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Considerations in the Application of Horizontal Directional Drilling to Pipeline Construction in the Arctic

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This paper was prepared for presentation at the Arctic Technology Conference held in Houston, Texas, USA, 7–9 February 2011.

Abstract

This paper assesses the current state of the art in horizontal directional drilling (HDD) for pipeline installation, reviews analytical methods associated with HDD pipeline design and installation, and presents concepts useful in the application of HDD techniques to pipeline construction in the arctic. The current state of the art is defined by a review of recent commercial applications of HDD to pipeline construction. Details on completed projects defining feasibility limits with respect to length and pipe diameter are presented. Restrictions with respect to subsurface conditions are examined. Theoretical limits on HDD pipeline installation are explored including a discussion of analytical methods available to calculate pulling loads associated with very long HDD Installations. The paper concludes with conceptual design examples of how HDD installation might be applied to obstacles presented by the arctic environment.

Current State of the Art in Pipeline Installation by Horizontal Directional Drilling

Three primary characteristics govern the feasibility of an HDD installation: 1) subsurface conditions, 2) pipe diameter, and 3) drilled length. These three characteristics work in combination to limit what can be accomplished using existing HDD tools and techniques. Individual limits for each of these characteristics are discussed in the following paragraphs. It should be noted that, consistent with the objectives of this paper, this discussion is founded on commercial experience within the HDD Industry. The limits of directional drilling technology applied to drilling oil wells are not considered. While such tools and techniques may be applied to pipeline installation in the future, this paper discusses what is being utilized in the Pipeline Industry today.

Subsurface Conditions

The nature of the subsurface material through which the drilled path must pass is critical in determining the technical feasibility of an HDD pipeline installation. For a pipeline to be installed by HDD, either an open hole must be cut into the subsurface material so that installation of a pipeline by the pullback method is possible, or the properties of the subsurface material must be modified so that the soil behaves in a fluid manner allowing a pipeline to pass through it.

In the open hole condition a cylindrical hole is drilled through the subsurface. Drilling fluid flows to the surface in the annulus between the pipe and the wall of the hole. Drilled spoil is transported in the drilling fluid to the surface. This is generally applicable to rock and cohesive soils. It may also apply to some sandy or silty soils depending on the density of the material, the specific makeup of the coarse fraction, and the binding or structural capacity of the fine fraction.

The open hole condition is difficult to achieve in soft cohesionless soils over a long horizontally drilled length. Nevertheless, pipelines are routinely installed by HDD in soft soils. The mechanical agitation of the reaming tool coupled with the injection of bentonitic drilling fluid will cause the soil to experience a decrease in shear strength. If the resulting shear strength is low enough, the soil will behave in a fluid manner allowing a pipe to be pulled through it.

The problematic subsurface condition most often encountered in evaluating the feasibility of an HDD installation is large grain content in the form of gravel, cobbles, and boulders. Other subsurface conditions which can impact the feasibility of an HDD installation include excessive rock abrasivity, poor rock quality, and solution cavities in karst formations.

Large Grained Formations: Soils consisting principally of large grained material present a serious restriction on the feasibility of HDD. Coarse gravel, cobbles, and boulders cannot be readily fluidized by the drilling fluid, nor are they stable enough to be cut and removed in a drilling fluid stream as is the case with a crossing installed in competent rock. A boulder or cluster of cobbles will remain in the drilled path and present an obstruction to a bit, reamer, or pipeline. Such material must be mechanically displaced by drilling tools. If the characteristics of the large grained formation are such that mechanical displacement with HDD tools is not possible, HDD installation may not be technically feasible. Fortunately, problematic large grained soils are normally encountered in limited formations. Coarse overburden may overlay bedrock or a finer grained formation amenable to penetration by HDD. If the overburden is not too deep, it can be removed by excavation or penetrated with a surface casing. HDD can then proceed through the amenable formation.

Excessive Rock Abrasivity: Exceptionally abrasive rock can hamper all phases of an HDD project. Frequent trips to replace worn bits and reamers can result in extended construction durations and corresponding unacceptable increases in construction cost.

Poor Rock Quality: An HDD installation through poor quality (extensively fractured or jointed) rock can present the same problems as large grained deposits. Cutting a hole through such materials may cause the overlying rock to collapse creating obstructions during subsequent passes.

Solution Cavities: Solution cavities present in karst formations can have a substantial impact on the feasibility of an HDD installation. While the wall of a competent rock hole serves to limit the deflection of the drill string, penetration of a void leaves the drill string unconstrained potentially allowing it to deflect laterally. Continued rotation of a drill string subjected to such a deflection can result in failure of the drill pipe due to low-cycle fatigue.

Pipe Diameter

The general practice in the HDD industry is to ream a hole twelve inches larger than the outside diameter of the pipeline to be pulled into the hole. For example, a 48-inch hole would be reamed for a 36-inch pipeline; a 60-inch hole would be reamed for a 48-inch pipeline. The diameter of the pipeline to be installed is therefore limited by the torsional capacity of drill pipe necessary to rotate a large diameter reaming tool. Experience in the mining industry with raise bores indicates that reaming tools in diameters exceeding anything contemplated for a pipeline (in excess of 10 feet) can be rotated with long strings of drill pipe.[1] HDD Industry experience with large diameter pipeline installation is detailed below.

Demonstrated Maximum Pipe Diameter

The feasibility of HDD for installation of very large diameter welded steel pipelines is demonstrated by experience in 2004 on the Cross Island Pipeline Project for The National Gas Company of Trinidad and Tobago. This 56-inch diameter pipeline project included three HDD crossings in lengths of 2,230 feet (680 meters), 2,517 feet (767 meters), and 2,415 feet (736 meters). Seventy-two inch reaming tools were employed.[2]

The explosion of new natural gas transmission pipeline construction over the last three years has made HDD installation of 42-inch diameter pipe common, if not routine. This is demonstrated by the fact that, in the last three years alone, the author’s engineering firm has designed fifty (50) 42-inch HDD crossings with a total length of over twenty miles. The length of eight of these crossings exceeded 4,200 feet (1,300 meters) with the longest exceeding 5,500 feet (1,700 meters).

Drilled Length

The HDD process is accomplished in three stages, pilot hole, prereaming, and pullback. Length limitations in each stage are discussed in the following paragraphs.

Pilot Hole Limitations

An HDD pilot hole must be drilled in compression. That is, weight on bit must be achieved by thrusting the drill pipe away from the drilling rig. This is unlike a traditional vertical drilling operation where drill collars can be placed at the downhole end of the drill string to provide weight on bit while maintaining the string in tension. Drill pipe buckling becomes a problem, depending on soil conditions, and the combination of pipe bending and rotation can lead

[1] John D. Hair, “Pipeline Landfall Construction By Horizontal Drilling”, *Civil Engineering in the Arctic Offshore*, Proceedings of the Conference Arctic 85 sponsored by the American Society of Civil Engineers, 1985, p. 795

[2] Sharon M. Bueno, “Tinidad Becoming Natural Gas Giant”, *Trenchless Technology International*, November 2004

to failure through low cycle fatigue. **Pilot hole length is limited by the capacity of the drill pipe to withstand the combination of compressive, bending, and torsional loads**.

An HDD pilot hole is directionally drilled by orienting the asymmetry of the bottom hole assembly by rotating the drill string at the drilling rig. As pilot hole distances increase, the orientation of the bottom hole assembly becomes more difficult to control. Actions taken at the drilling rig several thousand feet behind the bottom hole assembly may not translate clearly to reactions at the leading edge. **Pilot hole length is limited by the ability to accurately steer**.

An HDD pilot hole must achieve either an open hole or fluidized condition in the soil to allow penetration. Regardless of whether an open hole or fluid condition is established downhole, long horizontal distances can present problems. Suspension of cuttings is difficult to maintain over long horizontal distances. Cuttings may accumulate around the pipe causing it to get stuck. Experience has shown that the fluidized condition degrades over time if the soil is not agitated and exposed to bentonite drilling fluid flow. The soil essentially heals up. Drill pipe, and pipelines, have become stuck during HDD operations and been abandoned in place. **Pilot hole length may be limited by the ability to maintain a hole in the subsurface**.

Prereaming and Pullback Limitations

Drill pipe is typically rotated in tension during prereaming and pullback. Therefore, the limitations associated with drill pipe compression and low cycle fatigue described for pilot hole drilling do not come into play. Additionally, concerns with steering are also not applicable. **Horizontal distance during prereaming and pullback is limited by the ability to maintain an open hole or fluid condition to such an extent that drill pipe, reaming tools, and product pipe can be moved along the drilled path without exceeding the capacity of the pipe or drilling rig**.

Demonstrated Maximum Pilot Hole Distance

Feasible pilot hole distance using a single rig is indicated by experience on the Cooper River Crossing at Charleston, South Carolina, in 2004. This 8-inch welded steel power transmission cable pipe extended over a length of 7,100 feet (2,164 meters).[3] The feasibility of drilling a pilot hole over 7,000 feet (2,134 meters) with a single rig was reinforced by an Elizabeth River Crossing completed in late 2009 for Virginia Natural Gas. This 24-inch welded steel natural gas pipeline extended over a length of 7,357 feet (2,242 meters)[4].

Drilled Intersects: Improvements in downhole surveying technology have made it possible to drill one pilot hole into another from opposite ends of a drilled segment. Use of the drilled intersect technique may effectively double the maximum pilot hole length to 14,000 feet (3,676 meters). However, the ability to steer into another pilot hole at a distance of 7,000 feet (2,134 meters) has not been demonstrated. The practical limit of this technique may be closer to 12,000 feet (3,658 meters) to allow for some overlap as one pilot hole is sought out by another.

Two installations completed on the Arabian Gulf Coast in Saudi Arabia in January of 2009 demonstrate the capabilities of the drilled intersect method. These installations were parallel 24-inch and 30-inch steel pipelines and extended over a length of 10,000 feet (3,050 meters).[5] Another notable drilled intersect was completed in March of 2006 in British Columbia, Canada.[6] The 6-inch Buckinghorse Creek Crossing extended over a horizontal length of 6,562 feet (2,000 meters) and penetrated to a depth of more than 755 feet (230 meters)

Pulling Load Calculation by the PRCI Method

A method to estimate HDD pulling loads was published by the Pipeline Research Committee at the American Gas Association, now known as the Pipeline Research Council International (PRCI), in the 1995.[7] The PRCI Method involves modeling the drilled path as a series of segments to define its shape and properties during installation. The individual installation loads acting on each segment are then resolved to determine a resultant tensile load for each segment. The estimated pulling load required to install the entire pull section in the reamed hole is equal to the sum of the tensile loads acting on all of the defined segments.

In utilizing the PRCI Method, engineers should be aware that pulling loads are affected by numerous variables, many of which are dependent upon site-specific conditions and individual contractor practices. Such variables cannot easily be accounted for in a theoretical calculation method designed for use over a broad range of applications. For this reason, theoretical calculations are of limited benefit unless combined with engineering judgment derived from experience in HDD

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[3] "Cooper River Crossing", *Trenchless Technology*, October 2004

[4] Stephen Tait, "HDD Makes Natural Gas Pipeline Project Possible", *Trenchless Technology*, October 2009

[5] "Success for HDD intersects in Saudi Arabia", *Trenchless International*, July 2009

[6] Tom Teer and Dan Billig, "Horizontal Intersects in Canada", *Trenchless Technology*, December 2006, pp. 48-50

[7] *Installation of Pipelines By Horizontal Directional Drilling, An Engineering Design Guide* (Washington: Pipeline Research Committee at the American Gas Association, 1995) Section 5

construction. Nevertheless, observations on numerous HDD installations suggest that the technical basis for the method is sound and the method can be used to predict HDD pulling loads reliably under most conditions.[8]

A description of HDD installation loads and a method for estimating these loads follows.

Tension

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

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

Frictional Drag

Frictional drag between the pipe and soil is determined by multiplying the bearing force that the pull section exerts against the wall of the hole by an appropriate coefficient of friction. A reasonable value for coefficient of friction is 0.3 for a pipe pulled into a reamed hole filled with drilling fluid.[9] It should be noted that this value can vary with soil conditions. A very wet mucky soil may have a coefficient of friction of 0.1 while a rough and dry soil (unlikely in an HDD installation) may have a coefficient of 0.8.[10]

For straight segments, the bearing force can be determined by multiplying the segment length by the effective unit weight of the pipe and resolving this force into a radial component based on the angle of the segment. For curved segments, calculation of the bearing force is more complicated since additional geometric variables must be considered along with the stiffness of the pipe.

Fluidic Drag

Fluidic drag resulting from drilling fluid surrounding the pipe is determined by multiplying the external surface area of the pipe by an appropriate fluid drag coefficient. A reasonable value for fluidic drag coefficient is 0.025 pounds per square inch.[11] The external surface area of any segment defined in the drilled path model can easily be determined based on the segment's length and the outside diameter of the pull section.

Effective Weight of Pipe

The effective weight of the pipe is the unit weight of the pull section minus the unit weight of any drilling fluid displaced by the pull section. This is typically expressed in pounds per foot. The unit weight of the pull section includes not only the product pipe, but also its contents (ducts, internal water used for ballast, etc.) and external coatings if substantial enough to add significant weight (i.e. concrete coating). Calculating the weight of drilling fluid displaced by the pull section requires that the density of the drilling fluid either be known or assumed. For HDD installations, drilling fluid density will range from approximately 8.9 pounds per gallon to approximately 11 pounds per gallon.[12,13] Where use of a high end value for fluid density is warranted for a conservative analysis, 12 pounds per gallon represents a reasonable upper limit.

The pulling load from the effective weight of the pipe is determined by resolving the effective weight into an axial component based on the angle of the segment.

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[8] Jeffrey S. Puckett, "Analysis of Theoretical Versus Actual HDD Pulling Loads", *Volume Two, New Pipeline Technologies, Security and Safety*, Proceedings of the ASCE International Conference on Pipeline Engineering and Construction sponsored by the American Society of Civil Engineers, 2003, p. 1352

[9] *Installation of Pipelines By Horizontal Directional Drilling, An Engineering Design Guide*, p. 41

[10] Manual of Practice No. 108, *Pipeline Design for Installation by Horizontal Directional Drilling* (Reston, Virginia: American Society of Civil Engineers, 2005), p. 21

[11] Puckett, p. 1352

[12] *Drilling Fluids In Pipeline Installation By Horizontal Directional Drilling, A Practical Applications Manual* (Washington: Pipeline Research Committee at the American Gas Association, 1994), p. 30

[13] *Horizontal Directional Drilling, Good Practices Guidelines* (HDD Consortium, 2001), p. 3-25

Bending

The pull section is subjected to elastic bending as it is forced to negotiate the curvature of the hole. This induces a normal bearing force against the wall of the hole. These normal forces influence the tensile load on the pipe as a component of frictional drag. The PRCI Method accounts for these increased bearing forces by modeling a curved segment as a beam in three point bending. The curvature and deflection of the beam are known from the data input in the drilled path model. Reactions are calculated using standard beam relationships.

Conceptual Maximum Pulling Load Calculations

Theoretical limits of HDD pipeline installation using today's tools and technology may be indicated by conceptual pulling load calculations using the PRCI Method. Five cases, as described below, have been run for presentation in this paper. In all cases the maximum allowable pulling load was governed by generally available drill pipe and set at 1,000,000 pounds. The analysis was conducted at the point at which the entire pull section was in the hole. A Specified Minimum Yield Strength of 70,000 pounds per square inch was used for line pipe. The "base case" length was set at two miles (10,560 feet) (3,219 meters) for a simple drilled path design consisting of two sag bends joined by three straight tangents. The radius of curvature for the sag bends was set at one half of the industry design standard (1200 times the nominal pipeline diameter) to approximate a "worse case" condition for installation stresses.

Case 1, Two Mile 52-inch with No Ballast, examines the feasible length for a very large diameter pipeline. The pipeline wall thickness is set at 1.250 inches to provide a D/t ratio of around 40. The calculated pulling load is 2,120,357 pounds, which violates the maximum allowable pulling load of 1,000,000 pounds and indicates that HDD installation of this case is not feasible using today's tools and techniques. No installation stress limiting criteria are violated.

Case 2, Two Mile 52-inch with Ballast, examines the impact of applying buoyancy control during pull back for a very large diameter pipeline. This is a common practice on large diameter HDD installations. The pulling load is calculated with the pipe full of water and the pipeline wall thickness is reduced to 0.750 inches which provides a D/t ratio of 69. The calculated pulling load is 1,095,767 pounds, which still violates the maximum allowable pulling load of 1,000,000. However, this analysis indicates that a two mile installation of a 52-inch pipeline may be feasible with foreseeable modifications to today's tools and techniques. No installation stress limiting criteria are violated.

Case 3, Two Mile Heavy 52-inch with No Ballast, examines the impact of increasing wall thickness to decrease the buoyant force for a very large diameter pipeline. The pipeline wall thickness is set at 2.000 inches which provides a D/t ratio of 26. The calculated pulling load is 820,042 pounds, which indicates that this installation is feasible from an HDD perspective. However, the general feasibility of 2.0 inch wall thickness pipe is questionable and an examination of such is outside the scope of this paper. No installation stress limiting criteria are violated.

Case 4, Three Mile 24-inch with No Ballast, examines the feasible length for a mid-range diameter pipeline. The pipeline wall thickness is set at 0.625 inches to provide a D/t ratio of 36. The calculated pulling load is 788,946 pounds, which indicates that HDD installation of this case is feasible using today's tools and techniques. No installation stress limiting criteria are violated.

Case 5, Two Mile 36-inch with No Ballast, examines the feasible length for a large diameter pipeline. The pipeline wall thickness is set at 1.000 inches, which provides a D/t ratio of 36. The calculated pulling load is 968,380 pounds, which indicates that HDD installation of this case is feasible using today's tools and techniques. No installation stress limiting criteria are violated.

Obstacles in the Arctic Environment

The benefits of HDD for crossing obstacles in the arctic environment are the same as those in more hospitable environments. That is, HDD provides an economically advantageous method for installing a pipeline at a deep depth of cover without the need to excavate a trench from the surface along the HDD alignment. This benefit is typically applied to pipeline river crossings. In considering application of HDD to obstacle crossings in the arctic, it is beneficial to review past accomplishments.

The Colville River Crossing is one of the most, if not the most, significant HDD installation completed to date in discontinuous permafrost under arctic winter conditions. The Colville River Crossing is located on the North Slope of Alaska approximately five miles northeast of the town of Nuiqsut. The crossing consists of four drilled segments each designed to be 4,259 feet (1,298 m) long. The four segments are: a 20-inch casing carrying a 14-inch oil pipeline; an 18-inch casing carrying a 12-inch seawater pipeline; an 8-inch casing carrying fuel, fiber optic, and electrical power lines; and an 8-inch cathodic protection pipeline.

Subsurface surveys at the Colville Crossing indicated that the drilled segments would pass through predominately fine-grained soils with scattered deposits of gravel and cobbles. The soils on either side of the active channel are frozen to depth. The soil beneath the main channel is thawed and presented similar conditions to those encountered on numerous successful HDD installations in the United States Gulf Coast Region.

Construction of the Colville Crossing took place over two winter construction seasons with work being conducted off of ice pads and access to the work site along an ice road. Initial plans called for all of the drilled segments to be installed during 1998. However, significant drilling problems delayed progress and only the 8-inch utility casing was completed. Lessons learned during the 1998 effort were applied in 1999 and the remaining three segments were completed without significant drilling problems. Two HDD spreads working 24-hours per day were employed both years. This was necessary to accomplish installation of the drilled segments within the restricted winter construction season.

Thaw Unstable Permafrost may be avoided by using HDD to select the formation through which the pipeline will be installed. If a thaw stable formation can be identified at a deep depth, HDD can be applied to economically install the pipeline within the thaw stable formation. Facilities would have to be provided at the end points of the HDD segment to secure the pipeline as it passes through the thaw unstable permafrost. This can be accomplished through the application of thermal siphons. While today's feasible HDD length may be limited to around two miles, HDD segments can be "stitched" together to allow a longer length of deep burial. HDD segments can be placed end to end to essentially stitch a pipeline below ground over a long distance. In addition to the benefits to pipeline security of deep burial, environmental impact will be significantly reduced by the elimination of above ground pipelines supported on thermal piles. Only the "hardened" HDD segment endpoints will extend above the surface.

The HDD stitching concept can be applied to allow the placement of a pipeline in thawed soils beneath a river. The HDD endpoints can be located adjacent to a flood plain boundary, or at a hardened point within the flood plain, and the pipeline stitched along, or beneath, the river. The pipeline can traverse the flood plain in a series of diagonal tangents, or through side bends that take the route to and from the banks and beneath the river.

Ice scour damage associated with pipeline landfalls in the arctic may be avoided by using HDD. HDD is regularly employed to install pipeline landfalls in temperate regions because the trenchless nature of HDD eliminates impact to sensitive coastal environments and problems associated with construction operations and pipeline integrity in active surf zones. The capability to select a deep elevation, out of the reach of scouring ice, provides pipeline designers with an economical solution to a significant pipeline integrity threat.

Conclusions

The HDD Industry has demonstrated the following capabilities:

1. HDD pilot holes can be drilled over lengths of approximately 2.3 miles (3.7 kilometers);
2. Large diameter welded steel pipelines (up to 36-inch) over lengths of up to 2.0 miles (3.2 kilometers) can be installed using today's tools and techniques;
3. Smaller diameter welded steel pipelines (up to 20-inch) over lengths of up to 2.3 miles (3.7 kilometers) can be installed using today's tools and techniques; and
4. HDD operations can be conducted in the arctic environment, including drilling in permafrost.

Therefore, any plan to develop oil and gas reserves in the arctic should consider the application of HDD to a wide range of obstacles both unique to the arctic environment and common to pipeline construction in more temperate regions.