CONSIDERATIONS IN THE DESIGN AND INSTALLATION OF HORIZONTALLY DRILLED PIPELINE RIVER CROSSINGS

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ABSTRACT

With the development and acceptance of directionally controlled horizontal drilling techniques for installing pipeline river crossings, river activity (meandering and scour) together with subsoil stratification considerations have become increasingly important in crossing design and construction. This is due to two (2) factors. First, subsurface conditions are critical to the success of a drilled placement. Contractors require as much knowledge as can be practically obtained in order to accurately price, adequately plan, and efficiently execute such an installation. Additionally, the cost of a drilled crossing is principally a function of length rather than depth of cover. Consequently the second, and perhaps more important, factor is the flexibility in crossing geometry afforded by the drilled method. With proper fore knowledge, the designer is able to select a soil stratum/pipe configuration which is inherently stable, potentially immune to river disturbance, and environmentally non-disruptive.

The authors will present a review of directionally controlled horizontal drilling techniques for pipeline installation by describing the state-of-the-art of the process vis-a-vis subsurface conditions. River activity mechanisms will be discussed relative to their effect on crossing design. A typical crossing site investigation - involving a geotechnical exploration as well as topographic hydrological surveys - will be presented. The presentation will conclude with recommended improvements to techniques for investigations, designing, and executing drilled pipeline river crossings.

INTRODUCTION

History. The directionally controlled horizontal drilling process being utilized today to install pipelines beneath rivers is an outgrowth of the technology and methods developed for drilling directional oil wells. A pilot hole drilled for a river crossing installation is very similar to an oil well, only horizontal. Of course, this is a crucial difference which has presented horizontal drilling contractors with significant challenges and developmental problems. These challenges have been met and the drilling system being applied today offers many advantages to pipeline system designers and owners.

Horizontal drilling was first employed in the installation of a pipeline river crossing in 1971 by Pacific Gas & Electric Company. This involved a 4 inch (10 cm) diameter crossing of the Pajaro River near Watsonville, California. Drilled length was approximately 600 feet (183 m). Although this application was successful, use of the technique was limited to small diameter, short crossings until the late seventies when it had reached a developmental stage allowing it to be applied economically over a wide range of diameters and lengths.

Acceptance. The successful development of the technique is demonstrated by reviewing its utilization since the first installation in 1971. During the years between 1971 and 1979, a total of only 36 crossings were installed by horizontal drilling with applications limited to the United States. In the seven years that followed this period, over 175 installations were completed with operations extending to South America, Europe, and Asia. As of the summer of 1987, an additional 125 installations have been completed. The technique has been principally utilized in the Petroleum Industry on cross country pipeline transmission systems, but is gaining acceptance for municipal water and sewer lines and submarine power and telecommunications cable crossings.

CONSTRUCTION PROCESS EQUIPMENT

The process employed in the majority of horizontally drilled river crossings today is a two stage process. The first stage consists of drilling a small diameter pilot hole along a designed directional profile. The second stage involves enlarging this pilot hole to a diameter which will accommodate the pipeline, or conduit, and pulling it back into the enlarged hole.

Pilot Hole. Pilot hole directional capability is accomplished by using a small diameter, typically less than 3 inch (7.6 cm), nonrotating drill string with an angular offset and/or a deflection shoe at the leading end. This offset creates a steering bias in its direction and plane. If a change in direction is required, the drill string is rotated so that the direction of bias is the same as the desired change in direction. Mechanical cutting action, when required, is provided by a downhole mud motor. Drilling progress can also be achieved by hydraulic cutting action with a jet nozzle.

The actual path of the pilot hole is monitored during drilling by taking periodic readings of the inclination and azimuth of the leading end. These readings, in conjunction with measurements of the distance drilled since the last survey, are used to calculate the vertical coordinates relative to the initial entry point on the surface. Survey readings are taken by a downhole survey system which is placed directly behind the leading end. It senses the orientation of the leading end relative to the earth's magnetic field as well as the orientation of the steering bias and transmits this information to the surface where it is interpreted. Typically, position measurements are taken every joint (30 feet, 9.1 m) and plotted against a designed profile drawing. If unacceptable deviations are shown, the drill string is withdrawn over the unacceptable length and the pilot hole redrilled to acceptable limits.

Periodically during pilot hole drilling, a larger diameter pipe is rotated concentrically over the nonrotating drill string. This washover pipe prevents sticking of the smaller nonrotating string, thus allowing its drilling bias to be feely oriented. It also maintains the pilot hole if it becomes necessary to withdraw the steerable string. When both the steerable string and the washover pipe breakout of the far bank of the river opposite the horizontal drill rig, the pilot hole is complete. The steerable string is then withdrawn leaving the washover pipe beneath the river along the designed profile.

Ream and Pullback. Enlarging the pilot hole is accomplished using either prereaming passes prior to pipe pullback or simultaneously during pullback.

For prereaming, reaming tools are attached to the washover pipe at the exit point. The reamers are then rotated and drawn to the drilling rig thus enlarging the pilot hole. Drill pipe is added behind the reamers as they progress toward the drill rig. This insures that a string of pipe is always maintained in the drilled hole.

For smaller diameter lines (typically 20 inch, 51 cm, or less), prereaming passes are omitted and the final installation pass is undertaken upon completion of the pilot hole. In this case, the prefabricated pipeline pull section is attached behind the reaming assembly instead of more drill string. A swivel is utilized to connect the pull section to the reamer assembly to minimize torsional stress imposed on the pipeline. The decision on whether or not to preream is based largely on soil conditions and is not finalized until after the pilot hole has been completed and data obtained during its drilling reviewed.

Pipeline pull section fabrication and handling during installation typically do not differ significantly from a cut-and-cover installation. Pull sections are fabricated in one continuous length, if possible, to avoid shutdown periods during pullback - for tie-in welds - and are supported during installation in such a manner that axial loads imposed on the line as it enters the drilled hole are minimized.

DOWN HOLE SOIL BEHAVIOR MECHANISMS

The behavior of the soil downhole during installation of a pipeline river crossing by directionally controlled horizontal drilling has not been completely defined. As with any subsurface construction method, it is somewhat inconsistent and therefore difficult to predict. The procedure being applied today has been developed by contractors using trial and error methods with emphasis on results rather than theory. Basically, two conceptual models can be applied. These are open hole structural behavior and fluid structural behavior. In considering these two concepts, emphasis is placed on the pullback stage of operations as this is the most critical time and the stage when most problems are experienced.

Open Hole Structure. Under these conditions, reaming operations actually produce an open hole filled with drilling fluid. The principal cutting action is mechanical. Mud flow from the reamers to the surface, via the established hole, is possible with associated transportation of cuttings. Mud flow rates are designed to provide a velocity in the open hole which will maintain cuttings in suspension. Reamer progress is set at a value which will produce a volume of cuttings which will balance with the volume capable of being transported by the drilling mud flow. Practices and procedures similar to those used in drilling vertical oil wells can be applied.

Fluid Structure. In this case, reaming does not produce a structurally sound, open hole. Rather, injection of drilling mud downhole fluidizes the soil structure allowing the pipeline to be pulled through it. The principal cutting action is hydraulic. Mud flow rates are designed to provide a positive pressure downhole and reamer progress is maximized to complete installation while the soil is still in its disturbed fluid state. This procedure can be viewed as similar to jetting a pile into place.

Behavior Relative to Soils Classification. Cohesive (clay) soil and rock will generally behave with the characteristics of an open hole structure. It is possible to ream a large structurally competent hole which will stay open over a reasonable time period. Although reamer progress may be difficult due to balling up of cuttings, clay is considered to be an ideal material for horizontally drilled pipeline installation. Drillability of rock is dependent on its strength/hardness. Cohesionless silt and sand will generally behave in a fluid manner. However, if such materials are suffiently dense, they can exhibit structurally sound properties. Further, grain size gradation is critical to the behavior of cohensionless soil during reaming operations. As grain size increases into the gravel and cobble ranges, maintaining the fluid structure becomes more difficult with installation problems occurring.

Soils Encountered in River Crossings. Unfortunately, soils encountered in river beds rarely fall totally into one of the categories discussed above. Most will be cohensionless alluvial deposits. However, combinations of both soil types and rock can be expected and contractors must prepare to react to changing conditions.

PROCESS LIMITATIONS

To date, the longest crossing installed using horizontal drilling is beneath the St. Lawrence River near Trois Rivieres, Quebec. This project involved approximately 6,000 feet (1830 m) of 8 inch (20 cm) line and was completed in 1983. The largest diameter is 42 inches (107 cm) over a length of approximately 1750 feet (530 m). This was completed beneath the Panaro River in northern Italy. Installations of 40 inch (102 cm) pipelines over lengths less than 2000 (610 m) feet have also been accomplished with regularity. These limits will embrace most economic pipeline applications.

The primary factor limiting the application of directionally controlled horizontal drilling techniques is adverse subsurface conditions. Installations through strata which contain significant - in excess of 75 percent by weight - amounts of gravel or larger granular material are very difficult to execute. This is particularly true where random boulders or lenses of cobbles are present. These large grain materials cannot be suspended in drilling mud and therefore will not behave as a fluid. Nor are they usually in a structure which will allow them to be mechanically cut for piecemeal removal by mud circulation. Instead, they tend to become lodged in and around the reaming assembly or pull section and thereby prevent successful pullback accomplishment.

The presence of rock formations also present problems for horizontal drillers. Installations have been successfully completed in rock. However, as rock strength increases, so does the mechanical effort required for cutting it. The limits of readily available drill pipe and reaming tools are thus exceeded. This problem is magnified when the reaming assembly has been designed for alluvial deposits and/or the rock strength is inconsistent.

DESIGN CONSIDERATIONS

Pipe Material and Coatings. Pipe installed by directionally controlled horizontal drilling will be subjected to tension and external pressure during installation. Theoretically, neither of these forces will be particulary severe. However, their presence should be born in mind when selecting pipe for the river crossing. The exterior of the pipe should be as smooth as possible and externally upset joints should be avoided.

Welded steel is typically the preferred material for horizontally drilled river crossings. Since most are also in pressurized service, the grade of steel and wall thickness determined by internal pressure design requirements exceeds those necessary to withstand temporary construction stresses. Experience in the petroleum industry indicates that steel pipe can be protected against external corrision by a combination of coatings and cathodic protection. If the crossing will be used to transmit material which subjects the pipe to internal corrosion, internal coating can also be applied. Another solution to this problem is to use a polyethylene liner within an outer steel casing. It is also possible to install polyethylene pipe as the carrier pipe in a drilled crossing. However, if this option is selected, external collapse pressure, due to installation and hydrostatic head forces, should be carefully analyzed. This is particularly critical for larger diameters. Because of the typical minimum depth of undisturbed cover (15 feet, 4.6 m) involved with drilled crossings, external weight coating is not required for flotation resistance.

Crossing Alignment - River Activity Mechanisms. To efficiently use the advantages offered by horizontal drilling, primary consideration must be given the obstacle itself, i.e. the river. A river is a dynamic entity which transports water and entrained soil material from its source to its mouth. In accomplishing this, a large path - a valley - is established in the pre-existing earth material. The extent of such a valley is dependent upon the stream's ability to vertically scour, and horizontally meander into, the surrounding soils. Capacity for this river "activity" is primarily a function of the current's velocity, which in turn is controlled by the stream's hydraulic gradient.

For the most part, a river's hydraulic gradient will vary over geological time but remain constant over much shorter periods. Consequently, a river's long term ability to erode boundary soil conditions will:

- produce a valley during periods of steep hydraulic gradients
- partially fill, with alluvial sedimentation, the previously formed valley in times of shallow hydraulic gradients.

Further discussion of the mechanisms driving hydraulic gradient change, i.e. long term river activity, is outside the scope of crossing design interest.

During the short term, i.e. the crossing's economic life, the river regimen (mechanism for positioning/shaping of the channel within the valley) is driven by the stream's seeking equilibrium between current speed, i.e. entrainment capacity, and the erodability of the previously deposited alluvium. Because alluvial soil conditions are not completely uniform, the river channel location and cross section configuration must vary in attaining such balance: the river will meander and scour to preserve its "established" hydraulic gradient. Of course any non-earth anomolies in the bed also generate river activity. Conventionally placed or exposed pipelines, bridge piers, docks, mattresses, rip-rap, etc. tend to attract/direct response by the river's current.

In essence, an understanding of the river regimen is the first step in predicting in situ soil conditions as well as projecting future horizontal and vertical channel movements. This in turn affects design of the pipeline geometry: the line must be planned for placement in amenable soil conditions sufficiently far removed from likely channel activity to preclude disruption during the crossing's intended life.

Crossing Alignment - Vertical Location. Selection of pipeline depth below the existing thalweg (point of lowest channel bottom elevation) should rationally be based on the river's demonstrated capacity for scour. Scour potential, greatest during floods, is often times indicated by a zone or layer, of "resistive" soil material contained in the alluvium. Examples of this are: substrata of gravel (whose particle size is sufficient to resist entrainment by the river during normal flows) contained within a mass of more easily scourable sand; a significantly denser sand layer underlying relatively loose sand, i.e. a "conditional interface; and non-alluvially deposited material (clay or rock) beneath alluvial silt/sand, i.e. the river valley boundary conditions. Placing the directionally drilled line beneath, or in, such scour limit indicators provides a protective cap/encasement. Additionally, dense non-erodable sands and non-alluvial clays generally offer optimum conditions for drilling conduct.

Crossing Alignment - Horizontal Location. Avoidance of line disruption by river meander is normally dependent on the ability to assess the river's capability for attacking its banks. Bank attack can occur through direct erosion, i.e. washing away of soil material, and/or collapse due to destabilization brought about by subaqueous slope erosion, i.e. development and propogation of landslides. In either case, the result will be relocation of the existing channel which will hazard a crossing's overbends/sagbends. Quantitative data as to bank material strengths and toughness are necessary for computation of erosion potential and slope stability safety factors.

Another aspect of meander assessment is determination of the potential for gross channel relocation: re-establishment of the river in a location different from the existing position. Examples of this are: meander cutoffs to form oxbow lakes; reactivation of inactive channels; reoccupation of former courses; and development of entirely new paths. This type of horizontal movement is driven by channel activity elsewhere, both upstream and downstream, as the river adjusts its length to preserve the established hydraulic gradient. For example, a significant meander cutoff generates the potential for queing up elsewhere along the channel. Conversely, development of a large meander bend allows for channel straightening at another location. Primarily at risk from gross channel relocation are the on-land approaches to the crossing proper.

Assessment of the river's potential for meandering allows crossing entry/exit point and angle selection for avoidance of bank attack and, in some instances, gross channel relocation.

Drilled Path Geometry. Designing a drilled profile is a fairly straightforward exercise in geometry. A typical profile will consist of tangents connecting two natural sagbends. Radii of curvature for the bends is calculated using the following formulae:

$$R = 100\,d \quad \text{or} \quad R = \frac{Er}{\text{SMYS}\,(f)\,(12)}$$

Where: R= Radius of curvature of circular sagbends in feet
E= Modulus of elasticity for steel
r= Outside radius of pipe in inches
SMYS= Specified minimum yield strength of pipe steel in psi
d= Nominal diameter of the pipe in inches
f= Allowable bending stress factor

The first formula is based on experience and sets the radius at a value which will generally prevent binding or undue loads from occurring during installation. The second formula calculates the theoretical bending stress in the extreme fibers of the pipeline to insure that allowable limits are not exceeded. The maximum value for radius calucated by either formula is the value used in designing the drilled profile.

Other variable parameters which must then be set are the deepest point on the profile, or the PI elevation; the relative location of the entry and exit points, or the drilled length; and the entry and exit angles. Once these values are assigned, as described in the following sections, the remaining positions on the profile can be calculated using simple trigonometry and standard circular curve relationships. The profile is then plotted on a cross section survey of the river and reviewed to see if all design constraints are satisified.

Typically, a minimum depth of cover of 15 feet (4.6 m) should be maintained in designing a drilled profile to provide a margin of safety against downhole "blowout". Entry angles should be held to between 8 and 20 degrees with the horizontal. These limits are due chiefly to equipment limitations. Exit angles should be designed to allow easy breakover support. That is, the exit angle should not be so steep that the pull section must be severely elevated in order to guide it into the drilled hole.

SITE INVESTIGATION

The four major components of a site investigation for a drilled crossing are a topographic survey, a hydrographic survey, a geological review, and a geotechnical survey. Although each may be performed by specialized engineering consultants, it is important that the results be integrated onto a single plan and profile drawing which will form the basis of any contract and be used by the drilling contractor to price, plan, and execute the crossing. Since this drawing will also be used to make the working profile, which will be the basis for downhole navigation, accurate measurements are essential.

Topographic Survey. The purpose of the topographic survey is to accurately describe the working areas where construction activities will take place. Both horizontal and vertical control must be estabished for use in referencing hydrographic and geotechnical data. A typical survey should include overbank profiles on the centerline range extending from approximately 150 feet (46 m) landward of the entry point to the length of the prefabricated pull section(s) landward of the exit point. Survey ties should also be made to topographic features in the vicinity of the crossing.

Hydrographic Survey. The purpose of the hydrographic survey is to accurately descibe the waterway bottom contours. A typical survey should consist of fathometer readings along the centerline range and approximately 100 feet (30 m) upstream and downstream. This scope can be expanded to include more upstream and/or downstream ranges if this data is required to analyze future river bottom activity.

Geological Review. An essential step in engineering a horizontally drilled crossing is to gain an overall understanding of the earth materials - types and origins - constituting the site vicinity. Objective of the geological review, and component potolomological assessment, is establishment of the river valley's boundary/internal conditions and development mechanism(s). This information will assist in determining the river's past/future capacity for activity; help tailor the follow-on site specific geotechnical survey (borings, etc.); and indicate the potential for anomolies contained in the alluvium: gravel or boulder zones of glacial deposition, cemented Marine sediments from ancient coastal regions, etc.

Geological data can generally be obtained from published sources. Unless a specific study is available (as is the case for a large river), potomological information must be derived from site records and/or review of "obsolete" (archival) topographic maps. In any case, geological/potomological findings must be tempered by an onsite reconnaissance.

Outcome of the geological review is development of an initial crossing geometry. Based on this, the follow-on site specific exploration and engineering can be effectively planned and efficiently conducted.

Geotechnical Survey. This must accurately describe site specific subsurface conditions affecting river activity and crossing installability. It will normally consist of borings, laboratory testing of recovered samples, and engineering analyses of the resulting data.

Spacing/Depth of Borings. Derived from pre-exploration engineering, borehole spacing and depth will depend on the crossing configuration (probable length and penetration depth) plus expected soil conditions. As a prerequisite, all borehole locations and surface elevations must be surveyed.

Borings spaced 300 to 500 feet (90 to 150 m) on centers for relatively short crossings, and 500 to 800 feet

(150 to 245 m) on centers for longer crossings, are adequate unless significant soil anomolies are expected. Then, a closer spacing - dependent on the probable anomoly extent - should be employed. Marine (in river) borings will be necessary for longer crossings. Shorter crossings will not require such expensive exploration components unless subchannel conditions critical to crossing design/placement cannot be determined from land boreholes. Alternately, should access to the crossing site by land be untenable, borings from a barge in the channel may be the only means for subsurface exploration. Alignment of the borings should be within 100 feet (30 m) of the crossing's intended course - exact correspondence is necessary if small, drilling restrictive anomolies (boulders, etc.) are likely. For the most part, all non-Marine subsurface penetrations should be grout sealed upon completion to restore site integrity and prevent crossing installation interference: leakage of drilling mud, etc. Depths of the borings should be sufficient to define pertinent soil conditions and explore the material which the pipe installation must negotiate. Usually, sampling to 30 feet (9 m) below the crossing's expected penetration depth will be adequate. In some instances, however, deeper penetration into the underlying non-alluvial soils constituting the valley base conditions will be necessary to adequately evaluate the site.

For large jobs, two field explorations may be warranted. A few widely spaced, though deep, borings may be conducted initially. Once the line is actually designed, a more closely spaced, depth restrictive set of borings can then be made to define anomolies at potentially critical points: pipe sagbends, etc.

Sampling Techniques. Sampling of the borings should involve obtaining undisturbed cores as well as standard penetration test (SPT) specimens. Undisturbed Shelby tube samples - generally of cohesive (clay) soil, i.e. open hole structure soil - will allow detailed strength testing as well as deformability and permeability evaluations. Such information is important to conducting bank stability/erodability analyses and drilling performance assessments. SPT sampling (blow counts for N valves) - usually of granular (gravel, sand, and silt) soil, i.e. fluid behavior structure soil - will provide emperical in situ densities as well as classification samples. Testing of these samples is critical to assessing granular soil drillability when gravel is present. Also of importance is the conduct of rock coring when Shelby tube/SPT impenetrable strata are encountered. This will define possible anomolies as well as the makeup of river valley base materials.

Throughout the course of borings, records should be kept of drilling performance: type of bit used, ease of penetration, etc. Such information should be transmitted to the directional drilling contractor for use in tailoring equipment and conducting the pipe bore.

Laboratory Testing. All undisturbed core samples should be subjected to strength testing - generally unconfined compression checks. Particular attention should be paid to the existance of prefactures ("slickensides"), organics/roots, and other such anomolous features in these specimens. These conditions will bear on directional drilling performance as well as river activity potential. If required, more sophisticated strength testing plus permeability and deformability analyses can be run. Clay soil classification testing should consist of Atterberg limit determinations. When necessary, minerological evaluation of rock specimens can be made.

SPT sampled material should be subjected to sieve analyses for grain size distribution determination, especially if gravel is present. Data for assessment of drillability, as well as resistance to river activity, will result.

RECOMMENDED IMPROVEMENTS

Site Investigation. Primary focus should be on developing a more detailed picture of the crossing site's subsurface conditions. While sampled boreholes will continue as the major source of such information, their cost and execution timing limit the "volume" of subsoils which can be explored. This limitation is especially critical when directional drilling restrictive anomolies (boulders, etc.) are possible.

Supplementation/extension of sampled borehole data is possible through conduct of piezo-electric cone penetrometer (PCPT) soundings (an intrusive exploration technique) and performance of non intrusive, near surface geophysical surveys: vibro sonic procedures, ground penetrating radar studies, etc. Intrusive PCPT soundings allow a more closely spaced exploration at a reduced cost and timing than sample borings. However, since no samples are obtained for actual observation/testing, necessary calibration of the penetrometer readings precludes exclusive PCPT use. Also, the sounding holes, like sample boreholes, must be grout sealed on completion. Non intrusive surveys permit evaluation of virtually the entire site. Relative stratification, conditional interfaces, anomolies, etc. can be observed. However, as with PCPT soundings, no actual material specimens are produced.

To improve future geotechnical surveys, a nonintrusive study should first be made of the crossing alignment. This will allow more efficient location of the intrusive exploration components: sampled boreholes and CPCT soundings. In concert, the resulting data, will more fully define pertinent in situ conditions.

Pilot Hole Logging. Experience gained while drilling a pilot hole is important in preparing for pullback. However, at the present time, this information is limited to drilling performance and thus restricted to the area directly in the path of the pilot string. Development of an instrument, akin to an electric log, which could be drawn through the wash pipe after completion of the pilot hole and sense the surrounding soil characteristics would significantly reduce the risk of encountering an obstruction during reaming and pullback operations. This is especially critical in areas where random boulders are present. Also of interest would be quantification of drilling fluid pressure down hole at the drill bit. This information, and the ability to monitor such parameter during actual pilot hole drilling, may prove crucial in instances where mud pressures are likely to intrude into, or even fracture, the surrounding soils.

Pulling Load Analysis. At the present time, the pulling force required during installation is predicated on experience for a given pipe diameter and soil type. The two principal components considered are the force necessary to cut the hole in advance of the pipe and the friction forces which must be overcome to pull the pipe along the open hole. It is also realized that for larger diameters the stiffness of the pipe is an important factor although calculations are generally not made to assess this impact.

A sound analytical method which takes into account all factors is needed for calculating installation pulling loads. The method should be time dependent so that variations of load as the pull section proceeds through bends can be determined. This information can then be utilized by contractors to take steps to reduce the loads or insure that equipment is on hand, or can be modified, to overcome them.

An example of how this advance knowledge can be used to reduce pull load is in pull section buoyancy adjustment. For a straight section of pipe being pulled into a reamed hole, the optimum buoyancy is neutral. This allows the pipe to be suspended in the hole without a force either up or down against the hole wall. Sliding friction forces are minimized. For a section of pipe being pulled around a sagbend, however, neutral may not be the optimum buoyancy. Without either negative or positive buoyancy, the only force available to overcome the section's stiffness and deflect it around the bend must be transmitted from the rig through the reaming assembly. If buoyancy is adjusted, it can induce a bending moment and assist in deflecting the pipe. Buoyancy can be altered by internally weighting the pull section during pullback.

CONCLUSION

Horizontally drilled pipeline river crossing technology, conceived less than two decades ago, is now coming of age. Quantified past experience shows a variety of earth material and river activity conditions can be efficiently - and permanently - negotiated by this construction method. Through engineered improvements to site investigation, procedural conduct, and equipment configuration; continued advances in the state-of-the-art will occur.