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An American National Standard

Standard Guide for Use of Maxi-Horizontal Directional Drilling for Placement of Polyethylene Pipe or Conduit Under Obstacles, Including River Crossings[1]

This standard is issued under the fixed designation F 1962; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This guide describes the design, selection considerations, and installation procedures for the placement of polyethylene pipe or conduit below ground using maxi-horizontal directional drilling equipment. The pipes or conduits may be used for various applications including telecommunications, electric power, natural gas, petroleum, water lines, sewer lines, or other fluid transport.

1.2 Horizontal directional drilling is a form of trenchless technology. The equipment and procedures are intended to minimize surface damage, restoration requirements, and disruption of vehicular or maritime traffic with little or no interruption of other existing lines or services. Mini-horizontal directional drilling (min-HDD) is typically used for the relatively shorter distances and smaller diameter pipes associated with local utility distribution lines. In comparison, maxi-horizontal directional drilling (maxi-HDD) is typically used for longer distances and larger diameter pipes common in major river crossings. Applications that are intermediate to the mini-HDD or maxi-HDD categories may utilize appropriate "medi" equipment of intermediate size and capabilities. In such cases, the design guidelines and installation practices would follow those described for the mini- or maxi-HDD categories, as judged to be most suitable for each situation.

1.3 The values stated in inch-pound units are to be regarded as the standard. The values given in parentheses are for information purposes only.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of the regulatory limitations prior to use.* Section 6 contains general safety information related to the use of maxi-horizontal directional drilling equipment.

2. Referenced Documents

2.1 *ASTM Standards:*

D 420 Guide to Site Characterization for Engineering, Design, and Construction Purposes[2]
D 422 Test Method for Particle-Size Analysis of Soils[2]
D 1586 Test Method for Penetration Test and Split-Barrel Sampling of Soils[2]
D 1587 Practice for Thin-Walled Tube Geotechnical Sampling of Soils[2]
D 2113 Practice for Diamond Core Sampling for Site Investigations[2]
D 2166 Test Method for Unconfined Compressive Strength of Cohesive Soil[2]
D 2435 Test Method for One-Dimensional Consolidation Properties of Soils[2]
D 2447 Specification for Polyethylene (PE) Plastic Pipe, Schedules 40 and 80 Based on Controlled Outside Diameter[3]
D 2513 Specification for Thermoplastic Gas Pressure Pipe, Tubing, and Fittings[3]
D 2657 Practice for Heat-Joining of Polyolefin Pipe and Fittings[3]
D 2850 Test Method for Unconsolidated, Undrained Compressive Strength of Cohesive Soils in Triaxial Compression[2]
D 3035 Specification for Polyethylene (PE) Plastic Pipe (SDR-PR) Based on Controlled Outside Diameter[3,4]
D 4186 Test Method for One-Dimensional Consolidation Properties of Soils Using Controlled-Strain Loading
D 4220 Practices for Preserving and Transporting Soil Samples[2]
D 4318 Test Method for Liquid Limit, Plastic Limit, and Plasticity Index of Soils[2]
D 4767 Test Method for Consolidated-Undrained Triaxial Compression Test on Cohesive Soils[2]
D 5084 Test Method for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter[5]
F 714 Specification for Polyethylene (PE) Plastic Pipe

[1] This guide is under the jurisdiction of ASTM Committee F-17 on Plastic Piping Systems and is the direct responsibility of Subcommittee F17.67 on Trenchless Plastic Pipeline Technology.

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[2] *Annual Book of ASTM Standards*, Vol 04.08.
[3] *Annual Book of ASTM Standards*, Vol 08.04.
[4] *Annual Book of ASTM Standards*, Vol 08.02.
[5] *Annual Book of ASTM Standards*, Vol 04.09.

(SDR-PR) Based on Outside Diameter[3]

F 1804 Practice for Determining Allowable Tensile Load for Polyethylene (PE) Gas Pipe during Pull-In Installation[3]

2.2 *Other Standards:*

ANSI Preferred Number Series 10

ANSI/EIA/TIA-590 Standard for Physical Location and Protection of Below-Ground Fiber Optic Cable Plant[6]

OSHA-3075 Controlling Electrical Hazards[7]

TR-NWT-000356 Generic Requirements for Optical Cable Innerduct[8]

3. Terminology

3.1 *Definitions:*

3.1.1 *horizontal directional drilling, HDD, n*—a technique for installing pipes or utility lines below ground using a surface-mounted drill rig that launches and places a drill string at a shallow angle to the surface and has tracking and steering capabilities.

3.1.1.1 *Discussion*—The drill string creates a pilot bore hole in an essentially horizontal path or shallow arc which may subsequently be enlarged to a larger diameter during a secondary operation which typically includes reaming and then pullback of the pipe or utility line. Tracking of the initial bore path is accomplished by a manually operated overhead receiver or a remote tracking system. Steering is achieved by controlling the orientation of the drill head which has a directional bias and pushing the drill string forward with the drill head oriented in the direction desired. Continuous rotation of the drill string allows the drill head to bore a straight path. The procedure uses fluid jet or mechanical cutting, or both, with a low, controlled volume of drilling fluid flow to minimize the creation of voids during the initial boring or backreaming operations. The drilling fluid helps stabilize the bore hole, remove cuttings, provide lubricant for the drill string and plastic pipe, and cool the drill head. The resultant slurry surrounds the pipe, typically filling the annulus between the pipe and the bored cavity.

3.1.2 *maxi-horizontal directional drilling, maxi-HDD, n*—a class of HDD, sometimes referred to as directional drilling, for boring holes of up to several thousand feet in length and placing pipes of up to 48 in. (1¼ m) diameter or greater at depths up to 200 ft (60 m).

3.1.2.1 *Discussion*—Maxi-HDD is appropriate for placing pipes under large rivers or other large obstacles (Fig. 1). Tracking information is provided remotely to the operator of the drill rig by sensors located towards the leading end of the drill string. Cutting of the pilot hole and expansion of the hole is typically accomplished with a bit or reamer attached to the drill pipe, which is rotated and pulled by the drilling rig.

3.1.3 *mini-horizontal directional drilling, mini-HDD, n*—a class of HDD, sometimes referred to as guided boring, for boring holes of up to several hundred feet in length and placing pipes of typically 12 in. (300 mm) or less nominal diameter at depths typically less than 25 ft (7 m).

3.1.3.1 *Discussion*—Mini-HDD is appropriate for placing local distribution lines (including service lines or laterals) beneath local streets, private property, and along right-of-ways. The creation of the pilot bore hole and the reaming operations are typically accomplished by fluid jet cutting or the cutting torque provided by rotating the drill string, although mud motors powered by the drilling fluid are sometimes used for hard or rocky soil conditions. The use of such mud motors would only be applicable for the larger mini-HDD machines. The locating and tracking systems typically require a manually operated overhead receiver to follow the progress of the initial pilot bore. The receiver is placed above the general vicinity of the drill head to allow a determination of its precise location and depth, indicate drill head orientation for determining steering information to be implemented from the drill rig.

3.1.4 *pipe dimension ratio, DR, n*—the average specified diameter of a pipe divided by the minimum specified wall thickness.

3.1.4.1 *Discussion*—For pipes manufactured to a controlled outside diameter (OD), the DR is the ratio of pipe outer diameter to minimum wall thickness. The standard dimension ratio (SDR) is a specific ratio of the outside diameter to the minimum wall thickness as specified by ANSI Preferred Number Series 10.

NOTE 1—Lower DR values correspond to thicker, stronger pipes.

[6] Available from the Electronics Industries Association, 2001 Pennsylvania Ave., N.W., Washington, DC, 20006.

[7] Available from the Occupational Health and Safety Administration, 200 Constitution Ave. N.W. Washington, DC 20210.

[8] Available from Bellcore, 60 New England Ave., Room 1B252, Piscataway, NJ, 08854-4196.

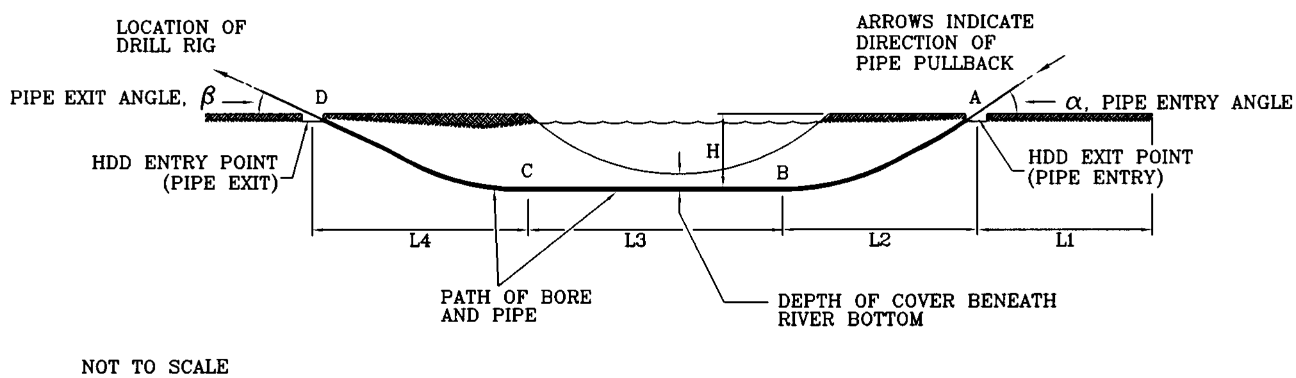

FIG. 1 Maxi-HDD for Obstacle (for example, River) Crossing

4. Preliminary Site Investigation

4.1 *General Considerations*—A maxi-HDD project, such as that associated with a river crossing, is a major event that will require extensive and thorough surface and subsurface investigations. Qualified geotechnical engineers should perform the work for the owner in preparation for planning and designing of the bore route. The information should also be provided to the potential contractors to provide guidance for the bidding stage and subsequent installation. The contractor may perform additional investigations, as desired. Since typical maxi-HDD projects represent river crossings, the following procedures are described in terms of the specific investigations and issues arising in such cases. The general procedures, however, may be appropriately interpreted to also apply to non-river crossings, such as under land-based obstacles including highways, railways, etc.

4.2 *Surface Investigation* **(1, 2)**[9]

4.2.1 *Topographic Survey*—A survey should be conducted to accurately define the working areas described in 4.1 for the proposed crossing site. Horizontal and vertical references must be established for referencing hydrographic and geotechnical data. The survey should typically include overbank profiles on the anticipated path center-line, extending about 150 ft (75 m) landward of the bore entry point to the length of the (pre-fabricated) pull section landward of the bore exit point. The survey information should be related to topographical features in the vicinity of the proposed crossing. Existing topographical information may be available from the U.S. Geological Survey, or Federal, state, or county publications. Aerial photographs or ordnance surveys may be useful, especially for crossing land-based obstacles in urban areas, since these may indicate the presence of demolished buildings and the possibility of old foundations, as well any filled areas **(3)**. It is also necessary to check available utility records to help identify the precise location of existing below-ground facilities in the vicinity, including electric power, natural gas, petroleum, water, sewer, or telecommunications lines. The presence of existing pipelines, support pilings, etc., containing significant steel mass should be noted since this may cause interference with magnetically sensitive equipment guidance or location instrumentation.

4.2.1.1 *Drill Rig (Bore Entry) Side*—The available area required on the side of the drill rig must be sufficient for the rig itself and its ancillary equipment. In general, the size of the required area on the rig side will depend upon the magnitude of the operation, including length of bore and diameter of pipe to be placed. Typically, a temporary workspace of approximately 150 ft (45 m) width by 250 ft (75 m) length will be sufficient. These dimensions may vary from 100 by 150 ft (30 by 45 m) for shorter crossings of 1000 ft (300 m) or less, to 200 by 300 ft (60 by 90 m) for medium or long crossings.

4.2.1.2 *Water Supply*—Water storage and facilities for mixing, storing, and pumping drilling fluid will require significant space. Although it is standard practice to draw fresh water found at the location for mixing the drilling fluid, alternate water supplies may be required to obtain proper drilling fluid characteristics. Hard or salty water is undesirable, although additives may be used to create the proper pH value. It may be necessary to provide access for trucks to transport water or to provide for the installation of a relatively long surface pipe or hose connecting a remote hydrant.

4.2.1.3 *Pipe (Bore Exit) Side*—Assuming the pipe to be placed is too large a diameter to be supplied on a reel (for example, larger than 6 in. (150 mm)), sufficient space is required at the side opposite that of the drill rig, where the bore will exit and the pipe be inserted, to accommodate a continuous straight length of pre-fabricated pipe. The space for the straight length will begin approximately 50 to 100 ft (15 to 30 m) from the anticipated bore exit and extend straight landward at a width of 35 to 50 ft (10 to 15 m), depending upon the pipe diameter. In the immediate vicinity of the bore exit (pipe entry), an area of typically 50 ft (15 m) width by 100 ft (30 m) length is required; for relatively large diameter pipes (larger than 24 in. (600 mm), or in cases of difficult soil conditions, an area of 100 ft (30 m) width by 150 ft (45 m) length should be provided.

4.2.2 *Hydrographic/Potamological Survey*—For crossing significant waterways, a survey should be conducted to accurately describe the bottom contours and river stability to establish suitability for the design life of the pipeline. Typically, depths should be established along the anticipated center-line, and approximately 200 ft (60 m) upstream and downstream; closer readings may be required if it is necessary to monitor future river activity. Consideration should be given to future changes in river bank terrain. Washouts, bank migrations, or scour can expose pipe.

4.2.3 *Drilling Fluid Disposal*—The means for disposal of the drilling fluid wastes must be considered. The volume of drilling fluid used will depend upon the soil characteristics but is typically on the order of 1 to 3 times the volume of removed soil. Most drilling fluids use bentonite or polymer additives which are not generally considered to be hazardous. However, local regulations should be followed regarding disposal.

4.2.3.1 *Drilling Fluid Recirculation*—Occasionally, drilling fluid recirculation is used to reduce overall material and disposal costs. If drilling fluid recirculation is contemplated, a means must be considered for transporting any fluid exhausted from the opposite (bore exit) side, during the pullback operation, to the rig side. This may be accomplished by truck, barge, or a temporary recirculation pipe line on the bottom of the waterway (for river-crossings). The recirculation line must be adequate to prevent accidental discharge into the waterway.

4.3 *Subsurface Investigation*—The overall technical and economic feasibility of the maxi-HDD process is highly dependent upon the properties of the soil formation through which the penetration will be accomplished. Thus, an accurate and thorough geotechnical investigation must be performed by a qualified engineer, including review of existing information and site specific studies for the proposed location. This information will be used to produce design drawings (including final bore route, pipe design, and bore design), construction specifications, and permit applications as well as to provide

[9] The boldface numbers in parentheses refer to the list of references at the end of this standard.

information for the contractors upon which to select appropriate tools and methods for the actual construction. While the guidelines given in the following sections point out general procedures or types of information, or both, which could be developed, unforeseeable site-specific variables make the thoroughness and accuracy of any site characterization study directly dependent on the skill, experience, and inquisitiveness of the investigating engineer. Therefore, the investigator should define the configuration, extent, and constituency of the investigation. Site characterization information must go beyond just defining soil conditions along the bore path to include a forecast of future conditions (that is, river meanders and scours) and to anticipate the affect of the maxi-HDD process on site conditions.

4.3.1 *Preliminary Study*—The subsurface investigation should begin with a review of existing data such as may be obtained from published soil reports (for example, Soil Conservation Service Report, U.S. Geological Survey, U.S. Army Corps of Engineers reports, etc.) or records from previous construction projects. In particular, data from nearby pipe or cable river-crossings, or bridge foundation construction should be examined. The results of this study will be used to define the initially recommended bore penetration profile path.

4.3.2 *Test Borings* **(1,2,4)**—Site-specific data must be obtained to fully characterize and verify the conditions through which the proposed bore path will be created. Refer to Guide D 420, Test Method D 1586, Test Method D 1587, Test Method D 2213 and Practice D 4220. Data collection should be aimed at identifying earth materials at the site and at exploring subsurface stratification (including identification of the boundary between rock and other strata, presence of cobbles or boulders and other anomalies such as old tree stumps and fill debris). The location, depth, and number of borings should be determined by the engineer based on the preliminary study, anticipated future changes in site conditions (river meanders, scours, etc.), and modifications of soil conditions during construction. These borings should be located at a sufficient lateral distance (to either side) from the proposed bore path to avoid boring into the test hole, and the holes should be sealed with grouting to avoid potential leakage paths for drilling fluid during the actual installation. Following completion of the detailed route design (Section 7), additional test borings may be desirable at critical points such as bends.

NOTE 2—In environmentally sensitive areas, possible restrictions may exist on the location or number of test borings.

4.3.3 In addition to test borings, dynamic cone testing or developing non-intrusive techniques such as ground penetrating radar or sonar may be used to identify stratification and areas with anomalies. Such probing techniques may be applied in the proximity of known conditions determined by a boring to obtain proper calibration, and then extended towards untested areas at relatively close intervals to identify irregularities between borings. If needed, additional borings may then be made at intermediate points of interest **(3,4)**.

4.3.4 *Soil Analysis* **(2,5,6)**—The geotechnical study should evaluate several parameters, including soil classifications, (Refer to Test Methods D 4318 and D 4220.) strength and deformation properties, (Refer to Test Methods D 1586, D 2166, D 2435, D 2850, D 4186, and D 4767.) and groundwater table behavior. (Refer to Test Method D 5084.) Although some field evaluation and in-situ testing should be included, the geotechnical investigation should emphasize laboratory testing in order to obtain more accurate and meaningful quantitative results. If rock is encountered, the borings should penetrate sufficiently to verify whether or not it is bedrock. The relevant soil testing methods listed in Section 2 should be followed. In general, the following specific data should be obtained from the borings:

4.3.4.1 Standard classification of soils, (Refer to Test Method D 4318),

4.3.4.2 Gradation curves for granular soils, as described in Test Method D 4220,

4.3.4.3 Standard penetration test values, as described in Test Method D 1586,

4.3.4.4 Cored samples of rock with rock quality designation (RQD) and percent recovery,

4.3.4.5 Unconfined compressive strength, as described in Test Method D 2166,

4.3.4.6 Moh's hardness for rock samples,

4.3.4.7 Possible contamination (hazardous waste),

4.3.4.8 Groundwater location, type, and behavior, and

4.3.4.9 Electrical resistivity or mineralogical constituents.

4.3.5 For river crossings, the results from the preliminary study and site specific tests should be combined in a comprehensive report describing the geotechnical subsurface conditions beneath the river bottom plus the stream's potential for meandering and scouring. The results must then be considered by the owner, the engineer, and potential contractors, with regard to compatibility with the state-of-the-art of directional drilling technology for cost-effectively completing the task. If necessary, the crossing location may be altered to a more favorable crossing site. In this case, many of the surface and subsurface investigations may have to be repeated for the new proposed crossing location and bore path.

4.3.6 *Feasibility*—Soil conditions are a major factor affecting the feasibility and cost of using maxi-HDD in a given geographic area. Table 1 indicates the suitability of horizontal directional drilling as a function of the general characteristics of the soil conditions in the area and depths of interest **(3,5)**. The "generally suitable" category presumes knowledgeable, experienced contractors or personnel using appropriate equipment. Such contractors are assumed to have a minimum of one year field experience and completed approximately 30 000 ft (10 km) of construction in related projects. The size and type machines considered appropriate for particular installations are a function of bore length, final hole diameter, and soil conditions. Various type drill heads, mud motors, reamers, and drilling fluid capabilities are available for various ground conditions. The conditions under which "difficulties may occur" may require modifications of routine procedures or equipment, such as the use of special purpose drill heads or optimized drilling fluids. Some cases will entail "substantial problems" and may not be economically feasible for directional drilling using present technology. The potential for problems to occur increases with the presence of gravels, boulders, or cobbles or with transitions from non-lithified

TABLE 1 Soil Conditions and Suitability of Horizontal Directional Drilling[A]

Soil Conditions	Generally Suitable	Difficulties May Occur	Substantial Problems
Soft to very soft clays, silts, and organic deposits		X	
Medium to very stiff clays and silts	X		
Hard clays and highly weathered shales	X		
Very loose to loose sands above and below the water table (not more than 30 % gravel by weight)		X	
Medium to dense sands above or below the water table (not more than 30 % gravel by weight)	X		
Very loose to dense gravelly sand, (30 % to 50 % gravel by weight)		X	
Very loose to dense gravelly sand (50 % to 85 % gravel by weight)			X
Very loose to very dense gravel			X
Soils with significant cobbles, boulders, and obstructions			X
Weathered rocks, marls, chalks, and firmly cemented soils	X		
Slightly weathered to unweathered rocks		X	

[A]For additional information, see Ref. **(5)**.

material into solid rock. In such cases, other drilling locations or construction alternatives should be considered unless special circumstances dictate the need for directional drilling at the present location, even at high costs associated with special rock drilling techniques, etc.

5. Safety and Environmental Considerations

5.1 *General Considerations*—Injury to personnel may result from the mechanical and hydraulic machine operations directly related to the drilling operation or from striking of electric power lines or buried pipelines. In addition, the scale of maxi-HDD operations may involve additional equipment and accessories required for the lifting and handling of heavy drill rods, drill heads, reamers, etc., as well as the product pipe or conduit. Additional precautions relating to specific auxiliary equipment must be followed, but is beyond the scope of this standard. Non-essential personnel and bystanders should not be allowed in the immediate vicinity of the maxi-HDD equipment. Barriers and warnings should be placed a minimum of 30 ft (10 m) from the edge of the equipment or associated hardware. Safety precautions are to be followed by all personnel and at both ends of the bore path. Inadvertent contact with electric power, natural gas, or petroleum lines may result in hazards to personnel or contamination. If possible, any in-service pipeline in the proximity of the bore should be de-activated during the construction. In general, the possibility of injury or environmental impact caused by damage to working or powered subsurface facilities or pipelines during the initial boring or backreaming operations is reduced by appropriate adherence to regulations and damage prevention procedures, as outlined in Section 6.

5.2 *Work Clothing*—**Caution:** Loose clothing or jewelry should not be worn since they may snag on moving mechanical parts. Safety glasses or OSHA approved goggles, or both, and OSHA approved head gear should be worn at all times. Protective work shoes and gloves must be worn by all personnel.

5.3 *Machine Safety Practices*—Contractors must comply with all applicable OSHA, state, and local regulations, and accepted industry practices. All personnel in the vicinity of the drill rig or at the opposite end of the bore must be properly trained and educated regarding the potential hazards associated with the maxi-HDD equipment. For electrical hazards, see OSHA 3075. Personnel shall be knowledgeable of safe operating procedures, safety equipment, and proper precautions. Courses and seminars are available in the industry, including training provided by the equipment suppliers.

5.3.1 The operation of the drill rig requires rotation and advancement or retraction of the drill rods. Drill rig operation is typically accomplished using chain drives, gear systems, and vises which may potentially lead to personal injury due to the moving mechanical components. All safety shields or guards must be properly mounted. The equipment must be checked at the beginning of each work day to verify proper operation.

5.3.2 *Hydraulic Fluid*—The hydraulic oil lines powering the drill rig operate under pressures of several thousand psi (hundreds of bars). The hoses and connectors must be properly maintained to avoid leaks.

5.3.2.1 **Caution:** If a leak is suspected, it should be checked by using a piece of cardboard or other object, but not hands or any other part of the body. The high pressure hydraulic fluid can penetrate the skin, burn, or cause blood poisoning. Before disconnecting any hydraulic lines, the system pressure should be relieved.

5.3.3 *Drilling Fluid*—Drilling fluid pressures will vary depending upon the equipment design and operator preference; pressures of several thousand psi (hundreds of bars) are possible. The hoses and connections must be properly maintained to avoid leaks.

5.3.3.1 **Caution:** Suspected leaks should be checked by using a piece of cardboard or other object. Avoid the use of hands or any other part of the body to check for a leak. Before individual drill rods are inserted or removed from the drill string, it must be verified that the drilling fluid pressure has been shut off and allowed to decrease; otherwise, high pressure fluid will squirt from the joint and possibly cause injury to personnel. The drilling fluid pressure gage must be checked to verify the pressure has been relieved before disconnecting any rods.

NOTE 3—If the pressure does not decrease in a short interval following pressure shut off, the fluid jet openings at the drill head may be clogged. Special care must then be made when disconnecting the rod. It may be necessary to retract the drill string or expose the drill head to clear the jets before continuing the operation. To avoid injury from the drill head and drilling fluid, all personnel should maintain a safe distance from the exit point of the bore as the drill head surfaces. The pressure should be shut off as soon as the drill head exits.

5.4 *Construction Effects on Site*—It is assumed that the preliminary site investigations included analyses to verify the stability of embankments, roads, or other major features to be traversed. It is necessary to ensure that the maxi-HDD operation will not negatively impact the site upon completion. In many cases, it will be appropriate to use grouting to seal the final bore path hole or the end portions of the hole following the installation of the pipe to prevent future flow or environmental contamination. Particularly sensitive areas include statutorily designated areas, such as wetlands, natural and scenic waterways, or contaminated or waste disposal sites. If the bore will pass through, or in close proximity to, a contaminated area, special spoils monitoring and disposal procedures must be followed, consistent with applicable Federal, state, or local regulations.

5.4.1 *Drilling Fluid*—The most common drilling fluid additive is bentonite, a naturally occurring clay. When added to water, the resulting fluid provides desired properties including viscosity, low density, and lubricity. The bentonite material used should be National Sanitation Foundation (NSF) certified. Disposal should be in accordance with local laws and regulations. The bentonite-water slurry is not a hazardous material unless it becomes mixed with toxic pollutants. The waste material is usually considered as typical excavation spoils and can be disposed or by means similar to other spoils. If other additives are of concern or hazardous material disposal is required, it may be necessary to de-water the spoils, transport the solids to an appropriate disposal site, and treat the water to meet disposal requirements.

5.4.2 The utility access pits which may be present at both ends of the bore are convenient receptacles for collecting used drilling fluid. If not present for utility access, small pits should be provided at both ends to serve as such receptacles. Depending upon soil permeability, the pits may be lined with an appropriate material or membrane. The pits should be emptied as necessary. Some maxi-HDD systems use drilling fluid recirculating systems to reduce the volume of spoils. If the geotechnical investigation revealed the existence of soil conditions conductive to fluid migration, such as through prefractures in surrounding clay or soil mass permeability, this condition must be anticipated and accounted for in the drilling operation.

6. Regulations and Damage Prevention

6.1 *General Considerations*—The owner of the proposed pipeline should obtain any required drilling permits and is responsible for obtaining approvals from the Federal, state, or local jurisdictions or other agencies that may be affected by the work. The preliminary investigations (Section 4) should identify appropriate site locations and paths, including safe separations from other facilities such as electric power, natural gas, or petroleum lines. If the constraints for a particular maxi-HDD bore are such as to be in the vicinity of known facilities, the affected owners must be contacted and strict procedures for location and marking followed. If a maxi-HDD bore interconnects points under the jurisdiction of several states or governing bodies, then the regulations of all parties must be considered, including relevant permits. Special restrictions may exist, including restoration regulations, in environmentally sensitive habitat areas.

6.2 *Environmental, Health, and Safety Plan*—When required, each contractor that will work on the project must submit an environmental, health, and safety plan. Items to consider are the responsibilities of the plan, reporting, employee training, MSDS sheets for materials being used, emergency telephone numbers for police, fire department, and medical assistance, fire prevention, sanitation, and industrial hygiene.

6.3 *Environmental and Archaeological Impact Study*—Most projects using maxi-HDD will require procurement of various environmental permits. When an environmental permitting plan must be prepared, it should include a list of required permits (for example, USAE, USEPA), the time needed to prepare permits, and an estimated date of issuance. Items to consider are solid and hazardous materials and waste management, wetlands, burial grounds, land use, air pollution, noise, water supply and discharge, traffic control and river and railroad transportation.

6.4 *Waterways* (see ANSI/EIA/TIA-590)—The U.S. Army Corps of Engineers (USAE) regulates activities involving interstate bodies of water, including marshes and tributaries, as well as intrastate waters which could affect interstate or foreign commerce. The organization is responsible for work affecting such waterways, including to the headwaters of freshwater streams, wetlands, swamps and lakes. The Regional District Engineer of the USAE will advise applicants of the types of permits required for such proposed projects. In addition, a state or local, or both, agency environmental review and permit may be required.

6.5 *Railroad Crossings* (see ANSI/EIA/TIA-590)—The chief engineer of the railroad should be consulted for the approved methods of crossing the railroad line. For spur tracks or sidings, the tract owner should be consulted. Railroads normally require cased pipes at crossings to prevent track washouts or damage in the event of pipeline rupture. (At the time of writing of this standard, an American Railway Engineering Association (AREA) committee is studying the use of HDD for uncased and cased crossing of railroads for both plastic and steel gas pipelines.)

7. Bore Path Layout and Design

7.1 *General Considerations*—For maxi-HDD projects, such as river crossings, the bore path should be designed and specified by the engineer representing the owner prior to the contractor bidding process. Based upon the preliminary surface and subsurface investigations, the path will be selected to place the pipe within stable ground and isolated from river activities for the design life of the utility line. The ground through which the path will traverse must be compatible with maxi-HDD technology. In general, for maxi-HDD projects, the design path will lie within a vertical plane. If necessary, lateral curvature is possible, consistent with the capabilities of the equipment and the product pipe. The path should be clearly designated in an integrated report summarizing the results of the surface and subsurface investigations, and should be used for pricing, planning, and executing the operation.

7.2 *Steering and Drill Rod Constraints*—The planned path must be consistent with the steering capability of the drill string and the allowable radius of curvature of the steel drill rods based upon the corresponding bending stresses in the steel rods and joints. Although some soil conditions will inhibit sharp steering maneuvers, path limitations will often be based upon fatigue strength considerations of the rods. A given rod may be able to withstand a single bend cycle corresponding to a relatively sharp radius of curvature, but the rotation of the rod during the boring operation results in flexural cycles which may eventually cause cumulative fatigue failure. The diameter of the drill rod is an important parameter affecting its stiffness, steering capability, and the allowable bend radii. A conservative industry guideline indicates the minimum bend radius should be approximately:

$$(R_{rod})_{\min} = 1200\ D_{rod} \quad (1)$$

where:

$(R_{rod})_{min}$ = medium recommended bend radius of drill rod, in. (mm), and

D_{rod} = nominal diameter of drill rod, in. (mm).

This applies to bends in horizontal (plan) or vertical (profile) planes.

7.3 The proposed path should avoid unnecessary bends. Such trajectories may be difficult to follow and may lead to oversteering and excessive bends, resulting in increased stresses in the drill rods and greater required pulling forces during the installation of the pipe. The local radius of curvature of the path at any point may be estimated by:

$$R = \frac{\Delta S}{\Delta \phi} \quad (2)$$

where:

R = local radius of curvature along path segment, ft (m),

ΔS = distance along path, ft (m), and

$\Delta \phi$ = angular change in direction, rad.

NOTE 4—The angle in radians is equal to the angle in degrees × 0.0175. (One radian equals 57.3°.)

Thus, if ΔS is selected to be equal to 30 ft (10 m) (for example, one rod length for some maxi-HDD machines) a change of 0.1 rad (6°) corresponds to a radius of curvature of 300 ft (100 m).

7.4 *Bore Paths Profile (Vertical Plane) Trajectory* **(1,2)** —A typical obstacle crossing, such as that represented by a river is illustrated in Fig. 1.

7.4.1 The following parameters must be specified in defining the bore path:

7.4.1.1 Bore entry (pipe exit) point,

7.4.1.2 Bore exit (pipe entry) point,

7.4.1.3 Bore entry (pipe exit) angle,

7.4.1.4 Bore exit (pipe entry) angle,

7.4.1.5 Depth of path, (for example, depth of cover of pipe beneath river bottom), and

7.4.1.6 Path curvatures.

7.4.2 *Bore Entry (Pipe Exit)*—The bore entry point must be accurately specified consistent with the pipe route, equipment requirements, and preliminary topographical investigations. Bore entry angles should be in the range of 8 to 20° (0.15 to 0.35 rad) from the ground surface, preferably 12 to 15° (0.20 to 0.25 rad) from the ground surface. These angles are compatible with typical equipment capabilities.

7.4.3 *Bore Exit (Pipe Entry)*—The bore exit point must also be accurately specified consistent with the pipe length and topographical investigations. Bore exit angles should be relatively shallow, preferably less than 10° (0.15 rad). A shallow angle will facilitate the insertion of the pipe into the bore hole while maintaining the minimum radius of curvature requirements. Relatively steep angles will require greater elevation of the pipe to maintain the required bend radii.

7.4.4 *Path Profile*—The proposed path should optimally lay within a vertical plane including the bore entry and exit points. The arcs of the bore path and straight sections (that is, after achieving desired depth) must be defined, including the radii of curvature and approximate points of tangency of curved and straight segments. The curvatures must be compatible with both the steel drill rods (Eq 1) and the PE pipe or conduit (Section 8). It should be noted that even larger bend radii (lower curvatures) will further reduce lateral flexural bending loads on the pipe and drill rods as they traverse the route, thereby helping avoid additional increases in tensile loads associated with their stiffness effects. Typically, the path should ensure a minimum depth of cover of 15 ft (5 m) beneath the river bottom as projected over the design life of the pipe line, including allowance for scouring **(2,4)**. This will overcome buoyancy effects and help overcome the tendency for the drill head to rise towards the free surface, thereby complicating the steering operation.

NOTE 5—The Directional Crossing Contractors Associations (DCCA) **(7)** recommends a minimum depth of 20 ft beneath the river bottom.

7.4.4.1 *Average Radius of Curvature*—The average radius of curvature for a path segment (that is, A-B or C-D in Fig. 1) reaching to or from a depth required to pass beneath an obstacle, may be estimated from the bore exit or entry angle, respectively, and the depth of the bore:

$$R_{avg} = \frac{2H}{\theta^2} \quad (3)$$

where:

R_{avg} = average radius of curvature along path segment, ft (m),

θ = bore exit or entry angle to surface, rad, and

H = depth of bore beneath surface, ft (m).

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

$$L = \frac{2H}{\theta} \quad (4)$$

where:

L = horizontal transition distance, ft (m).

It must be noted that departures from a uniform radius will result in locally smaller radii.

7.4.4.2 The resultant path will determine the stresses to be exerted upon the pipe during the installation and service life. The product pipe design must therefore be analyzed based upon the final selected path, following the pipe design and selection procedures given in Section 8.

8. Pipe Design and Selection Considerations

8.1 *General Guidelines*:

8.1.1 Maxi-HDD applications typically require detailed analysis of the pipe or conduit in relation to its intended application. Due to the large anticipated pulling loads and potentially high external pressure, a careful analysis of the PE pipe must be performed, subject to the route geometry, to verify or determine an appropriate DR (or pipe wall thickness). The analysis should consider both the installation forces occurring during pull-back and the long-term operational loads.

8.1.2 *PE Pipe*—Pipes made from either high density polyethylene (HDPE) or medium density polyethylene (MDPE) are suited for directional drilling. PE pipe specifications include Specifications D 2447, D 2513, D 3035, and F 714. If such pipe is provided in short segments, the individual units should be joined using a butt-fusion technique in accordance with Practice D 2657. This will allow the inherent strength of the PE pipe to be maintained during the placement process and when subjected to other operational stresses. Small diameter pipe of continuous length may be provided on reels. Table X1.1 gives modulus and strength values for typical pressure-rated HDPE and MDPE resins.

8.1.3 *Cable Conduit Applications*—For cable conduit applications, including electric power and telecommunications, small diameter pipe may be supplied on a continuous reel including internal pull line or the cable itself, as pre-installed by the manufacturer. In addition, the pipe may be provided with the interior surface pre-lubricated. Such features will be in accordance with that specified by the owner or engineer. Requirements for telecommunications applications, including HDPE pipe with various internal surface profiles, including smoothwall or ribbed are specified in TR-NWT-000356.

8.2 *Pipe Loading*:

8.2.1 *Operational and Installation Loads*—The pipe will be subject to loads during its long-term operation and during the installation process. It is the responsibility of the owner (or the owner's contractor or engineer) to determine the design and selection of the pipe to serve the function intended and withstand the operational stresses at the directionally drilled section as well as at other sections along the pipe line. This practice deals primarily with the loads imposed during the directional drilling process and earth and groundwater loads during operation (post-installation).

8.2.2 *Internal (Operational) Pressure Loads*—It is the responsibility of the owner (or owner's contractor or engineer) to determine the nominal diameter and wall thickness appropriate for the intended application. For example, if the pipe will be used for the pressurized flow of liquids or gases, it is necessary to determine the nominal diameter based on flow capacity requirements and the minimum wall thickness (or DR) to withstand the corresponding circumferential stresses on a long term basis. Specification D 2513, D 3035, or F 714 may be used to determine an initial estimate of the corresponding maximum dimension ratio (DR) for PE pipe.

8.2.3 *External (Operational) Hydraulic and Earth Loads*—The pipe will be subjected to hydrostatic external pressure due to the height of water or drilling fluid (or slurry) above the maximum depth of placement relative to the entry or exit point, and earth loads and liveloads due to load transfer through the deformation of the soil around the borehole **(8)**. If borehole deformation is minimal (such as in rock) or does not deform the pipe, the only loading applied to the pipe is the hydrostatic external pressure. When earth load does reach the pipe, load reductions from the geostatic stress (arching) may be anticipated. The reductions may be significant when the in situ soil is normally- or over-consolidated. On the other hand, in under-consolidated soils such as river deposits, the earth load on the pipe may equal the prism load (adjusted for buoyancy in the case of a river crossing). The external pressure applied to the pipe equals the total stress, that is, it is the sum of the effective earth pressure, reduced for arching, and the hydrostatic pressure. In some cases, the mud-slurry pressure will offset the earth pressure. As the earth load applied to directional drilled pipe is dependent on the depth of cover, borehole diameter, mud-slurry properties, drilling and back-reaming techniques, and the in situ soil properties, among other things, a geotechnical engineer should be consulted. See X2.2 for a discussion earth load calculations. Liveload pressure can be transmitted to shallow directional drilled pipe. For shallow applications, it is likely that the pipe is subjected to the same liveload and earth pressures as an entrenched pipe.

8.2.3.1 *Net External Pressure*—The net external pressure, P_{net}, is the differential pressure between the inside and outside of the pipe. The external operational load applied to the pipe may be decreased or totally off-set by internal pressure occurring within the pipe. Likewise, the external load may increase with the occurrence of negative pressure (vacuum) inside the pipe. The net external pressure may vary at different times in the life of the pipeline. For instance, during pressurized flow, the net external pressure may be zero but during a shut-down or prior to service, considerable external pressure may be applied. An analysis should be made of all potential external loadings, internal pressurization or vacuum events, and of their duration of occurrence, so that the net external pressure and its duration is determined for each cycle of the pipeline's service life.

8.2.4 *Pipe Resistance to External Loads*—The pipe must be of sufficient thickness (or DR ratio) to withstand the net external pressure without collapsing or deflecting unduly during each cycle of the operational life of the pipeline. (The effects of external hydrosatic loads applied during the installation phase are discussed in 8.2.8.2.)

NOTE 6—Spangler's Iowa Formula is typically not applicable to directional drilled pipes as the mud-slurry (unless cemented) on setting develops only the consistency of a soft clay which will not provide significant side-support for the pipe.

8.2.4.1 *Pipe Deflection (Ovality)*—Deflection reduces the pipe's resistance to external collapse pressure. Earth loads, longitudinal bending (bore path curvature), and buoyancy forces during installation will produce ring deflection in the pipe. Formulas for calculating earth load deflection, buoyancy deflection, and curvature-induced deflection along with permissible deflection limits are given in Appendix X2. When bore path curvature is limited to the guidelines given in Note 7 and the DR is 21 or less, ovality due to longitudinal bending can generally be ignored. Filling the pipe with water during the placement operation will reduce the buoyancy force (see 8.2.6) and greatly eliminate the possible short-term collapse. The effective external pressure would then be equal to that corresponding to the actual external differential pressure due to the head of drilling slurry minus the internal pressure due to that of the water inside the pipe.

8.2.4.2 *Unconstrained Collapse*—The following version of Levy's equation may be used to determine the allowable external pressure for directional drilled pipe:

$$P_{ua} = \frac{2E}{(1-\mu^2)}\left(\frac{1}{DR-1}\right)^3\frac{f_o}{N} \quad (5)$$

where:

P_{ua} = allowable external collapse pressure, psi (kPa),
E = apparent (time-corrected) modulus, psi (kPa), for the grade of material used to manufacture the pipe, and time and temperature of interest,
μ = Poisson's Ratio (long term loading = 0.45, short term loading = 0.35),
DR = dimension ratio (OD/t),
f_o = ovality compensation factor (see Fig. 2), and
N = safety factor, generally 2.0 or higher.

For design, the allowable collapse pressure, P_{ua}, *must equal or exceed the net effective pressure,* P_{net}. *The modulus of elasticity and Poisson's ratio are a function of the duration of the anticipated load. Modulus values are given in Table X1.1. If the safety factor in Levy's equation is set equal to one, the equation gives the critical collapse (buckling) pressure. Table X1.3 gives the critical collapse pressure for different DR's of HDPE pipe. For design purposes, the critical collapse pressure must be reduced by a safety factor and by ovality compensation to obtain an allowable stress,* P_{ua}. *When using Table X1.3 for determining pipe's resistance to buckling during pull-back, an additional reduction for tensile stresses is required. In general, if the resulting DR value is lower than that determined by the initial selection criteria based upon internal pressure considerations, the lower value must be used as corresponding to a required thicker, stronger pipe.*

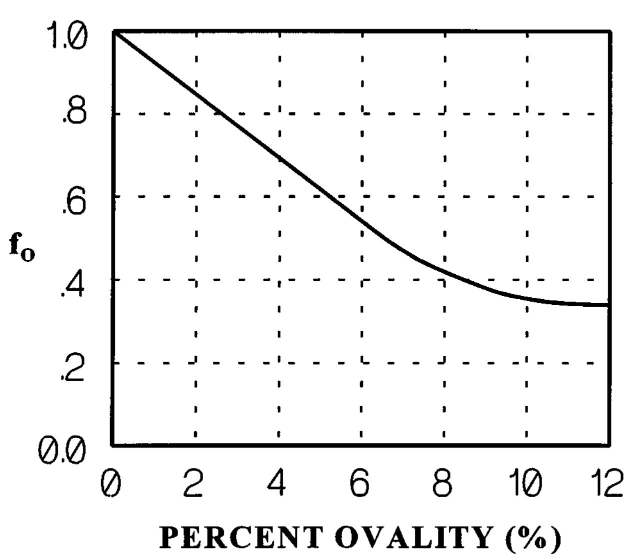

FIG. 2 Ovality Compensation Factor

8.2.4.3 For a pipe that will be supported by grouting, the allowable external collapse pressure increases (is enhanced) by a factor of approximately 4 **(1)**. Accordingly, the allowable pressure obtained from Levy's Equation, Eq 5, can be increased by a factor of 4. However, the enhancement will not apply to unsupported pipe until the grouting is fully effective. A period of 1 week may be conservatively assumed.

8.2.5 *Axial Bending Stress*—The radii of curvature for segments of the bored path, as indicated in Fig. 1, must be sufficiently large to ensure minimal bending strains and stresses within the pipe or conduit. The recommended minimum bend radius may be provided by the manufacturer, and corresponds to the following peak axial strain level:

$$\epsilon_a = \frac{D}{2R} \quad (6)$$

where:

ϵ_a = peak axial strain, in./in. (mm/mm),
D = outer diameter of pipe, in. (mm), and
R = local radius of curvature, in. (mm).

The corresponding axial bending stresses may be calculated by:

$$\sigma_a = E_a\,\epsilon_a \quad (7)$$

where:

σ_a = peak axial stress, psi (kPa),
E_a = apparent modulus of elasticity, psi (kPa) (see Table X1.1).

NOTE 7—Some PE pipe manufacturers recommend an allowable bending radius to diameter ratio of approximately 40 or 50 to 1 during pull-back to minimize the effect of ovaling due to tensile loads.

See X2.5 for calculating ovality induced by bending curvature.

8.2.5.1 *PE Pipe*—In general, the relatively stiff drill rods will require considerably larger bending radii than the flexible PE pipe. The resulting path radii for passing beneath a major obstacle, such as a river, are typically at least an order of magnitude greater than the minimum recommended for the plastic pipe. The corresponding bending strains and stresses are therefore usually not of major significance. However, the curvature required for the pipe to enter or exit the bore hole may be more severe and must be externally controlled to avoid excessive strains or stresses in these areas.

8.2.6 *Pulling Force*—The pipe pullback operation is illustrated in Fig. 1, which shows the geometry of the path including the depth, entry and exit curves, and the possibly straight interim segment beneath the river or obstacle to be crossed. The required tensile force at the leading end of the product pipe will vary during the operation and is, in general, less than that experienced at the drill rig due to the additional load on the balance of the drill string still within the bore hole and that due to any simultaneous reaming operation. The tensile forces on the pipe result from the fractional drag forces acting on the sides of the pipe due to the weight or buoyancy forces as it is pulled into and along the hole, force amplifications due to pulling the pipe around the curves, and resistance due to the pipe stiffness. The resultant forces will depend upon whether the pipe is empty or deliberately weighted (for example, filled with ballast) to reduce the buoyancy. For the purposes of estimating the peak force on the product pipe, the load is calculated at the 4 transition points, A, B, C, D shown in Fig. 1 **(1)**. The greatest load on the pipe would typically be at point D. The corresponding loads may be estimated by the following equations:

$$T_A = \exp(v_a\alpha)\,(v_a w_a (L_1 + L_2 + L_3 + L_4)) \quad (8)$$

$$T_B = \exp(v_b\alpha)\,(T_A + v_b|w_b|L_2 + w_b H - v_a w_a L_2 \exp(v_a\alpha)) \quad (9)$$

$$T_C = T_B + v_b|w_b|L_3 - \exp(v_b\alpha)(v_a w_a L_3 \exp(v_a\alpha)) \quad (10)$$

$$T_D = \exp(v_b\beta)\,(T_C + v_b|w_b|L_4 - w_b H - \exp(v_a\alpha)(v_a w_a L_4 \exp(v_a\alpha))) \quad (11)$$

where:

T_A = pull force on pipe at point A, lbf (N),
T_B = pull force on pipe at point B, lbf (N),
T_C = pull force on pipe at point C, lbf (N),
T_D = pull force on pipe at point D, lbf (N),
L_1 = additional length of pipe required for handling and thermal contraction, ft (m),
L_2 = horizontal distance to achieve desired depth, ft (m),
L_3 = additional distance traversed at desired depth, ft (m),
L_4 = horizontal distance to rise to surface, ft (m),
H = depth of bore hole from ground surface, ft (m),
$\exp(X)$ = e^x, where e = natural logarithm base (e = 2.71828),
v_a = coefficient of friction applicable at the surface before the pipe enters bore hole,
v_b = coefficient of friction applicable within the lubricated bore hole or after the (wet) pipe exits,
w_a = weight of empty pipe, lbf/ft (N/m),
w_b = net upward buoyant force on pipe in bore hole, lbf/ft (N/m),
α = bore hole angle at pipe entry (or HDD exit, at side opposite drill rig), rad, and
β = bore hole angle at pipe exit (or HDD entry, at same side as drill rig), rad.

The exponential factors correspond to the capstan effect, reflecting increased bearing pressure caused by the pipe pulled against the inside surface of the bend.

NOTE 8—Although the actual value of L_1 may be considered to be approximately 100 ft (30 m) to allow for handling at both ends of the bore, including possible thermal contraction, it is recommended that a larger value of L_1(for example, 200 to 250 ft (60 to 75 m)) be used in Eq 8 to account for the actual path length along the arc. In some cases, L_3 may be equal to zero.

8.2.6.1 If additional pipe length (to accommodate subsequent elastic, viscoelastic, or thermal contractions) is pulled through the bore hole by using a pulling force applied in a horizontal direction at the drill rig side, resulting in an additional bend of angle β at the surface, there may be a further increase in the pull force T_D. The total force would correspond to that of multiplying the value of T_D, as calculated by Eq 11, by the additional factor $\exp(v_b\beta)$. Furthermore, depending upon the total force magnitude and the local bend radius at this point, the corresponding sidewall bearing pressure at the inside of the bend may cause collapse of the pipe or conduit. This procedure should therefore be avoided in preference to pulling additional pipe length in a direction along the pipe exit (bore entry) angle.

8.2.6.2 *Pipe Stiffness*—The equations in 8.2.6 do not explicitly account for the resistance due to the pipe stiffness at curves along the bore path. This effect will be reduced for sufficiently large radii and greater clearance within the bore hole, but may still represent a significant contribution. Thus, Eq 8-11 and associated calculations should be considered primarily as estimates for the purposes of investigating the overall feasibility of the installation and providing an understanding of the effect of the other parameters. The operational procedures (Section 9) include methods for limiting the actual pulling force applied to the pipe to provide confidence in the integrity of the installed pipeline.

8.2.6.3 *Coefficient of Friction*—The coefficient of friction depends on the characteristics of the surfaces bearing against each other, the presence of any lubrication, and whether there is relative motion between the surfaces. The degree of friction immediately prior to slippage is generally greater than the level during subsequent sliding. Although brief interruptions in the placement process are necessary during the removal of the drill rods during the pullback operation, it is important to attempt to complete the operation without extensive interruptions, which may allow the bore hole to collapse or the pipe to become embedded in the surrounding soil. The value for v_b represents the lubricated value for the pipe in the bore hole as surrounded by drilling fluid and mud slurry assuming minimal interruptions. It is recommended that the pipe external to the bore hole be supported such as to provide as low a coefficient of friction v_a as possible.

NOTE 9—Suggested design values for the frictional coefficients v_a and v_b are 0.5 and 0.3, respectively **(1)**. Where pipe is placed on rollers, v_a is typically considered equal to 0.1.

8.2.6.4 *Multiple Pipes*—If more than one pipe (that is, a bundle of small diameter pipes) is simultaneously pulled into the hole, higher overall loads will result due to the greater weight or buoyancy of the combination as well as an effectively amplified coefficient of friction v_b within the hole. The degree of amplification will depend upon the relative pipe and hole diameters and will be minimized for greater clearance within the borehole.

8.2.6.5 *Effective Weight and Buoyancy Forces*—The weight of the vacant pipe or conduit may be obtained from the manufacturer, or may be calculated by the following formula:

$$w_a = \pi D^2 \frac{(DR-1)}{DR^2} \rho_w \gamma_a \quad (12)$$

where:

w_a = weight of empty pipe, lbf/in. (N/mm),
γ_a = specific gravity of pipe material (for example, 0.955 for PE),
ρ_w = weight density of water times length unit conversion factor, lbf/in.^{3}(N/mm^3), and
D = outside diameter of pipe, in. (mm).

NOTE 10—The density of water is 3.61 × 10^{-2} lbf/in.^{3}(9.80 × 10^{-6} N/mm^3).

The net (upward) buoyant force on the vacant pipe surrounded by a drilling fluid or mud slurry may be calculated by:

$$w_b = \frac{\pi D^2}{4}\rho_w \gamma_b - w_a \tag{13}$$

$$w_b = \pi \frac{D^2}{4}\rho_w \left(\gamma_b - \frac{4\gamma_a(DR-1)}{DR^2}\right) \tag{14}$$

where γ_b equals specific gravity of mud slurry.

NOTE 11—The specific gravity of the mud slurry may be conservatively assumed to be 1.5 (see 8.2.3).

If the pipe is filled with water or fluid to serve as ballast, the buoyant force is reduced and is given by either:

$$w_b = \pi \frac{D^2}{4}\rho_w \left(\gamma_b - \gamma_c \left(1 - \frac{2}{DR}\right)^2\right) - w_a \tag{15}$$

$$w_b = \pi \frac{D^2}{4}\rho_w \left(\gamma_b - \gamma_c \left(1 - \frac{2}{DR}\right)^2 - \frac{4\gamma_a(DR-1)}{DR^2}\right) \tag{16}$$

where γ_c equals specific gravity of ballast fluid.

If the pipe is filled with water, then γ_c= 1; if the pipe is filled with mud slurry (that is, if an open-ended pulling grip is used that allows the drilling fluid or slurry to enter the pipe), then $\gamma_c = \gamma_b$, and the above formula becomes:

$$w_b = \pi D^2 \rho_w (\gamma_b - \gamma_a)\frac{(DR-1)}{DR^2} \tag{17}$$

For PE pipe, these procedures will typically result in a lower required pull force as calculated by Eq 8-11.

8.2.6.6 *Hydrokinetic Pressure*—A pressure gradient exists during the pipe pullback operation corresponding to that required to exhaust the drilling fluid out of the hole, towards the pipe entry area. Additional pressure surges are possible due to nonuniform pulling rates **(1,2)**. The flow of the drilling fluid along the length of the pipe results in a drag force which may be estimated by considering a balance of the forces acting on the fluid annulus in the bore hole due to the hydrokinetic pressure and the lateral shear forces acting on the pipe and walls of the bore hole:

$$\Delta T = \Delta P \frac{\pi}{8}(D_{hole}^2 - D^2) \tag{18}$$

where:
ΔT = pulling force increment, lbf (N),
ΔP = hydrokinetic pressure, psi (kPa × 10^{-3}), and
D_{hole} = backreamed hole diameter, in. (mm).

NOTE 12—ΔP is estimated to be 10 psi (70 kPa) **(1,6)**.

The term ΔT may be added to the pulling forces calculated by Eq 8-11 to obtain the total pull force at each corresponding point of the installation. This is shown explicitly in Eq 19.

NOTE 13—For a bundle of pipes, the term D^2 in Eq 18 is replaced by an equivalent sum of the corresponding quantities (diameters squared) for the individual pipes.

8.2.7 *Axial Tensile Stress*—The average axial stress acting on the pipe cross-section at point A, B, C, or D, including the increment for hydrokinetic pressure, is given by:

$$\sigma_i = (T_i + \Delta T)\frac{1}{\pi D^2}\left(\frac{DR^2}{DR-1}\right) \tag{19}$$

where:
T_i = T_A, T_B, T_C, or T_D, lbf (N), and
σ_i = corresponding stress, psi (kPa × 10^{-3}).

The highest average axial stress will occur at the pulling head. However, depending on the curvature of the borepath, the peak tensile stress may not occur at the pulling head, but in a curve. In the curve, the maximum tensile stress due to bending occurs in the outer fibers of the pipe. For each curve, the maximum tensile stress equals the sum of the bending stress, as in Eq 7, due the curvature and the average axial stress at that point due to pulling. The maximum tensile stress for each curve should be determined and compared with the average axial stress at the pulling head to determine the peak tensile stress, σ_p, occurring in the pipe:

$$\sigma_{pi} = \sigma_i + \sigma_{ai} \tag{20}$$

where:
σ_{pi} = peak tensile stress at *i*-th point (where *i* = A, B, C, or D), psi (kPa),
σ_i = average axial tensile pull stress *i*-th point (where *i* = A, B, C, or D), psi (kPa), and
σ_{ai} = outerfiber tensile stress (Eq 7) at *i*-th point (where *i* = A, B, C, or D), psi (kPa).

8.2.7.1 *Allowable Tensile Stress*—The peak tensile stress, σ_p, should be compared to the allowable stress at the anticipated installation temperature. Thus, it is required that:

$$\sigma p \leq SPS \tag{21}$$

where *SPS* equals safe pull tensile stress, psi (kPa × 10^{-3}) at the anticipated installation temperature. Under continuous load, polyethylene undergoes creep deformation. Therefore, the safe pull stress values are time and temperature dependent. See Table X1.1 for typical SPS values. The time interval for the installation depends upon the length and rate of pullback of the pipe. Pullback rates are on the order of several feet per minute, depending upon the soil conditions. If it is anticipated that the back-reaming process will be slow and difficult (see Section 9), it is recommended that a separate pre-reaming operation be used to allow a subsequent faster pipe pullback and shorter time interval for installation pull forces to be applied.

8.2.7.2 If necessary, the stress on the PE pipe or conduit may be reduced by increasing the pipe wall thickness (that is, lower SDR value) or, possibly, reducing the net buoyant force by filling the pipe with fluid ballast (as described in 8.2.7.1).

8.2.8 *Torsional Stress*—Torsional stresses are eliminated or minimized by the use of a swivel at the leading end of the pipe. Section 9 provides information for the selection of an appropriate swivel.

8.2.9 *Combined Loads During Installation*—The calculations allow a preliminary selection of the pipe DR consistent with the anticipated application, installation, and path characteristics. It is necessary, however, to finally consider the overall installation stresses due to the combination of loads which many be present simultaneously. If the combined stresses are not within the desired overall design margin, it may be necessary to select a thicker wall pipe or modify the installation parameters to relieve the resultant stresses.

8.2.9.1 *Reduced PE Collapse Strength*—For PE pipe, the presence of an axial tensile load will have a tendency to reduce the pipe's short-term resistance to collapse under external pressure, as otherwise estimated from Eq 5 **(1)**. In addition, the hydrokinetic pressure increment at the leading end of the pipe also increases the external hydrostatic pressure during this period. The modified equation to account for these effects is:

$$P_{pba} = \frac{2E}{(1-\mu^2)}\left(\frac{1}{DR-1}\right)^3\frac{f_O f_R}{N} \quad (22)$$

where f_R, the tensile pull reduction factor, is given by:

$$f_R = \sqrt{5.57-(r+1.09)^2} - 1.09 \quad (23)$$

and

$$r = \frac{\sigma_i}{2(SPS)} \quad (24)$$

σ_i = maximum average axial tensile pull stress from Eq 19, psi (kPa), and
SPS = safe pull tensile stress, psi (kPa).

The allowable collapse pressure, P_{pba}, should equal or exceed the sum of the net effective pressure during pull-back and the hydrokinetic pressure:

$$P_{pba} \geq P_{eff} + \Delta P \quad (25)$$

where:
P_{eff} = net effective pressure acting on pipe during pull-back, psi (kPa), and
ΔP = hydrokinetic pressure, psi (kPa).

NOTE 14—The modulus value used in Eq 22 and in the deflection calculation for determining ovality for use in Eq 22 during pull-back should be selected to match the time-interval of the pull-back.

8.2.9.2 The net effective external pressure term, P_{eff}, in Eq 25 corresponds to the external head of drilling fluid or slurry reduced by the internal pressure due to any fluid used as ballast. For the case of an open-ended pulling grip allowing the drilling fluid to serve as ballast (see 8.2.6.5), the net effective external pressure, P_{eff}, including the hydrokinetic pressure, is negligible and the possibility of collapse due to external pressure during the installation stage is essentially eliminated.

8.2.9.3 *Thermal Effects*—Potential effects due to thermal expansion may be minimized by allowing the pipe to reach temperature equilibrium with the soil before cutting the pipe to length to complete the installation.

8.2.10 *Combined Loads During Operation*—In general, it is the responsibility of the owner or owner's contractor or engineer to ensure that the design will be compatible with the long term operation of the pipe line, including sections away from that being placed by the drilling operation, as well as sections in the vicinity of the crossing, both at the surface and passing beneath the obstacle.

8.2.10.1 *Thermal Stress*—Thermal stresses due to temperature differentials existing during the placement process may be considered small, as discussed in 8.2.10. However, possible thermal effects during long-term operation due to seasonal expansion or contraction at the surface, including at sections away from the drilled crossing, are not specific to the HDD process and should be considered by the owner as for non-drilled pipe lines, in combination with the other stress contributions.

9. Implementation

9.1 Due to the magnitude of the typical operation and complexity of the equipment and control systems, maxi-HDD requires a highly trained crew. See Mini-Horizontal Directional Drilling Manual. It is beyond the scope of this guide to provide operational procedures for the various equipment. Such training is generally provided by the manufacturer. Contractors should be required to demonstrate evidence of proper training for their crews, including classroom and field experience for the primary personnel. The following items represent some of the issues related to the implementation process for placement of pipe or conduit.

9.1.1 *Machine Size & Capability*—The size and capacity of the drilling equipment must be compatible with the thrust and torque required to perform the drilling, reaming, and pipe pullback operations. It is difficult to estimate the drill rig forces associated with the reaming operation, which may be significantly greater than that directly applied to the pipe itself during pullback (as estimated by the formulas in 8.2.4), particularly when both operations are performed simultaneously. The estimated forces applied to the pipe may be considered a minimum equipment requirement.

9.1.2 *Drill Unit Positioning*—The drill rig unit is positioned consistent with the discussion in Section 7 and the desired bore route and pipe depth. Proper anchoring is especially important for soft or sandy soils.

9.1.3 *Boring and Drill Rods*—HDD operations begin with the initial pilot bore. Different ground conditions will require different type drill heads for the pilot bore operation. The drill rods should be as least as strong as the equipment capability. The planned bore route should also be compatible with drill rod capabilities with respect to cumulative fatigue stresses (Section 7). Proper care and handling of the drill rods is important to avoid breakage during boring or backreaming. The rod threads must be cared for and properly coated (greased) when inserted into the drill string. Proper torque should initially be applied to the drill rods as added at the bore entry to avoid potential loosening of the rods and loss of connection in the ground.

9.1.4 *Washover Pipe*—For many maxi-HDD operations, a washover pipe is inserted over the drill string as the bore progresses to support the hole and reduce torque. This steel pipe may be removed during the backreaming operation. If reaming is not required, the washover pipe may be left in place and used as a casing into which a group of small plastic pipes may be placed by a later independent pulling operation.

9.1.5 *Drilling Fluid Usage*—Drilling fluids serve a critical role in maxi-HDD operations. The fluid powers the mud-motor at the front of the drill string that bores the pilot hole. The fluid also provides lubrication during the pilot boring, reaming, and pullback operations to reduce the required torque and thrust or pullback loads. In addition, the drilling fluid stabilizes the bore hole, cools the drill head (and internal circuitry), and removes cuttings and spoils. The crew must be trained in the proper use of drilling fluids and the appropriate types for various ground conditions. Note that excessive drilling fluid pressures or volumes may result in greater disposal problems or appearances at undesired surface locations as the fluid penetrates through fissures.

9.2 *Tracking and Locating*:

9.2.1 *Location Interval*—In order to maintain the actual bore along the planned path, the pilot bore must be carefully tracked, and path confirmation established at least once each 30 ft (10 m) interval (for example, when adding drill rods). For paths with horizontal or vertical turns, or in critical areas including the vicinity of other obstacles, shorter intervals for example, 15 ft (5 m) are recommended. In areas with pockets of cobbles or other obstacles that may divert the drill head, measurements should be made whenever contact with such obstacles is suspected. A misdirected drill head must be corrected as soon as possible.

9.2.2 *As-Built Drawings*—A record of the actual as-built bore path, including plan and profile views and vertical and horizontal deviations, indicating the relation to the planned path, must be submitted to the owner. Any information obtained during the initial bore regarding soil characteristics, etc. should be added. The experiences gained during the initial bore may be used to provide guidance for the backreaming operating, as well as for subsequent operations in the project area. Additional information should also be included, such as steering or correction commands, drilling fluid usage, and the type of drill head being used. Regarding the reaming and pullback operations, the pipe insertion velocity, duration, type and size of reamers (cutters or compactors), final bore hole size, drilling fluid usage, and required pullback forces should be recorded.

9.3 *Reaming*—In some maxi-HDD applications, a backreaming operation to increase the hole size may not be required (for example, when a small pipe is to be pulled back into the initial bore hole or, possibly, a bundle of small pipes is to be pulled into the remaining washover pipe by a separate procedure after completion of the HDD operation). However, a backreaming operation is typically performed to produce a hole size sufficiently large to readily install the pipe(s) or conduit. Appropriate cutters and compactors compatible with the soil conditions are required, including proper usage of drilling fluid. In some cases, several reaming (that is, pre-reaming) operations may be required. In general, pre-reaming is not required for placing pipe 20 in. (500 mm) or less in diameter, and the reaming and pipe pullback may be performed simultaneously. The pre-reaming operations allow relatively large holes to be created in stages, reducing the required torque and thrust loads at the machine. For difficult installations for which a high pulling load is anticipated, a pre-reaming operation will help ensure that the capability of the machine is not exceeded due to the combined forces due to increasing the hole diameter and pulling the pipe. The pullback operation may also then be performed at a faster rate, reducing the time the pipe is under axial load. In addition, pre-reaming reduces the possibility of voids or surface heaving or settlement, including unanticipated drilling fluid appearances. Hole diameter increments should be restricted to approximately 10 in. (250 mm) or less during a single pass. The final hole diameter is typically 50 % greater than the outer diameter of the pipe (or pipe bundle) to provide clearance for pipe grips, allow spoils flow, and reduce the required loads during the pipe pullback operation. During pre-reaming, additional drill rods must be available at the pilot bore exit which are connected to a swivel at the rear of the reamer and pulled into the hole to maintain the path.

9.3.1 *Grouting*—If grouting has been specified to fill the annulus of the hole surrounding the pipe(s), it may be pumped during the pullback operation, serving as drilling fluid. However, if the pullback encounters any difficulty, the grout can set-up. Consideration should be given to placing grout through a tremie pipe pulled in during pullback. The requirement and formulation of the grouting shall have been established in advance by the owner and the owner's engineer following the preliminary surface and subsurface studies and route planning, for environmental considerations, or to increase the long-term collapse resistance of the pipe or provide additional strength or mechanical protection. The grouting requires proper formulation consistent with desired set-up time; appropriate fluid pumps are required to handle the thicker fluid mixture. In may cases it may only be required to plug the entry and exit penetration points, possibly using a cement-bentonite mixture **(5)**.

9.4 *Gripping the Pipe*—If not supplied as a continuous length on a reel, it is assumed that the pipe(s) have been fused and tested prior to completion of the boring operation to avoid unnecessary delays in completing the installation. The bored and reamed hole may tend to close in or collapse after an extended period of time, significantly inhibiting or preventing the insertion of the pipe.

9.4.1 Due to the distance of the operation and the relatively high pullback loads generated, secure gripping procedures must be used. Basket-type or internal only grips are not recommended. The gripping method selected must allow essentially the full tensile rating of the pipe to be developed. Appropriate types may include an internal/external clamping or bolting device, or a fused PE pipe adapter with a built-in pulling eye. In the latter case, a smaller diameter section of the adapter may serve as a breakaway link protecting the main section of pipe (see 9.4.3). In general, the end of the pipe should be plugged or sealed to prevent contamination during the pull-back operation. However, if it is desired to allow the mud slurry to serve as ballast (see 8.2.5), a gripping method should be used that allows the fluid to enter the pipe. Several pipes may be pulled simultaneously, but the position of the grips should be staggered, if necessary, to avoid a single large bulge.

9.4.2 *Swivel*—A swivel is required between the reamer or compactor preceding the pipe to prevent the transmission of torsional loads to the pipe. The rating of the swivel should be somewhat larger than the lower of the pull force capability of the drill rig or the total strengths of the bundle of pipes to be installed, but not excessively greater. Inefficiencies in overly large swivels may result in relatively significant twist transmitted to small pipes.

9.4.3 *Breakaway Link*—In general, the recorded pulling forces as indicated at the drill rig will exceed the tensions experienced by the pipe or conduit throughout most of the pullback process. Limiting these loads to that of the allowable pipe strength will generally be overly conservative. It is recommended that individual breakaway links be provided between the main swivel and the grip(s) at the pipe(s), to ensure that the pipelines are installed within allowable load levels. Broken links will require removal of the pipe(s) from the entry end, or possibly abandonment. Following a determination of the problem, and an appropriate solution, another attempt may be made, possibly requiring a new bore path.

9.4.3.1 Each breakaway link rating should be within the safe pull tensile load, also called the allowable tensile load of its corresponding pipe. See Table X1.1.

9.4.3.2 Although less desirable, a single breakaway link may be used for a bundle of pipes. The corresponding safe working loads for the individual pipes in the bundle are added to determine the total safe working load and the corresponding rating of the breakaway link. If a breakaway swivel is used as the breakaway link, and not specifically designed for direct exposure with soil, this item should be cleaned well after each application. The use of such a breakaway swivel does not eliminate the need for the main swivel described in 9.4.2.

9.5 *Handling the Pipe*—Extreme care must be exercised when handling the pipe to ensure that it is not subject to excessively sharp bends which may cause a kink or other damage to the pipe. Section 8 provides appropriate guidelines, including discussion of the combined effects of bending loads and tension in the pipe. Particular areas of concern typically include the pipe entry or exit points. It is important to minimize bending of the pipe as it enters the bore hole, consistent with 7.3, 7.4.4 and 8.2.7, and to ensure low friction on the portion of the pipe outside the hole. This may be accomplished by the use of appropriate lifting equipment and roller stands to reduce friction. Due to the potentially high tensile load at the pipe exit, it is especially important to avoid sharp bends at this point.

10. Inspection and Site Cleanup

10.1 *Completion and Inspection*—It is necessary to minimize any residual stresses or strains remaining in the pipe following the installation, due to the imposed pulling forces and potential thermal expansion or contraction. Thus, the pipe should be allowed to achieve mechanical and thermal equilibrium with its surroundings prior to cutting the pipe at either end. Premature cutting of the pipe may allow the ends to shrink back into the hole. The pipe may be cut after it has been verified that there has been insignificant movement at the pipe entry end and negligible residual tensile load at the drill rig end. If any fluid or slurry was allowed to enter the pipe to serve as ballast (see 8.2.6), the fluid must be purged and the pipe thoroughly flushed and cleaned.

10.1.1 *Integrity*—Some pipes, such as for gas or fluid transport, may be required to pass hydrostatic pressure or leakage tests, before or after pullback, or both, as specified by the owner. For pipes to be used as paths for cables, the integrity of the path should be verified by pulling a "pig" through the installed pipe prior to splicing or terminating.

10.1.2 *Visual Inspection*—The pipe exiting the borehole should not show signs of yielding or necking-down. The surface of the pipe should be inspected for gouges or scratches. Gouges or scratches in excess of 10 % of the minimum wall thickness should be assessed as to whether pipe is suitable or not for pressure service.

10.1.3 *Bore Path*—The as-built drawings shall be submitted to the owner's representative to indicate the pipe was placed at the proper location and depth, or within acceptable limits. Maintaining an appropriate minimum depth of cover beneath the river bottom is critical, including margin to account for scouring, to avoid subsequent exposure or damage. Recording of the exact location will help avoid damage during any future construction activities in the area. In addition, records of pullback forces at the drill rig, breakaway link ratings, installation rate, final hole diameter, grouting information, etc., should be recorded and provided.

10.2 *Cleanup*—After inspection and approval by the owner or representative, the surface area must be restored to its original condition. The site must be cleaned of equipment, tools, and spoils. All drilling fluid must be cleaned from the site or its vicinity and properly disposed of, consistent with Section 6.

APPENDIXES

(Nonmandatory Information)

X1. MATERIAL PROPERTIES OF POLYETHYLENE

X1.1 *Material Properties of Polyethylene*—Typical values for the apparent modulus of elasticity and tensile strength at 73°F (23°C) for medium density (PE 2406) and high density polyethylene (PE3408) resins are presented in Table X1.1. Consult the manufacturer for specific applications.

TABLE X1.1 Apparent Modulus of Elasticity and Safe Pull Tensile Stress at 73°F

Typical Apparent Modulus of Elasticity			Typical Safe Pull Stress		
Duration	HDPE	MDPE	Duration	HDPE	MDPE
Short-term	110 000 psi (800 MPa)	87 000 psi (600 MPa)	30 min	1300 psi (9.0 MPa)	1000 psi (6.9 MPa)
10 h	57 500 psi (400 MPa)	43 500 psi (300 MPa)	60 min	1200 psi (8.3 MPa)	900 psi (6.2 MPa)
100 h	51 200 psi (350 MPa)	36 200 psi (250 MPa)	12 h	1150 psi (7.9 MPa)	850 psi (5.9 MPa)
50 years	28 200 psi (200 MPa)	21 700 psi (150 MPa)	24 h	1100 psi (7.6 MPa)	800 psi (5.5 MPa)

X2. POST–INSTALLATION LOADS AND DEFLECTION OF HORIZONTAL DIRECTIONAL DRILLED PIPES

X2.1 Allowable Tensile Load—The safe pull tensile load for a pipe is equal to its allowable tensile load ATL, which can be calculated from the safe pull tensile stress SPS, as follows:

$$ATL = (SPS)\,\pi\, D^2\left(\frac{1}{DR} - \frac{1}{DR^2}\right) \quad \text{(X2.1)}$$

where:
D = pipe outer diameter, in. (mm),
SPS = safe pull stress, psi (kPa), and
DR = pipe dimension ratio (outer diameter/minimum wall thickness).

For gas pipes, see Practice F 1804 for determining ATL.

X2.2 *Earth Pressure Calculation*—The soil load on directional drilled pipe is essentially dependent on the depth of cover, borehole diameter, mud-slurry properties, and the in situ properties. Earth and live-load pressures are transferred to the pipe through the deformation of the soil around the borehole. As the deformation occurs, a cavity of loosened soil forms above the borehole. This cavity is filled by soil sloughing from above it. The process causes the soil to bulk, that is, the density of the sloughed soil is less than the density of the undisturbed soil. The sloughing process continues until an equilibrium is reached where the stiffness of the sloughed soil is sufficient to resist further sloughing from the soil above. This bulking state results in arching of load around the pipe (that is, the earth load applied to the pipe is less than the geostatic stress (or prism load).) There is a lack of published equations for calculating earth loads on directional pipes. However, equations have been published for calculating loads on jacked pipe. Although the applicability of these equations to directional drilling has not been confirmed, they are likely applicable where the PE is installed in a mud slurry. The normal jacking procedure like the directional drilled process overcuts the hole but the overcut is typically less than 10 % of the pipe diameter with jacked pipe, whereas with directional drilled pipes the overcut may be 50 %. Equations for calculating the loads occurring on jacked-pipe due to the bulking process are given by O'Rourke et al. Another interpretation of arching above jacked-pipe is given in **(10)**. Stein's method in Ref. **(10)** considers the process of arching to be similar to trench arching. Only Stein's method is given below as O'Rourke's method in Ref. **(9)** involves extensive calculations and typically results in lesser load than Stein's method. Credit for arching should only be considered where the depth of cover is sufficient to develop arching (typically exceeding five pipe diameters), dynamic loads such as traffic or rail loads are insignificant, the soil has sufficient internal friction to transmit arching, as confirmed by a geotechnical engineer.

X2.2.1 Use of Terzaghi's equation as given in Eq X2.2 for calculating earth loads on jacked pipe is suggested in Ref. **(10)**. Note that the friction angle, has been reduced in Terzaghi's equation by 50 %.

$$P_{EV} = \frac{\kappa\gamma H}{144\,\frac{in.^2}{ft^2}} \quad \text{(X2.2)}$$

$$\kappa = \frac{1 - exp\left(-2\frac{KH}{B}\tan\left(\frac{\delta}{2}\right)\right)}{2\frac{KH}{B}\tan\left(\frac{\delta}{2}\right)} \quad \text{(X2.3)}$$

[For metric units, the conversion factor of 144 in^2/ft^2 should be dropped]

where:
P_E = external earth pressure, psi (kPa),
Y = soil weight, pcf (kN/m^3),
H = depth of cover, ft (m),
κ = arching factor,
B = "silo" width, ft (m),
δ = angle of wall friction, degrees (for directional drilling, assume $\delta = \phi$, and ϕ = angle of internal friction, degrees.), and
K = earth pressure coefficient given by:

$$K = \tan^2\left(45 - \frac{\phi}{2}\right) \quad \text{(X2.4)}$$

The silo width must be estimated based on the application. It varies between the pipe diameter and the borehole diameter. A conservative approach is to assume the silo width equals the borehole diameter. (If the effective soil weight is used the groundwater pressure must be added back into Eq X2.2 to get the total external pressure acting on the pipe. The effective soil weight is the dry unit weight of the soil for soil above the groundwater level; it is the saturated unit weight less the weight of water for soil below the groundwater level.)

X2.3 *Earth Load Deflection*—Earth load is generally applied at the pipe crown with a reaction at the invert. As slurry provides essentially no side-support, there is little pressure at the springline to restrain vertical deflection. The primary resistance to deflection is provided by the pipe's stiffness. Whereas, actual soil loads will occur over a good portion of the top and bottom halves of the pipe, Ref. **(11)** gives two ring deflection formulas for uniform loading on the top half of a pipe in the Appendix of the text. One formula assumes the pipe's invert is supported on a rigid, flat base while the other assumes the invert reaction load is uniform around the bottom half of the pipe. Neither case fits exactly what occurs with directional drilled pipe but the average of the two formulas may come close.

$$\frac{\Delta}{D} = \frac{\dfrac{0.0125P_E}{E}}{12\,(DR-1)^3} \qquad \text{(X2.5)}$$

where:
D = pipe diameter, in. (mm),
Δ = ring deformation, in. (mm),
P_E = earth pressure, psi (kPa),
DR = pipe dimension ratio, and
E = modulus of elasticity, psi (kPa).

X2.4 *Buoyant Deflection*—An external pressure difference between crown and invert occurs when pipe is submerged in grout due to the difference in grout head pressure across the pipe. The pressure difference applies a force which deflects the invert upward toward the crown, thus creating ovality. Deflection is given by Eq X2.6. This can be converted to percent deflection by multiplying it by 100.

$$\frac{\Delta}{D} = \frac{0.1169\gamma_w\left(\dfrac{D}{2}\right)^4}{EI} \qquad \text{(X2.6)}$$

where:
Δ = ring deflection, in. (m),
D = pipe diameter, in. (m),
Y_w = weight of fluid in borehole, lbs/in.^{3} (to convert fluid weight from lbs/ft^3 to lbs/in^3 divide by 1728) (kN/m^3),
E = modulus of elasticity, psi (kPa), and
I = moment of inertia of pipe wall cross-section (t^3/12), in.^{4}/in. (m^4/m).

X2.5 *Reissner Effect*—Longitudinal bending of a pipe induces ovality. For entrenched pipes this ovality is usually ignored as it is oriented transverse to earth load deflection. In a directional drilled pipe ovality is additive to earth load deflection. For DR 21 or lower pipes, when the bending radius is greater than or equal to 40 pipe diameters, the ovality is negligible. Ovality in terms of percent deflection can be calculated from the Reissner equation:

$$\frac{\Delta y}{D} = \left(\frac{2}{3}\right) z + \left(\frac{71}{135}\right) z^2 \qquad \text{(X2.7)}$$

$$z = \frac{\frac{3}{2}(1 - \mu^2)(D - t)^4}{16t^2R^2} \qquad \text{(X2.8)}$$

where:
μ = Poisson's ratio,
D = pipe OD, in. (mm),
t = pipe wall thickness, in. (mm),
R = radius of curvature, in. (mm), and
$\Delta y/D$ = deflection, in./in. (mm/mm) (convert to percent by multiplying by 100).

X2.6 *Deflection Limits*—The limiting deflection (in percent) is determined by the geometric stability of the deflected pipe, hydraulic capacity, and the strain occurring in the pipe wall. It has been observed that for PE, pressure-rated pipe, subjected to soil pressure only, no upper limit from a practical design point of view seems to exist for the bending strain **(12)**. Therefore, for non-pressure pipes or conduits the safe long-term deflection is 7.5 % of the diameter. When subjected to internal pressure in addition to soil pressure, the localized bending strain resulting from deflection combines with the hoop tensile strain caused by internal pressure to produce a higher, localized tensile fiber-stress. However, as the internal pressure is increased the pipe re-rounds and the bending strain is reduced. At high pressures, the bending strain is reduced and the ring tensile stress approaches that due to internal pressure alone. For calculation method, see Ref. **(13)**. This fact coupled with the ductility of PE permits the designer to ignore the combined effect of pressure and deflection. In lieu of an exact calculation based on allowable strain, the designer can use the safe long-term design deflection values for pressure pipe shown to Table X2.1.

X2.6.1 Design deflections are for use in selecting DR and for field quality control. Field measured deflections exceeding the design deflection do not necessarily indicate unstable or over-strained pipe. In this case, an engineering analysis of such pipe should be performed before acceptance.

TABLE X2.1 Safe Long-Term Design Deflection values for Buried Pressurized Polyethylene Pipe

DR or SDR	Deflection Limits as % of Diameter
21	7.5
17	6.0
15.5	6.0
13.5	6.0
11	5.0
9	4.0
7.3	3.0

X3. CRITICAL BUCKLING PRESSURE FOR HDPE PIPE

X3.1 *Critical Buckling Pressure*—Table X3.1 gives the critical collapse pressure for HDPE pipes. The values do not contain a safety factor nor any compensation for ovality or pulling force. See 9.2.3.1 for discussion.

TABLE X3.1 Critical Collapse Pressure for Unconstrained HDPE Pipe[A,B,C] at 73°F

NOTE—**Table does not include ovality compensation or safety factor.**

	Pipe SDR, psi, ft H_2O, in Hg						
Service Life	7.3	9	11	13.5	15.5	17	21
Short-term	1003, 2316, 2045	490, 1131, 999	251, 579, 512	128, 297, 262	82, 190, 168	61, 141, 125	31, 72, 64
100 h	488, 1126, 995	238, 550, 486	122, 282, 249	62, 144, 127	40, 92, 82	30, 69, 61	15, 35, 31
50 years	283, 653, 577	138, 319, 282	71, 163, 144	36, 84, 74	23, 54, 47	17, 40, 35	9, 20, 18

[A]Axial Tension during pull-back reduces collapse strength.
[B]Full vacuum is 14.7 psi, 34 ft water, 30 in Hg.
[C]Multipliers for temperature rerating:

60°F (16°C)	73.4°F (23°C)	100°F (38°C)	120°F (49°C)
1.08	1.00	0.78	0.63

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