j}\right)^{\frac{1}{2}} = 75.99 \text{ in} \]

\[ U = \frac{\frac{\text{arc1}}{j}}{j} \quad U = 27.5613 \]

\[ X = 3 \cdot \frac{\theta_{c1}}{12} - \left(\frac{1}{2}\right)^{-\text{tanh} \left(\frac{U}{2}\right)} \]

\[ X = 485.6 \text{ in} \]

\[ Y = 18 \left(\frac{\text{arc1}}{12}\right)^{2} - 2 \left(1 - \frac{1}{\cosh \left(\frac{U}{2}\right)}\right) \]

\[ Y = 542536.8 \text{ in}^2 \]

\[ N_{x} = \frac{T_{3\text{avgassumed}} \cdot h - W_s \cdot \cos \left(\frac{\theta_{s1}}{2}\right) \cdot Y}{X} \quad N = 1165.7 \text{ lbf} \]

\[ \Delta T_3 = T_3 - T_2 \quad \text{fric} = \left|N \cdot \mu_{soil}\right| \quad \text{fric} = 116.6 \text{ lbf} \]

\[ \text{DRAG} = \pi \cdot D \cdot \text{arc1} \cdot \mu_{mud} \quad \text{DRAG} = 567.5 \text{ lbf} \]

**EXAMPLE 7-5C**  Calculated Force Required to Pull Back PE Pipe and the Safety Factor Against Collapse
EXAMPLE 7-5D Calculated Force Required to Pull Back PE Pipe and the Safety Factor Against Collapse
EXAMPLE 7-5E  Calculated Force Required to Pull Back PE Pipe and the Safety Factor Against Collapse

\[ X = 3 \frac{L_{arc2}}{12} - \left( \frac{1}{2} \right) \tanh \left( \frac{U}{2} \right) \quad X = 613.59 \text{ in} \]

\[ Y = 18 \left( \frac{L_{arc2}}{12} \right)^2 - \left( \frac{1}{2} \right)^2 \left( 1 - \frac{1}{\cosh \left( \frac{U}{2} \right)} \right) \quad Y = 788700.2 \text{ in}^2 \]

\[ N = \frac{N_{avgassumed} \cdot h - W_s \cdot \cos \left( \frac{\theta \cdot c}{2} \right)}{Y} \quad N = 2232.47 \text{ lb} \]

\[ \Delta T_5 = T_5 - T_4 \quad \text{fric} = \left| N \cdot \mu_{soil} \right| \quad \text{fric} = 223.25 \text{ lb} \]

\[ \text{DRAG} = \pi \cdot D \cdot L_{arc2} \cdot \mu_{mud} \quad \text{DRAG} = 681 \text{ lb} \]

\[ \Delta T_5 = 2 \cdot \text{fric} + \text{DRAG} + W_s \cdot L_{arc2} \cdot \sin \left( \frac{\theta \cdot c}{2} \right) + T_{hk} \quad \Delta T_5 = 1067.74 \text{ lb} \]

\[ T_5 = \Delta T_5 + T_4 \quad T_5 = 10365.6 \text{ lb} \quad \text{Pull load at point 5} \]

\[ T_{avg2} = \frac{T_5 + T_4}{2} \quad T_{avg2} = 9831.73 \text{ lb} \]

\[ \frac{T_{avg2} - T_{5avgassumed}}{T_{5avgassumed}} = 0.100 = 0 \quad \text{if this does not fall within the 10% limit pick new assume tension.} \]

**Straight Section at point 6**

\[ \Delta T_6 = T_6 - T_5 \quad \text{fric} = W_s \cdot L_{arc2} \cdot \cos \left( \frac{\theta \cdot c}{2} \right) \cdot \mu_{soil} \quad \left| \text{fric} \right| = 87.7 \text{ lb} \]

\[ \text{DRAG} = \pi \cdot D \cdot L_{arc2} \cdot \mu_{mud} \quad \text{DRAG} = 263.38 \text{ lb} \]

\[ \Delta T_6 = \left| \text{fric} \right| + \text{DRAG} + W_s \cdot L_{arc2} \cdot \sin \left( \frac{\theta \cdot c}{2} \right) + T_{hk} \quad \Delta T_6 = 347.24 \text{ lb} \]

\[ T_6 = \Delta T_6 + T_5 \quad T_6 = 10712.8 \text{ lb} \quad \text{Pull load at point 6} \]
EXAMPLE 7-5F  Calculated Force Required to Pull Back PE Pipe and the Safety Factor Against Collapse

\[ T_{\text{total}} = \Delta T_2 + \Delta T_3 + \Delta T_4 + \Delta T_5 + \Delta T_6 \]

\[ T_{\text{total}} = 10712.8 \text{ lb} \quad \text{Total pull load of the pipe} \]

**Approximate Axial Bending Stress:**

Radius of curvature should not exceed 40 times the pipe OD to minimize ring kinking.

\[ r = 40\text{-D} \quad r = 28.75\text{ft} \quad R > r \text{ Okay} \]

**Bending Strain**

\[ \varepsilon_{\text{ain}} = \frac{D}{2R_1} \quad \varepsilon_{\text{ain}} = 0.0004 \quad \text{equals pipe entry bending strain in/in.} \]

\[ \varepsilon_{\text{ex}} = \frac{D}{2R_2} \quad \varepsilon_{\text{ex}} = 0.0004 \quad \text{equals pipe exit bending strain in/in.} \]

**Bending Stress:**

\[ \delta_{\text{ain}} = E_{24} \varepsilon_{\text{ain}} \quad \delta_{\text{ain}} = 20.7\text{psi} \quad \text{equals pipe entry bending stress} \]

\[ \delta_{\text{ex}} = E_{24} \varepsilon_{\text{ex}} \quad \delta_{\text{ex}} = 20.66\text{psi} \quad \text{equals pipe exit bending stress} \]

\[ \delta_{\text{allow}} = \delta_{\text{sp}} - \frac{E_{24} D}{2R_2} \quad \delta_{\text{allow}} = 1079.3\text{psi} \quad \text{Allowable bending stress} \]

Compare axial tensile stress due to pullback force with allowable tensile stress (1079 psi).

**Average estimated axial stress** acting on the pipe cross-section at points 1, 2, 3, 4.

\[ \sigma_1 = \frac{T_1}{\pi D^2 \left( \frac{DR^2}{DR - 1} \right)} \quad \sigma_1 = 0\text{psi} \]

\[ \text{RESULT}_1 = \begin{cases} \text{return "PASS" if } \sigma_1 < \delta_{\text{allow}} & \text{RESULT}_1 = "PASS" \\ \text{return "FAIL." otherwise} & \end{cases} \]

\[ \sigma_2 = \frac{T_2}{\pi D^2 \left( \frac{DR^2}{DR - 1} \right)} \quad \sigma_2 = 46.75\text{psi} \]
EXAMPLE 7-5G  Calculated Force Required to Pull Back PE Pipe and the Safety Factor Against Collapse

\[
\sigma_3 = \frac{T_3}{\pi D^2} \frac{DR^2}{DR - 1} + \frac{E_{24} D}{2 R_1} + \delta_{ain} \quad \sigma_3 = 147.7\text{psi}
\]

\[
\text{RESULT}_3 = \begin{cases} 
\text{"PASS"} & \text{if } \sigma_3 < \delta_{allow} \\
\text{"FAIL"} & \text{otherwise}
\end{cases} \quad \text{RESULT}_3 = \text{"PASS"}
\]

\[
\sigma_4 = \frac{T_4}{\pi D^2} \frac{DR^2}{DR - 1} \quad \sigma_4 = 481.39\text{psi}
\]

\[
\text{RESULT}_4 = \begin{cases} 
\text{"PASS"} & \text{if } \sigma_4 < \delta_{allow} \\
\text{"FAIL"} & \text{otherwise}
\end{cases} \quad \text{RESULT}_4 = \text{"PASS"}
\]

\[
\sigma_5 = \frac{T_5}{\pi D^2} \frac{DR^2}{DR - 1} + \frac{E_{24} D}{2 R_2} + \delta_{aex} \quad \sigma_5 = 578\text{psi}
\]

\[
\text{RESULT}_5 = \begin{cases} 
\text{"PASS"} & \text{if } \sigma_5 < \delta_{allow} \\
\text{"FAIL"} & \text{otherwise}
\end{cases} \quad \text{RESULT}_5 = \text{"PASS"}
\]

\[
\sigma_6 = \frac{T_6}{\pi D^2} \frac{DR^2}{DR - 1} \quad \sigma_6 = 554.65\text{psi}
\]

\[
\text{RESULT}_6 = \begin{cases} 
\text{"PASS"} & \text{if } \sigma_6 < \delta_{allow} \\
\text{"FAIL"} & \text{otherwise}
\end{cases} \quad \text{RESULT}_6 = \text{"PASS"}
\]
Breakaway links should be set so that the pull-back force applied to the pipe does not exceed 1079 psi.

\[ F_b = \delta_{SP} \frac{2}{4} \left( \rho^2 - \Delta D^2 \right) \]
\[ F_b = 21245.9 \text{ lbf} \]

RESULT \( T_{\text{pull}} = \) return "PASS" if \( T_{\text{total}} < F_b \)
RESULT \( T_{\text{pull}} = "FAIL" \) otherwise

**Estimate safety factor against ring collapse during pullback**

\[ H = 35.16 \text{ ft} \]
\[ \text{depth}_5 = 16.84 \text{ ft} \]

**External hydraulic load:**

\[ P_{\text{ext}} = P_w \cdot h \]
\[ P_{\text{ext}} = 21.26 \text{ psi} \]

**External static head pressure:**

\[ P_{\text{max}} = P_{\text{ext}} + \text{hydro pressure} \]
\[ P_{\text{max}} = 26.26 \text{ psi} \]

**Find the estimated critical collapse pressure:**

Calculate the ring deflection. Use the larger of the deflections resulting from (a) soil loads assuming no side support or from (b) buoyant deflection due to mud weight:

\[
\begin{array}{|c|c|c|c|c|c|c|c|}
\hline
\text{Non-Pressure (% of Dia.)} & 21 & 17 & 15.5 & 13.5 & 11 & 9 & 7.3 \\
\hline
\text{Pressure pipe (% of Dia.)} & 7.50 & 7.50 & 7.50 & 7.50 & 7.50 & 7.50 & 7.50 \\
\hline
\end{array}
\]

\[
\% \Delta D = \frac{0.0125 \cdot P_{\text{max}}}{E_{\text{long}}} \cdot 100 \]
\[ \% \Delta D = 13.97 \]

**EXAMPLE 7-5H** Calculated Force Required to Pull Back PE Pipe and the Safety Factor Against Collapse
EXAMPLE 7-5I  Calculated Force Required to Pull Back PE Pipe and the Safety Factor Against Collapse

\[
\% \Delta D_b = \frac{0.88 \mu_{\text{AD}} D \cdot (\text{DR} - 1)^4}{E_{\text{long}} \cdot \text{DR}} \cdot 100 \quad \% \Delta D_b = 0.127 \quad \text{Buoyant deformation}
\]

Use highest load to determine the safety factor against buckling.

\[
\sigma_o = 0.35 \quad \text{Ovality compensation factor based on ovality above and table.}
\]

\[
\frac{\sigma_o}{N} = 1 \quad \text{Safety Factor}
\]

\[
P_{uc} = \frac{2E_{\text{long}}}{1 - v^2} \left( \frac{1}{\text{DR} - 1} \right)^3 f_o \frac{f_T}{N} \quad P_{uc} = 24.75\text{psi} \quad \text{Critical unconstrained buckling pressure (safety factor applied)}
\]

\[
S_{\text{buckling}} = \frac{P_{uc}}{P_{\text{max}}} \quad S_{\text{buckling}} = 0.942
\]

Tensile ratio based on assumed 1079 psi pull stress calculation:

\[
r = \frac{\sigma_o}{2.5\text{allow}} \quad r = 0.22
\]

\[
f_r = \sqrt{5.57 - (r + 1.09)^2} - 1.09 \quad f_r = 0.87 \quad \text{tensile reduction factor}
\]

Estimated collapse pressure with reduction for tensile pulling force:

\[
P_{cr} = \frac{2E_{24}}{1 - v^2} \left( \frac{1}{\text{DR} - 1} \right)^3 f_o f_r \quad P_{cr} = 43.97\text{psi} \quad \text{SF} = \frac{P_{cr}}{P_{\text{max}}} \quad \text{SF} = 1.67 \quad \text{Safety factor against collapse during pull}
\]
8.1 HDD Tracking

One of the primary areas for technological advancement in HDD technology is in location and guidance systems. Having the technology and skill to locate the drill head is vital to the success of any HDD crossing. When HDD technology was first used for utility crossings, just completing the crossing was often considered a successful project. It was not uncommon for a bore to end up with the drill head in the middle of the street, missing the intended target. As the industry has developed and the market has grown, locating systems have become more accurate, dependable, and sophisticated. There are several manufacturers that specialize in location equipment, and it is a very competitive industry. Because of the competition, locator technology is constantly advancing to the point where it is now possible to install sewer lines on grade using HDD. The two most common methods currently in use are the walkover system and the wireline steering tool system. Both systems provide excellent performance in an interference-free environment and have an accepted place in the HDD market.

Walkover System

The type of locator most commonly used in HDD is a walkover system. Walkover systems, as the name implies, require that the locator operator walk over the top of the drill head with a receiver to determine its depth and position. Figures 8-1 and 8-2 show typical walkover-system equipment.
Today’s mini or midi HDD walkover tracking systems evolved from cable locators, while the maxi HDD systems primarily use well-drilling-based accelerometers and magnetometers. Currently locators provide remote data display of pitch-and-roll orientation, temperature, battery status, heading, overheating, and logs of the bore path at depths up to 140 feet.

The walkover method relies on a transmitter or sonde that is placed in a housing located behind the drill bit, a portable handheld receiver, and an optional remote monitor to interpret the drilling data at the drill rig.

The sonde sends a signal to the surface, where it is picked up by a receiver held by the locator. The ability of the transmitter to overcome interference is related to the signal strength and frequency. Literature provided by manufacturers often promises accuracy ranges of $+/- 2$ to $+/- 5$ percent of depth. The locator is able to monitor the path of the bore by reading and analyzing the data provided by the receiver. The receiver processes this signal and provides important pieces of information such as pitch, roll, and depth.

The remote monitor is not a required item; however, it reduces drilling time by providing the HDD rig operator with the information needed to position the drill head. Remote displays attach to the drill rig and display the pitch, roll, and depth information that are on the receiver. This makes it possible for the drill-rig operator to see what the locator operator is seeing. These tools are very useful for the
drill rack operator when trying to position the drill head at a specific clock position or for determining how much of a pitch change is being made while steering.

Pitch is the inclination of the drill head and can be expressed in degrees or as a percent of slope, depending on the locator being used. Pitch as a percent of slope is used most often in the field. If the pitch is zero, the drill head is level from end to end. If there is a minus pitch reading, the drill head is pointing down. A positive reading means the drill head is coming up. By knowing what the pitch reading is, it is easy to calculate how much depth change there will be in the next 10 feet. For example, if the pitch reading is +10 percent, the head will rise one foot in the next 10 feet that the bore advances.
Roll is the rotational position of the duckbill and is very important when making a steering correction. Steering changes are made by thrusting forward without any rotation. The rotational position of the duckbill determines which direction the drill head will move. Roll is commonly referred to as the “clock face” in the field. When the operator of the drill rig faces the direction in which the drill is advancing, 12 o’clock is up, 6 o’clock is down, 3 o’clock is right, and 9 o’clock is left.

FIGURE 8-3  Walkover Process

FIGURE 8-4  Bottom-hole Assembly
The duckbill can be positioned to move in two directions at the same time. An example is the 2 o’clock position, which would cause the drill head to move mainly to the right and a little up. A 7 o’clock steer would cause the drill head to move mainly down and a little to the left. Because of patents, some locator manufacturers have divided the clock face into more segments. However, the vast majority of operators in the field use a 12-segment clock when giving and receiving steering commands.

To determine the depth of the drill head, the receiver must be directly on top of it. The receiver converts the signal coming from the sonde and displays the depth. While walkover systems can track bores up to 140 feet, accuracy decreases with increased depth. For example, at 5 feet accuracy could be within 0.1 to 0.25 feet, while at 75 feet it could be only within +/− 3.75 feet.

In general, walkover systems are the most economical method of guidance within certain technical parameters. Benefits of the walkover system include:

1. **Cost.** After the initial investment cost, the primary expense incurred is the relatively low-cost but frequent replacement of batteries and the more costly but infrequent replacement of sondes.
FIGURE 8-6  Tracking Positions
2. **Operational efficiency.** A skilled locator can operate a walkover system efficiently. The basics of reading and interpreting the signals must be mastered along with a strong commitment to quality in order to ensure a high degree of accuracy. The quality of the walkover system can be enhanced by full mapping of the bore.

3. **Production rate.** The rapid interpretation of data and expedient decision-making result in a higher production rate as compared to other systems.

4. **Mapping.** Walkover systems can now supply computer-generated bore logs.

Disadvantages of the walkover system include:

1. **Terrain.** Obstacles such as busy freeway intersections or river crossings cannot be physically walked over.

2. **Interference.** Often magnetic interference from overhead power lines or underground traffic signals, buried trash, or rebar in foundations will interfere with accurate signal readings.

3. **Depth.** Walkover systems can be limited by depth or other influences related to the bore.

**Wireline System**

Wireline steering tools are used for long, deep crossings as well as any crossing where walkover tools cannot be used. Wireline location systems are similar to walkover systems. The major difference is the sonde itself. Instead of being powered with “C” cell batteries, power is provided through an insulated wire that exits the rear of the sonde. The wire runs through the drill stem and exits at the rack. The wire is then attached to a 12V or 24V automotive-type battery. Consequently, the battery life of the sonde is not a consideration since the battery is above ground and can be recharged without pulling the drill stem out of the hole. With the wireline system the bore path is monitored during the pilot bore by taking readings of the inclination and azimuth of the probe. The signal is transmitted from the sonde to the remote display on the rack through the wire or through wireless means such as electromagnetic telemetry. Boring with a wireline system is more time-consuming than using a standard walkover system because of the time required to attach a new section of wire every time the rod is changed. Benefits of a wireline steering tool system include:

1. **Depth.** Since power and signals are conducted by the wire, there is virtually no limit to the depth or length that a bore may be guided.

2. **Accuracy.** A wireline system may be used with an auxiliary system that utilizes a surface grid. This grid forms a magnetic field and results in increased
accuracy. The information produced is transmitted to the surface computer and printed out for evaluation.

3. **Record keeping.** The computer produces hard data that can be used to produce accurate as-built data for the drill.

4. **Efficiency.** There is no tripping out of the hole to replace batteries, a frequent occurrence in time-consuming hard rock bores.

Disadvantages of a wireline steering tool system include:

1. **Cost.** Initial cost and/or rental of manpower and equipment have been somewhat prohibitive in the lower-priced utility markets. However, this potential drawback is often eliminated by the increased success rate and accuracy of completing a difficult bore.

2. **Interpretation of data.** Expertise in operating the equipment requires training that is not readily available or cost-effective for many contractors.

3. **Wireline connections.** Making connections requires time. Shorts can occur in the wire, resulting in poor readings and adding to the loss in productive time required to locate them.

### Interference and HDD Location Systems

Depth, direction, pitch, and roll are the basic information displayed by HDD receivers. The transmitter inside the sonde generates a magnetic field, which the receiver interprets as depth and direction. A second type of a signal is used to broadcast data, which includes pitch, roll, transmitter temperature, and battery status. If properly calibrated and used with no outside interference, these receivers provide the accurate information needed for steering. When drilling in or around urban areas, interference is almost always present.

Interference is usually defined as active or passive. Active interference puts out a signal or generates its own magnetic field. Anything electrical puts out a magnetic field to some extent. Examples of active interference are power lines, traffic loops, fiber trace lines, and invisible dog fences. Do not assume that if there is no evidence of electrical interference on the ground that none is there. Active interference can result in erratic signal strength and depth readings, loss of pitch and roll data, and inaccurate calibration, which may lead to depth errors.

Passive interference does not emit a signal of its own. Passive interference is anything that blocks, absorbs, or distorts a magnetic field. Examples of passive interference are metal structures, rebar, and salt water. Anything that is conductive has the potential to act as passive interference. The effects of passive interference may be incorrect depth readings, incorrect drill head location and direction reports, blocked information, and incorrect calibration, all of which may lead to depth errors.
It is important to identify where interference is coming from and to determine its effect on the locating equipment. Before any drilling operations, walk the bore path with the transmitter turned off while looking for signal readings on the receiver. High signals indicate interference. The higher the signal level, the greater the interference level. Receiver brands display signals in various formats. This makes it difficult to provide hard and fast rules. In all instances the amount of signal being read by the receiver from the transmitter needs to exceed the interference by a significant amount to ensure adequate location. Based on the data from this walkdown, the areas that are subject interference should become clear. The first walkdown primarily checks for effects on the depth readings.

The second part of the test involves the transmitter. The purpose of this test is to determine the reliability of the pitch-and-roll signal reception. At any given depth the receiver will see a pitch/roll signal of a given strength from the transmitter in the ground. The question is whether this signal is powerful enough to overcome the interference. One method often used is to simulate the bore by inserting batteries in the transmitter and carrying it so that it is 1.5 times the anticipated drill depth removed from the receiver, which is being walked down the bore path. If the pitch-and-roll information is not affected during this test, you can assume that the bore is not affected by interference. Although this test is quite effective, it cannot pick up all potential problems.

When dealing with interference, consider the following options for resolving the conflict. After the interference source is identified, determine if it can be turned off. Security systems, invisible dog fences, and in some cases power can often be shut off temporarily. Determine the separation from the interference source. This often requires locating off the drill path using advanced methods, such as off-track guidance or remote steering. The drill path may effectively be out of range of the interference but still within range of the transmitter. Using a stronger transmitter is often an effective way of overcoming interference, and using a transmitter with a different operating frequency may provide better results for the area.

**Surveying in Rock Formations**

In the past, drilling in solid rock with mid-size or smaller HDD equipment was not an option. The reason was that the batteries in the transmitter would arc from the vibration and cause the transmitter to turn on and off. Eventually the constant shock on the transmitter would cause it to fail. The heat buildup from the friction resulting from the rock drilling was also a problem. However, recently the industry has made great strides in rock drilling. Equipment has been developed to isolate the transmitter from side and front shock load by incorporating the use of vibration-dampening isolators. These isolators greatly reduce shock and vibration to the transmitter and also increase battery life. The isolators are located on both ends...
of the transmitter and provide a tight fit that keeps the transmitter from rattling around in the housing.

In the past the batteries for the transmitters were two “C” cell batteries that were soldered together and shrink-wrapped. Today, most tracking companies offer a one-piece lithium battery, which gives the transmitter 150 to 200 hours of operation. This lithium battery eliminates intermittent information by reducing the amount of connection areas.

Heat is the primary enemy of all transmitters. When drilling in abrasive solid rock or cobble, there is a tremendous amount of heat transfer from the drill head to the transmitter housing. The bentonite slurry commonly used in HDD applications helps to compensate for this problem. The slurry assists in moving the cuttings out of the drilled hole and cools the transmitter. Most transmitters fail when the temperature exceeds 220 degrees F. Some of these transmitters can be serviced in the field, while others have to be sent back to the manufacturing company for repair or reprogramming. Some transmitters on the market today are double-insulated with fiberglass to help keep the heat away. All manufacturers of tracking equipment have the ability to display the transmitter temperature. Remember, this temperature is calculated inside the transmitter. The outside temperature of the drill head and transmitter housing can be much greater. Keep this in mind when the transmitter temperature starts to rise.

When drilling in rock, the process is very slow. A 10-foot rod could take one hour or longer to bore. There are transmitters on the market that can be programmed to stay “on” until the battery or batteries lose power. This feature keeps the drill operator from rotating the drill head and losing the face orientation. With the help of tracking equipment rock and cobble drilling can be accomplished.

Surveying Water Crossings

Many water crossings can use a walkover locating system. The alternative is to use a wireline steering tool, which typically involves renting specialized tooling and operating personnel. This is usually a costly option; however, on some of the larger, more exacting crossings wireline systems are the appropriate method for HDD surveying. A good drill plan is critical for water crossings. Anything from commercially available drill-planning software to a pencil and pad of paper will assist in developing a proper plan.

While drill planning is always a good idea, it is even more important when crossing water for a variety of reasons. First and foremost is that incomplete or inadequate locating information should be anticipated. A drilling plan helps prepare for and handle the unexpected. Minimally, a rod-by-rod listing of planned pitch and depth, as well as basic topography information, should be on hand before the crossing begins. This allows the rig operator to follow the planned drill profile. The
locator out in front only has the responsibility for determining left and right direction. Assuming the ground conditions do not allow the drill stem to follow the planned path, the decision-making process for steering corrections becomes much easier when you have a plan to compare your drill data to.

There are several special items of consideration for water crossings. One item is the salinity of the water body. Salt water will degrade the transmitted signal, causing erroneous depth readings. The effect can be so great that a traditional battery-powered transmitter is not a viable option. Some manufacturers of walkover locating systems offer a hard-wired transmitter, which transmits pitch-and-roll information back up the wire to the drill-rig operator. This information is constant, regardless of any outside interference or salinity. The depth and directional information, however, may not be adequate to track through the salt water due to signal degradation. Depending on the specific heading or line requirements of the crossing, the lack of directional information may not be a problem. If it is, the more sophisticated wireline guidance tools would be the only remaining option.

Boats are commonly used for locating over water; however, it is important to use non-metal boats made out of fiberglass, wood, or rubber. This eliminates any interference caused by the boat itself. If using an outboard, shut it off during locating (if possible), as the electrical noise of the ignition may interfere with the pitch/roll signal and depth readings. Stringing a cable across the water to keep the boat steady and on course may also be a consideration. The cable also serves as the intended drill path. If possible, station spotters on either side of the water crossing. The spotter on the far side acts as a moving marker, while the near side spotter sights down the drill path. Once the locator on the boat has found the drill head, the spotter on the near side can sight in the boat and radio to the target person on the far side and line him or her up with the boat. This will indicate the direction of the bore and give a fixed, predicted crossing point. The point can be compared with the desired crossing point, and the appropriate steering corrections, if required, can be made.

### 8.2 HDD Survey

#### Bore-Profile Calculations

A basic understanding of triangles is important for the planning, surveying, and construction of HDD installations. Figure 8-7 is an example of a right triangle.

Using the length of any one of the elements, the length of the unknown elements of the triangle can be calculated with the following equations.

If “\( a \)” is known:

\[
    c = \frac{a}{\cos(\theta)} \quad \text{Equation 8-1} \quad \text{and} \quad b = a \tan(\theta) \quad \text{Equation 8-2}
\]
Or the angle can be calculated by using:

\[ \theta = \tan^{-1}\left(\frac{b}{a}\right) \quad \text{Equation 8-3} \quad \text{or} \quad \theta = \cos^{-1}\left(\frac{a}{c}\right) \quad \text{Equation 8-4} \]

If “b” is known:

\[ a = \frac{b}{\tan(\theta)} \quad \text{Equation 8-5} \quad \text{or} \quad c = \frac{b}{\sin(\theta)} \quad \text{Equation 8-6} \]

Or the angle can be calculated by using:

\[ \theta = \sin^{-1}\left(\frac{b}{c}\right) \quad \text{Equation 8-7} \quad \text{or} \quad \theta = \tan^{-1}\left(\frac{b}{a}\right) \quad \text{Equation 8-8} \]

If “c” is known:

\[ a = c \cdot \cos(\theta) \quad \text{Equation 8-9} \quad \text{or} \quad b = c \cdot \sin(\theta) \quad \text{Equation 8-10} \]

Or the angle can be calculated by using:

\[ \theta = \sin^{-1}\left(\frac{b}{c}\right) \quad \text{Equation 8-11} \quad \text{or} \quad \theta = \cos^{-1}\left(\frac{a}{c}\right) \quad \text{Equation 8-12} \]
Figure 8-8 is an example of a bend in the HDD pipe. For many HDD applications the desired bending radius is determined from the pipe stress analysis, and the desired angle is determined from the bore-path profile. Using the desired radius and angle the values for “c” and “b” can be determined from the following equations:

\[ c = R \theta \quad \text{Equation 8-13} \]  
\[ b = R(1 - \cos(\theta)) \quad \text{Equation 8-14} \]

With the calculated value of “b,” the value of “a” can be calculated from the following equations:

\[ a = \sqrt{b(2R - b)} \quad \text{Equation 8-15} \]  
\[ a = \sqrt{2Rb - b^2} \quad \text{Equation 8-16} \]

In some instances the desired horizontal and vertical distances are known. In this case the bending radius can be calculated from the following equation:

\[ R = \frac{a^2 + b^2}{2b} \quad \text{Equation 8-17} \]

For pipeline construction the term “rise over run” is typically used for surveying. This refers to the amount of the elevation gain or loss (usually in feet) over a survey distance. Figure 8-9 is an example of the term. The elevation change over a known distance can be used to calculate the percent slope (or pitch) and the angle using the following equations:

\[ \%\text{slope} = \frac{\text{rise}}{\text{run}} \times 100 \quad \text{Equation 8-18} \]  
\[ \text{angle} = \tan\left(\frac{\text{rise}}{\text{run}}\right) \quad \text{Equation 8-19} \]

\[ \text{run} = \frac{\text{rise}}{\text{pitch}} \times 100 \quad \text{Equation 8-20} \]  
\[ \text{rise} = \frac{\text{run} \times \text{pitch}}{100} \quad \text{Equation 8-21} \]
Construction Monitoring

This section describes some of the construction-monitoring requirements relative to HDD operations. The primary objectives of construction monitoring on an HDD installation are to ensure that the contractor interprets the contract and design documents properly and to ensure that actual drilling is documented. In doing this, it is important for the inspector to document his observations and actions. Should a question or dispute arise during or after the installation, the inspector’s notes will provide the only source of confirming data. Since a drilled installation

FIGURE 8-8  Typical Bend in HDD Pipe
is typically buried with deep cover, its installed condition cannot be confirmed by visual examination.

**Drilled Path**

The drilling contractor will typically rely on the owner’s staking to locate the drilled segment. Two locations, the entry and exit points, should be staked. The elevations of the staked locations as well as the distance between them should be checked against the values on which the design is based. The contractor's pilot-hole accuracy depends on the accuracy of the relative location, both horizontally and vertically, of these two points. The exit-point coordinates will also provide a benchmark for measuring down-hole survey errors. If possible, the contractor should have a clear line of sight between the entry and exit points for use in orienting the down-hole survey instrument. If a clear line of sight is not possible, the owner should stake points so that the drilled-path centerline or a reference line can be established for survey-instrument orientation.

**Pilot Hole**

Monitoring of the drilled path is accomplished during pilot-hole drilling. Initially, a reading of the magnetic heading is taken to establish a reference line on which all drilled-path data and calculations will be based. Other pertinent data needed to accurately locate the pilot-hole drilling bit includes the bottom-hole assembly length,
the length from the drilling bit to the down-hole probe, and the drilling-rig setback distance from the entry point.

The actual path of the pilot hole is monitored during drilling by taking periodic readings of the inclination and azimuth of the down-hole probe. Readings are typically taken after drilling a single joint, or approximately 30 feet. These readings are used to calculate the horizontal and vertical coordinates of the down-hole probe as it progresses along the pilot hole. Data and calculations from the readings typically include the following items:

- **Survey**: points at which readings are taken by the down-hole probe; surveys are usually tracked in a numerical sequence (1, 2, 3...) corresponding to the number of joints drilled
- **Course length**: the distance between two down-hole surveys as measured along the drilled path
- **Measured length**: the total distance of a down-hole survey from the entry point as measured along the drilled path; also, the sum of the course lengths
- **Inclination**: the angle at which the down-hole probe is projecting from the vertical axis at a particular survey point; vertically downward corresponds to zero degrees
- **Azimuth**: the angle at which the down-hole probe is projecting in the horizontal plane at a particular survey point; magnetic north corresponds to zero degrees
- **Station**: the horizontal position of a down-hole survey measured from an established horizontal control system
- **Elevation**: the vertical position of a down-hole survey measured from an established vertical control system
- **Right**: the distance of a down-hole survey from the design-path reference line; positive values indicate right of the reference line while negative values indicate left of the line
- **Bit to probe**: the distance from the drilling bit (leading edge) to the down-hole probe
- **Heading**: the magnetic line of azimuth to which the drilled-path reference line corresponds
- **Rig setback**: the distance from the drill bit when first placed on the drilling rig as measured from the staked entry point
- **BHA length**: the length of the bottom-hole assembly.

**HDD Performance**

There are two basic areas of concern with HDD performance, the position and curvature of the pipeline. First, the pipeline must be installed so that the drilled length, depth of cover, and entry/exit angles specified by the design are achieved. Second,
the installation must not curve along the drilled path in such a way that the pipeline will be damaged during installation or overstressed during operation. The actual position of the drilled path cannot be readily confirmed by an independent survey. Therefore, it is necessary to have a basic understanding of the down-hole survey system being used and be able to interpret the readings. It is not necessary to observe and approve the drilling of each joint. However, progress should be monitored on a routine basis and problems addressed so that remedial action can be taken as soon as possible. The inspector should ensure that bends with a radius of curvature less than the design (minimum allowable) are not drilled. If a tight radius occurs, the joint or joints should be redrilled or reviewed with the design engineers as soon as possible to ensure that the codes and specifications governing the design of the pipeline are not violated.

**Down-Hole Survey Calculations.** Down-hole-survey calculation methods are discussed in detail in API Bulletin D20. Three different methods from this bulletin are presented here for use on HDD pipeline installations. The three commonly used methods are the average angle, balanced tangential, and minimum curvature methods. The equations for these three methods are used to calculate the horizontal and vertical distances from the entry point as well as the distance from the reference line. Symbols used in the equations are defined below:

- \( CL \) = course length
- \( I_1 \) = inclination angle of the previous survey point
- \( I_2 \) = inclination angle of the current survey point
- \( A_1 \) = deflection angle from the heading of the previous survey point
- \( A_2 \) = deflection angle from the heading of the current survey point
- \( HD \) = horizontal distance between the previous and current survey points
- \( RT \) = differential distance from the reference line between the previous and current survey points; also called “RIGHT” to indicate the distance right (positive value) or left (negative value) of the original reference line
- \( VT \) = vertical distance between the previous and current survey points

The average-angle method uses the average of the previous and current azimuth/inclination angles to project the measured distance along a path that is tangent to this angle. The equations are:

\[
HD = CL \cos \left( \frac{(A_1 + A_2)}{2} \right) \sin \left( \frac{(I_1 + I_2)}{2} \right) \quad \text{Equation 8-22}
\]

\[
RT = CL \sin \left( \frac{(A_1 + A_2)}{2} \right) \sin \left( \frac{(I_1 + I_2)}{2} \right) \quad \text{Equation 8-23}
\]
The balanced tangential method assumes that half the measured distance is tangent to the current inclination/azimuth projections and that the other half is tangent to the previous inclination/azimuth projections:

\[ VT = CL \times \cos\left(\frac{(I1 + I2)}{2}\right) \]  \hspace{1cm} \text{Equation 8-24}

The minimum curvature method is similar to the balanced tangential method; however, the tangential segments produced from the previous and current inclination/azimuth angles are smoothed into a curve using a ratio factor \((RF)\). This ratio factor is defined by a dogleg angle \((DL)\), which is a measure of the change in inclination/azimuth:

\[ DL = \cos^{-1}\left\{\cos(I2 - I1) - \sin I1 \times \sin I2 \left[1 - \cos(A2 - A1)\right]\right\} \]  \hspace{1cm} \text{Equation 8-28}

\[ RF = \left(\frac{2}{DL}\right) \times \tan\left(\frac{DL}{2}\right); \quad RF = 1 \text{ for small angles } (DL < 0.25 \text{ degrees}) \]  \hspace{1cm} \text{Equation 8-29}

\[ HD = \left(\frac{CL}{2}\right) \times \left(\sin I1 \times \cos A1 + \sin I2 \times \cos A2\right) \times RF \]  \hspace{1cm} \text{Equation 8-30}

\[ RT = \left(\frac{CL}{2}\right) \times \left(\sin I1 \times \sin A1 + \sin I2 \times \sin A2\right) \times RF \]  \hspace{1cm} \text{Equation 8-31}

\[ VT = \left(\frac{CL}{2}\right) \times \left(\cos I1 + \cos I2\right) \times RF \]  \hspace{1cm} \text{Equation 8-32}
Any one of these three methods may be used to track the down-hole probe position and ensure conformance to the directional tolerances of the design. To track the probe over a specified measured distance, the values from these equations must be summed over the specified length.

The same angle readings used in the previous calculations are also used to determine the radius of curvature of the drilled path. The radius of curvature calculations are based on the relationship:

\[
R = \frac{c}{\theta} \quad \text{Equation 8-33}
\]

where:
- \( c \) = arc length in feet
- \( \theta \) = angular distance in radians

For a specific drilled length, the radius of curvature is calculated using the following formula:

\[
R_{\text{drilled}} = \left( \frac{L_{\text{drilled}}}{\theta_{\text{drilled}}} \right) \left( \frac{180}{\pi} \right) \quad \text{Equation 8-34}
\]

where:
- \( R_{\text{drilled}} \) = the radius of curvature over a specified drill length in feet
- \( L_{\text{drilled}} \) = drilled length in feet
- \( \theta_{\text{drilled}} \) = change in angle over the drilled length in degrees

Typically, the radius of curvature is checked for conformance over any three joint-course lengths using the following equation:

\[
R_3 = \left( \frac{L_3}{\theta_3} \right) \frac{180}{\pi} \quad \text{Equation 8-35}
\]

where:
- \( R_3 \) = the radius of curvature in feet over \( L_3 \)
- \( L_3 \) = course length in feet over any 3 joints, no less than 75 feet and no greater than 100 feet
- \( \theta_3 \) = total change in angle in degrees over \( L_3 \)

The inspector should review the contractor’s operations to ensure that the pull section is adequately supported during pullback. Roller stands should be provided as well as lifting equipment capable of moving the string into the drill hole. The section should not be dragged on the ground. All breakover bends should be made with a radius long enough to ensure that the pipe is not overstressed.
## FIGURE 8-10  HDD Daily Report

<table>
<thead>
<tr>
<th>Daily Report</th>
</tr>
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<tbody>
<tr>
<td><strong>Date:</strong></td>
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<tr>
<td><strong>Percent Complete:</strong></td>
</tr>
</tbody>
</table>

**Description of Activities:**

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**Comments:**

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### FIGURE 8-11 HDD Survey Tabulation Sheet

<table>
<thead>
<tr>
<th>Survey Tabulation Sheet</th>
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<tbody>
<tr>
<td>Date:</td>
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<tr>
<td>Bit to Probe:</td>
</tr>
<tr>
<td>Azimuth:</td>
</tr>
<tr>
<td>Rig Setback:</td>
</tr>
<tr>
<td>BHA Length:</td>
</tr>
<tr>
<td>Raw Data</td>
</tr>
<tr>
<td>TruTracker Data</td>
</tr>
<tr>
<td>Calculations</td>
</tr>
<tr>
<td>Survey #</td>
</tr>
<tr>
<td>----------</td>
</tr>
</tbody>
</table>
### FIGURE 8-12  HDD Radius of Curvature Analysis

#### Radius of Curvature Analysis

<table>
<thead>
<tr>
<th>Date:</th>
<th>Project:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Notes:</td>
<td></td>
</tr>
</tbody>
</table>

#### Radius of Curvature Per N Surveys

<table>
<thead>
<tr>
<th>Survey #</th>
<th>1</th>
<th>3</th>
<th>5</th>
<th>7</th>
<th>10</th>
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</table>
9.1 General Information

As briefly discussed in Chapter 2, the contractual feasibility of HDD projects is an important issue and can have a major impact on whether the project should be performed with this method of construction. Once it has been determined that a HDD project is technically and economically feasible, the contractual feasibility must be determined. This task can often be performed based on experience with past projects and close coordination between the engineers and qualified HDD contractors. If the project appears to be contractually feasible, a set of contract, or bid, documents must be prepared. The contract documents are used to solicit bids from contractors and to govern construction of the crossing. Contract documents clearly present the technical, commercial, and legal requirements of the project. Most HDD projects are bid as turnkey (lump-sum), footage, and/or daywork (per-diem) contracts.

9.2 Turnkey Contracts

Many HDD projects can be economically bid using standard turnkey contract forms. Often owners prefer this type of contract due to the fixed costs. However, owners should be aware that there is an associated risk with turnkey contracts. If the project becomes economically unfeasible for the HDD contractor, he or she may walk away from the project before completion. Assuming that project completion is required by the owner, this is certainly a risk. Methods of sharing risks
between the owner and contractor are discussed later in this chapter. Risk sharing greatly reduces the chances of a contractor walking off the job.

To reduce the chances of project failure, it is important that the scope of work is understood and that the technical specifications and drawings are accurate. With turnkey contracts the contractor is paid a fixed amount for delivering a drilled segment in accordance with the project plans and specifications. In most cases payment is based on performance and does not vary with the time or effort. For most turnkey contracts the HDD contractor furnishes the equipment and labor and performs the services required to install the product pipe as specified by the owner; payment is due upon the successful installation of the product pipe in accordance with the contract documents. For many turnkey projects certain portions of the operations are performed on a daywork basis. An example of a turnkey contract is provided in Appendix A (courtesy of DCCA).

9.3 Footage Contracts

Footage contracts, if properly written, can be advantageous to both owners and contractors. With footage contracts the contractor is paid for each foot of pilot hole drilled. An advantage over the turnkey contract is that the bid may contain various per-foot unit prices for different subsurface conditions, such as bedrock. This reduces the risk for the contractor and in many instances will result in lower average-per-foot bids for the owner. If no problems are encountered, the owner will often experience lower project costs than with the turnkey contract. Footage contracts also require that the HDD contractor furnish all the equipment, labor, and services needed to install the product pipe as specified in the contract documents. Payment to the HDD contractor at the stipulated price per foot of pilot hole drilled is due after the successful installation of the product pipe in accordance with the contract documents. For many footage projects certain portions of the operations are performed on a daywork basis. An example of a footage contract is provided in Appendix B (courtesy of DCCA).

9.4 Daywork Contracts

This type of contract is usually preferred by HDD contractors, as all or most of the risk is placed on the owner. For daywork contracts the contractor is paid a fixed amount per day, or some other unit of time, for providing a spread of equipment in accordance with the contract documents. Payment is based on the passage of time regardless of the progress made. When operating on a daywork basis, the HDD
contractor is paid at the contract rates and assumes only the obligations and liabilities stated in the contract. Except for any obligations and liabilities specifically assigned to the HDD contractor in the contract, the owner is solely responsible and assumes liability for all consequences of operations by both parties. This type of contract is often preferred on high-risk crossings. If bid as a turnkey or footage contract, high-risk crossings normally come in at very high unit rates, subject to any risk sharing by the owner. Based on the actual problems encountered during the crossing, the owner may experience lower costs with the daywork contract compared to the other contracts.

The daywork contract usually does not specify contractor performance in terms of a completed installation. However, contractor performance is required and should be clearly defined in the contract documents. The required performance should identify the required equipment, materials, and staff needed to complete the project. For daywork contracts, items that can be contracted on a lump-sum basis, such as mobilization and site preparation, should be broken out and priced separately. A sample bidding form for use with a daywork contract is provided in Table 9-1.

9.5 Risk Sharing

Sharing risks with the contractor can significantly reduce the bid prices on a project. This is particularly true in HDD construction. Because of the evolving nature of HDD technology, the industry has employed many contract-form variations. Typically, these variations involve negotiating some type of completion incentive into a turnkey or daywork contract. Significant advances have been made because of owner willingness to assume the risk of cost overruns or completion failure for prospective installations that were not contractually feasible. However, a daywork contract requires much greater oversight by the owner than a typical lump-sum contract. Serious misunderstandings are possible when a standard lump-sum contract form is used for a daywork contract applied to a state-of-the-art drilled river crossing.

Costs

As previously discussed, each type of contract has its advantages and disadvantages. During the preliminary project analysis and planning it is important that the various types of contracts are evaluated and the preferred type for the project identified. Someone experienced with the HDD construction industry is an important asset during this evaluation period. The choice of the type of contract may have a significant impact on the eventual price of the bids and the project. It is usually in
CONTRACTOR proposes to furnish the equipment (fueled, lubricated and maintained), materials and services described on Exhibit “A” for the following rates.

1.0 Mobilization and Rig-up to include all costs involved with transporting CONTRACTOR’S equipment, materials and labor to the jobsite and assembling it complete and ready for operation.

$ ________________ Lump Sum

2.0 Pilot Hole Directional Drilling Operations to include items 1.1, 1.2, 1.3, 1.4, 1.5, and 1.7 on Exhibit “A”. Costs are to be based on a single 10 hour shift operating 7 days per week. Payment will be made based on actual hours working or on ready standby. No payment will be made for equipment downtime or maintenance.

2.1 $ ________ per operating hour

2.2 $ ________ per standby hour

Pilot Hole Directional Drilling Operations conducted in excess of 10 hours per day.

2.3 $ ________ per operating hour

3.0 Reaming and Pull Back Operations to include items 1.1, 1.2, 1.3, 1.5 and 1.7 on Exhibit “A”. Costs are to be based on a single 10 hour shift operating 7 days per week. Payment will be made based on actual hours working or on ready standby. No payment will be made for equipment downtime or maintenance.

3.1 $ ________ per operating hour

3.2 $ ________ per standby hour

Reaming and Pull Back Operations conducted in excess of 10 hours per day.

TABLE 9-1A  Sample Daywork Bid Form
3.3 $_______ per operating hour

4.0 Drilling Mud (not including fresh water) quoted in delivered units. $_______

5.0 Rig-down and Demobilization to include all costs involved with disassembling and removing Contractor’s equipment, materials and labor from the jobsite. $_______ Lump Sum

EXHIBIT “A”
To Daywork Bid dated _______________

CONTRACTOR _______________

1.0 EQUIPMENT, MATERIALS AND SERVICES TO BE FURNISHED BY CONTRACTOR:
The machinery, equipment, tools, materials, supplies, instruments, services and labor listed below, including fuel, lubricants and maintenance shall be provided at the expense of CONTRACTOR unless otherwise noted.

1.1 Horizontal Drilling Rig:
Complete horizontal drilling rig, designated by CONTRACTOR as Rig No. the major components being the ramp, carnage, turntable, vise system, power system and control system. Rig performance parameters are listed below:
Max. Tensile Capacity _________ pounds @ _________ feet per minute
Max. Thrust Capacity _________ pounds @ _________ feet per minute
Torsional Capacity foot-pounds _________ @ _________ revolutions per minute
Max. Travel Speed _________ feet per minute
Max. Rotating Speed _________ revolutions per minute

TABLE 9-1B  Sample Daywork Bid Form
TABLE 9-1C  Sample Daywork Bid Form

Engine: Make, Model, and H.P. ____________________

1.2 Drilling Mud System:
Complete drilling mud system consisting of water/mud intake system, mud tank with mixing system, mud pumps and solids control system. Performance parameters are listed below:
Mud Tank Capacity _______ bbls.

Mud Pumps: Make, Model, Capacity ______________

Engine: Make, Model, and H.P. __________

1.3 Drill Pipe:
Specification and Quantity ________

1.4 Down Hole Survey System:
General Description ______________

1.5 Down Hole Drilling Tools:
General Description ______

1.6 Drilling Mud (not including fresh water):
General Description ______

1.7 Labor:
Skilled labor required to operate the drilling rig and associated equipment provided by Contractor on single shift; ten (10) hour basis is listed below:

<table>
<thead>
<tr>
<th>Description</th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>_______</td>
<td>______</td>
</tr>
</tbody>
</table>

2.0 EQUIPMENT, MATERIALS AND SERVICES TO BE FURNISHED BY OPERATOR:
The machinery, equipment, tools, materials, supplies, instruments, services and labor listed below, including any transportation required, shall be provided at the expense of the Company unless otherwise noted.

2.1 Access to the rig site
2.2 Rig site cleared and graded
2.3 Fresh water at rig site
2.4 Transportation and disposal of excess drilling mud.
2.5 Fabricated and tested pipeline pull section ready for installation.
2.6 Equipment required to handle pipeline pull section prior to and during installation.

3. OTHER PROVISIONS

| TABLE 9-1D | Sample Daywork Bid Form |

| 9.5 Risk Sharing | 249 |
for the owner and the risk for the contractor. This is usually the best situation for all concerned.

**Unknown Subsurface Condition Risk**

As discussed in earlier chapters of this book, all HDD projects have a degree of uncertainty. Even the best subsurface survey methods do not allow for a detailed definition of every area of a broad subsurface space. For all HDD crossings there is a risk of operational problems due to this uncertainty. For turnkey contracts all or most of this risk is assumed by the contractor. To keep the costs of turnkey projects lower, many owners are sharing part of the risk with the HDD contractor. For turnkey contracts the contractor will prepare the bid with the appropriate contingency cost included to offset the anticipated risk. Usually the bid is based on all the information gathered by the owner or engineer and the contractor’s knowledge of the project. Unless unusual circumstances are encountered, a contractor should be entitled to extra compensation due to changed conditions. For example, if bedrock is encountered after the subsurface survey indicates none; the contractor should be allowed extra compensation. Effective subsurface surveys will usually eliminate this type of problem, but they do happen. However, changes such as encountering gravel where borings indicated coarse sand are not sufficiently different to require compensation. Another example is encountering cobbles or boulders in a glacial geologic area. Even though the test bores may not have penetrated a boulder, random cobbles and boulders can be a characteristic of glacially deposited soils.

**9.6 Technical Specifications and Drawings**

As with all projects, the plan and profile drawings for a HDD project should complement the technical specification by providing a clear presentation of the crossing design as well as the results of topographic, hydrographic, and geotechnical surveys. The project drawings are used by the HDD contractor to produce a working profile that will be used for down-hole navigation. Figure 9-1 is an plan-view drawing, and Figure 9-2 is a profile drawing of a HDD crossing.
Chapter 9  •  HDD Contracts

FIGURE 9-2  HDD Profile Drawing
A sample technical specification for a HDD project on a natural gas pipeline follows:

**SAMPLE TECHNICAL SPECIFICATION**
**SECTION 15196**
HORIZONTAL DIRECTIONAL DRILLING (HDD)
STEEL NATURAL-GAS PIPELINE

**PART 1 GENERAL**

This section covers the installation of the natural-gas pipeline by HDD. HDD is a trenchless excavation method that is accomplished in two phases. The first phase consists of drilling a small-diameter pilot hole along a designed directional path. The second phase consists of enlarging the pilot hole to a diameter suitable for installation of the pipe and pulling the pipe into the enlarged hole. HDD is accomplished using a specialized horizontal drilling rig with ancillary tools and equipment.

**1.1 SCOPE OF WORK**

This Contract covers the general material and construction services required for the installation of a section of natural-gas pipeline for the HENRY LINK HIGHWAY PROJECT. The WORK will consist of the HDD installation of approximately 405 linear feet of 8-inch gas pipe and connection of the new pipeline to the existing 8-inch natural-gas pipeline as shown in the project plans. The new pipe will be tested at 375-psig and operated at 250-psig.

Plans will be furnished by OWNER and/or ENGINEER to the CONTRACTOR with an appropriate material list. The OWNER shall supply the CONTRACTOR with all materials necessary for the completion of the WORK specified herein, except where it is expressly stated that the CONTRACTOR shall furnish materials. The CONTRACTOR shall regulate his supplies so that at all times there will be a sufficient quantity of material on site to prevent any delay to the WORK. The drawing package for this bid package includes Plan and Profile Sheets, Standard Details, Erosion and Sediment Control Details, and Piping Details. The pipe was positioned from a field investigation of the area and is located on the alignment sheets in reference to existing structures or edge of pavement (EP) as determined in the field. The location of existing structures and pavement edges on the alignment sheets may be distorted slightly in some areas; however, the dimensional callouts of the pipe location are accurate to true physical conditions.

**1.2 STANDARDS**

The WORK covered by these Specifications consists of the performance of all operations and the furnishing of all labor, equipment, materials, supplies, and other facilities as required for the construction of the natural-gas pipeline, complete, tested, and accepted. All WORK on the natural-gas pipeline shall be performed in accordance with: Title 49 of the Code of Federal Regulations, Chapter I, Part 192 (49 CFR 192), Transportation of Natural and Other Gas by Pipeline: Minimum Federal Safety Standards, and any other applicable standards that are hereby incorporated into these Specifications by reference. For purging and gas-up operations the CONTRACTOR shall comply with the requirements of SubPart N, Qualification of Pipeline Personnel, in 49 CFR 192.

**1.3 MATERIALS**

These material specifications cover only those materials that, by use, have been found satisfactory for the purpose intended. No material purchased under these specifications shall be used until OWNER has given approval.
1.4 DRUG TESTING

All employees of the CONTRACTOR who will be involved with construction operations under this contract shall be required to participate in an anti-drug/drug-testing program. This program shall be administered in accordance with Title 49 of the Code of Federal Regulations, Chapter I, Part 199 (49 CFR 199), Drug Testing, and Subtitle A, Part 40, Procedures for Transportation Workplace Drug Testing Programs. The CONTRACTOR shall furnish the OWNER with documentation of participation in a qualified drug-testing program. Prior to the performance of any welding and/or tie-in operations, a negative (no evidence of drug use) test must be documented for all employees who will be involved with these operations. Initial and subsequent documentation shall be recorded and submitted to the OWNER on the CONTRACTOR Drug Screening Statement included with the Contract Documents.

1.5 SAFETY

Suitable barricades, lights, applicable signs, flag staff, and watch staff shall be provided when required by the OWNER and/or the North Carolina Department of Transportation in all areas in which WORK is performed. All safety-related equipment specified herein shall be in full compliance with the minimum governing regulation subject to approval of the ENGINEER and shall be included in the CONTRACT price. General construction operations applicable to gas-facilities installation shall be performed in accordance with Title 29 of the Code of Federal Regulations, Chapter I (29 CFR 1926), Occupational Safety and Health Standards for the Construction Industry, and any other applicable standards that are hereby incorporated into these Specifications by reference.

1.6 MEASUREMENT AND PAYMENT

For the purposes hereof, the term “turnkey basis” means that the CONTRACTOR shall furnish the equipment and labor and perform all the services as herein provided to install the gas pipeline as specified by the OWNER in the project plans and specifications. Subject to the terms and conditions hereof, payment to the CONTRACTOR is earned upon the successful installation of the gas pipeline specified by the OWNER. Unless otherwise agreed to prior to the commencement of operations, payment for the services provided by the CONTRACTOR to the OWNER on a turnkey basis shall be due when the CONTRACTOR completes the installation of the gas pipeline and performs the services as specified in the project plans and specifications. Payment for such work shall be due and payable upon presentation of an invoice to the OWNER and OWNER’s acceptance of the work as specified in the project plans and specifications.

1.7 CONSTRUCTION SCHEDULE

Prior to the commencement of the WORK, the CONTRACTOR shall submit to the OWNER for review the schedule of the proposed construction operations. The OWNER shall cooperate with the CONTRACTOR in arrangements for continuity of service and operation of valves and other control facilities. The construction schedule shall indicate the sequence of the WORK, the time of starting and completion of each part, the installation date for each major item of WORK, and the time for making connections to existing piping. The CONTRACTOR will revise the schedule each week to reflect any changes in the progress of the WORK.

1.8 CONTRACTOR QUALIFICATIONS

HDD pipe installation shall be done only by an experienced CONTRACTOR with a minimum of 3 years of experience in horizontal directional drilling. The CONTRACTOR shall have successful
directionally drilled pipe of 6-inch and larger diameters. The CONTRACTOR shall use only competent and skilled Workers for the performance of any and all WORK on the gas pipeline system, as specified herein. The CONTRACTOR shall furnish evidence, as required by and to the satisfaction of the OWNER, that the specified testing requirements have been met for each employee prior to their utilization on the WORK.

1.8.1 WELDING QUALIFICATIONS
Testing and certification of welders, whether by destructive or nondestructive inspection methods, shall be in accordance with American Petroleum Institute Standard 1104 (API 1104), Standard for Welding Pipelines and Related Facilities, which is hereby incorporated by reference and made a part of these Specifications. The OWNER will certify all project welders.

PART 2 PRODUCTS

2.1 MATERIALS
The CONTRACTOR shall submit to OWNER all manufacturers’ data and certificates for the following items:

- Piping Materials
- Valves
- Piping Specialties
- Welding Consumable Materials

The CONTRACTOR shall submit to OWNER all Information, Data Sheets, and Manuals for items provided by suppliers and manufacturers.

2.2 STEEL GAS PIPE
All steel pipes shall conform to API 5L X52 specifications. The pipe shall be seamless or electric-resistance-welded (ERW) steel pipe as specified in ASME B31.8. Butt-weld fittings shall be in accordance with ASME B16.9. All steel pipes shall be plain-end and beveled for welding.

Steel pipe shall be plant-coated with Fusion Bonded Epoxy External Line Pipe Coating. Approved products are 3M #206N FBE Coating and NAP-GARD #2500 FBE Coating. Uniform cured film thickness shall be 12 mils 2 mils. Pipe for Horizontal Directional Drills will be coated additionally with Powercrete or 12 mils 2 mils of Lilly 20/40.

The minimum steel-pipe properties are as follows:
- Scope: 8-inch, API 5L, X-52, 0.250-inch wall thickness
- Steel Making Process: basic oxygen or electric arc furnace, fully killed; fine-grained practice
- Pipe Making Process: seamless or ERW
- Material Chemistry, percent by weight: CE <0.42%; S <0.01%
- Tensile Properties: excess strength <20 ksi
- Fracture Toughness: per API 5L
- Mill Test Pressure: 100% SMYS
- Nondestructive Examination: Entire weld seam and plate, calibrated to mill speed
- Coating: Fusion Bonded Epoxy; 12-mils 2 mils
- Loading and Transport: per API RP5L1

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2.3 STEEL-PIPE FITTINGS

Steel butt-weld fittings including elbows, tees, reducers, and caps shall be factory-made wrought steel butt welding fittings conforming to the ASME Specification B16.9. All fittings shall be seamless and beveled accordingly to accommodate welding to pipe. All fittings shall be of the same grade and wall thickness as the gas pipe. Steel flanged fittings including bolts, nuts, and bolt patterns shall be in accordance with ASME B16.5.

2.4 PIPE COATING

2.4.1 INSPECTION OF PIPE COATINGS

CONTRACTOR shall inspect pipe during receipt from the pipe supplier. Any damage to the protective covering during transit and handling shall be repaired before installation. After field coating and wrapping have been applied, the entire pipe shall be inspected by an electric holiday detector with impressed current set at a value in accordance with NACE RP0274 using a full-ring, spring-type coil electrode. The holiday detector shall be equipped with a bell, buzzer, or other type of audible signal that sounds when a holiday is detected. All holidays in the protective covering shall be repaired immediately upon detection. Labor, materials, and equipment necessary for conducting the inspection shall be furnished by the CONTRACTOR.

PART 3 EXECUTION

3.1 EQUIPMENT, TOOLS, LABOR, AND MATERIALS TO BE FURNISHED BY CONTRACTOR

The CONTRACTOR shall provide all materials, equipment, tools and labor necessary for the completion of the WORK specified herein, including but not limited to: excavation, trenching, and boring equipment; pipe cutting and welding equipment and supplies; pipeline testing equipment; dewatering equipment; traffic-control devices; and any and all applicable safety equipment that may be required. The CONTRACTOR shall supply all the material items necessary for the completion of the WORK specified herein, including but not limited to: all pipe materials, valves, fittings, select fill, sand, and gravel; concrete; asphalt; testing equipment and fittings; erosion and sediment-control materials; protective rock shields; and field-applied pipeline coating materials. Workmanship, tools, equipment, and materials shall be of good quality meeting established industry standards. The CONTRACTOR shall, as required by OWNER, furnish satisfactory evidence as to the kind and quality of materials. Only equipment that will not damage the surfacing along any improved road surfaces shall be used. When crossing improved road surfaces with equipment that will damage it, wood boards, flat pads, or other approved methods shall be used to prevent damage to the surface.

3.2 EROSION AND SEDIMENT CONTROL

The CONTRACTOR shall provide a means of protecting and minimizing the effects of erosion and sediment displacement to the construction area and all immediate surrounding areas that may be affected by the construction activity. Methods most suitable to the site and soil conditions shall be employed to intercept sediment-carrying runoff from the site and remove the maximum practical amount of sediment from the storm runoff. Erosion- and sediment-control measures including but not limited to silt fences, storm drain inlet protectors, soil-stabilization mats, temporary seeding, and permanent seeding shall be installed and maintained as indicated on the Plans, or as otherwise directed by the ENGINEER.
3.3 RIGHTS-OF-WAY AND EASEMENTS

Generally the WORK will be carried out within the rights-of-way of state, county, and city streets and roadways. The CONTRACTOR shall be familiar with and follow all provisions pertinent to construction within such rights-of-way as provided in the latest edition of the North Carolina Department of Transportation policies and procedures for accommodating utilities on Highway rights-of-way. When it is required that the CONTRACTOR perform WORK on private property, the CONTRACTOR shall provide twenty-four (24) hours’ minimum advance notice to all affected landowners and/or tenants. The necessary rights-of-way and construction easements for the natural-gas pipeline will be provided by the OWNER. The CONTRACTOR shall confine construction operations to the immediate vicinity of the project location and shall further use due care in placing construction tools, equipment, excavated materials, and pipeline materials and supplies so as to cause the least possible damage to property and the least interference with traffic. The placing of such tools, equipment, and materials shall be subject to the approval of the OWNER.

The CONTRACTOR shall conduct the construction in such a manner as to cause the least inconvenience to the citizens of the area, thereby maintaining good public relations. The CONTRACTOR shall not unnecessarily interfere with the use of any public or private improvements, including landscaping; nor shall he or she unnecessarily damage such improvements. The CONTRACTOR shall repair any damage to such improvements to pre-construction condition, or as otherwise directed by the OWNER. The CONTRACTOR shall strive to maintain, at all times during the execution of the WORK, continuous ingress and egress to all affected parcels and traveled ways. When ingress and egress to affected parcels must be blocked, due to the direct executing of the WORK, twenty-four (24) hours’ advance notice must be given to the affected property owner. In no case shall the blocking of ingress and egress be allowed for more than twenty-four (24) hours consecutively.

3.4 MAINTENANCE OF TRAFFIC

The CONTRACTOR shall be required to provide maintenance of traffic within the construction area for the duration of the construction period, including during any temporary suspension of WORK. Maintenance of traffic shall be performed in accordance with the current additions of the NCDOT Policies and Procedures for Accommodating Utilities on Highway Right-of-Ways. The OWNER may require that the CONTRACTOR submit a Traffic Maintenance Plan prior to commencing WORK on a particular portion of the WORK. If the CONTRACTOR is asked to submit such a plan, WORK must not commence on the portion of the project covered by the plan until the Traffic Maintenance Plan is approved by the OWNER. The amount of roadway closure shall be limited to the immediate WORK area and shall be in accordance with the above-mentioned manuals and specifications.

3.5 SUBMITTALS

All procedures or material descriptions requiring OWNER or ENGINEER approval shall be submitted not less than three (3) weeks prior to commencing any horizontal-directional-drilling activities at the crossing location. The CONTRACTOR shall submit the following items to the OWNER:

1. Shop Drawings
2. Weld X-ray Records
3. Test Records
4. Welders’ Certification Records
5. Construction Schedule covering all phases of the horizontal directional drilling
6. Plan and Profile Plots of the pilot bore at intervals not to exceed 25 feet; these plots shall be updated as the pilot hole advances
7. Disposal Plan for drilling mud
8. Survey Records

3.6 AS-BUILT DOCUMENTS

Upon the completion of the WORK, the CONTRACTOR shall provide the OWNER with one complete set of Plans recording the installation of the job. The as-built Plans shall be updated daily during the course of construction. As-built documentation shall, as specified herein, include the following minimum information, as applicable:

1. Any parts of the WORK that vary from what is indicated in the Construction Plans shall be neatly and clearly marked and dimensioned on the as-built drawings. Where a deviation occurs, the main shall be located relative to the nearest station or at the location of the deviation. Where sizes or types of the materials installed differ from the Construction Plans, the type and size installed shall be clearly noted.

2. Where possible, the location of all valves, bends, sleeves, plugged or capped ends, and any other fittings installed shall be measured to the nearest fire hydrant, light pole, sewer manhole, or other fixed object. A minimum of two dimensions shall be provided for each item located and shall be labeled on the as-built drawings.

3.7 PAVEMENT REMOVAL AND DISPOSAL

Removal of pavement includes cutting of the pavement, breaking of the pavement surface, and excavating the pavement using conventional trenching and hand and pneumatic equipment. Pavement removal includes removal of all layers of bituminous asphalt and concrete pavement necessary to properly install the pipe and/or appurtenances. Removal of bituminous and concrete pavement shall correspond to ditch widths limited to the nominal diameter of the pipe being installed plus two (2) feet for mainline pipe. Cutting of the pavement for trenches or bell holes shall be performed using appropriate pavement saw(s) and shall be cut back and squared off in a neat and workmanlike manner. Pavement cutting shall be required in all direct burial applications, as indicated on the Construction Plans, as required by permit, or as directed by the OWNER. Where pavement is cut and replaced, the CONTRACTOR shall cut the edges to a straight and even line before repairing the pavement. Nonuniform edges will not be permitted or accepted. All pavements removed as part of the WORK shall be removed from the job site and disposed of in accordance with the requirements of Federal, State, County, City, and all applicable environmental regulations.

3.8 RESTORATION

3.8.1 BITUMINOUS PAVING
All aggregate, mineral filler, bitumen, and prime coat shall be in accordance with the North Carolina Department of Transportation Standard Specifications for Roads and Structures (NCDOT Specifications), latest edition. Aggregates shall include stone, gravel, slag, and sand. Mineral filler shall include limestone dust, Portland cement, or other inert material. Bitumen shall include asphalt and tar cement. Prime coat shall include asphalt cutback, tar, or asphalt emulsion.

3.8.2 ASPHALT CONCRETE BASE COURSE
Asphalt concrete base course material shall be Type H, conforming to the requirements of Section 640 of the NCDOT Standard Specifications for Roads and Structures (NCDOT Specifications), latest edition.
3.8.3 COURSE AGGREGATE
Aggregate base course material shall be Type A or Type B, conforming to the requirements of Section 520 of the NCDOT Standard Specifications for Roads and Structures (NCDOT Specifications), latest edition. Course aggregate used for road repair and replacement shall consist of crushed stone, crushed slag, or crushed or uncrushed gravel with clean, hard, tough, and durable pieces free from adherent coatings and deleterious amounts of friable, thin, elongated, or laminated pieces; soluble salts; or organic materials and shall conform to the requirements Section 545 of the North Carolina Department of Transportation Standard Specifications for Roads and Structures (NCDOT Specifications), latest edition.

3.8.4 CLEANUP
The CONTRACTOR shall keep the right-of-way reasonably clear of construction debris during the progress of the WORK. Cleanup shall consist of all WORK necessary to restore the damaged area to preconstruction condition. This operation shall include, but not be limited to, the removal of excess excavated materials, equipment, rock and other materials that cannot be placed in the trench backfill. Cleanup shall also consist of the repairing of trenches, disposal of vegetative debris, and reseeding and mulching or sodding as directed by OWNER. Seeds shall comply with the applicable state and federal seed laws. Seeds shall not be stored in the same area with other materials harmful to seed germination. The rate at which the seed mix shall be applied shall be in accordance with the N.C. Department of Transportation Division ENGINEER and the District Landscape ENGINEER. After the required rate of seed has been administered, the CONTRACTOR shall cover the seed with straw.

3.8.5 PAVEMENT AND CONCRETE STRUCTURE REPLACEMENT
The CONTRACTOR shall replace roadway, driveway, and walkway surfaces necessarily removed for the installation of the main and service line piping. It is the intent of these Specifications that the CONTRACTOR return all paved surfaces affected by the WORK to as near preconstruction condition as possible in conformance with approved methods.

3.9 HORIZONTAL DIRECTIONAL DRILLING (HDD)

3.9.1 VARIATION IN PLAN PROFILE
The grades and radius shown on the contract drawings are for the design presented on the contract drawings and are intended for reference only. The exact profile of the HDD drill may be modified by the CONTRACTOR based on field and equipment conditions. The CONTRACTOR shall maintain the entry and exit locations and control-point elevations shown on the drawings unless otherwise approved by the ENGINEER. The bend radius shown on the drawings are minimums and shall not be reduced. Control-point elevations shown indicate the minimum cover and shall not be reduced.

3.9.2 PROTECTION OF UNDERGROUND FACILITIES
The CONTRACTOR shall undertake the following steps prior to commencing HDD operations in a location that might contain underground facilities:

1. Contact the utility location/notification services for the construction area.
2. Positively locate and stake all existing lines, cables, or other underground facilities including exposing facilities that are located within 10 feet of the designed drilled path.
3. Modify drilling practices and down-hole assemblies to prevent damage to existing facilities.
The CONTRACTOR shall be responsible for locating all underground facilities regardless of OWNER and Engineer’s previous efforts in this regard. The CONTRACTOR shall be responsible for all losses and repairs occasioned by damage to underground facilities resulting from drilling operations.

3.9.3 TOLERANCES AND TESTS
The CONTRACTOR shall at all times provide and maintain instrumentation that will accurately locate the pilot hole, measure drill-string axial and torsional loads, and measure drilling fluid-discharge rate and pressure. OWNER and ENGINEER will have access to these instruments and their readings at all times.

The CONTRACTOR shall plot the actual horizontal and vertical alignment of the pilot bore at intervals not exceeding 25 feet. This “as-built” plan and profile shall be updated as the pilot bore is advanced. The CONTRACTOR shall grant OWNER and ENGINEER access to all data readouts pertaining to the position and inclination of the bore head. When requested, the CONTRACTOR shall provide explanations of the position monitoring and steering equipment. The actual exit point shall be located within three (3) feet laterally of the exit point shown on the drawings. Longitudinally the actual exit point shall be no more than ten (10) feet short or ten (10) feet past the exit point shown on the drawings. OWNER and ENGINEER shall approve the alignment of the pilot bore before the back reaming phase or the pipe pulling may commence. If the pilot bore fails to conform to the above tolerances, OWNER or ENGINEER may, at his or her option, require a new pilot bore to be made.

3.9.3.1 Directional Tolerance
The pilot hole shall be drilled along the path shown on the plan and profile drawings to the tolerances listed in these specifications. However, in all cases, right-of-way restrictions shall take precedence over the listed tolerances. Regardless of the tolerance achieved, no pilot hole will be accepted if it will result in any part of or the entire pipeline being installed in violation of right-of-way restrictions. In all cases, concern for adjacent utilities and/or structures shall take precedence over the listed tolerances. Listing of tolerances does not relieve CONTRACTOR from responsibility for safe operations or damage to adjacent utilities and structures.

The CONTRACTOR shall at all times handle the steel pipe in a manner that does not overstress the pipe. Vertical and horizontal curves shall be limited so that wall stresses do not exceed 0.50 of the yield stress. If the pipe is buckled or otherwise damaged as determined by the ENGINEER, the damaged section shall be removed and replaced by the CONTRACTOR at his or her expense.

3.9.4 DRILL-PATH RECORDS
The CONTRACTOR shall provide as-built construction drawings or plans depicting the design entry and exit points and angles, the horizontal and vertical alignment, design drilling radius, and minimum design cover at control points. The horizontal and vertical plan scale shall be 1 inch: 20 feet.

3.9.5 INSTALLATION
The CONTRACTOR, subject to the requirements of these specifications, will determine the exact method and techniques for completing the HDD crossings. Excavated mud pits constructed in the entry and exit areas will be limited to the pipe bore-hole area only. The CONTRACTOR shall obtain water for construction.
3.9.5.1 Construction Layout
The CONTRACTOR shall locate the positions of the entry and exit pits, establish elevation and horizontal data for the bore-head control and lay out the pipe-assembly area.

3.9.5.2 Overpulling
After the steel pipe has been pulled into the reamed pilot hole, the pipe shall be pulled through so that a minimum of 10 feet of steel pipe is exposed at the end of the bore. The pipe shall be cleaned so that the exterior coating can be examined for damage.

3.9.5.3 Closure
After cutting off overpull and prior to testing, the CONTRACTOR shall install weld end caps on each end of the crossing. Following installation of end caps, the CONTRACTOR shall pressure-test the drilled section of pipe in accordance with OWNER specifications.

3.9.5.4 Handling Drilling and Mud Cuttings
During the HDD operations, the CONTRACTOR shall make adequate provisions for handling any muddy water, drilling mud, or cutting. These contaminants shall not be discharged into waterways. When the CONTRACTOR’s provisions for storing muddy water, drilling mud, or cuttings on-site are exceeded, the contaminants must be hauled away to a suitable legal disposal site. After completion of the directional drilling WORK, the entry and exit pit locations shall be restored to their original conditions. The CONTRACTOR shall comply with all provisions of any permits. To the extent practical, the CONTRACTOR shall maintain a closed-loop drilling-fluid system and a drilling-fluid-cleaning system that will allow return fluid to be reused.

3.9.5.5 Ream and Pullback
Prereaming operations shall be conducted at the discretion of the CONTRACTOR. All provisions of this Specification relating to simultaneous reaming and pulling back operations shall also pertain to prereaming operations. The maximum allowable tensile load imposed on the pull section shall not exceed the value stated in the project plans. A swivel shall be used to connect the pull section to the reaming assembly to minimize torsional stress imposed on the section. The pull section shall be supported on rollers as it proceeds during pullback so that it moves freely and the pipe and corrosion coating are not damaged. The pull section shall be installed in the reamed hole in such a manner that external pressures are minimized. Any damage to the pipe resulting from external pressure during installation shall be the responsibility of the CONTRACTOR.

Buoyancy modification shall be used at the discretion of the CONTRACTOR. Any buoyancy-modification procedure proposed for use shall be submitted to OWNER or ENGINEER for approval. The CONTRACTOR is responsible for any damage to the pull section resulting from buoyancy modification.

3.9.5.6 Coating Inspection
The pull section is coated for corrosion-control purposes and shall be inspected for holidays with a holiday detector as it enters the hole. Any coating damage found shall be repaired. Inspection and repair of pipe coating shall be conducted in accordance with the applicable Specifications.
3.9.5.7 Drilling Fluids

No fluid will be utilized that does not comply with environmental regulations. The CONTRACTOR is responsible for obtaining, transporting, and storing any water required for drilling fluids. The CONTRACTOR shall maximize recirculation of drilling-fluid surface returns. Disposal of excess drilling fluids is the responsibility of the CONTRACTOR and shall be conducted in compliance with all environmental regulations, right-of-way and workspace agreements, and permit requirements. The CONTRACTOR shall conduct the HDD operation in such a manner that drilling mud is not forced through the channel subbottom into the waterway.

The CONTRACTOR shall employ his or her best efforts to maintain full annular circulation of drilling fluids. Drilling-fluid returns at locations other than the entry and exit points shall be minimized. In the event that annular circulation is lost, the CONTRACTOR shall take steps to restore circulation. If inadvertent surface returns of drilling fluids occur, they shall be immediately contained with hand-placed barriers (e.g., hay bales, sand bags, silt fences, etc.) and collected using pumps as practical. If the amount of the surface return is not great enough to allow practical collection, the affected area shall be diluted with fresh water and the fluid will be allowed to dry and dissipate naturally. If the amount of the surface return exceeds what can be contained with hand-placed barriers, small collection sumps (less than 5 cubic yards) may be used. If the amount of the surface return exceeds what can be contained and collected using small sumps, drilling operations shall be suspended until surface return volumes can be brought under control.

3.10 COMPLETION OF DIRECTIONAL DRILLING

Subject to the contract provisions, should the HDD crossing be lost or damaged while the CONTRACTOR is engaged in the performance of WORK hereunder on a turnkey basis, all such lost of or damage to the hole shall be borne by the CONTRACTOR; and if the hole is not in condition to be carried to the contract length as provided in the plans, CONTRACTOR shall, at his or her option, either:

1. Commence a new HDD crossing without delay at CONTRACTOR’s cost. If the directional drilled pipe is not installed or the CONTRACTOR abandons the effort, the CONTRACTOR will forfeit all payment for the crossing.
2. If the directional drilled pipe is not completed but is installed so that it can, in ENGINEER’s opinion, be completed by conventional cut and cover (or other techniques), the CONTRACTOR may complete the WORK in such a fashion as approved by the ENGINEER and OWNER.
3. To obtain such approval, the CONTRACTOR shall submit a plan for completion for approval. The ENGINEER and OWNER will establish conditions necessary to obtain a completed pipeline equivalent to the one originally specified.
4. Completion and successful testing of the approved plan will entitle the CONTRACTOR to full payment at the applicable lump-sum amount in the Proposal.
5. Failure to complete the crossing or partially completed crossing by directional drilling or as approved will result in forfeiture of all payment.
6. In event of failure to successfully install the directional drilled pipe, the CONTRACTOR shall retain possession of the steel pipe and remove it from the site. The bore hole shall be completely filled with grout or sand so as to prevent future settlement. If the steel pipe cannot be withdrawn, it shall be cut off at least 3 feet below ground; the annular space shall be grouted; and weld end caps shall be installed at each end or at one end if the other is inaccessible.
7. No partial payments will be made for partially completed horizontal directional drill crossings completed by conventional cut-and-cover methods.
3.11 PIPELINE TESTING, CLEANING, AND DRYING

3.11.1 GENERAL

The natural-gas pipeline shall be leak- and strength-tested by hydrostatic (water) testing. The purpose of the leak-and-strength test is to ensure the strength and integrity of the pipeline and to establish the MAOP. OWNER shall maintain the resulting test records on file for the life of the pipeline.

3.11.2 SAFETY

All pressure tests shall be conducted with due regard for the safety of people and property. When the test pressure is above 400 psig, appropriate precautions shall be taken to keep people not engaged in the testing operations clear of the testing area while the hydrostatic test is in progress. Only approved tools are to be used for test assemblies and plugs. Any tool or fitting that shows evidence of wear or damage that may affect its safe use shall be repaired or replaced. Every reasonable precaution to protect employees and the public shall be taken during testing. Construction in the immediate vicinity of the pipeline shall be discontinued during the period of the strength test and not commence until the pipeline has been blown down to 100 psig or lower internal pressure. During pigging of the pipeline, the CONTRACTOR shall ensure that the exiting pigs are contained within the ditch line and that they cannot escape and cause damage to people or property. Notify and approval from responsible agencies (e.g., Department of Environment and Natural Resources, Water Quality Division and local agencies, etc.) is required, and water must be disposed in accordance with applicable regulations. If possible, the use of hoses for filling and dewatering should be avoided. If hoses must be used, they shall be securely staked and chained to the ground. Hoses and connecting fittings used for the test shall be rated equal to, or above, the maximum hydrostatic test pressure.

3.13 TEST RECORDS

The CONTRACTOR shall provide the Leak/Strength Test Report to OWNER after a successful test has been conducted. In addition to the leak/strength field pressure test, a pressure-recording chart will be made to document the test and to validate the MAOP of the pipeline. The recording chart used should be appropriate for the test pressures and duration listed above. The recording pens shall be in good condition, cleaned and filled with sufficient ink to last the duration of the test. Documentation on the chart shall include:

- Exact time and pressure at the start and at the end of the test
- Job project number
- Test description and location
- Test date(s)
- Environmental factors (temperature, raining, snowing, etc.)
- Name of person entering the data
- Pipe sizes, grades, and wall-thickness information
- Length of tested pipeline
- Test medium and duration
- Maximum and minimum test pressures
- Pressure at high and low elevations
- Name of CONTRACTOR and person responsible for the test
- Recording-gauge number, range, and last calibration date
- Location of the recording gauge on the pipeline
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