

# Postconstruction Evaluation of Horizontal Directional Drilling Installations

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**Abstract:** Recently, questions have arisen concerning the compactive nature of drilling fluids within the annular space during horizontal directional drilling (HDD) operations. To address these concerns, a field and laboratory study was conducted to provide both a qualitative and a quantitative assessment of the annular space. The study consisted of installing 61 m (200 ft) bore lengths of 100 mm (4 in.), 200 mm (8 in.), and 300 mm (12 in.) SDR 17 high density polyethylene pipe in two different soil mediums: clay and sand. Subsequently, the pipes were excavated with visual and strength measures of each of the installations taken at time periods of 1 day, 1 week, 2 weeks, 4 weeks, and 1 year after installation to assess the annular space region over time. Additionally, samples of the drilling fluid were evaluated both in the field and at a laboratory. This paper presents the results of this research initiative and provides qualitative and quantitative information on borehole annular space integrity during HDD installations. The study revealed that: (1) the integrity of the annular space was maintained, as little evidence of voids was present; and (2) the strength properties increased over time through apparent consolidation, or equalization, with the native soil.

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## Introduction

New underground infrastructure construction is an important aspect for a developing municipal environment. Installing this new infrastructure using traditional trenching techniques, particularly open cut construction, can equate to high social costs. These social costs include noise pollution, traffic disruption, aesthetic factors, and negative public perception. The use of trenchless construction methods can enable installation of pipelines and other conduits under these sensitive areas while providing minimal disruption in comparison to traditional trenching methods.

Horizontal directional drilling (HDD) is a trenchless technology that has the capacity to install a wide variety of pipe materials into the ground. This process provides an alternative over the traditional open cut methodology while providing a number of benefits. For example, the HDD process can decrease the costs of installing underground conduit, as the operation can be performed more quickly, requires less working space, and can be conducted without disruption to surface activities (traffic and pedestrian areas). When utilized under a watercourse, the HDD method can provide reduced environmental impacts and increased productivity in comparison to an open cut operation (Allouche et al. 2000).

Horizontal directional drilling (HDD) is one of the fastest growing trenchless construction methods. Smaller drilling rigs are typically used for the installation of telecommunication residential service cables. Larger rigs are capable of installing pipelines up to 1,200 mm (48 in.). With this growth comes an ever-increasing need for gaining a better understanding of the physical nature of this construction process and its influence on the surrounding medium. While HDD has been employed in North America since the 1970s, there are still some municipalities and regulatory bodies that are wary of allowing the process due to negative perceptions regarding the annular space region of the installed pipe. The volume of fluid found in the area between the outer edge of the product pipe being installed and the edge of the reamer is known as the annular space. In particular, some agencies are concerned that voids will be found in the annular space region due to the use of drilling fluids to replace native soils. Voids could result in instability of the installed product pipe and potential subsidence of the surface. It is hoped that the results of this research will make these municipalities and regulatory agencies more aware of the capabilities of the HDD process and curb any concerns regarding the long-term effects on the annular space created during these operations. Thus, these agencies can consider the use of HDD for new infrastructure development programs.

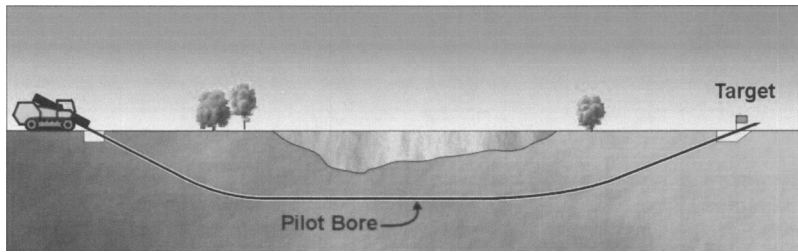
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## Drilling Procedure

The installation of pipe and conduit is typically performed in three distinct phases: (1) pilot bore; (2) reaming; and (3) pipe pullback (*Guidelines* 1998). The pilot bore phase consists of using a small diameter drill head launched from the surface at an entry angle between 8° and 16° to the horizontal. This pilot bore proceeds downward until the desired depth is achieved and the orientation of the drill is brought to horizontal. Drilling continues along a horizontal path, or a given grade in the case of gravity



**Fig. 1.** Horizontal directional drilling pilot bore process

sewers, until it is brought to the surface through a predetermined exit location. During the pilot bore operation, the drilling rig operator has the ability to steer the drilling head in any direction. Steering is accomplished by pushing the sloped drill head without rotation to the required alignment. Further information on steering may be found in Allouche et al. (2000).

During the drilling process (Fig. 1), the location, orientation, rotation, and depth of the drill head is tracked (or surveyed) by either a manual walkover or a wireline location system. Typically, a magnetic device, known as a transmitter, or sonde, is placed inside the drill bit housing. The transmitter emits an electromagnetic signal field that can be tracked using a hand-held locating device. These hand-held devices interpret the magnetic signals from the transmitter and display the depth, pitch, and roll (i.e., rotation position) of the drill head. Hand-held devices have their limitations, as they can receive interference from sources including buried utilities, steel structures, and power lines; and they are risky to use for watercourse crossings and under surface obstacles. To mitigate interference, proper procedures must be followed, as described by Bennett et al. (2001).

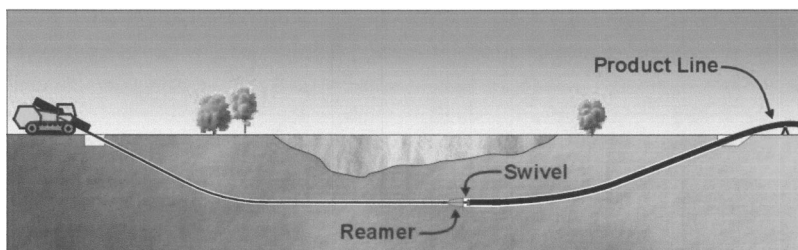
When hand-held tracking systems are unable to be utilized due to surface site access restrictions or drilling depth, the directional drilling contractor can implement the use of a wireline system. These systems consist of a measuring instrument that is mounted in the drill head where the transmitter for a walkover system would normally be located. This measuring device tracks the bore path and transmits information through the wires that run inside the drill pipe. The azimuth and inclination of the drilling tool is collected and calibrated through the use of a computer system. The wireline system has an accuracy of  $\pm 2\%$  in both plan and profile regardless of the borehole depth; however, it is also very time consuming, as the wireline needs to be reconnected with each additional drill rod. Wireline systems are useful when the bore path navigates under a deep water body, where conventional tracking units would not be effective.

Once the pilot hole has reached the exit pit, the drill head is removed and a reamer is attached. The purpose of the reaming operation is to enlarge the borehole prior to the installation of the

permanent product pipe pullback process. Throughout the reaming operation, the borehole is typically enlarged to 1.5 times the diameter of the product line that is to be installed; however, this may be adjusted according to the soil conditions encountered and the overall length of the installation. This oversizing allows for a reduction in the frictional effects that are imposed upon the product pipe during installation and can reduce the associated bending stresses near the entry and exit regions. For larger diameter pipes, several reaming passes, known as prereaming, typically occur, with increasing reamer diameter sizes used to reach the desired upsizing to the final diameter. The last reaming pass is conducted in conjunction with the pipe pullback process (Fig. 2).

During the pipe pullback process, the product line is attached to the reamer with a swivel link assembly. This swivel link allows the reamer to rotate without rotating the product pipe that is being installed. This helps to decrease the torsional stress on the pipe during the pullback phase. Additionally, the swivel link may be designed to break if the force on the product pipe exceeds a precalculated limit. This prevents the product pipeline from being overstressed, as the breakaway link will fail prior to any structural damage of the permanent pipe. Additionally, during a pullback operation, it is preferred that the pipe is completely fabricated prior to the pullback operation. The risk of the pipe becoming stuck in the borehole can increase substantially if the pulling operation is stopped for the incremental connection of the individual pipe segments.

Drilling fluid plays an important role in the directional drilling operation and is utilized for all stages of the HDD operation. Drilling fluid is primarily composed of bentonite clay mixed with water and may have polymers and other agents added. During the pilot bore phase, the drilling fluid serves several purposes, such as stabilizing the borehole, removing the drilled cuttings, reducing the torque on the drill string, lubricating the drill pipe, and cooling both the drill bit and the housing containing the electromagnetic transmitter. Drilling fluid is dispersed through the reamer orifices during the reaming phase and aids in the cutting of the native soil, provides lubrication of the reamer drill string in the borehole, transports the cuttings, provides hole stability, and pre-



**Fig. 2.** Horizontal directional drilling pullback process

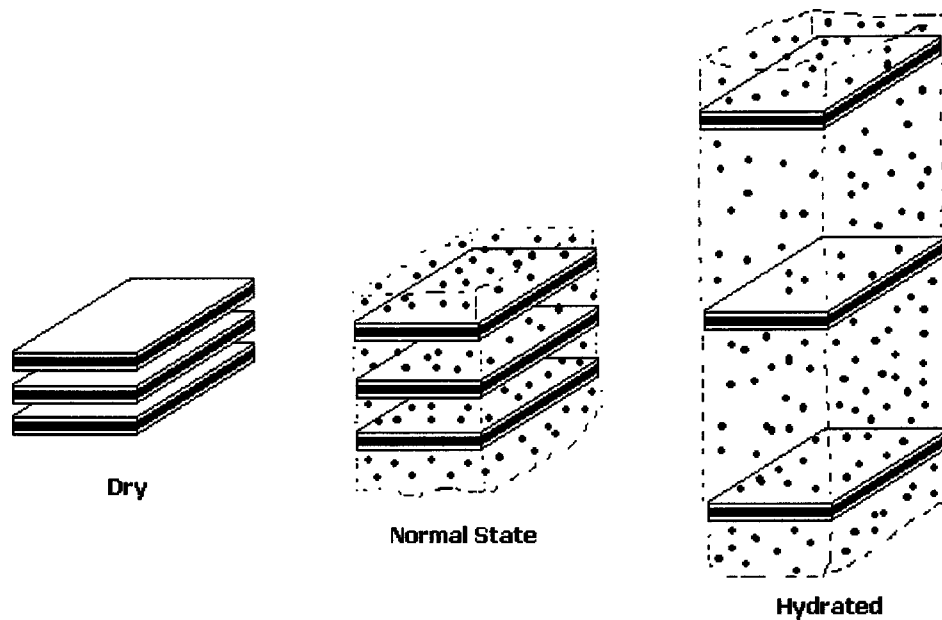


Fig. 3. States of bentonite platelets

vents the enlarged reamed borehole from collapsing. During the pullback phase and final reaming phase, the drilling fluid not only aids in the reaming action, as mentioned previously, but also provides lubrication to the product pipe. This lubrication decreases the frictional effects from the contact of the pipe with the borehole wall and may reduce the chances of the product line becoming stuck during the pullback phase.

### Previous Work

There has been limited prior work performed in assessing the annular space region created during horizontal directional drilling (HDD) installations. Staheli and Bennett (1997) performed testing on three 162 m (530 ft) HDD installations of 300 mm (12 in.) diameter steel pipe near Vicksburg, Miss., to monitor changes in pore pressures before, during, and after installation to assess impact on stability. Dye tracers were added to the drilling fluid to enable visual determination of suspected fluid migration. Postconstruction investigation of the annular space performed immediately after installation revealed a relatively limited migration path of drilling fluid, suggesting no evidence of significant voids in the annular space region.

Knight et al. (2001) undertook a field research program where two 200 mm (8 in.) diameter SDR 17 high density polyethylene (HDPE) pipes of 55 m (180 ft) and 90 m (290 ft) lengths were installed at a depth of 2 m (6.5 ft) below the ground surface. Excavations were performed on the 55 m (180 ft) pipe approximately 2 years after installation to gain a visual perspective of the annular space. The research concluded that there was no evidence of significant voids present in the annular space region. Although it provides an excellent foundation for this research, a major limitation of the research conducted by Knight et al. (2001) was that information on the annular space was captured on one installation in a single soil medium (clayey-silt mixed with silty-sand) without considering short-term effects. This research examines the annular space region in two soil mediums, with six installations, excavating 1 day, 1 week, 2 weeks, 4 weeks, and

1 year after installation to assess and evaluate the annular space over the first year of the typical life of a borehole.

### General Drilling Fluid Functions and Properties

Drilling fluid is composed of a carrier fluid (water) and drilling fluid additives (bentonite and/or polymers). Bentonite is a naturally occurring clay mineral (montmorillonite) that forms a mud when mixed with water. When bentonite is mined, the clay platelets (flat plate-like particles), which have been subjected to high confining stresses, are closely compressed and have very little water between them. An “aggregate” is a unit of stacked clay platelets. When water enters between some of the clay platelets, it immediately causes them to disperse, separating the clay platelets as illustrated in Fig. 3. The dispersion of the bentonite is aided by shearing through good quality mixing equipment. In fact,  $1.64 \times 10^{-5} \text{ m}^3$  or one cubic inch of bentonite, if mixed until it is broken down to single platelets, would have enough surface area to cover 66 football fields (Bennett et al. 2001).

Drilling fluids are characterized by the following properties; (1) viscosity; (2) gel strength; (3) fluid loss and fluid density; (4) filtration control and filter cake; (5) sand content; (6) pH; and (7) lubricity. To create the optimal drilling fluid, each of these factors must be considered. It should be noted that the native soil exerts the greatest influence on the selection of a drilling fluid mixture. Therefore, it is imperative that the native soil is properly identified and characterized to facilitate selection and formulation of the proper drilling fluid.

The principal functions of drilling fluids used in horizontal directional drilling are

- Transporting drill cuttings to the surface by suspending and carrying them in the fluid stream flowing in the annulus between the drilled bore wall and the drill pipe and product pipe.
- Cleaning the buildup of soil on drill bits or reamer cutters by directing fluid streams at the cutters.
- Cooling the downhole tools and electronic equipment.

**Table 1.** Composition of Drilling Fluids Used in Research Project

Pipe designation	Number of batches	Water (L)	Bore-Gel (kg)	EZ-Mud	Con Det	Other
100 mm (4 in.) clay	1	3,407	68	2 L	2 L	—
200 mm (8 in.) clay	2	3,407	68	2 L	2 L	—
300 mm (12 in.) clay	2	3,407	68	4 L	2 L	0.91 No-Sag
100 mm (4 in.) sand	1	3,407	113	—	—	—
200 mm (8 in.) sand	1	3,407	113	—	—	1.13 No-Sag
300 mm (12 in.) sand	2	3,407	113	—	—	2.26 No-Sag

- Lubricating to reduce the friction between the drill pipe and product pipe and the bore wall.
- Stabilizing the bore, especially in loose or soft soils, by building a low permeability filter cake, and exerting a positive net hydrostatic pressure against the bore wall. The filter cake along with positive hydrostatic pressure reduces collapse of the bore and prevents formation fluids (i.e., groundwater) from flowing into the bore or drilling fluids from exiting the bore into the formation (i.e., loss of circulation).
- Providing hydraulic power to downhole tools such as mud motors.

When the drilling fluid is pumped into the borehole, the fluid, just like water, attempts to flow through the soil. However, the bentonite platelets will start to plaster or shingle off the wall of the borehole and form a filter cake that seals off the flow of fluid from the bore into the native soil. The ideal filter cake is smooth, forms quickly during construction of the borehole, reduces migration of drilling fluid into the formation, and reduces intrusion of both groundwater and soil into the bore. Optimum filter cake thickness should range between 0.8 mm (1/32 in.) and 2.4 mm (3/32 in.).

The water that does manage to filter through the cake is referred to as the “filtrate.” Filter cake quality can be improved to reduce the amount of filtrate entering the surrounding soil. This can be accomplished by one of two methods: (1) adding more bentonite (more platelets); or (2) using certain polymers in conjunction with bentonite to tighten the filter cake. It is more effective to use a bentonite/polymer mix because it is less viscous, more pumpable, and flowability in the annular space will be maximized due to the shear-reducing properties of the fluid (i.e., more slurry will flow).

In addition to providing a filter cake layer, the drilling fluid must provide suspension characteristics or gel strength. The drilling fluid must be able to support, suspend, and carry the cuttings. If the fluid cannot suspend the drilled material, that material will quickly settle out of suspension and pack around the drill pipe or around the product line being pulled. Even if the fluid has a high viscosity (i.e., thick fluid) it may have a very low carrying capacity (i.e., gel strength). Proper control of gel strengths is an important factor in avoiding excessive downhole pressures. Gel strength is usually checked with a clean fluid. When solids are added to this fluid, the drilling fluid properties change drastically. The yield value of a drilling fluid (not the gel strength) is the measurement of the drilling fluid’s internal resistance to flow and thus the carrying capacity of the fluid when it is moving. Gel strength and yield value are more important parameters in horizontal drilling than viscosity. Plain water has low viscosity and no gel strength or yield and polymers by themselves have high viscosity but low gel strength and yield. Therefore, bentonite is required to provide the necessary carrying capacity for cuttings from coarse soils.

At times, additives such as detergents are added to the drilling

fluids to counteract some of the formation characteristics such as swelling and stickiness commonly found in expansive clays. Other additives are used to adjust the pH of the fresh water constituent of the drilling fluid.

For HDD, the proper drilling fluid mixture is heavily dependent upon the soil encountered. It must be formulated for the anticipated geological conditions. For simplicity, soil conditions may be defined as either a coarse soil (i.e., sand and gravel) or a fine soil (i.e., clay, silt, and shale). When drilling through sand and gravel, a drilling fluid needs to serve two important functions: stabilization of the borehole and suspension and transportation of cuttings. When drilling through clay, the same functions need to be performed; however, an additional requirement of the fluid is to retard swelling and reduce sticking of the soil to the downhole tooling and product line being installed. Geological conditions may vary between fine and coarse soils; consequently, different combinations of drilling fluid additives will be needed to perform the required functions under actual conditions. In general, for coarse soils, bentonite should be used, while for fine soils, polymers (possibly added to a bentonite base) are recommended. When drilling through sands and gravel, drilling fluids may migrate from the bore into the native soil formation. Bentonite and lost circulation materials reduce fluid losses into the formation.

To create the optimal drilling fluid, each one of the seven individual factors must be considered. Undoubtedly, the native soil will dictate first and foremost what type of drilling fluid is required. Once the native soil is properly identified, the suitable drilling fluid can be chosen and then modified for optimal performance.

## Field Test Drilling Fluid Composition

The drilling fluid mixtures that were utilized during the installations in this research and the fluid properties are presented in Tables 1 and 2, respectively. For each batch, a cup of soda ash (approximately 0.45 kg) was also added into the mixture to ensure that the pH of the makeup water remained at an optimal level of 8.5–9.5. At this level, the Bore-Gel, the primary drilling fluid component, reacts better with the makeup water and the overall drilling fluid is able to optimally perform its necessary functions. Bore-Gel is comprised mainly of sodium bentonite, which provides the primary function of stabilizing the borehole and removing the cuttings. EZ-Mud is a liquid polymer that is used as a borehole stabilizer and prevents reactive clay from swelling. Con Det is a wetting agent that aids in the cleaning of the drill bit and counteracts the sticking tendencies of clays. No-Sag is a gel strength enhancer that enables better suspension of cuttings and increases the carrying capacity for solids suspension. The constituents of the drilling fluid are all products that are produced by

**Table 2.** Initial Drilling Fluid Properties

Pipe designation	Fluid viscosity (s)	Gel strength (kg/100 cm <sup>2</sup> )	Fluid density (kg/L)	Filtrate (cc/7.5 min)	Sand content (%)	pH
100 mm (4 in.) clay	45	0	1.03 (1.15)	4.2 (4.3)	0 (2.5)	9
200 mm (8 in.) clay	45	0	1.03 (1.14)	4 (4.3)	0 (2.5)	9
300 mm (12 in.) clay	45	0	1.03 (1.15)	4 (3.6)	0 (3)	9
100 mm (4 in.) sand	40	0	1.01 (1.55)	4.1 (4.4)	0 (20)	9
200 mm (8 in.) sand	40	0	1.01 (1.55)	4.8 (4.5)	0 (20)	9
300 mm (12 in.) sand	40	0	1.01 (1.55)	4.8 (4.5)	0 (20)	9

Note: ( ) indicates final readings taken during backreaming.

Baroid IDP. These products (and many others) are key components used by directional drilling contractors to maximize drilling performance for a wide range of HDD projects.

### Field Evaluation

Field testing was performed at two different locations in order to evaluate the annular space region in both a cohesive and a cohesionless soil medium. This involved the installation of 61 m (200 ft) bore lengths of 100 mm (4 in.), 200 mm (8 in.), and 300 mm (12 in.) SDR 17 high density polyethylene (HDPE) pipe in two different soil mediums: clay and sand. The depth of each installation was based on pipe diameter: 600 mm (2 ft) for the 100 mm (4 in.) diameter pipes, 900 mm (3 ft) for the 200 mm (8 in.) diameter pipes, and 1,200 mm (4 ft) for the 300 mm (12 in.) diameter pipes. Field locations were chosen based on the homogeneous consistency of the soil, the topography of the site, and the ability to leave the pipe in the ground for a period of one year to conduct long-term analysis. The two locations used for this research were the University of Alberta Farms in Edmonton, Alberta, and the Sil Silica sand pit in Bruderheim, Alberta, Canada.

#### *University of Alberta Farms, Edmonton, Alberta*

The University of Alberta Farm site was chosen because it provided the cohesive soil medium for this research. The upper 4 m (12 ft.) of the soil at this site consists of uniform homogeneous lacustrine Lake Edmonton Clay with a unit weight of approximately 18 kN/m<sup>3</sup> (Zhang 1999). Laboratory testing of soil samples revealed a moisture content of approximately 27%. These installations were performed on June 13 and 14, 2000.

#### *Sil Silica Sand Pit, Bruderheim, Alberta*

The sand site is located in one of Sil Silica's sand pits in Bruderheim, Alberta. The site was not completely level; however, it contained a homogeneous medium of consistently fine sand, satisfying the cohesionless requirement, from the surface to beyond the testing depths. The classification of the soil is medium grained sand to silty sand with an approximate unit weight of 18–19 kN/m<sup>3</sup> (Zhang 1999). Laboratory testing revealed a moisture content of approximately 5%. The installations were performed over a period of two days from July 11 to 12, 2000.

### Installation Process

Each installation was conducted using generally accepted drilling practices to ensure that the data collected reflected not only good

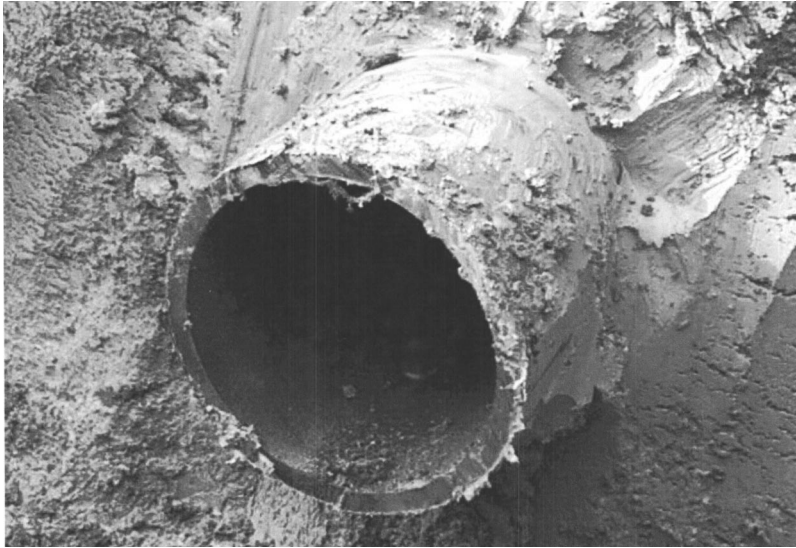
drilling practice but also captured the methods and techniques utilized by the majority of drilling contractors. To this extent, the contractor used fluted type reamers in both the clay and sand soils. Reamers were sized according to the rule of thumb practice of having reamers 1.5 times the diameter of the product pipe being installed (Guidelines 1998; Bennett et al. 2001). Subsequently, on the 100 mm (4 in.) pipe installation, a 150 mm (6 in.) reamer was used in a one-pass installation, a 300 mm (12 in.) reamer was used on the 200 mm (8 in.) product pipe with a one-pass installation, and a 450 mm (18 in.) reamer was used on the 300 mm (12 in.) pipe with a pre-ream using the 300 mm (12 in.) reamer. Additional information on generally accepted drilling practices can be found in Ariaratnam and Allouche (2000).

Both the clay and sand installations were excavated at sections along the borepath in intervals of 1 day, 1 week, 2 weeks, 4 weeks, and 1 year after installation to visually assess the integrity of the annular space. The annular space region, which is comprised of drilling fluid mixed with native soil, is defined as the region between the outside diameter of the installed pipe and the wall of the borehole. The analysis of the annular space region commenced once the installations of the HDPE pipes were completed. These observations were imperative to obtain a better understanding of the annular space region over time.

### Post-Installation

Once the installation of a pipe is achieved, it remains untouched until the next day. Because the 100 mm (4 in.) and 200 mm (8 in.) pipes were installed in one day, they were both excavated the following day after the installation of the 300 mm (12 in.) pipe. It was felt that the 1 day excavation for the 300 mm (12 in.) pipe was not necessary, because an indication of the state of the annular space could be observed sufficiently enough through the 100 mm (4 in.) and 200 mm (8 in.) installations. After the initial 1 day excavation, the pipes were excavated collectively 1 week, 2 weeks, 4 weeks, and 1 year postinstallation. The cross-section excavations were conducted along the horizontal section of the borepath near the exit pit side and continued toward the entry pit on subsequent excavations. All the excavations were done using a backhoe, with hand digging employed around the perimeter of the pipes. The backhoe excavated to about 0.3 m (1 ft.) below the depth of installation, and then the hand shovel was used to expose the pipe. Once the area was excavated, a saw was used to cut through the exposed pipe, subsequently leaving an open cross section to analyze.

People have hypothesized about the short-term and long-term postinstallation state of the annular space, yet very few have actually conducted research in this area. Subsequently, this research involved the evaluation and assessment of:



**Fig. 4.** 200 mm (8 in.) clay excavation at 1 day

- The placement of the pipe in relation to the annular space,
- Any existence of voids in the annular space, and
- The state of the annular space in terms of strength, texture, and composition.

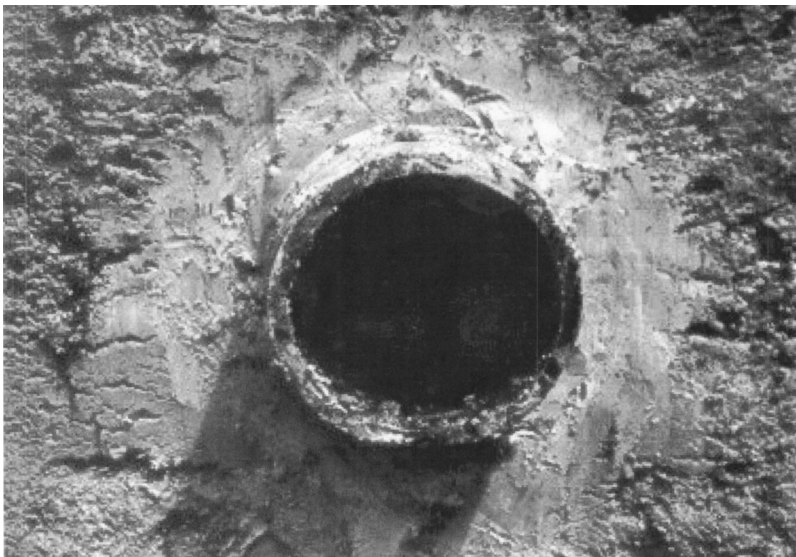
During the visual examination of the annular space, a geotechnical in situ test was performed to assess the unconfined shear strength of the annular space and native soil. It should be noted that shear strength tests were only performed in the clay site, as this property is never evaluated in cohesionless soils such as sand. The in situ tests were preferred over the laboratory tests due to the fact that a change in environmental conditions (i.e., pressure, moisture content) and disturbance of the samples when extracted, handled, and subsequently tested can greatly influence the test results.

In situ tests and visual assessments validate the hypothesis that all of the pipes that were installed would remain secure, with no evidence of any potential movement. Surface monitoring points

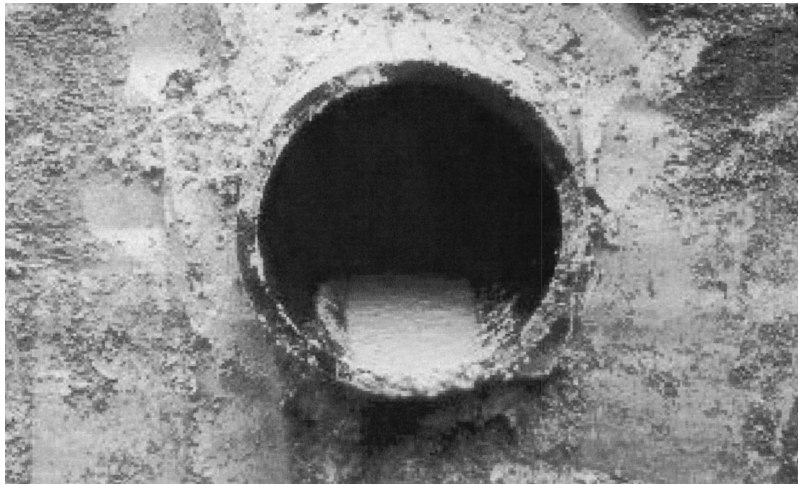
placed along the installations revealed that no ground settlement occurred at the surface during installation. Additionally, no ground settlement was observed over time.

### Moisture Content

Moisture content is defined as the ratio of the weight of the water to the weight of the solid particles in a soil medium. The moisture content in sands generally lies between 10 and 30%, while in clay it can range from less than 5 to over 300%. The importance of moisture content in a soil mass cannot be understated, as it can have a significant effect on some of the characteristics and behavior of a soil. For example, in fine-grained soils such as clay, high moisture content can greatly reduce the shear strength. At every excavation, five samples were collected from each installation to



**Fig. 5.** 200 mm (8 in.) clay excavation at 1 week



**Fig. 6.** 200 mm (8 in.) clay excavation at 2 weeks

determine moisture content of the annular space and the respective soil medium.

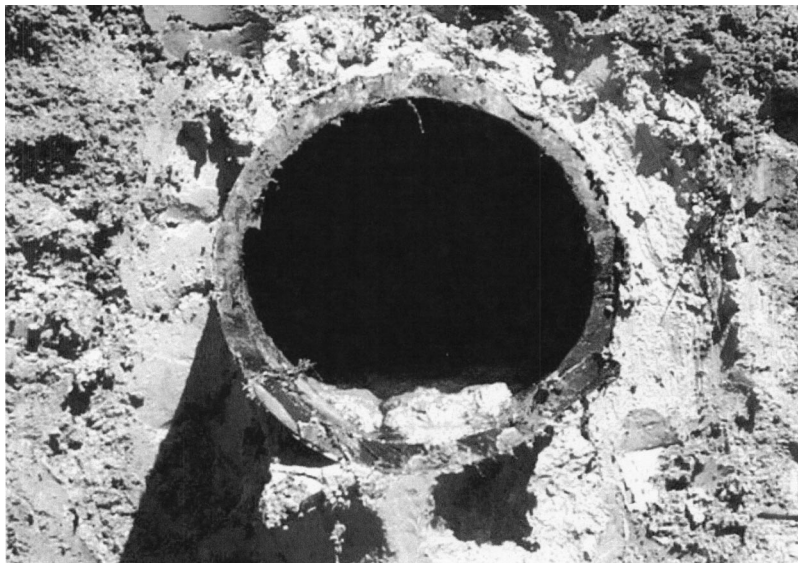
The moisture content of the clay averaged 27%, while the annular space averaged 38% up to 4 weeks after installation. Analysis of the annular space from the 1 year excavation revealed a decrease in moisture content to 32%. This indicates that equalization of the annular space and the native clay seemed to have occurred, as evidenced by the 6% reduction in moisture content exhibited in the annular space.

The moisture content of the sand averaged 5%, while the annular space averaged 22% up to 4 weeks after installation. Similar to the clay site, the analysis of the annular space from the 1 year excavation revealed a decrease in moisture content to 12%. It appears that, over time, an equalization of the annular space and the surrounding soil medium occurs, thereby increasing the strength properties of the annular space.

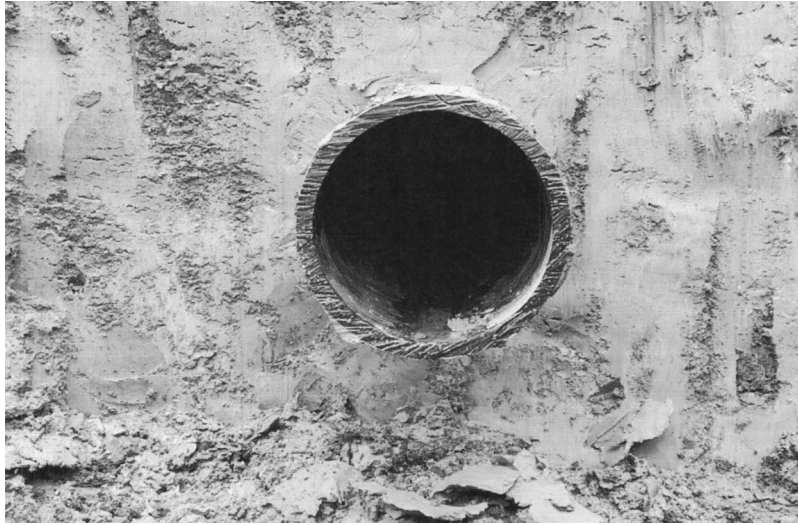
### Clay Site Analysis

At each cross-sectional excavation, photographs were taken to visually capture the in situ state of the annular space over time. Figs. 4–8 illustrate the annular space region of the 200 mm (8 in.) diameter installed pipe at various time intervals. As observed, the HDPE pipe is generally centered within the annular space region with no evidence of voids, which supports the findings of Knight et al. (2001). Additionally, clay, being a cohesive soil, enables the drilling fluid to remain within the boundaries of the annular space, thereby permitting the fluid to set up/solidify. In situ analysis of the unconfined shear strength of the drilling fluid revealed that the properties increase over time within the annular space region.

Comparing the 1 week excavation (Fig. 5) to the 1 year excavation (Fig. 8) reveals that the visual annular space actually de-



**Fig. 7.** 200 mm (8 in.) clay excavation at 4 weeks



**Fig. 8.** 200 mm (8 in.) clay excavation at 1 year

creases over time and is relatively nonexistent in the 1 year excavation. It appears that, over time, the amount of water present in the annular space decreases and the texture of the annular turns into a more solid state. This is similar to the finding of Knight et al. (2001), that the moisture content in the annular space is only slightly higher than that of the surrounding soil after 2 years. This may be attributed to equalization between the annular space region and the native soil formation. In addition, there is no evidence of the existence of voids in any of the cross sections, as confirmed by the photographs. These findings were also evident in the 100 mm (4 in.) and 300 mm (12 in.) installations.

### Sand Site Analysis

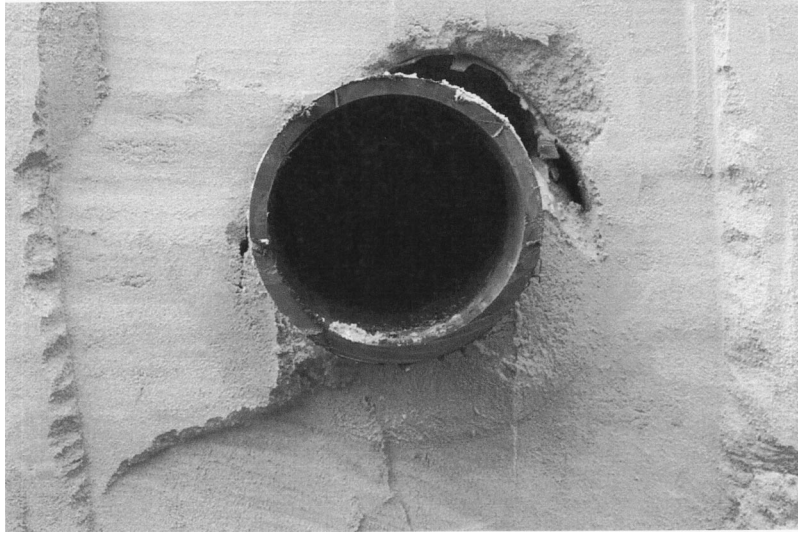
For the pipe installations in sand, it was difficult to determine whether voids existed in the annular space. Because of the distur-

bance created when excavating and cutting the pipe, the slurry in the fragile and very liquefied annular space had a tendency to flow out of the cross section that was just created. Once the slurry stopped flowing and the annular space was intact, a clear and evident sign of a slight void was present in the 200 mm (8 in.) installation, as illustrated in Figs. 9–13. In each excavation, the voids always occurred beside the pipe at 90° and never below or directly above. It is difficult to assess whether these voids existed before the cross sections were excavated or whether they resulted from the disturbance that was created when the cross section was made. Some questions were answered once closer inspection of the annular space with the void was made. When examining the void, it was evident that the void was not local to that cross section but in fact spread continuously through the formation. This void was predominant found only in the 100 mm (4 in.) and 200 mm (8 in.) installations, indicating that this may be an iso-



**Fig. 9.** 200 mm (8 in.) sand excavation at 1 day





**Fig. 10.** 200 mm (8 in.) sand excavation at 1 week

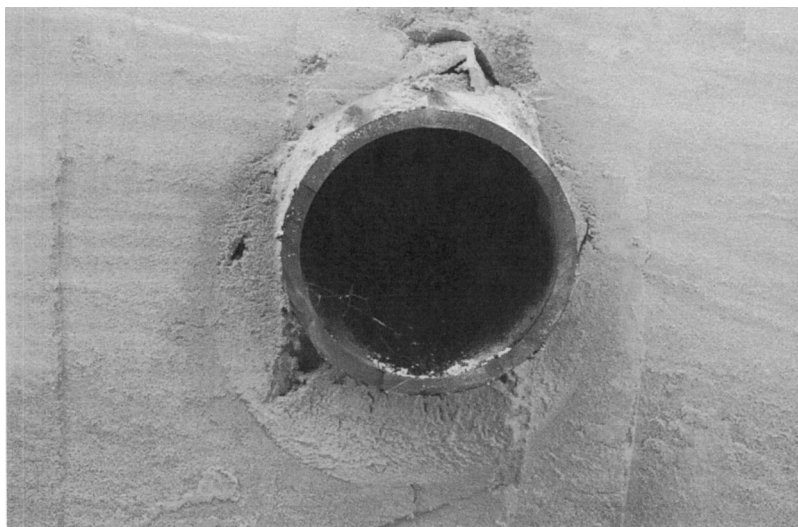
lated incident caused by the actual soil medium encountered. Additionally, it is suspected that these voids may have been formed due to the fluid permeating into the surrounding cohesionless sand formation. The 1 year excavation of the 200 mm (8 in.) pipe (Fig. 13) revealed no presence of voids whatsoever in the annular space. Therefore, the presence of voids is not thought to be a problem during HDD installations in sand; however, any short-term voids that may be present will more than likely be eliminated through redistribution of the soil with the annular space over time. It is important to recognize that more solids are present in the annular space region and provide support to the installed product pipe. Additionally, the presence of small voids are not a cause for alarm, as the surrounding native soil retains its compactive effort, which is difficult to achieve using traditional open-cut trenching methods of pipe installation.

In comparison to the clay installations, the analysis revealed that the HDPE pipe in all three of the sand installations tended to settle in the upper region of the annular space. This is a result of buoyant forces acting on the pipe in the cohesionless sand, result-

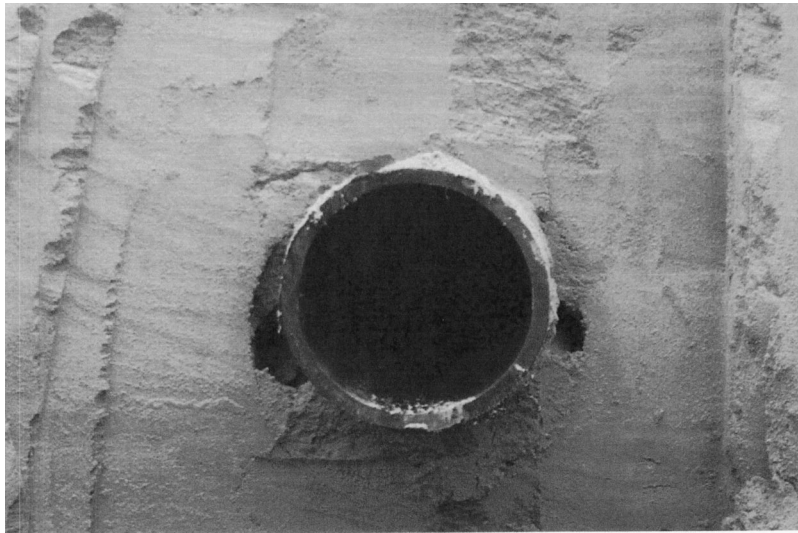
ing in the pipe “floating” upwards. In such installations, particularly when crossing under a water body, it is often the practice to weigh down the pipe by filling it with water to counteract the buoyant upward forces.

### Unconfined Shear Strength Test

A pocket penetrometer was used in analyzing the unconfined shear strength ( $\text{kg}/\text{cm}^2$ ) of the annular space. The pocket penetrometer was only utilized at the clay site, because it is only applicable in fine-grained soil. For each cross-sectional excavation that occurred in fine-grained clay, the pocket penetrometer was used to determine the unconfined shear strength (Fig. 14). Comparisons were subsequently made between the different pipe installations to assess the change in shear strength over time. The pocket penetrometer field test was performed at various locations in the annular space surrounding each installation. Fig. 15 reveals that the



**Fig. 11.** 200 mm (8 in.) sand excavation at 2 weeks



**Fig. 12.** 200 mm (8 in.) sand excavation at 4 weeks

unconfined shear strength of the annular space material increases over time. For example, the initial readings for the three installations were between 0.1 and 0.25 kg/cm<sup>2</sup>, which converged to 0.6–0.7 kg/cm<sup>2</sup>, recorded at the 1 year excavation. The existing clay medium exhibited unconfined shear strengths between 0.8 and 1.1 kg/cm<sup>2</sup> from measurements taken approximately 300 mm (12 in.) away from the installed pipe. This increase may be explained by the consolidation of the surrounding soil medium within the annular space over time and the slow hydration of the native clay in the slurry, thereby increasing the strength properties around the installed pipe.

### Conclusions and Recommendations

The findings of a field and laboratory study conducted to provide both a qualitative and a quantitative assessment of the annular space region during horizontal directional drilling installations are presented in this paper. Observations of the annular space region at various time intervals after installation indicate that small voids

may initially be present in cohesionless soils due to the permeation of fluid into the surrounding native material. However, it is important to realize that more solids are present in the annular space region, thereby providing support to the installed product pipe. No voids were detected in any of the installations in the cohesive soil.

The shear strength of the annular space is dependent on the characteristics of the native soil and its reaction with water. As was evident when comparing the clay and sand installations, the state of the clay annular space was far more solidified than the sand installation. It also exhibited strength and cohesive characteristics while the annular space in sand was fluid-like. In addition, the sand installations did exhibit initial voids, which is another sign of noncohesion. Measures of the unconfined shear strengths of the annular space in the clay soil medium indicate that it reaches about 70–80% of the native soil after 1 year. This is an important consideration, because these measures would be difficult to achieve from open cut installation methods.

Even within the same soil site, or even the same installation, there are differences between every cross section. Because the



**Fig. 13.** 200 mm (8 in.) sand excavation at 1 year



**Fig. 14.** Field measurement of unconfined shear strength of annular space

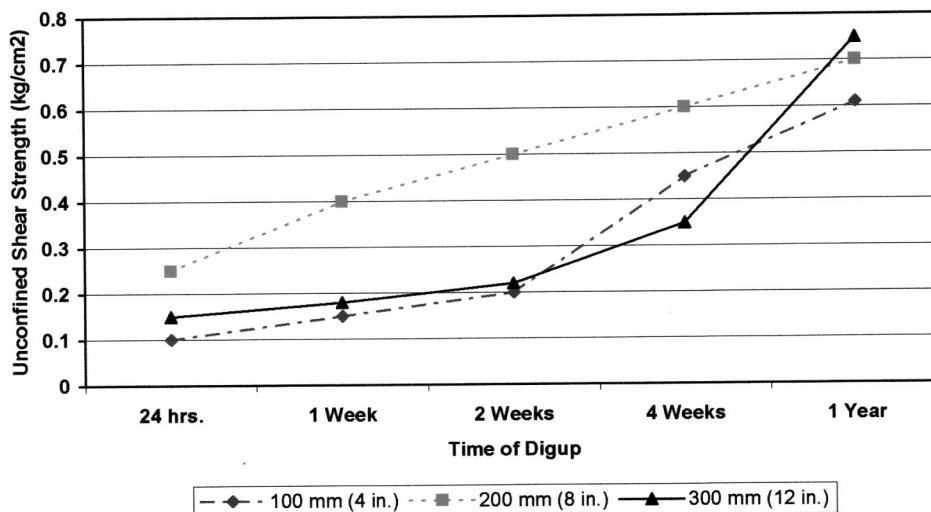
soil naturally exhibits different stratum or pockets of compositions, strengths, and moisture content, the annular space reflects this as well. The annular space was discovered to change in shape, texture, composition, shear strength, and moisture content from cross section to cross section. In all cases, the diameter of the annular space region decreased over time to the point that it equalized (or consolidated) with the native soil. The moisture content of the clay averaged 27%, while the annular space averaged 38% up to 4 weeks after installation. Analysis of the annular space from the 1 year excavation revealed a decrease in moisture content to 32%. The moisture content of the sand averaged 5%, while the annular space averaged 22% up to 4 weeks after installation. Similar to the clay site, the analysis of the annular space from the 1 year excavation revealed a decrease in moisture content to 12%. It appears that, over time, an equalization of the annular space and the surrounding soil medium occurs, thereby increasing the strength properties of the annular space.

The primary and most important function of the postinstallation annular space is to behave like the native soil and provide

security to the installed pipe. In situ tests and visual assessments validate this notion, as all of the pipes that were installed remained secure, with no evidence of any potential movement. Surface monitoring points placed along the installations revealed that no ground settlement occurred at the surface during installation. Additionally, no ground settlement was observed over time.

Much information may be obtained from field studies of construction processes such as the research described in this paper. The final results should provide owners, contractors, manufacturers, engineers, and others interested in directional drilling with a better understanding of the influence that HDD installations have on the surrounding medium. The six pipes installed and the 28 cross sections that were excavated and analyzed support the opinion that the annular space does provide the necessary attributes for the short-term and long-term success of a pipe installation using horizontal directional drilling.

Recommendations for future research include expanding the scope of research to include other soil mediums, pipe diameters, and pipe material. This could include drilling in mixed soil con-



**Fig. 15.** Unconfined shear strength of annular space over time

ditions along a continuous borepath. Additionally, it would be beneficial to assess the annular space using different mixtures of drilling fluid and at different depths of installation. Continued long-term evaluation of the annular space after installation to assess the unconfined shear strength over a longer time horizon is recommended. This could provide additional validation of the long-term integrity of the installed pipe. Furthermore, more elaborate strength tests or other geotechnical in situ or laboratory tests to measure properties of the annular space could be utilized. Assessment of the annular space in installations made below the water table is suggested for comparison with the results presented in this research.

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