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Pipeline Design *for* Installation *by* Horizontal Directional Drilling

Second Edition

Horizontal Directional Drilling
Design Guideline Task Committee

Edited by Eric R. Skonberg, P.E.
Tennyson M. Muindi, P.E.

ASCE

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Pipeline Design for Installation by Horizontal Directional Drilling

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Prepared by
the Horizontal Directional Drilling Design Guideline Task Committee
of the Technical Committee on Trenchless Installation of Pipelines of
the Pipeline Division of the American Society of Civil Engineers

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MANUALS AND REPORTS ON ENGINEERING PRACTICE

(As developed by the ASCE Technical Procedures Committee, July 1930, and revised March 1935, February 1962, and April 1982)

A manual or report in this series consists of an orderly presentation of facts on a particular subject, supplemented by an analysis of limitations and applications of these facts. It contains information useful to the average engineer in his or her everyday work, rather than findings that may be useful only occasionally or rarely. It is not in any sense a "standard," however; nor is it so elementary or so conclusive as to provide a "rule of thumb" for nonengineers.

Furthermore, material in this series, in distinction from a paper (which expresses only one person's observations or opinions), is the work of a committee or group selected to assemble and express information on a specific topic. As often as practicable the committee is under the direction of one or more of the technical divisions and councils, and the product evolved has been subjected to review by the executive committee of the division or council. As a step in the process of this review, proposed manuscripts are often brought before the members of the technical divisions and councils for comment, which may serve as the basis for improvement. When published, each work shows the names of the committees by which it was compiled and indicates clearly the several processes through which it has passed in review, so that its merit may be definitely understood.

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CHAPTER 1

INTRODUCTION

1.1 SCOPE

This manual of practice addresses the design of major pipeline or duct segments to be installed by horizontal directional drilling (HDD). Generally speaking, major pipeline segments are greater than 500 ft in length and greater than 4 in. in diameter. They are installed by medium to large HDD drilling rigs (midi- to maxi-HDD drilling rigs). The design practices described in this manual are not generally applicable to small trenchless segments of pipe, duct, or cable installed by "mini-HDD" drilling rigs.

Horizontal directional drilling is a trenchless excavation method that is accomplished in three 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. The third phase consists of pulling the pipe into the enlarged hole. Horizontal directional drilling is accomplished using a specialized horizontal drilling rig with ancillary tools and equipment.

This manual has been prepared to serve as a guide for design engineers and presumes that the user has knowledge of the HDD installation process and pipeline design methods. Topics covered are limited to those related to HDD installation. Other sources of information and design methods should be consulted for guidance on designing the pipeline to satisfy service requirements. This manual is not a general design handbook for pipelines, and it is not meant to replace sound engineering judgment. Users of this manual should recognize that HDD installations are complicated civil engineering works and that only experienced professional engineers should undertake their design.

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CHAPTER 2

PREDESIGN SURVEYS

2.1 INTRODUCTION

A successful HDD project requires that surface features and subsurface geotechnical and utility data be gathered and incorporated into its design. Trenchless installation methods require the design engineer to provide the contractor with sufficient information to reasonably anticipate the obstacles that may be encountered and how drilling operations should be carried out. During the design phase, surface and subsurface survey information assists in determining the suitability of utility installation by the HDD process.

This section describes data that need to be gathered and presented to enhance the prospects for a successful HDD installation. Obtaining and providing accurate surface and subsurface information result in fewer installation problems and change orders during the work.

2.2 SURFACE SURVEY

Once HDD is selected as the installation method, a surface survey is typically performed. Prior to conducting the actual survey, the design engineer should investigate the site to determine the limits of work required for equipment staging and setup, pipe layout, and areas of potential impact such as adjacent utilities or structures. The survey should be performed in an area sufficient in size to show equipment set-up and storage locations. Typical staging areas required for HDD construction projects are discussed in Chapter 5.

The survey should be conducted along the proposed drill path centerline for a width of approximately 100 ft. Each HDD project has specific staging requirements that should be identified by the design engineer prior to initiating the field survey.

Information to be gathered during the survey should include, but not be limited to, the following:

- Existing grade elevation data referenced to a public datum if practical;
- Surface features such as roadways, sidewalks, utility poles, overhead power lines, fire hydrants, etc.;
- Ledge or rock outcrops;
- Boring/test pit locations;
- Waterways;
- Potentially delineated wetlands;
- Culverts;
- Visible subsurface utility landmarks such as manholes or valve boxes; and
- Structures such as buildings, towers, or bridges adjacent to the proposed drilled path.

A plan view of a finished survey for a major HDD river crossing is shown in Figure 2-1. Contours are useful, but not imperative, because HDD activities on the surface are limited to entry and exit point work areas. It is important to note that HDD crossings designed with significant elevation differences between entry and exit present unique challenges to HDD construction and should be readily apparent in the design drawing. Controlled aerial photographs, if recently taken, are commonly used and can eliminate the need for surveying many surface features.

Waterway crossings may also require a hydrographic survey. The hydrographic survey should include tidal ranges and edges of waterways. It should be conducted along the proposed drill path and include data as appropriate upstream and downstream of the path. As with the surface survey, bottom contours are useful but not imperative unless dramatic variations in bathymetric elevations are anticipated. Most drilled paths are designed well below a waterway bottom, and small variations in elevation do not affect design.

2.3 SUBSURFACE INVESTIGATION

Once the surface survey data have been obtained, evaluation of subsurface features can be initiated. Subsurface feature concerns that may affect HDD design and therefore should be investigated include the presence of existing utilities, adjacent structure foundations or other manmade obstructions, and geotechnical and hazardous materials conditions along the proposed HDD alignment.

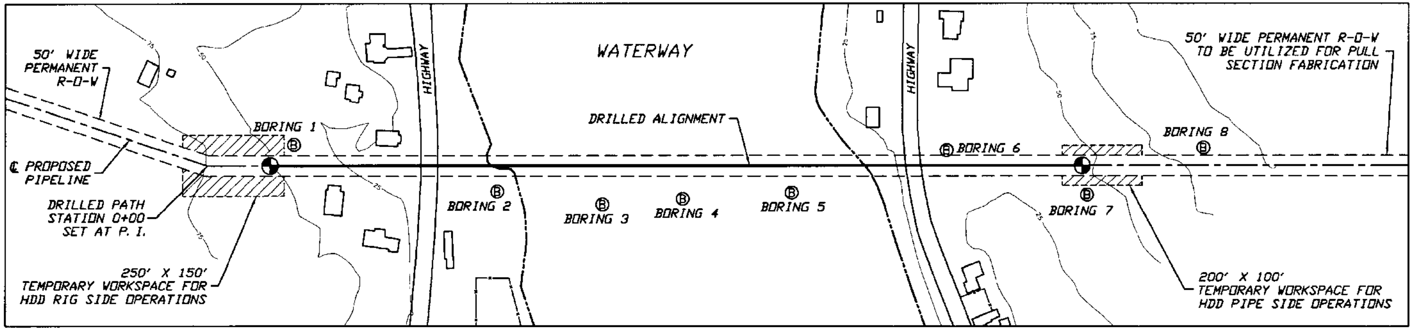

Figure 2-1. Survey of a major HDD river crossing

2.3.1 Utility Research

Utility survey information is important to the planning and execution of the HDD project. Unlike conventional open-cut installations, HDD projects require the contractor to install the utility line in the "blind." Unable to see possible obstructions, the contractor should be given as complete and accurate a record of potential conflicts and utility clearances as may be obtained by reasonable and diligent inquiry. Guidance with respect to subsurface utility research may be found in CI/ASCE 38-02 (ASCE 2002).

The designer should also be aware of code requirements related to the degree of utility research required. For example, Section 434.13.5(a) of ASME B31.4-2009 (2010, p. 49) requires the crossing plan and profile drawings to include all "pipelines, utilities, cables, and structures that cross the drill path, are parallel to and within 100 ft (30 m) of the drill path, and that are within 100 ft (30 m) of the drilling operation, including mud pits and bore pits." Alternate codes may not contain such specific details. The designer should research utility location and depiction requirements on a project-specific basis prior to initiation of the process.

The first step in obtaining subsurface utility information is accomplished during the surface survey by locating visible subsurface utility landmarks. Knowing where valve boxes, manholes, and other structures are located provides a starting point for utility research. The design engineer should exercise due diligence in not only identifying what utilities are located along the proposed HDD path, but also in determining their horizontal and vertical positions, especially if the existing utility was installed via HDD construction.

One method of obtaining utility data is to contact the local "One Call" locating service. This service can be reached by dialing 8-1-1 from anywhere in the United States and is a somewhat easy and straightforward way to identify and locate utilities that are members of the One Call network. In areas where One Call assistance is not provided during the design phase of work, municipalities and private utility companies should be contacted to obtain the required information. Additional research is often necessary, however, because not all utilities belong to the One Call Network and One Call Locates are not always clear with respect to depth. This is particularly true in the case of utilities installed by HDD. Post-construction locating methods are often not effective because of the significant depth of HDD installations.

Obtaining as-built record drawings gives the design engineer location information and identify many, if not all, of the utility lines that could be encountered. However, because of the possibility of inaccurate information, relying solely upon record drawings may not be sufficient for construction. Because of the potential impact and damage to utility lines due to HDD operations, the contractor must conduct additional investigations before beginning work to verify utility line locations where they are at risk of damage by new construction activities.

Generally, if the HDD alignment is expected to pass within 10 ft of an existing utility, physically confirming the location prior to initiating HDD operations if possible is prudent. Utilities located more than 10 ft away may also require physical locating depending on specific requirements of the utility owner or the presence of unusual ground conditions along the proposed HDD alignment near the existing utility.

Methods of confirming subsurface utility locations include

- Pipe locators,
- Ground-penetrating radar,
- Probing,
- Manual excavation,
- Vacuum excavation, and
- Seismic survey.

2.3.1.1 Pipe Locators Utility lines can have both horizontal and vertical locations identified by means of surface applied pipe locators. Pipe locators can be instruments that simply detect underground lines by means of a magnetic field application similar to a metal locator. More sophisticated locators require imposing an electric current on the utility line. Applied current travels along the utility and is detected and traced with the pipe locator. Nonmetallic pipe, such as PVC or high-density polyethylene (HDPE), that has not been installed with a tracing wire cannot be detected with a pipe locator. Some underground utility lines such as electric and cable television lines can produce a detectable signal as long as current is flowing through them. Pipe locators are generally less accurate with depth, but can be extremely accurate in locating utilities buried less than 12 ft deep, depending on conditions.

2.3.1.2 Ground-Penetrating Radar Ground-penetrating radar (GPR) utilizes radio waves to detect underground lines and surfaces. When an object is detected, the radio waves reflect back to the receiver that records the information. The data are downloaded to a computer, and a profile of the utility and geologic information is plotted for interpretation. Subsurface obstructions such as rock and groundwater surfaces are also detected by GPR and can result in misinterpretation of the gathered data. Because interpretation of the data is a critical element in GPR surveys, this method should be used in conjunction with other subsurface survey methods to improve the accuracy of the information. GPR is most useful at depths of less than 20 ft when the density of the object or utility in question contrasts greatly with the surrounding ground. GPR is also highly dependent on soil type and moisture content. GPR is more effective in dry sands than in wet soils and does not work well in clay soils and soils that are salt contaminated, or in identifying pipe made of clay.

2.3.1.3 Vacuum Excavation Nondestructive vacuum excavation is used to physically remove soil and expose the utility lines being investigated. Unlike test pitting, which is performed by means of excavation equipment such as a backhoe, vacuum excavation removes the soils by means of high-pressure air or water jetting. This method reduces the risk of damage to existing utility lines. The water or air loosens the soil, which in turn is vacuumed into a truck for replacement upon completion of the survey. Vacuum excavation allows for physical identification of horizontal and vertical alignments of utility lines and pipe materials and provides the designer with information concerning soil types and water table levels. Conventional vacuum excavation is limited to depths of approximately 20 ft and is most effective in unsaturated, medium density, gravel size, or less granular soils. Excavation holes must be large enough to allow for visual inspection of the uncovered utility lines.

2.3.1.4 Seismic Surveys Seismic surveys require that a small explosive charge or impact by means of sledgehammer be initiated and detected via a series of detectors or geophones spaced along the path of the utility line. A time recorder is used to record the time of origin of the wave and the time of arrival at each detector. Similar to GPR, the water table and type of subsurface material affect the data output; therefore, proper interpretation of the data is critical and greater density contrasts tend to yield more beneficial results. Seismic surveys are generally used in uncongested areas or locations where deep utility installations exist. Once the subsurface utility information is obtained, it should be correlated to determine possible conflicts and then included in the survey base drawings.

2.3.2 Geotechnical Investigation

A second phase of subsurface investigation for HDD projects is the determination of soil conditions. Once the proposed routing has been identified, a geotechnical investigation should be performed. The geotechnical investigation should be tailored to suit the complexity of the installation being designed. Investigations for complex installations should consist of two phases: a general geologic review and a geotechnical survey. A geotechnical survey alone may be sufficient for simpler installations.

A general geologic review involves examining existing geological data to determine what conditions might be encountered in the vicinity of the installation. Existing data may be available from construction project records in the area of the HDD (buildings, piers, bridges, levees, etc.).

Such an overall review provides information that may not be developed from a geotechnical survey consisting only of exploratory borings. It also allows the geotechnical survey to be tailored to the anticipated conditions at the site, thus enhancing the effectiveness of the survey.

A typical geotechnical survey consists of taking exploratory borings to collect soil samples for classification and laboratory analysis. Methods utilized in the survey of underground utilities, as described previously, can also be incorporated into the geotechnical survey.

The number, location, and depth of exploratory borings should be determined taking into account site-specific conditions such as the general geology of the area, availability of access, availability of existing data, cost, etc. Borings should be located off of the drilled path centerline to reduce the possibility of drilling fluid inadvertently surfacing through the borings during HDD operations. The borings should penetrate to an elevation 20 to 30 ft below the depth of the proposed drill path to provide information for design modifications and anticipated pilot-hole deviations during construction. Areas of geologic transition and/or significant contrast in physical ground properties can present unique challenges to HDD construction and should be carefully scrutinized with greater frequency of investigation.

Sampling interval and technique should be set to accurately describe subsurface material characteristics taking into account site-specific conditions. Typically, split spoon samples are taken in soil overburden at 5-ft depth intervals in accordance with ASTM D1586-11 (2011). Where rock is encountered, it should be cored in accordance with ASTM D2113-08 (2008), to the maximum depth of the boring. The following data should be developed from exploratory soil borings:

- Standard classification of soils in accordance with ASTM D2487-10 (2011);
- Gradation curves for granular soils containing gravel;
- Standard penetration test (SPT) values where applicable (generally unconsolidated ground);
- Cored samples of rock with lithologic description, rock quality designation (RQD), and percent recovery;
- Unconfined compressive strength (UCS) for representative rock samples (frequency of testing should be proportionate to the degree of variation encountered in rock core samples);
- Mohs hardness for rock samples;
- Unit weight;
- Atterberg limits;
- Cohesion coefficient;
- Soil friction angle; and
- Depth to water table.

Steps for abandoning the exploratory borings based on local requirements must be undertaken. At a minimum, borings must be backfilled in a manner that will minimize the possibility of drilling fluid migration along the borehole during subsequent HDD operations. A mixture containing cement grout and a bentonite product to promote expansion is recommended. Cuttings from the drilling operation may be incorporated into the backfill mixture if considered beneficial. The upper 5 ft of land-based borings should be backfilled with the surrounding soil.

The results of the subsurface survey should be presented in the form of a geotechnical report containing engineering analysis, boring logs, test results, and a profile of the subsurface conditions. It is also useful, but not imperative, to present exploratory boring logs on the drilled path profile. An example of this is shown in Figure 2-2.

It should be noted that the presentation of geotechnical information by the design engineer can have significant contractual implications. This topic is examined in ASCE (2007), which also discusses concepts of a geotechnical baseline report (GBR) and a geotechnical data report (GDR). If establishing a contractual statement of subsurface geotechnical conditions that may be encountered during the directional drilling is desired, a GBR or GDR may be included in the contract documents.

A GDR can include detailed descriptions of the field and laboratory methods and procedures utilized in the subsurface exploration program. Typical information includes boring logs, laboratory test results, and profile data.

For more complex projects, consideration may be given to preparing a GBR for inclusion in the documents. The GBR is typically limited to interpretive discussion and baseline statements and refers to the information contained in the GDR.

However, in establishing a contractual statement of subsurface geotechnical conditions for an HDD project, it should be remembered that the conditions along a drilled path are rarely visible. Verifying actual subsurface conditions encountered versus the established baseline conditions is generally not possible. Experienced engineering judgment should be applied in evaluating and allocating risk, while taking into account site-specific conditions.

2.3.3 Hazardous Material Investigation

Because the drilling operations produce spoil materials that require handling and disposal, soil and/or groundwater samples should be taken during the utility and geotechnical investigations. During the geotechnical and utility excavation programs, soils and groundwater should be examined by both visual and olfactory means to determine if potential hazardous materials exist. Samples should be analyzed to identify

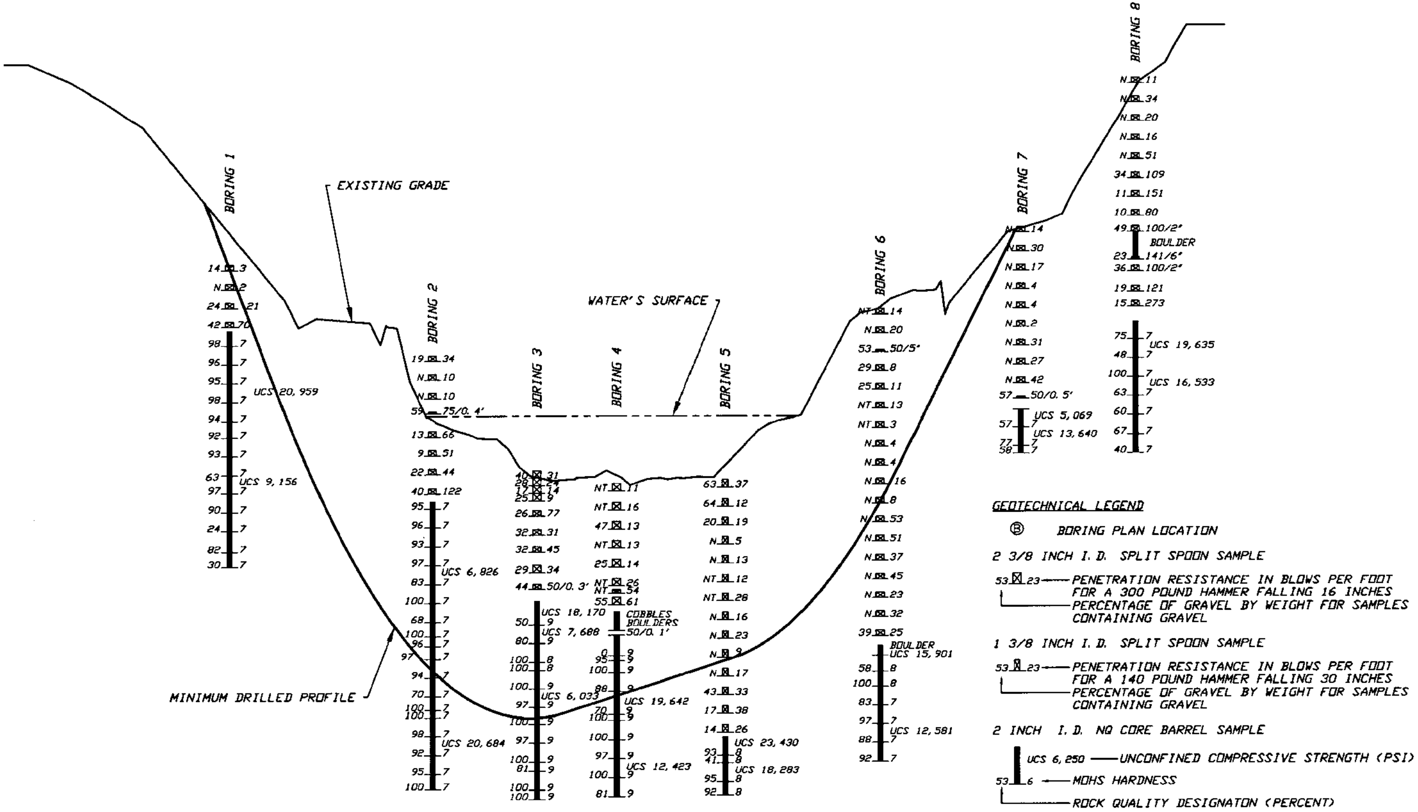

Figure 2-2. Geotechnical report showing results of a subsurface survey

hazardous waste problems. Testing varies depending upon the site and actual conditions encountered; however typical analysis can include

- Volatile organic compounds (VOCs),
- Base/neutral extractable organic compounds,
- Total petroleum hydrocarbons (TPH),
- RCRA 8 metal analyses,
- Pesticides, and
- Polychlorinated biphenyls (PCBs).

Samples should be taken and analyzed in accordance with applicable state and EPA regulations and methods. When hazardous materials or contaminated soils are encountered, special consideration should be given to selecting an appropriate pipe material for these conditions.

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CHAPTER 3

DRILLED PATH DESIGN

3.1 INTRODUCTION

A properly designed HDD installation includes a specific drilled path design. The first step in designing a drilled path consists of defining the obstacles to be crossed. At first glance this seems to be a simple task; however, obstacles in today's construction environment can be complicated and subtle. This can be illustrated by considering a river crossing.

The water body is the obvious obstacle; however, a river is a dynamic entity. Channels can migrate vertically and horizontally. A successfully designed drilled path takes into account not only the present location of the channel, but also its potential future locations (Hair and Hair 1988, O'Donnell 1978). Additional obstacles can be associated with a river. A riparian barrier of trees may need to be preserved and thus included in the drilled path. An environmentally sensitive wetland may be associated with the river and included in the drilled path. Conversely, the actual bank-to-bank distance of a river may exceed that which is technically or economically feasible for an HDD installation. In this case the drilled segment may be designed to cross the deep channel of the waterway using marine equipment to support the rig and construct approaches through shallower water where cut-and-cover construction is more economical.

Once the obstacle has been defined and the approximate desired HDD length is established, designing and specifying a drilled path is an exercise in geometry (Hair and Hair 1988). The location and configuration of a drilled path are defined by

- Penetration angles,
- Design radius of curvature,

- Points of curvature and tangency, and
- Desired vertical depth of cover.

A consideration in designing the drilled path is the minimization of drilled length. Minimizing the drilled length of an HDD crossing reduces installation costs. However, the design must also consider availability of workspace at the entry and exit locations such that the HDD can be feasibly constructed within the physical site constraints. Lastly, the design is often influenced by the geologic conditions identified and placed at depths most amenable to the HDD process. A typical designed drilled path is shown in Figure 3-1.

The typical drilled path shown follows a straight alignment in the horizontal plane. The designer should be aware that HDD offers the flexibility to change alignment through horizontal curves, similar to the change of vertical position through the use of vertical curves. However, horizontal curves can be difficult to drill accurately and, depending on the deflection angle, can significantly increase pulling forces. The three-dimensional combined curvature in both the vertical and horizontal planes should also be considered. Therefore, horizontal curves should only be used after due consideration and analysis have been given to their potential negative effect on constructability.

3.2 PENETRATION ANGLES

Penetration angles are measured from horizontal. Entry angles are limited by equipment capabilities and should generally be designed between 8° and 20° (Directional Crossing Contractors Association 1995, Hair and Hair 1988). Most horizontal drilling rigs are designed to function best between 10° and 12°. However, for large-diameter pipelines, entry angles may be less than 8°.

Exit angles should be designed to provide ease in breakover support of the pull section. High exit angles require the pull section breakover bend to be supported at an elevated position during pull back. Exit angles should generally range from 5° (for large-diameter steel pipelines) to 12°. As part of a general constructability review, the design engineer should check pull section handling requirements to evaluate the constructability of the design.

3.3 DEPTH OF PENETRATION

The depth of penetration is controlled primarily by the definition of the obstacle. However, the design engineer should also consider other

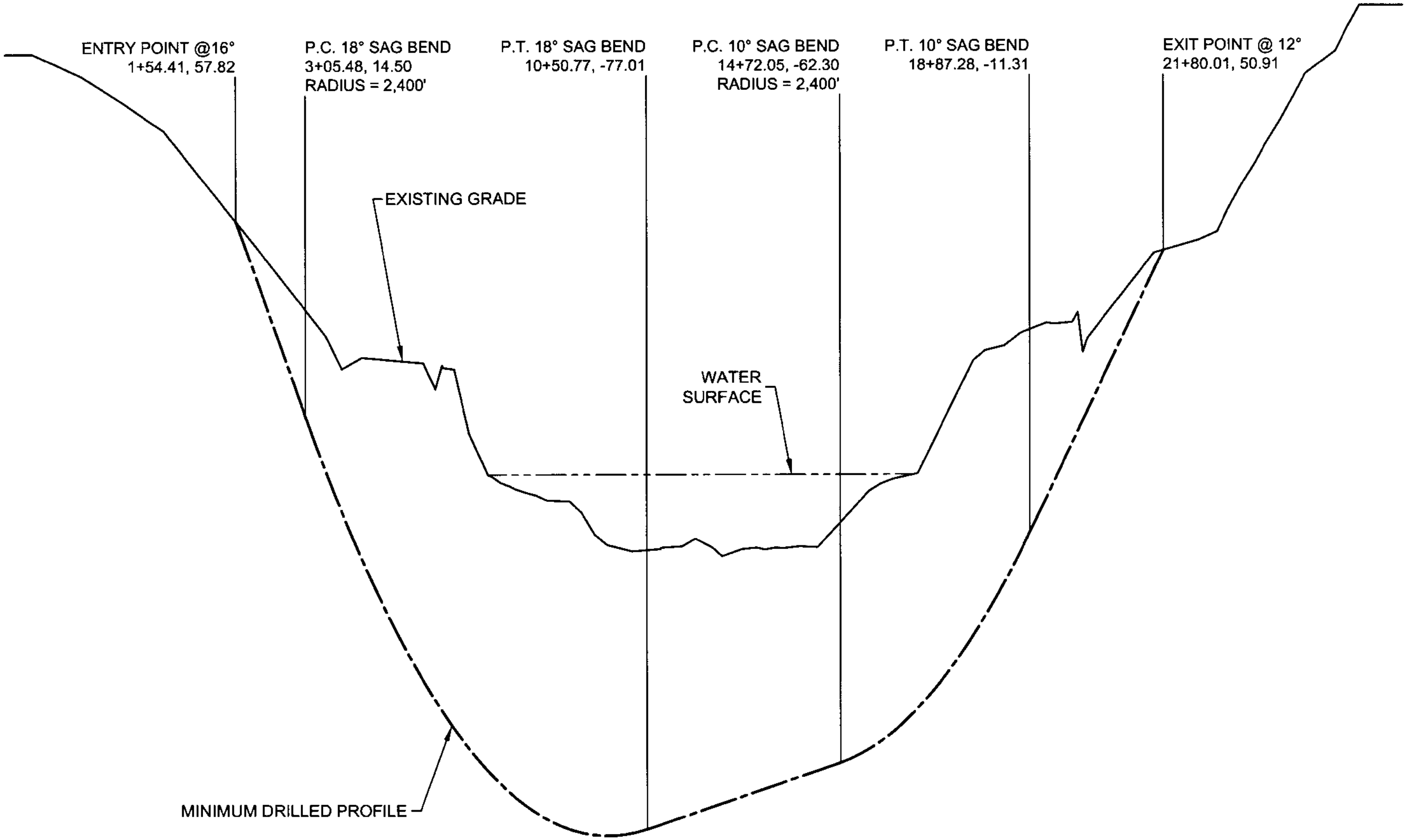

Figure 3-1. Typical designed drilled path

factors, such as geotechnical features, when selecting a penetration elevation. A minimum of 15 ft of separation beneath the obstacle should be maintained (Directional Crossing Contractors Association 1995, Hair and Hair 1988). Twenty-five ft is recommended as a standard separation distance and for less favorable drilling conditions. This minimum provides a margin for error in surveying methods both before and during construction. It should be noted that permit requirements may exceed these values. In determining the depth of penetration, the design engineer should take into account the risks of inadvertent drilling fluid returns and surface settlement or heaving. Where questions exist, depth of penetration should be increased because increased depth typically has a minor effect on construction costs unless more difficult ground conditions are encountered at greater depth.

3.4 RADIUS OF CURVATURE

The radius of curvature typically used in designing HDD paths is estimated to be equal to 100 ft per in.-diameter of the pipe to be installed, e.g., 36-in. pipe would require a 3,600-ft radius, or 1,200 in. per in.-diameter, e.g., 36-in. pipe would require a 43,200-in. radius (3,600 ft). This connection between pipe diameter and radius of curvature is derived from established practice for steel pipe rather than from theoretical analysis. Reduction of the design radius from this standard is possible, particularly for crossings utilizing alternate pipe materials such as high-density polyethylene (HDPE) pipe, fusible polyvinyl chloride pipe (FPVC), or ductile iron pipe (DIP).

For instance, the cold bending radius for HDPE pipe in HDD and other pull-in applications is usually limited to 40 to 50 times the diameter. The preferred installed radius for full-length, flexible restrained joint DIP is 100 ft per in.-diameter; however, the flexible restrained joint is capable of significantly reduced values. In these cases, the lower limit of radius is generally controlled by the capabilities of the drill pipe being used.

However, reduction in radius increases bending stress and pulling load on steel pipe. For flexible restrained joint DIP bending stress is not an issue, but a similar increase in pulling load is encountered. These factors are discussed in more detail in Chapter 4.

3.5 DIRECTIONAL ACCURACY AND TOLERANCES

It is important that the design engineer be aware that the actual drilled path cannot be constructed exactly on the specified drilled path. The specified drilled path serves as a reference line against which downhole survey data can be compared to assess conformance with design. Allowable deviations from the specified drilled path must be provided taking into account constraints at a particular location.

This is particularly critical where HDD is being used to install a gravity sewer. The required line and grade tolerances may not be achievable or may be achievable only after multiple pilot holes have been attempted.

Generally, a greater tolerance specified does afford a more economical HDD construction by the drilling contractor by minimizing the required frequency of pilot hole redrilling. Differences between the specified drilled path and the actual drilled path are caused by the downhole tooling and the driller's ability to control changes in direction plus the inaccuracies in downhole surveying methods and variations in subsurface conditions. A reasonable target at the pilot-hole exit location is 10 ft left or right and minus 10 ft to plus 30 ft in length (Directional Crossing Contractors Association 1995).

3.6 DRILL-AND-INTERSECT METHOD

The achievable length of an HDD installation has significantly increased in the past few years with the development of the "intersect" drilling method. This method consists of drilling pilot holes from each side of the installation and intersecting the pilot holes.

Intersecting pilot holes require a great deal of drilling precision. The benefits of implementing this method should be carefully weighed against the level of experience of the drilling contractor.

3.7 MULTIPLE-LINE INSTALLATIONS

HDD installations often involve multiple lines. Multiple-line installations can be achieved by placing individual pipes in individual holes along roughly parallel paths or by placing a bundle of lines in one drilled hole.

Where multiple lines are to be placed in individual holes, decisions must be made with respect to vertical and horizontal spacing. A site-specific evaluation of directional accuracy is necessary and should take into account the drilled length, subsurface conditions, possible downhole survey system interference, and the practicality of utilizing a surface-monitoring system. In some instances parallel crossings can be installed utilizing the ParaTrack magnetic guidance system via the "ranging" technique. Ranging involves placing a guide wire within an installed pipeline, as opposed to above ground along the centerline, and steering subsequent crossings in relation to the known position of the wire.

When parallel crossings are to be installed, the drilled path tolerances must be set so that the pilot holes are not drilled so close to one another that damage could result during reaming and pull-back operations. Downhole surveying and as-built documentation are discussed in Chapter 6.

Multiple lines may be placed in a single drilled hole by joining them to a common pulling head and installing them as a bundle (American Gas Association 1995). It is not necessary that the lines be tied together in a fixed bundle, although this can yield benefits when installing HDPE pipe because the tensile capacity of the bundle is greater than the tensile capacity of an individual line. If separation of steel lines is required for cathodic protection reasons, pipe spacers can be used. Pipe separation may also be required if the pipeline is to be subject to certain types of in-line inspection in the future, such as magnetic flux leakage tools. However, spacers should be avoided if possible because they can increase drag. Pipe bundles may roll during installation. This should be taken into account in planning for tie-ins to approach piping at each end of the drilled segment.

3.8 CASINGS

Casings are rarely used in HDD installations because they require an additional step in the construction process and thus increase cost. Where casings are employed, it is usually to provide strength to resist installation loads as in the case of an HDPE within a steel casing. HDPE may have been selected because of its resistance to corrosion during operation, but it may not have the tensile capacity to resist installation loads over a long drilled segment. The steel casing provides the structural strength needed for HDD installation. From an HDD design standpoint, no differentiation is made between a casing and carrier or product pipe. HDD operations are essentially the same.

This is not to be confused with surface casing, which is temporarily installed to stabilize near-surface soils. Surface casing is usually removed after the HDD installation.

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CHAPTER 4

PIPE DESIGN

4.1 INTRODUCTION

Load and stress analysis for an HDD pipeline installation is different from similar analyses of conventionally buried pipelines because of the relatively high tension loads, bending, and external fluid pressures acting on the pipeline during the installation process. In some cases these loads may be higher than the design service loads (American Gas Association 1995). Pipe properties such as strength and wall thickness must be selected such that the pipeline can be both installed and operated within customary risks of failure. Analysis of the loads and stresses that govern pipe specification can most easily be accomplished by breaking the problem into two distinct events: (1) installation and (2) operation.

4.2 INSTALLATION LOADS

During HDD installation, a continuously fused or welded pipeline segment is subjected to tension, bending, and external pressure as it is pulled through a prereamed hole. Bending is not normally considered when installing pipeline segments with flexible restrained joints, such as DIP, because of the joint's ability to articulate as it is pulled through the hole. The stresses and failure potential of the pipe are a result of the interaction of these loads (American Gas Association 1995). To determine if a given pipe specification is adequate, HDD installation loads must first be estimated so that the stresses resulting from these loads can be calculated. The purpose of this section is to describe the loads that act on a pipeline during installation by HDD and to present methods for estimating these loads.

4.2.1 Tension

Tension on the pull section results from three primary sources: (1) frictional drag between the pipe and the wall of the hole, (2) fluidic drag from viscous drilling fluid surrounding the pipe, and (3) the effective (submerged) weight of the pipe as it is pulled through the hole. In addition to these forces that act within the drilled hole, frictional drag from the portion of the pull section remaining on the surface (typically supported on rollers) also contributes to the tensile load on the pipe.

Additional loads that the horizontal drilling rig must overcome during pull back result from the length of the drill string in the hole and the reaming assembly that precedes the pull section. These loads don't act on the pull section and therefore have no effect on pipe stresses. Nonetheless, if a direct correlation with the overall rig force is desired, loads resulting from the reaming assembly and drill string must be estimated and added to the tensile force acting on the pull section.

Calculation of the tensile load required to install a pipeline by HDD is complicated due to the fact that the geometry of the drilled path must be considered along with properties of the pipe being installed, subsurface materials, and drilling fluid. Assumptions and simplifications are typically required. A theoretical pulling load may be calculated by hand or with the aid of one of several commercially available software packages.

Regardless of the method used to calculate an HDD pulling load, the design engineer should be aware that numerous variables affect pulling loads, many of which depend upon site-specific conditions and individual contractor practices. These include prereaming diameter, hole stability, removal of cuttings, soil and rock properties, drilling fluid properties, drilled path geometry, and the effectiveness of buoyancy control measures. Such variables cannot easily be accounted for in a theoretical calculation method designed for use over a broad range of applications. For this reason, theoretical calculations are of limited benefit unless combined with engineering judgment derived from experience in HDD construction.

The first step in calculating a pulling load is to analyze the drilled path. This analysis can be based on the designed drilled path, a "worst-case" drilled path, or "as-built" pilot-hole data, if available. Bearing in mind that most pilot holes are drilled longer, deeper, and to tighter radii than designed, a conservative approach in the absence of as-built pilot-hole data is to evaluate a worst-case drilled path that accounts for potential deviations from the design. This worst-case path should be determined based on allowable tolerances for pilot-hole length, elevation, and curve radius as defined in the contract documents. The design engineer should be aware that deviations in these parameters are typical and are often due to conditions beyond the control of the drilling contractor. For example, it would not be unusual to find deflections in a pilot hole that produced a bending radius approaching 50% of the design radius.

Existing pulling load calculation methods generally involve modeling the drilled path as a series of straight and/or curved segments as necessary to define its shape. The individual loads acting on each segment are then resolved to determine a resultant tensile load for each segment. The estimated force required to install the entire pull section in the reamed hole is equal to the sum of the tensile loads acting on all of the defined segments. It should be noted that both frictional drag and fluidic drag always increase the tensile load due to the fact that drag forces always retard pipe movement. However, the component of the tensile load resulting from the effective weight of the pipe may either be positive, negative, or zero depending on the buoyancy of the pipe and whether the pipe segment being evaluated is being pulled upward, downward, or horizontally.

4.2.1.1 Frictional Drag Frictional drag between the pipe and soil is determined by multiplying the bearing force that the pull section exerts against the wall of the hole by an appropriate coefficient of friction. A reasonable value for coefficient of friction is 0.3 for a pipe pulled into a reamed hole filled with drilling fluid (American Gas Association 1995). However, it should be noted that this value can vary with soil conditions. A very wet mucky soil may have a coefficient of friction of 0.1 while a rough and dry soil (unlikely in an HDD installation) may have a coefficient of friction of 0.8. For HDPE pipe sliding on the ground surface, ASTM F1962 (2011b) suggests a coefficient of friction of 0.5.

For straight segments the bearing force can be determined by multiplying the segment length by the effective unit weight of the pipe and the cosine of the segment's angle relative to horizontal. For curved segments, calculation of the bearing force is more complicated because additional geometric variables must be considered along with the stiffness of the pipe.

4.2.1.2 Fluidic Drag Fluidic drag between the pipe and viscous drilling fluid is determined by multiplying the external surface area of the pipe by an appropriate fluid drag coefficient. A reasonable value for fluidic drag coefficient is 0.025 lb/sq in. (Puckett 2003). The external surface area of any segment defined in the drilled path model can easily be determined based on the segment's length and the outside diameter of the pull section. For HDPE pipe, an alternate approach is given in ASTM F1962 (2011b).

4.2.1.3 Effective Weight of Pipe The effective weight of the pipe is the unit weight of the pull section minus the unit weight of any drilling fluid displaced by the pull section. This is typically expressed in lb/ft. The unit weight of the pull section includes not only the product pipe, but also its contents (ducts, internal water used for ballast, etc.) and external coatings if substantial enough to add significant weight (i.e., concrete coating). Calculating the weight of drilling fluid displaced by the pull section requires that the density of the drilling fluid either be known or assumed. For HDD installations, drilling fluid density ranges from approximately 8.9 lb/gal. to approximately 11.0 lb/gal. (water weighs 8.34 lb/gal.; American Gas Association 1994, Bennett and Ariaratnam 2008). Where use of a high-end value for fluid density is warranted for a conservative analysis, 12.0 lb/gal. represents a reasonable upper limit.

4.2.2 Bending

The pull section is subjected to elastic bending as it is forced to negotiate the curvature of the hole. For a pipe with welded or fused joints this induces a flexural stress in the pipe that depends upon the drilled radius of curvature. For steel pipe, the relatively rigid material's resistance to bending also induces a normal bearing force against the wall of the hole. These normal forces influence the tensile load on the pipe as a component of frictional drag. Stresses and forces induced by bending are not a significant concern for flexible restrained joint DIP.

4.2.3 External Pressure

During HDD installation, the pull section is subjected to external pressure from four sources: (1) hydrostatic pressure from the weight of the drilling fluid surrounding the pipe in the drilled annulus, (2) hydrokinetic pressure required to produce drilling fluid flow from the reaming assembly through the reamed annulus to the surface, (3) hydrokinetic pressure produced by surge or plunger action involved with pulling the pipe into the reamed hole, and (4) bearing pressure (capstan effect) of the pipe against the hole wall produced to force the pipe to conform to the drilled path.

Hydrostatic pressure depends upon the height of the drilling fluid column acting on the pipe and the density of the drilling fluid that surrounds the pipe. Drilling fluid density values are discussed in Section 4.2.1.3. The height of the drilling fluid column at any given location along the drilled path is typically equal to the elevation difference between that location and the point at which there is no drilling fluid in the reamed hole. Typically, but not always, drilling fluid extends to the entry or exit point, whichever is lower.

Hydrokinetic pressure required to produce drilling fluid flow can be calculated using annular flow pressure loss formulas. These results depend on detailed drilling fluid properties, flow rates, and hole configuration and, because of uncertainties involving these parameters, often require a substantial application of engineering judgment to determine a reasonable value. In most cases, annular flow during pull back is low velocity with low pressure losses.

Hydrokinetic pressure due to surge or plunger action and hole wall bearing pressure cannot be readily calculated and must be estimated using engineering judgment and experience.

4.3 OPERATING LOADS

The operating loads imposed on a pipeline installed by HDD are not significantly different from those imposed on a conventionally installed pipeline. As a result, existing procedures for calculating and limiting stresses can be applied. However, unlike a cut-and-cover installation in which the pipe is bent to conform to the trench, a continually welded or fused pipeline installed by HDD contains elastic bends. Flexural stresses imposed by elastic bending should be checked in combination with other longitudinal and hoop stresses to evaluate if acceptable limits are exceeded. The operating loads imposed on a pipeline installed by HDD are described below.

4.3.1 Internal Pressure

As with a pipeline installed by conventional methods, a pipeline installed by HDD is subjected to internal pressure from the fluid flowing through it. For design purposes, this pressure is generally taken to be the pipeline's maximum allowable operating pressure. The internal hydrostatic pressure from the depth of the HDD installation should be considered when determining the maximum internal pressure.

4.3.2 Bending

Elastic bends that are introduced during pull back remain in the pipe following installation and therefore must be considered when analyzing operating stresses. These bends are typically approximated as circular curves having a radius of curvature that is determined from as-built pilot-hole data. One common method of calculating the radius of an approximate circular curve in a single plane (i.e., vertical or horizontal) from pilot-hole data is presented below (American Gas Association 1995).

$$R_H, R_V = \frac{180}{\pi} \times \frac{L}{A} \tag{4-1}$$

where:
R_H = horizontal radius of curvature, ft;
R_V = vertical radius of curvature, ft;
L = length drilled (typically between 75 and 100), ft; and
A = change in azimuth (R_H) or inclination (R_V) over L, degrees.

To judge the suitability of an as-drilled pilot hole, it is important to consider the total, or combined, radius of curvature, which accounts for angular deflections in both the horizontal and vertical directions. It should be noted that horizontal curvature typically exists to some extent during drilling, even in crossings designed to be straight. Various methods are available to calculate combined radius, one of which is shown below.

$$R_C = \sqrt{\frac{R_V^2 R_H^2}{R_V^2 + R_H^2}} \tag{4-2}$$

where:
R_C = combined radius of curvature, ft.

The selection of a value for L is based on engineering judgment and accounts for the actual curvature of the pipe installed in the reamed hole as opposed to individual pilot-hole survey deflections.

4.3.3 Thermal Expansion

A pipeline installed by HDD is considered to be fully restrained by the surrounding soil. Therefore, stress is induced by a change in temperature from that existing when the line was constructed to that present during operation.

It should be noted that the fully restrained model is not necessarily true for all subsurface conditions. Obviously, a pipeline is not fully restrained during installation; otherwise, it could not be pulled through the hole. Engineering judgment must be used in considering thermal stresses and strains involved with an HDD installation.

4.3.4 External Pressure

To evaluate the impact of external pressure during operation, the minimum internal operating pressure of the pipeline should be compared with the maximum external pressure resulting from groundwater and earth load at the lowest elevation of the HDD installation.

The earth load on pipelines installed by HDD is generally a “tunnel load,” where the resulting soil pressure is less than the geostatic stress.

ASTM F1962 (2011b) recommends the following method for calculating earth loads on HDD installations.

$$P_e = \frac{\kappa \gamma H}{144} \tag{4-3}$$

where
P_e = external earth pressure, psi;
κ = arching factor;
γ = soil weight, pcf; and
H = depth of cover, ft.

The arching factor is calculated as follows.

$$\kappa = \left\{ \frac{1 - \exp\left[-2\left(\frac{KH}{B}\right)\tan\left(\frac{\delta}{2}\right)\right]}{2\left(\frac{KH}{B}\right)\tan\left(\frac{\delta}{2}\right)} \right\} \tag{4-4}$$

where:
K = earth pressure coefficient;
B = silo width (assumed to be reamed hole diameter), ft;
δ = angle of wall friction (assumed to equal ϕ); and
ϕ = angle of internal friction of soil.

The earth pressure coefficient is calculated as follows.

$$K = \tan^2\left(45 - \frac{\phi}{2}\right) \tag{4-5}$$

4.4 PIPE MATERIAL

Pipe to be installed by HDD should be smooth and flexible and have sufficient strength to resist tension, bending, and external pressure installation loads. Pipe installed using either the assembled-line or cartridge installation methods (Ariaratnam and Carpenter 2003) shall have either welded, fused, or, for segmented pipe, flexible restrained joints. Installation of welded or fused joint pipe sections is best accomplished by using the assembled-line method where the individual pipe sections, (steel, HDPE, or FPVC) are preassembled or fabricated (welded or fused) into long pull lengths prior to pull back. Flexible restrained joint pipe sections, typically available with ductile iron pipe, may alternatively be preassembled using the assembled-line method, or when site conditions restrict preassembling of long sections or when preferred, the cartridge method.

In the cartridge method individual pipe sections are assembled and pulled into the bore path one pipe length at a time.

Most HDD installations have been completed using welded steel pipe. This probably results from the fact that HDD grew out of the petroleum pipeline industry where the use of steel was dictated by high-pressure service. Although installation loads need to be checked by the design engineer, the strength of steel eliminates problems with installation loads in most cases. The high strength of steel also provides contractors with a safety factor during installation. Contractors have much more flexibility in applying remedial measures to free stuck pipe with steel than with alternate materials.

If acceptable from the standpoint of system design, alternate materials can provide several constructability benefits over steel pipe on an HDD installation. While steel pipe often necessitates a substantial "breakover" radius during pull back requiring the pull section to be lifted into an arc, HDPE and FPVC pipe can typically be pulled into the hole directly off of pipe rollers. If space is not available to fabricate the pull section in one continuous segment, this reduction in breakover length can reduce the number of tie-ins required. The flexibility of HDPE and FPVC pipe also provides more options for laying out the pull section as it can be bent around obstacles. Radius of curvature is generally not a concern when installing HDPE pipe because HDPE can normally withstand a tighter radius than can be achieved with the steel drill pipe used to drill the pilot hole. Therefore, the steel drill pipe limits borehole curvature. Also, the use of HDPE or FPVC pipe eliminates the need for field joint coating, and fabrication is typically faster and less expensive than steel fabrication. However, the tensile and pressure capacities of these materials are significantly less than those of steel and therefore pull-back distances of these pipe materials are less than that of steel pipe. Analysis of installation and operating stresses is critical to determine if HDPE or FPVC pipe is suitable for installation by HDD.

Ductile iron pipe may also be installed by HDD using a flexible restrained joint. These joints distribute thrust or pulling force around the bell and barrel and provide an allowable joint deflection with simultaneous joint restraint. As previously mentioned, they can also be assembled for "cartridge" installations where easements or rights-of-way are limited. Ductile iron pipe manufacturers have proprietary flexible restrained joints that they recommend for HDD applications. Therefore, individual manufacturers should be contacted for detailed parameters when designing an HDD segment using ductile iron pipe (Ductile Iron Pipe Research Association 2004). Joints with bulky glands or flanges that may result in increased drag and inhibit annular drilling fluid flow should be avoided. It should be noted that the flexibility provided by ductile iron pipe joints eliminates bending stresses in the pipe.

When contaminated soils are encountered, the pipe material should be evaluated for suitability of use in that environment.

4.5 STRESSES IN STEEL PIPE

This section addresses the stresses that are imposed on steel pipe during both the HDD installation process and subsequent operation. Methods that can be used to calculate these stresses are also presented.

4.5.1 Installation Stresses

As discussed in Section 4.2, a pipeline is subjected to three primary loading conditions during installation by HDD: tension, bending, and external pressure. A thorough design process requires examination of the stresses that result from each individual loading condition and an examination of the combined stresses that result from the interaction of these loads.

4.5.1.1 Tensile Stress (f_t) The tension imposed on a circular pipe during installation by HDD is assumed to act through the centroid of the cross section and therefore is uniformly distributed over the cross section. The tensile stress is determined by dividing the tension by the cross-sectional area. The maximum allowable tensile stress imposed on a steel pull section during installation should be limited to 90% of the pipe's specified minimum yield strength (American Gas Association 1995).

4.5.1.2 Bending Stress (f_b) Bending stress resulting from a rigid steel pipe being forced to conform to the drilled radius of curvature can be calculated using the following equation (Young 1989).

$$f_b = \frac{ED}{24R} \tag{4-6}$$

where:
f_b = longitudinal stress from bending, psi;
E = modulus of elasticity for steel, 29,000,000 psi (Timoshenko and Gere 1972);
D = outside diameter of pipe, in.; and
R = radius of curvature, ft.

Bending stress imposed on a steel-pull section during installation should be limited as follows (American Gas Association 1995). These limits are taken from design criteria established for tubular members in offshore structures and are applied to HDD installation because of the similarity of the loads on pipe (ANSI/API 2000).

$$F_b = 0.75F_y \text{ for } \frac{D}{t} \leq \frac{1,500,000}{F_y} \tag{4-7}$$

$$F_b = \left(0.84 - \frac{1.74F_yD}{Et}\right)F_y \text{ for } \frac{1,500,000}{F_y} < \frac{D}{t} \leq \frac{3,000,000}{F_y} \tag{4-8}$$

$$F_b = \left(0.72 - \frac{0.58F_yD}{Et}\right)F_y \text{ for } \frac{3,000,000}{F_y} < \frac{D}{t} \leq 300,000 \tag{4-9}$$

where:
F_b = maximum allowable bending stress, psi;
F_y = pipe specified minimum yield strength, psi; and
t = pipe wall thickness, in.

In the HDD industry, designing circular sag bends for steel pipelines at a radius of curvature of 1,200 times the nominal diameter of the product pipe is standard practice (refer to Section 3.4). This relationship has been developed over a period of years in the HDD industry and is based on experience with constructability as opposed to pipe stress limitations. Typically, the minimum radius determined using the stress-limiting criterion presented above is substantially less than 1,200 times the nominal diameter. For this reason, bending stress limits rarely govern geometric drilled path design but are applied, along with other stress limiting criteria, in determining the minimum allowable radius of curvature.

4.5.1.3 External Hoop Stress (f_h) Thin-walled tubular members, such as steel pipe, fail by buckling or collapse when under the influence of external hoop stress. A traditional formula established by Timoshenko for calculation of the wall thickness required to prevent collapse of a round steel pipe is as follows (Merritt 1968).

$$t = \frac{D}{12\left(\frac{864P_{\text{ext}}}{E}\right)^{\frac{1}{3}}} \tag{4-10}$$

where:
P_{ext} = uniform external pressure, psi.

Because pipe in an HDD pull section is not necessarily perfectly round and is subjected to bending and dynamic loading, a conservative factor of safety should be applied in checking pipe wall thickness using the above relationship. Generally speaking, diameter-to-wall thickness ratios for steel pipe to be installed by HDD should be held at 60 or below, although higher *D/t* ratios are appropriate if a high level of confidence exists in collapse analysis calculations or a counterbalancing internal pressure is to be applied during pull back (O'Donnell 1996).

As with bending, hoop stress resulting from external pressure can be checked using criteria established for tubular members in offshore structures (American Gas Association 1995). Applicable formulas are presented below (ANSI/API 2000).

$$f_h = \frac{P_{\text{ext}} D}{2t} \tag{4-11}$$

$$F_{he} = 0.88E\left(\frac{t}{D}\right)^2 \quad \text{for long, unstiffened cylinders} \tag{4-12}$$

$$F_{hc} = F_{he} \quad \text{for } F_{he} \le 0.55F_y \tag{4-13}$$

$$F_{hc} = 0.45F_y + 0.18F_{he} \quad \text{for } 0.55F_y < F_{he} \le F_y \tag{4-14}$$

$$F_{hc} = \frac{1.31F_y}{1.15 + \left(\dfrac{F_y}{F_{he}}\right)} \quad \text{for } 1.6F_y < F_{he} \le 6.2F_y \tag{4-15}$$

$$F_{hc} = F_y \quad \text{for } F_{he} > 6.2F_y \tag{4-16}$$

where:
f_h = hoop stress due to external pressure, psi;
F_{he} = elastic hoop buckling stress, psi; and
F_{hc} = critical hoop buckling stress, psi.

Using these formulas, hoop stress due to external pressure should be limited to 67% of the critical hoop buckling stress.

4.5.1.4 Combined Installation Stresses The worst-case stress condition for the pipe is typically located where the most serious combination of tensile, bending, and external hoop stresses occur simultaneously. This is not always obvious in looking at a profile of the drilled hole because the interaction of the three loading conditions is not necessarily intuitive. To be sure that the point with the worst-case condition is isolated, it may be necessary to do a combined stress analysis for several suspect locations. In general, the highest stresses occur at locations of tight radius bending, high tension (closer to the rig side), and high hydrostatic head (deepest point; American Gas Association 1995).

Combined stress analysis may begin with a check of axial tension and bending according to the following limiting criterion (American Gas Association 1995). The criterion is taken from practices established for design of tubular members in offshore structures with an increase in the allowable tensile proportion to make it consistent with established practice in the HDD industry (ANSI/API 2000).

$$\frac{f_t}{0.9F_y} + \frac{f_b}{F_b} \le 1 \tag{4-17}$$

where:

$$f_t = \text{tensile stress, psi.} \tag{4-18}$$

The full interaction of axial tension, bending, and external pressure stresses should be limited according to the following criteria (ANSI/API 2000, American Gas Association 1995).

$$A^2 + B^2 + 2\gamma|A|B \le 1 \tag{4-19}$$

where:

$$A = \left[\frac{(f_t + f_b - 0.5f_h)1.25}{F_y}\right]$$

$$B = 1.5\left(\frac{f_h}{F_{hc}}\right)$$

γ = Poisson's ratio, 0.3 for steel (ASME/ANSI 2010).

It should be noted that failure to satisfy the unity checks presented previously does not mean that the pipeline will necessarily fail by overstress or buckling. Rather, it indicates that the combined stress state places the design in a range where some test specimens under similar stress states have been found to be subject to failure (American Gas Association 1995).

4.5.2 Operating Stresses

The operating loads and stresses in a pipeline installed by HDD are not materially different from those that occur in pipelines installed by cut-and-cover techniques with one exception, elastic bending. A pipeline installed by HDD contains elastic bends. It is not bent to conform to the drilled hole as a pipeline installed by cut and cover is bent to conform to the ditch. Bending stresses imposed by HDD installation should be checked in combination with other longitudinal and hoop stresses experienced during operation to evaluate if acceptable limits are exceeded. Other longitudinal and hoop stresses that should be considered result from internal pressure, elastic bending, and thermal expansion and contraction (American Gas Association 1995).

4.5.2.1 Internal Hoop Stress (f_h) Hoop stress due to internal pressure is calculated as follows (ASME/ANSI 2010).

$$f_h = \frac{P_{\text{int}} D}{2t} \tag{4-20}$$

where:
f_h = hoop stress due to internal pressure, psi; and
P_{int} = uniform internal pressure, psi.

The maximum allowable hoop stress due to internal pressure is governed by the design standard applicable to the pipeline transportation system that contains the HDD segment being examined. For example, hoop stress is limited to 72% of the specified minimum yield strength for most liquid petroleum pipelines (ASME/ANSI 2010). For natural gas pipelines, hoop stress limitations range from 40% to 72% of the specified minimum yield strength (*Transportation* 2001).

4.5.2.2 Bending Stress (f_b) Bending stresses are calculated and limited as shown in Section 4.5.1.2.

4.5.2.3 Thermal Stress (f_e) Thermal stress resulting from changes in pipe temperature from the point in time at which the pipe is restrained by the surrounding soil to typical operating condition is calculated as follows (ASME/ANSI 2010).

$$f_e = E \propto (T_2 - T_1) \tag{4-21}$$

where:
f_e = longitudinal stress from thermal expansion, psi;
α = coefficient of thermal expansion, in./in./°F;
T_1 = pipe temperature at installation or completion of final tie-in, °F; and
T_2 = operating temperature, °F.

The high thermal conductivity of steel enables the temperature of the pipe to equalize with the surrounding soil within a matter of hours after construction. Because soil temperatures at the depth of most HDD installations are relatively constant, thermal stresses are typically a concern only when the temperature of the product flowing through the pipeline differs substantially from that of the surrounding soil, such as in hot oil pipelines or immediately downstream of a natural gas pipeline compressor station.

4.5.2.4 Combined Operating Stresses Hoop, thermal, and bending stresses imposed on the pipe during operation should be combined and checked to evaluate the risk of failure from combined stresses. This can be accomplished by examining the maximum shear stress at selected elements on the pipe. Maximum shear stress is calculated by the following formula (Timoshenko and Gere 1972).

$$f_v = \frac{f_c - f_l}{2} \tag{4-22}$$

where:
f_v = maximum shear stress, psi;
f_c = total circumferential stress, psi; and
f_l = total longitudinal stress, psi.

In this analysis, all tensile stresses are positive and compressive stresses are negative. The total circumferential stress is the difference between the hoop stress due to external pressure and the hoop stress due to internal pressure. The total longitudinal stress is the sum of the bending and thermal stresses and the longitudinal component of circumferential stress determined as follows.

$$f_{lh} = f_c \gamma \tag{4-23}$$

where:
f_{lh} = longitudinal component of circumferential stress, psi.

Presuming that hoop stresses are positive for pressurized steel pipelines, the pipe element that typically has the highest maximum shear stress is that which has the highest total longitudinal compressive stress. This element falls at the maximum distance from the neutral axis on the compression side of an elastic bend. Maximum shear stress should be limited to 45% of the specified minimum yield strength (ASME/ANSI 2010).

4.6 STRESSES IN HIGH-DENSITY POLYETHYLENE PIPE

This section presents methods that can be used to calculate installation and operational stresses in high-density polyethylene (HDPE) pipe along with stress-limiting criteria.

4.6.1 Installation Stresses

When installing HDPE pipe by HDD, installation stresses can often be reduced substantially by using rollers and filling the pull section with water as it is being pulled into the reamed hole. This practice has two primary benefits. First, with a specific gravity of less than 1, HDPE pipe is extremely buoyant when submerged in drilling fluid. Filling the pull section with water decreases the buoyant force exerted by the pipe on the top of the reamed hole, thereby reducing the pulling load. Second, the pressure exerted by the water in the pipe counteracts the external hydrostatic pressure exerted by the drilling fluid in the annulus. This increases the factor of safety relative to collapse.

4.6.1.1 Tension To determine if a given HDPE pipe specification is sufficient to resist the tensile loads encountered during HDD installation, a pulling load analysis should first be performed to estimate the force required to pull the pipe into a prereamed hole. To account for potential deviations from the drilled path design, this analysis should be based on the worst-case drilled path as described in Section 4.2.1. A methodology for estimating pulling load on HDPE pipe is given in ASTM F1962 (2011b).

Of primary concern with the installation of HDPE pipe by HDD is the possibility of tensile yield resulting from high axial forces applied to the pipe as it is pulled into the reamed hole. HDPE is susceptible to tensile yield not only because of its relatively low tensile yield strength, but also because the safe tensile load that can be applied to HDPE pipe is time dependent. HDPE pipe subjected to excessive tensile load continues to elongate until the load is released, potentially resulting in localized herniation in the pipe. According to ASTM F1804-08 (2012), allowable HDD installation tensile stress for HDPE pipe may be determined as follows (AWWA 2006).

$$f_t = S_y S_t T_y \tag{4-24}$$

where:
f_t = allowable tensile stress, psi;
S_y = tensile yield design factor
= 0.4 unless alternate value provided by the pipe manufacturer;
S_t = time under tension design factor, based on 5% strain

= 1.00 for 1 hour or less,
= 0.95 for more than 1 hour to 12 hours, and
= 0.91 for more than 12 hours to 24 hours; and
T_y = tensile yield strength at pipe installation temperature, psi
= 3,500 psi for PE4710 (typically at 73°F), and
= 3,000 psi for PE3608 (typically at 73°F).

Time under tension for an HDD pull back is generally less than one hour due to the fact that the tensile force applied by an HDD rig is released every 30 ft to remove drill pipe as opposed to being sustained for the entire duration of the pull-back operation. However, use of 0.95 for S_t is typical to include an element of conservatism in design.

The estimated pulling force should be compared against the allowable pulling force determined by multiplying the cross-sectional area of the pipe by the allowable tensile stress. If the estimated pulling force is less than the allowable pulling force, the pipe specification is considered to be suitable. However, it should be noted that pulling loads may exceed estimated values, especially if the pipe should become stuck, thus forcing the HDD contractor to apply greater than anticipated force to free the pipe.

4.6.1.2 Bending When installing HDPE pipe by HDD, bending stress is typically not critical. AWWA M55 (2006) states that HDPE pipe can be cold bent to a radius of 20 to 40 times the pipe diameter (although experience has shown that HDD design radii should be considerably more conservative than the AWWA M55 recommended radius because of the bending limits of the steel drill pipe).

For a 48-in. pipe, multiplying the outside diameter by 40 equates to a radius of 160 ft. This radius is substantially smaller than the radius that can be achieved during pilot-hole drilling with steel drill pipe. For example, the design radius for an HDD installation to be drilled using 5-in. drill pipe should typically not be less than 700 ft. The minimum bending radius for polyethylene pipe is given by

$$R = \frac{\alpha D}{12} \tag{4-25}$$

where:
R = minimum bend radius, ft;
D = outside diameter of pipe, in.; and
α = minimum bending ratio (taken from Table 4-1).

4.6.1.3 External Pressure Another critical issue with the installation of HDPE pipe by HDD is the possibility of pipe collapse due to external

Table 4-1. Minimum Bend Ratio

Dimension Ratio, DR	Minimum Bend Ratio, α
7, 7.3, 9	20
11, 13.5	25
17, 21	27

Table 4-2. Apparent Modulus of Elasticity at 73°F

Duration	*E* (PE3608)	*E* (PE4710)
Short term	125,000	130,000
10 hours	62,000	65,000
100 hours	52,000	55,000
1,000 hours	44,000	46,000
50 years	28,000	29,000
100 years	27,000	28,000

pressure exerted by the drilling fluid in the annulus. According to ASTM F1962 (2011b), the critical external collapse pressure of HDPE pipe may be determined using Levy's equation as follows:

$$P_c = \left(\frac{2E}{1-\gamma^2}\right)\left(\frac{1}{DR-1}\right)^3 S_o S_r \qquad (4\text{-}26)$$

where:

P_c = critical collapse pressure, psi;

E = apparent (time-corrected) modulus of elasticity, psi

(based on material grade, duration, and temperature of interest);

γ = Poisson's ratio for HDPE

= 0.45 for long-term loading,

= 0.35 for short-term loading;

DR = dimension ratio of pipe;

S_o = ovality compensation factor; and

S_r = tensile pull reduction factor.

In the absence of specific information from the pipe manufacturer, the values in Table 4-2 can be used for the time-dependent apparent modulus at 73°F (ASTM 2011b).

The ovality compensation factor can be determined from Table 4-3.

Table 4-3. Ovality Compensation Factor

% Ovality	S_o
0	1.0
2	0.85
4	0.70
6	0.55
8	0.43
10	0.36
12	0.35

A conservative value for the tensile pull reduction factor (S_r) is 0.65. This value is determined according to ASTM F1962 (2011b) with the maximum average axial tensile pull stress set at the safe pull tensile stress.

The critical collapse pressure should then be reduced by a factor of safety of 2 to yield the allowable external pressure during pull back. In most cases, installing HDPE pipe filled with water to counterbalance the external pressure and produce a net pressure that does not exceed the allowable is necessary.

When analyzing HDD pull-back operations, a service life of one day is appropriate. The external pressure exerted by drilling fluid of a known (or assumed) unit weight can be calculated as discussed in Section 4.2.3.

4.6.1.4 Mini-HDD Small drill rigs (less than 25,000 lb thrust) are often used to install small-diameter HDPE pipes. Typically these bores are executed less conservatively than large crossings. They may contain more directional corrections, have less cuttings removal, and rarely use water ballast to offset buoyant uplift. The Plastics Pipe Institute publishes a guideline for mini-HDD, TR-46, "Guidelines for Use of Mini-Horizontal Directional Drilling for Placement of High-Density Polyethylene Pipe" (2009).

4.6.2 Postinstallation Stresses

Postinstallation loading conditions that should be analyzed for HDPE pipe include both normal operation and an extended shutdown during which the HDPE pipe is empty.

4.6.2.1 Internal Pressure AWWA C906 (1999) and ASTM F714 (2011a) typically publish the internal pressure ratings of their products as a function of pipe dimension ratio (DR). These pressure ratings are based on the allowable hoop stress that can exist in the pipe wall continuously over a minimum service life of 50 years. The internal operating pressure of an HDPE pipeline should not exceed the internal pressure rating specified by the pipe manufacturer. Internal pressure considerations should be based on the lowest point of the installed pipe. Internal pressure rating can be determined using the formula presented as follows:

$$P_{\text{int}} = \frac{2f_h}{\text{DR}-1} \tag{4-27}$$

where:
P_{int} = internal pressure, psi; and
f_h = hydrostatic design stress, psi.

4.6.2.2 External Pressure If the maximum external pressure exceeds the minimum internal operating pressure, the pipeline is subjected to a differential external pressure equal to the difference between these pressures. This differential pressure should be less than the critical collapse pressure calculated in accordance with Section 4.6.1.3 and with $S_r = 1$.

External pressure resulting from earth load causes vertical deflection in HDPE pipe. This vertical deflection reduces the collapse strength proportional to the ovality compensation factor. Earth pressure may be calculated as described in Section 4.3.4. Vertical deflection is calculated as follows:

$$\frac{\Delta}{D} = \frac{15P_e(\text{DR}-1)^3}{E} \tag{4-28}$$

where:
$\frac{\Delta}{D}$ = percent ovality, used to determine the ovality compensation factor.

The safe long-term deflection of polyethylene pipe should be limited to the lesser of 0.5(DR – 1)% or 6%. In the case of an extended shutdown during which the HDPE pipe is empty, there is no operating pressure or hydrostatic pressure within the pipe. To protect the pipe from collapse under such conditions, the maximum external pressure should be compared against the critical collapse pressure for the maximum potential duration that the pipe would be empty.

4.6.2.3 Thermal Following installation, an HDPE pipe segment should be cut to length only after reaching thermal equilibrium with the surrounding soil. Good practice is to “overpull” the pipe to allow for the contraction of an HDPE pipeline after pulling. Contraction occurs as a result of thermal stabilization and relaxation from the pulling force. Soil temperatures at the depth of most HDD installations are fairly constant; therefore thermal expansion and contraction due to variation in soil temperature are typically minimal. As stated previously, a pipeline installed by HDD is considered to be fully restrained by the surrounding soil. Therefore, a buried HDPE pipeline operating at a temperature that differs from that of the surrounding soil may develop some initial thermal stress during start-up. However, these stresses are believed to dissipate over time through stress relaxation and are not considered to be critical.

4.7 DUCTILE IRON PIPE DESIGN CONSIDERATIONS

Ductile iron pipe is designed according to AWWA C150 (2002). The thickness of ductile iron pipe is determined by considering external loads and internal pressure separately.

4.7.1 Installation Stresses

During HDD installation a continuously fused or welded pipeline is subjected to tension, bending, and external pressure as it is pulled through a prereamed bore path. By comparison, flexible restrained joint DIP is subjected to only tension and external pressure, while flexural stresses from bending are not normally generated.

A string of flexible restrained joints being pulled is much like pulling a chain, in that the flexible joint articulates through the bore path and the joints remain fully restrained. Furthermore, during articulation the restraining segments change geometry within the bell socket. This change results in a redistribution of the pulling loads around the bell. The extent to which this redistribution is effective is a function of the geometry of the manufacturer's joint. It is only through actual joint testing and/or finite element analyses that the manufacturer can determine the allowable pulling load of the pipe.

4.7.2 External Loads

Ductile iron pipe is designed to resist external loads as a flexible conduit. That is, it relies on the support of the surrounding soils to resist external pressures resulting from soil loading, static ground water pressure, and static slurry pressure (i.e., drilling fluid). The earth load on pipelines installed by HDD is generally considered to be a "tunnel load," where the resulting soil pressure is less than the geostatic stress, as previously discussed in Section 4.3.4.

4.8 STEEL PIPE CORROSION COATING

Steel pipe is subject to corrosion and is therefore generally installed with an external corrosion coating. External coatings used in HDD installations should be well bonded to the pipe to resist soil stresses and have a smooth hard surface to reduce friction and maintain the corrosion barrier (Directional Crossing Contractors Association 1995).

Numerous external coating products are currently on the market, some designed specifically for HDD installations. Mill-applied thin film fusion-bonded epoxy is commonly recommended in a minimum thickness of 20 mils (Directional Crossing Contractors Association 1995).

It should be noted that concrete weight coating is not generally required on HDD installations as the deep, undisturbed cover provided in most cases serves to restrain buoyant pipelines (American Gas Association 1995).

4.8.1 Field Joint Coating

Field joint coatings must be compatible with the mill-applied coating and maintain a continuous, smooth, and abrasion-resistant surface. Twenty-five mils of fusion-bonded epoxy field applied in two-part powder form using an induction heater is commonly recommended. An alternative to this system is two-part liquid epoxy, also in a thickness of 25 mils. Tape coatings should never be used on field joints for an HDD segment due to friction-induced peeling and tearing, which makes the tape coating ineffective as a corrosion barrier (Directional Crossing Contractors Association 1995).

Reinforced shrink sleeves designed specifically for HDD installations are available. These sleeves should not be used in soil conditions such as gravel and boulders where they may be subject to peeling off during pull back.

4.8.2 Armoring Coatings

Coating loss due to abrasion from soil and very soft rock (i.e., shale and mudstone) is not a critical problem in HDD installations unless large, abundant inclusions of significantly harder material are likely to be encountered (i.e., cobbles and boulders). Coating loss occurs during HDD installations through hard abrasive rock (i.e., granite, quartzite, and hard sandstone). In general, bedrock with high unconfined compressive strength and Mohs hardness can be expected to be abrasive and cause coating wear. Point loads from sharp rock fragments and gravel may also gouge coating. Using an armoring coating, or abrasion-resistant overlay (ARO), over the corrosion coating can help preserve the integrity of the corrosion coating and minimize damage that can potentially occur as a result of HDD installation. The length and type of rock to be penetrated should be taken into consideration when specifying the armoring coating (Hair 2002). Generally speaking, an armoring coating of 40 mils provides adequate protection for most subsurface conditions. ARO applications exceeding 40 mils are possible, but the designer should consult the coating manufacturer to assess the risk of the coating cracking during pipe installation.

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CHAPTER 5

CONSTRUCTION IMPACT

5.1 INTRODUCTION

HDD offers much less impact than other methods on the environment and surrounding infrastructure. Because construction is limited to either side of an obstacle, there is minimal impact on traffic (road or waterway) and other buried utilities and structures. Regulators usually designate HDD because it is the least environmentally damaging alternative.

5.2 WORKSPACE

The HDD process has two major construction areas: the entry side and the exit side. Heavy equipment is required on each side of the crossing. A typical large HDD rig spread mobilization involves 7 to 15 tractor-trailer loads. Where possible, access should be provided the shortest distance from improved roads to minimize costs associated with additional right-of-way improvements that would otherwise be required to provide HDD access.

The entry side (sometimes referred to as the rig side) is where the HDD rig equipment is staged and assembled. This area generally has better access and more stable ground. HDD rigs come in various sizes and capacities depending on the size of the installation. Large HDD spreads include a rig unit, power unit, generators, drilling fluid mixing/recycling equipment, drill pipe, and downhole tools. The equipment is modular, so it may be set in a variety of configurations. A large HDD spread requires a minimum area of 100 ft wide by 150 ft long with no overhead obstructions. This area should be cleared, graded level, and hard standing. A typical rig-side layout is shown in Figure 5-1.

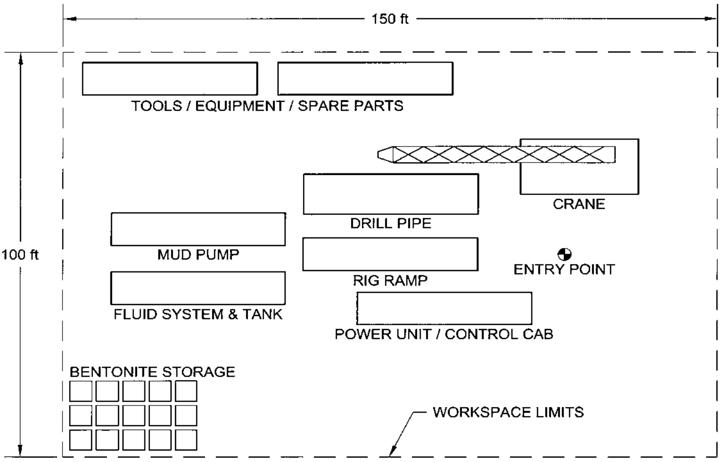

Figure 5-1. Typical rig-side layout

The exit side (sometimes referred to as the pipe side) is where the pipeline is fabricated. Ideally, there is space in line with the drill alignment of sufficient length to fabricate the pipeline into one string. Delays associated with connecting strings together during pull back increase risk for the HDD installation. The width of the workspace should be 50 ft, or normal for pipeline construction. If possible, additional temporary workspace should be obtained in the immediate vicinity of the exit location similar to the entry-side workspace to facilitate operation of additional HDD equipment if necessary, especially on larger, longer, or more difficult HDD crossings. A typical pipe-side layout is shown in Figure 5-2.

5.3 DRILLING FLUID

The drilling fluid is designed for the following:

- Hydraulic cutting of soft soils by use of high-velocity jets in the drill bit;
- Transmission of rotary power to the downhole mud motor;
- Lubrication, cooling, and cleaning the cutters;
- Transportation of cuttings and spoil by suspension in the fluid as it flows to the surface;
- Stabilization of the hole against collapse and minimization of fluid loss to surrounding formations;
- Reduction of friction between the drill pipe and pipeline to the wall of the drilled hole; and

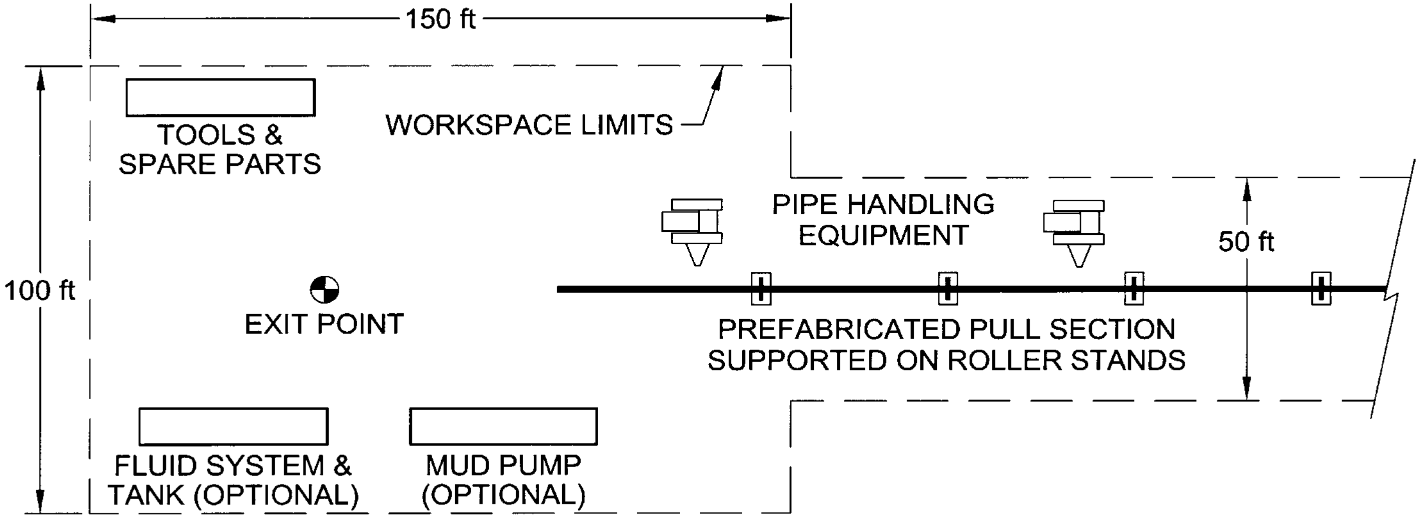

Figure 5-2. Typical pipe-side layout

- Modification of the soil by reducing the shear strength of the soil along the drill path.

5.3.1 Consumption and Characteristics

The drilling fluid is usually a mixture of fresh water, bentonite (sodium montmorillonite), and benign polymers. Bentonite is natural clay that is very hydrophilic, causing the clay particles to swell when mixed with water. This swelling increases the fluid viscosity and helps create an impervious coating on the wall of the drilled hole. Bentonite and several of its additives are nonhazardous as defined by the U.S. Environmental Protection Agency. Material Safety Data Sheets (MSDSs) are readily available from fluid additive suppliers.

HDD operations typically utilize significant quantities of fresh water. Consumption rates can range between 300 and 1,200 gal./min depending on the phase of HDD operations (i.e., less during pilot-hole drilling, more during reaming and installation). The fresh water is mixed with drilling fluid additives to obtain specific engineered characteristics for drilling performance.

5.3.2 Containment and Recycling

The drilling fluid is pumped from the drilling rig through the drill pipe to the cutters. Here it is released and circulates back to the surface in the annulus between the drill pipe and the drilled hole. At the surface, it is collected in "return pits." These pits typically have a volume of at least 500 cubic ft.

To make the drilling fluid suitable for reuse during pilot-hole drilling, reaming, and hole-conditioning operations, the cuttings and spoil must be continuously removed from the fluid as it returns to the surface. The drilling fluid returns are then processed through various levels of a solids control system. This system mechanically separates most fluid from the suspended solids so the fluid can be recirculated back downhole. However, complete separation of the solids from the liquid is typically not economically viable or necessary so the spoils requiring disposal range from semi-dry particulate to thick sludge.

Recirculation of drilling fluid is complicated in an HDD installation because the drilling fluid actually returns to the surface on either side of the obstacle. In many cases, two separate solids control systems are incorporated, or the drilling fluid is transported to the opposite work area by truck, barge, temporary pipe, etc. All of the spoils returning to the surface during pipe installation are typically disposed of as the fluid displaced by the pipe exits the borehole. Drilling fluid flow on an HDD installation is illustrated schematically in Figure 5-3.

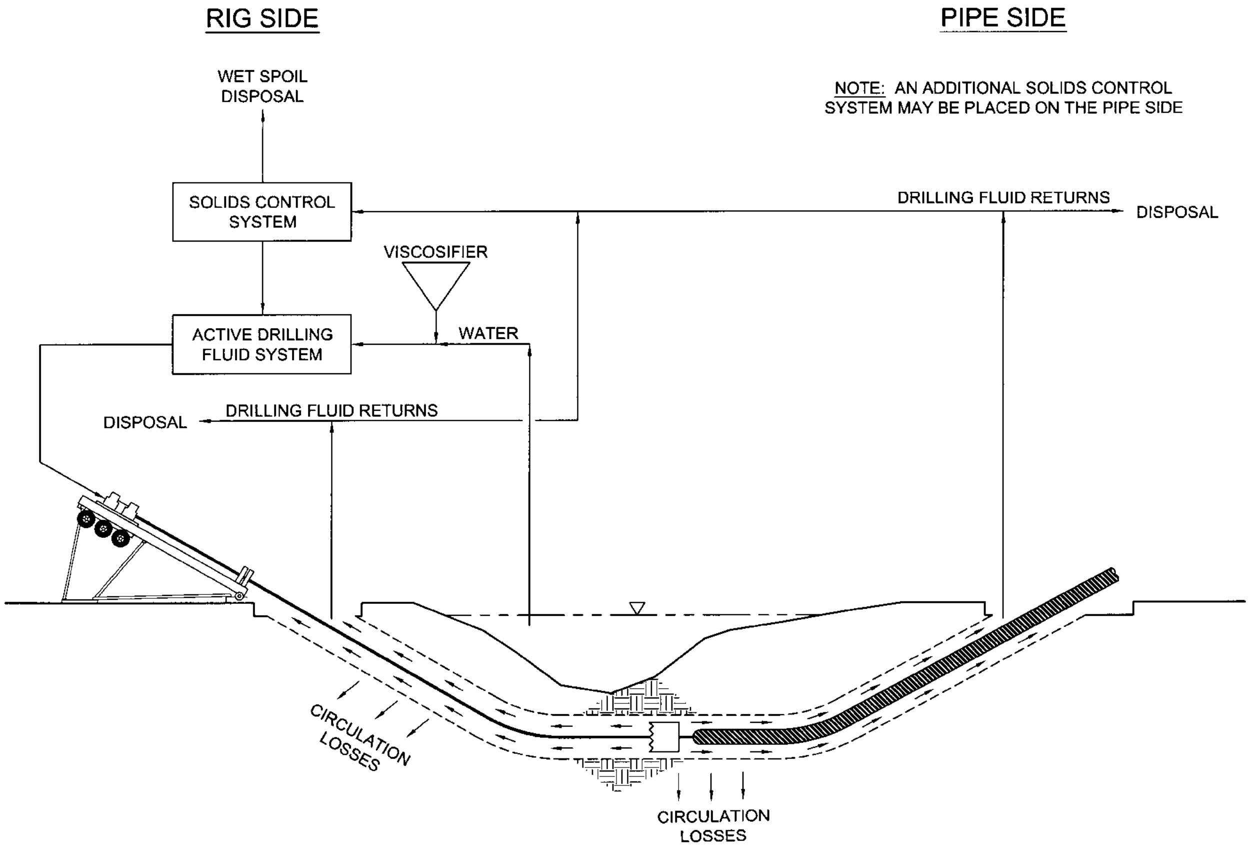

Figure 5-3. Drilling fluid flow on an HDD installation

5.3.3 Inadvertent Drilling Fluid Returns

The drilling fluid follows a path of least resistance and may not return to the containment pits but discharge to other areas along the HDD alignment. The following can increase the risk of inadvertent returns (commonly referred to as “frac outs”):

- Highly permeable soils such as gravel;
- Soils consisting of loose sands or very soft clays;
- Soil and bedrock materials with very low permeability but jointed or fractured (slickensided clays or rock fractures);
- Clay soils that have a tendency to swell in the presence of fluids;
- Considerable elevation differences between either the entry or exit point and ground elevations along the HDD alignment;
- Disturbed soils such as fill or in soils adjacent to piles or other structures;
- Areas along the HDD alignment where depth of cover is less than 40 ft;
- Locations along the HDD alignment where significant variations in density and/or composition of ground conditions are encountered (i.e., overburden/bedrock contact and other types of mixed-interface transition zones); and
- Use of inappropriate downhole tooling or drilling practices.

It is important to note that, although drilling fluid and pumping parameters can be adjusted to reduce the risk of inadvertent returns, their possibility cannot be eliminated. Research projects have been conducted in an attempt to identify the mechanisms that cause inadvertent returns and develop analytical methods for use in predicting their occurrence. Efforts have centered on predicting hydrofracturing. These programs have met with mixed success in providing a reliable prediction method (USACE 1998). However, predicting hydrofracture may identify areas of relatively higher risk. Engineering judgment and experience must be applied in utilizing the hydrofracturing model to predict the occurrence, or nonoccurrence, of inadvertent returns.

The impact of inadvertent returns is site specific. Although a small issue in an undeveloped location, inadvertent returns may present significant problems in a congested urban environment. The impact on waterways and wetlands is likened to the environmental effects of sedimentation, siltation, and turbidity from suspended solids.

Where HDD installations face a significant impact from inadvertent returns, the following may be considered:

- *Pressure while drilling (PWD) tool*: This tool provides real-time data of annular pressures behind the drill bit. The tool can indicate

sudden increases in annular pressures, which may indicate annular blockage or other problems.
- *Drilling fluid testing*: Frequent testing of drilling fluids being pumped downhole and returning to the surface provides relevant data to analyze for comparison with annular pressure calculations and to identify trends.
- *Drilling practices*: Drilling methods to increase the likelihood of maintaining drilling fluid returns during pilot-hole drilling include swabbing (retracting and reinserting each drilled joint) and the use of "weeper subs," which introduces drilling fluid to the annulus along the drilled profile.

Proper contingency planning is critical for an effective response to inadvertent returns. It is important not to delay or affect the HDD operations, particularly during prereaming or pull back. Planning should include

- Identifying methods of rapid detection (access to the drill alignment and associated areas);
- Having suitable containment materials (silt curtain, hay bales, sandbags, excavation tools, plywood sheeting, etc.) at the HDD site to contain an inadvertent return in the event it occurs;
- Identifying the length of time before cleanup begins (if in a traveled street then it is most likely immediate; however, it may be more suitable in other areas to allow the bentonite gel to set and dry);
- Listing regulatory agencies that should be notified in the case of an inadvertent return event;
- Establishing ingress/egress routes and methods into environmentally sensitive areas to minimize disturbance from equipment and personnel; and
- Determining short- and long-term monitoring requirements, if any, for areas of inadvertent fluid release that are not accessible and where mitigating measures are impractical or not feasible (i.e., flowing waterways, inaccessible wetlands, etc.).

5.3.4 Structural Failure by Piping

Failure of water-retaining structures such as levees can occur by the apparently sudden formation of a pipe-shaped discharge channel located near the dry base of the structure. Water flowing through such a channel can increase its size to a point at which the structure is undermined and fails completely. This type of failure is known as piping. Failures by piping can be caused by subsurface erosion that displaces soil until a channel is established between the dry and wet sides of the containment structure or by heaving and sudden displacement of soil on the dry side of the structure due to seepage pressure from the wet side exceeding the effective weight of the soil on the dry side (Terzaghi and Peck 1967).

Where a drilled path passes beneath a structure containing a waterway, such as a levee during flood, special consideration must be given to preventing damage to the structure by piping. The possibility of piping should be evaluated for conditions along the drilled path both during and after installation. For example, a flood control levee may not contain a waterway unless it is in flood. There may be no hydrostatic head differential between the riverward and landward sides of the levee when the waterway is within its banks. Piping cannot occur under these circumstances. However, during a flood, the hydrostatic head differential between the water surface and the land outside of the levee creates a situation where piping could occur.

Grouting the near-surface sections of the annulus around the pipeline can mitigate the risk of piping in an HDD installation. A nonshrink grout that mimics the properties of surrounding in situ soil is recommended. Depth of grouting can be determined by ensuring that enough overburden exists to provide a sufficient factor of safety against uplift pressure, as presented here:

$$\mathrm{FOS} = \frac{h_s \gamma_s}{H_w \gamma_w}$$

where:
h_s = grout depth, ft;
γ_s = total soil weight, pcf;
H_w = height of excess head above the bottom of the grout, ft; and
γ_w = unit weight of water, pcf.

5.3.5 Drilling Fluid and Cuttings Disposal

Land farming is the least costly option for disposal of drilling fluid after an HDD project. Excess materials are spread evenly over an open area and mixed with native soil. The site can either be along the construction right-of-way or in other areas nearby. In areas not delineated as wetlands, this is environmentally acceptable and permissions for this method should be obtained before construction begins. Alternatively, the materials may be disposed of at a nearby landfill. However, requiring the contractor to landfill this material may unnecessarily increase the cost of an HDD crossing, especially if local regulatory agencies allow less stringent disposal methods. Landfills typically require drying of the drilled spoil and operate during limited hours, which, combined with ever-increasing tipping fees, may have a significantly negative cost impact.

Proper documentation should be kept on the volume of material removed from the drill site, specific agreements with the property owner, any landfill licenses, and testing of the drilling fluid (refer to Section 2.3.3).

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CHAPTER 6

AS-BUILT DOCUMENTATION

6.1 INTRODUCTION

This section identifies HDD pilot-hole as-built documentation requirements. The accuracy of the pilot-hole as-built documentation and the preservation of this documentation are becoming more critical as utility corridors become more congested.

6.2 CONSTRUCTION STAKING

Two locations, the designed entry and exit points, should be staked prior to commencing HDD operations. The elevations of the staked locations and the distance between them should be checked against the values on which the design is based. If placement of the survey stakes precedes site grading, entry- and exit-point elevations should be resurveyed and noted accordingly. As-built accuracy depends directly on the accuracy of the relative location, both horizontally and vertically, of these two points. The desired mainline tie-in stationing and vertical depth requirements at the tie-in location should be carefully considered to establish appropriate set-back distances for the HDD entry and exit points.

6.3 DOCUMENTATION OF ACTUAL DRILLED PATH END POINTS

The location of the entry-point and exit-point stakes should be preserved until measurements are recorded identifying the actual locations where the drill bit penetrates grade relative to these survey stakes. Documentation of the actual entry and exit points is critical in producing an accurate as-built drawing. The downhole survey is based on the entry-point location, and the actual exit-point location provides a benchmark for measuring downhole survey error.

6.4 REQUIRED MEASUREMENTS PRIOR TO COMMENCING DRILLING OPERATIONS

Measurements required to survey the pilot hole during drilling should be recorded. These measurements, which are illustrated in Figure 6-1, include the bottom hole assembly length, the distance from the drill bit to the downhole probe, the distance from the staked entry point to the rig's vices, the recorded magnetic line azimuth, and steering tool information (manufacturer, supplier, serial number, recent shop calibrations, etc.). Additionally, each drill stem is measured and numbered in successive order. These measurements are used in pilot-hole survey calculations.

6.5 PILOT-HOLE AS-BUILT CALCULATIONS

The path of the pilot hole should be recorded during drilling by taking periodic inclination and azimuth readings of the downhole probe at intervals not to exceed 35 ft (10.67 m). The location of the downhole probe should be calculated using downhole survey methods that are discussed in detail in ANSI/API (1985).

6.6 PILOT-HOLE SURVEY DATA

Pilot-hole survey data are collected by the drilling contractor utilizing one of several commercially available systems. For maxi-rigs the system typically consists of a combination of a downhole magnetic-steering tool and a surface-monitoring system; however, in certain instances, maxi-rig operators may choose to utilize a gyroscopic steering tool. Mini- or midi-rigs commonly employ a "walkover" type system consisting of a downhole transmitter and a handheld receiver.

6.6.1 Surface Monitoring System

Magnetic-steering tools are often used in conjunction with a surface-monitoring system to correct and/or verify the initial magnetic line

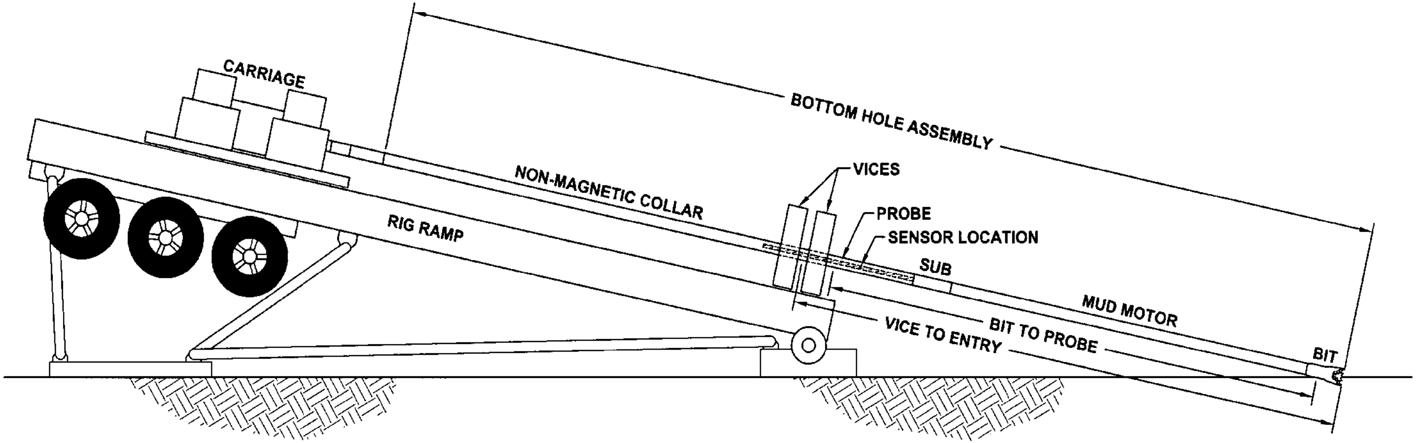

Figure 6-1. Required measurements for pilot-hole drilling

azimuth during drilling (this system also produces depth information but has vertical limitations). Magnetic interference affects the accuracy of the magnetic-steering tool measurements and is usually caused to varying degrees by the presence of manmade steel structures or magnetic-field-producing electric lines (surface and subsurface) and/or to a lesser degree by naturally occurring iron or magnetic mineral-bearing ground and magnetized drilling tools. A typical surface-monitoring system is shown schematically in Figure 6-2. The system uses a surface coil of known location to induce a magnetic field. The probe senses its location relative to this induced magnetic field and communicates this information to the surface (American Gas Association 1995).

Surface-monitoring data are generally more accurate than the values calculated using azimuth readings in the presence of magnetic interference that adversely affects the magnetic-steering tool measurements. Where the coil cannot be set directly on the obstacle being crossed, as with a major river, calculated values based on magnetic-steering tool measurements must be used. However, surface-monitoring data from coils on each bank can be used to correct and/or verify the magnetic line azimuth. This aids in providing more accurate calculated alignment values, thus improving the accuracy of the as-built drawing.

6.6.2 Gyroscopic-Steering Tool

Similar to magnetic-steering tools, gyroscopic-steering tools provide inclination and azimuth information used to calculate the position of the tool. Gyroscopic tools use sensors to take measurements relative to the earth's true north and, unlike magnetic-steering tools, are not affected by magnetic interference. Additionally, gyroscopic tools are well suited for crossings where placement of a surface coil is difficult or impossible due to the fact that data are transmitted via a wireline running through the drill string.

6.6.3 Walkover System

Walkover survey systems consist of a downhole transmitter, referred to as a sonde, and a handheld receiver. The transmitter emits an electromagnetic signal that is picked up by the receiver to ascertain the tool's position and orientation. Walkover systems, like magnetic-steering tools, are subject to magnetic interference. Additionally, their use is typically limited to crossings that are less than 70 ft (21.37 m) deep maximum, preferably not more than 50 ft (15.24 m) deep (Directional Crossing Contractors Association 1998). As the depth on the pilot bore increases, the signal of the walkover widens, creating a larger margin of error.

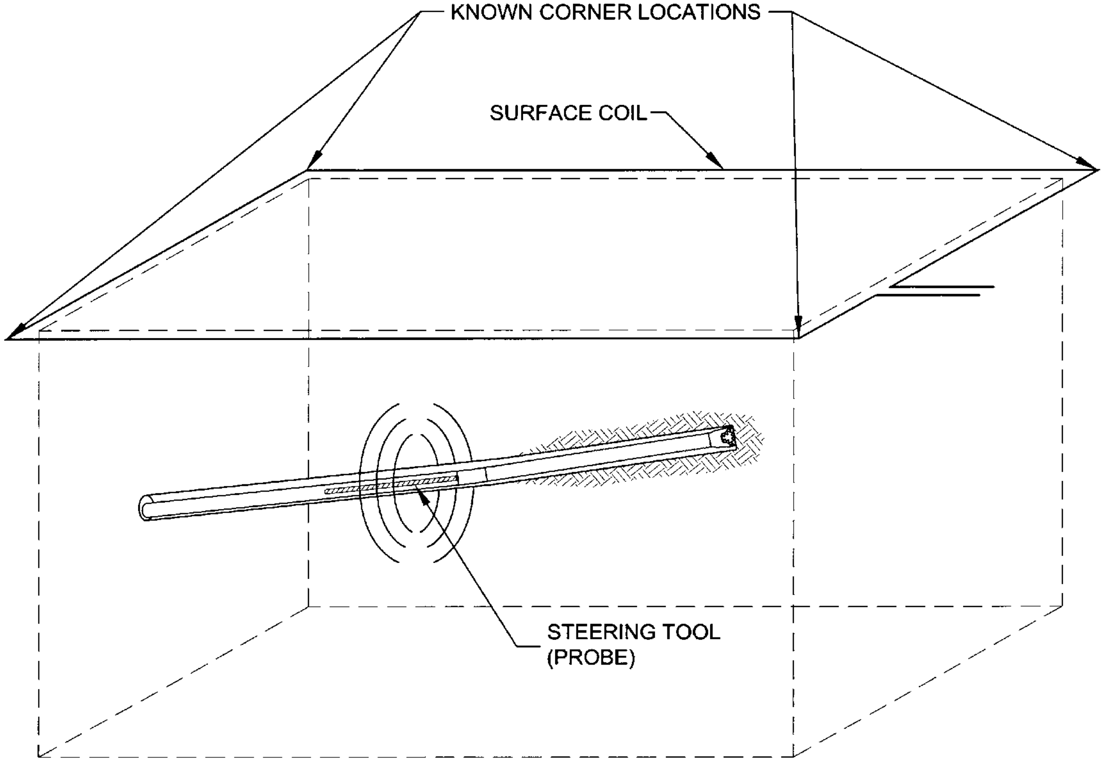

Figure 6-2. Schematic diagram of a typical surface-monitoring system

6.7 PILOT-HOLE AS-BUILT ERROR DISTRIBUTION

All of the downhole survey instruments used to track the pilot hole contain errors. Comparing the actual exit-point location with the anticipated exit-point location indicates this error. If the topographical survey is accurate and the downhole survey calculations are correct, then the observed difference in the two points results from inaccuracies in the downhole tool itself. This error should be distributed over the drilled path to yield an “as-built” profile.

6.8 PILOT-HOLE AS-BUILT DRAWING

The pilot-hole as-built drawing should include numbered nodes at each survey point in both the plan view and profile view referenced to a table of coordinates identifying the station, elevation, and offset for each node. Surface-monitoring data should be included if applicable. Survey error should be accounted for by establishing a plus or minus allowance in both alignment and elevation for the determined coordinate accuracy.

The pilot-hole as-built survey drawing identifies the location of the drilled pilot hole within determined survey accuracy. During prereaming operations, the pilot hole tends toward an “egg shape” due to the weight of the bottom hole assembly, especially in cases of softer ground and greater numbers of completed reaming passes. Therefore, the installed pull section may fall outside the pilot-hole survey accuracy identified on the drawing. If a more accurate determination of the location of the HDD segment is required, a postinstallation survey must be performed.

6.9 POSTINSTALLATION SURVEY

The preferred postinstallation survey method is the gyroscopic survey system. The survey includes two runs pulling a centralized gyroscope through the installed pull section, one in each direction, for increased confidence in the installed pull section position. The gyroscopic survey measures changes in gyro sensor alignment and integrates these changes over time providing a continuous survey of the installed pull section both laterally and vertically with a high degree of accuracy. A gyroscopic survey may add significant cost to an HDD crossing. Therefore, the necessity and benefit should be considered accordingly.

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GLOSSARY

annulus: In HDD, the annulus refers to the space that surrounds either the drill pipe or the product pipe and is enclosed by the borehole wall.

API: American Petroleum Institute located in Washington, DC.

ASTM: American Society for Testing and Materials located in West Conshohocken , Pennsylvania.

azimuth: Horizontal direction expressed as an angle measured clockwise from any meridian. In HDD, azimuths are typically measured from magnetic north.

back reamer: *See reamer.*

barrel reamer: An enclosed cylindrical soft soil-reaming tool with cutting teeth and fluid nozzles arrayed on the end faces. Barrel reamers may be designed with specific buoyancies to aid in hole enlargement.

bathymetric: Relating to measurement of depth below water.

bentonite: A colloidal clay, composed primarily of montmorillonite, that swells when wet. Because of its gel-forming properties, bentonite is a major component of drilling fluids.

bent sub: A short, threaded piece of pipe with an axial offset or angle that is used in a drill string to produce leading-edge asymmetry.

bottom hole assembly (BHA): The combination of bit, downhole motor, subs, survey probe, and nonmagnetic collars assembled at the leading edge of a drill string.

boulder: A particle of rock that does not pass through a 12-in. (300-mm) square opening.

breakover: In HDD, the overbend required to align the prefabricated pull section with the borehole during pull back without inducing plastic deformation or unacceptable flexural stresses in the pipe.

buoyancy control: Modification of the pull section's unit weight to achieve the desired buoyancy during pull back. In HDD, the most commonly used method of buoyancy control is to fill the pull section with water as it is installed in the borehole.

carriage: The component of a horizontal drilling rig that travels along the frame and rotates the drill pipe. It is analogous to a top-drive swivel on a vertical drilling rig.

clay: Soil made up of particles passing a No. 200 (75 µm) U.S. standard sieve that can be made to exhibit plasticity (puttylike properties) within a range of water contents. Clay exhibits considerable strength when air dry.

cobble: A particle of rock that passes through a 12-in. (300-mm) square opening and is retained on a 3-in. (75-mm) U.S. standard sieve.

conduit: A broad term that can include pipe, casing, tunnels, ducts, or channels.

control panel: A panel containing gauges, hydraulic valves, and controls that are used to operate the horizontal drilling rig.

cuttings: Soil or rock removed from the borehole as it is advanced or enlarged.

density: The mass or weight of a substance per unit volume. In HDD, drilling fluid density can be expressed in pounds per gallon (lb/gal.), pounds per cubic foot (lb/ft^3), or kilograms per cubic meter (kg/m^3).

desander: A centrifugal device (hydrocyclone) for removing sand from drilling fluid. Desanders are hydrocyclones larger than 5 in. (127 mm) in diameter.

desilter: A centrifugal device (hydrocyclone) for removing very fine particles, or silt, from drilling fluid. Desilters are hydrocyclones typically 4 or 5 in. (101–127 mm) in diameter.

directional drilling: *See horizontal directional drilling.*

downhole motor: A device that uses hydraulic energy produced by drilling fluid flow to achieve mechanical bit rotation.

downhole probe: *See magnetic-steering tool.*

drill bit: A tool that cuts soil or rock at the leading edge of a drill string, usually by mechanical means.

drilling fluid: A mixture of water, a viscosifier (typically bentonite), and/or polymers that is pumped to the drill bit or reamer to facilitate cutting, transport drilled spoil, stabilize the borehole, cool and clean cutters, and reduce friction between the product pipe and the wall of the hole.

drilling mud: *See drilling fluid.*

drill pipe: Tubular steel conduit fitted with special threaded ends called tool joints. The drill pipe connects the horizontal drilling rig with the bit or reamer and facilitates both pumping drilling fluid and advancing or retracting the bit or reamer.

drill stem: *See drill pipe.*

drill string: The total length of drill pipe in the borehole, including the bottom hole assembly.

duct: Small plastic or steel pipes that enclose wires or cables for electrical or communication usage.

entry point: The point on a drilled segment where the pilot-hole bit initially penetrates the ground surface. The horizontal drilling rig is positioned at the entry point.

entry/exit angle: The angle relative to the horizontal plane at which the drill string enters or exits the ground surface during pilot-hole drilling.

exit point: The point on a drilled segment where the pilot-hole bit emerges from the ground surface. The pipeline pull section is typically positioned at the exit point.

flycutter: An open circular, cylindrical, or radial blade soft-soil reaming tool with cutting teeth and fluid nozzles arrayed on the circumference and blades.

gel: In the HDD industry, an informal term for bentonite.

gradation curve: A plot of the distribution of particle sizes present in a soil sample.

gravel: Particles of rock that pass a 3-in. (75-mm) sieve and are retained on a No. 4 (4.75-mm) U.S. standard sieve.

grout: A pumpable mixture, typically comprising water, cement, fine sand, flyash, bentonite, and/or chemical components, that is commonly used to fill voids or annular spaces, strengthen incompetent soil or rock, or prevent the flow of groundwater.

hole opener: A rock-reaming tool that utilizes roller cutters to cut harder material than can be penetrated with a flycutter.

horizontal directional drilling (HDD): A trenchless excavation method that is accomplished in three 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. The third phase consists of pulling the pipe into the enlarged hole. Horizontal directional drilling is accomplished using a specialized horizontal drilling rig with ancillary tools and equipment.

hydrocyclone: A conical device that directs drilling fluid flow in a spiraling manner thereby setting up centrifugal forces that aid in separating solids from the fluid.

hydrographic survey: A survey of a body of water to determine the configuration of the bottom.

hydrostatic head: *See hydrostatic pressure.*

hydrostatic pressure: The force exerted by a body of fluid at rest; it increases directly with the density and the depth of the fluid and is expressed in psi or kPa. The hydrostatic pressure of fresh water is 0.433 psi per foot of depth (9.792 kPa/m). In drilling, the term refers to the pressure exerted by the drilling fluid in the borehole.

inadvertent return: Uncontrolled flow of drilling fluid to the surface at a location other than the entry or exit point.

inclination: The angular deviation from true vertical or horizontal. In drilling, inclination is typically expressed in degrees and is measured from vertical.

jetting: Advancing a drilled hole using the hydraulic cutting action generated when drilling fluid is exhausted at high velocity through the leading edge of a drill string.

lost circulation: The loss of whole drilling fluid to a formation, usually in cavernous, fissured, or coarsely permeable beds, evidenced by the complete or partial failure of the drilling fluid to return to the surface as it is being circulated in the hole.

lost circulation material (LCM): The collective term for substances added to drilling fluids when drilling fluids are being lost to the formations downhole.

lost returns: *See lost circulation.*

magnetic-steering tool: A device, commonly referred to as a "probe," containing instruments that measure inclination, azimuth, and tool face. A magnetic-steering tool is placed at the leading edge of the drill string and provides data that the driller uses to steer the string.

Mohs hardness: A relative scale of hardness based on 10 commonly available minerals that provides a measure of a mineral's resistance to scratching on a scale of 1 (softest) to 10 (hardest).

montmorillonite: A clay mineral often used as an additive in drilling mud. It is a hydrous aluminum silicate capable of reacting with such substances as magnesium and calcium.

One Call: A utility locator service that notifies the owners of buried utilities in a given location so that the utilities can be located prior to conducting an excavation.

overbend: In HDD, a vertical bend in the drilled path that progresses downward, or the vertical bend formed in the aboveground pull section during pull back when the pull section is elevated to achieve alignment with the borehole.

P.C.: Point of curvature

P.I.: Point of inflection

pilot hole: A small-diameter hole directionally drilled along a designed path in advance of reaming operations and pipe installation.

plunger effect: A sudden increase in borehole pressure brought about by the rapid movement of a larger pipe or cutting tool along a drilled or reamed hole.

polymer: A substance that consists of large molecules formed from smaller molecules in repeating structural units. Various types of polymers are used in commercial drilling fluid products to achieve a drilling fluid with specific properties.

preream: The act of enlarging a pilot hole by pulling or pushing cutting tools through the hole prior to commencing pipe installation.

P.T.: Point of tangency

pull back: The act of installing a pipeline in a horizontally drilled hole by pulling it to the horizontal drilling rig from the end of the hole opposite the rig.

pull-back force: The tensile load applied to a drill string during the pull-back process.

pull-back swivel: The device placed between the rotating drill string and the pipeline pull section to minimize torsion transmitted to the pull section during HDD installation.

pull section: A prefabricated pipeline segment typically staged near the HDD exit point prior to being installed in the drilled hole.

R-O-W: Right-of-way.

reamer: A cutting tool that is pushed or pulled through the borehole to enlarge the hole to a diameter sufficient for installation of the product pipe.

rock: Any indurated material that requires drilling, wedging, blasting, or other methods of brute force for excavation.

rock quality designation (RQD): A modified core recovery value that expresses, as a percentage, the total length of all sound rock core pieces more than 4 in. (101.6 mm) in length divided by the total length of the rock core run. RQD provides an indication of the fractured nature of rock.

sag bend: In HDD, a vertical bend in the drilled path that progresses upward.

sand: Particles of rock that pass a No. 4 (4.75-mm) U.S. standard sieve and are retained on a No. 200 (75-μm) U.S. standard sieve.

shale shaker: A device that utilizes vibrating screens to remove larger solid particles from circulating drilling fluid. The fluid passes through the screen openings while solids are retained and moved off of the shaker by the vibrating motion.

side bend: In HDD, a horizontal bend in the drilled path.

silt: Soil passing a No. 200 (75-μm) U.S. standard sieve that is nonplastic or very slightly plastic and that exhibits little or no strength when air dry.

soil: Any unconsolidated material composed of discrete solid particles with gases or liquids between.

spoil: Excavated soil or rock.

standard classification of soils: Classification of soils according to a widely used classification system, typically the Unified Soil Classification System described in ASTM D2487 (2010).

standard penetration test (SPT): An indication of the density or consistency of soils determined by counting the number of blows required to drive a 2-in. outside diameter split spoon sampler 12 in. using a 140-lb hammer falling 30 in. The sampler is driven in three 6-in. increments. The sum of the blows required for the last two increments is referred to as the "N" value, blow count, or standard penetration resistance.

steering tool: *See magnetic-steering tool.*

sub: A short threaded piece of pipe used in a drill string to perform a special function.

tool face: The direction of the asymmetry of a directional drilling string. A directional drilling string progresses in the direction of the tool face. Tool face is normally expressed as an angle measured clockwise from the top of the drill pipe in a plane perpendicular to the axis of the drill pipe.

trip: The act of withdrawing (tripping out) or inserting (tripping in) the drill string.

twist off: To break or separate the drill string downhole, typically due to mishandling or metal fatigue in the pipe.

vices: The devices mounted on the frame of a horizontal drilling rig that grip the drill pipe and allow it to be made up (screwed together) or broken (unscrewed).

viscosity: A measure of the resistance of a liquid to flow. Resistance is brought about by the internal friction resulting from the combined effects of cohesion and adhesion.

wash pipe: A drill pipe that is run, or rotated, concentrically over a smaller drill pipe so that the smaller (internal) pipe can be freely moved or rotated.

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