Surface Heave Mechanisms in Horizontal Directional Drilling

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Abstract: Damage resulting from directionally drilled crossings has become a concern for municipalities and contractors due to the increased popularity of this trenchless installation method. Surface heave is one mechanism through which directionally drilled installations may damage existing surface structures such as pavements and foundations. Several factors contribute to the development of surface heave including backream rate, borehole pressure, downhole tooling, depth of cover, annular space size, and geotechnical properties. This paper presents and discusses results of a detailed field experiment which monitored surface heave under various installation characteristics. Four borepaths were designed to implement a full factorial examination to determine the interaction of backream rate, depth of cover, drill mud flow, and reamer type have on the development of surface heave. With greater understanding of how drilling practices affect the development of surface heave, practitioners of this technology may better plan installations to minimize the impact of their operation.

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Introduction

In recent years, horizontal directional drilling (HDD) has become the preferred construction method for the installation of new underground infrastructure. Being a trenchless method of installation, HDD is particularly suited for locations that are inaccessible by conventional open cut techniques. This may include situations where the proposed installation lies in an environmentally sensitive location; or for the crossing of roads, highways, railway lines, and water courses. The low environmental and social impact of this technology has made directional drilling extremely viable and desirable by municipalities where there is a high investment in surface infrastructure, congestion of existing buried utilities, and where the costs of restricting business or commuter traffic would make open cut alternatives inconvenient. With the utilization of directional drilling, a municipality can reduce the costs associated with restoration, shoring existing utilities, traffic control and detours, as well as the cost of disruption to local business and residential traffic. As a result of this demand for conscientious construction practices, the horizontal directional drilling industry has grown substantially over the past 20 years (Allouche et al. 2000). With this growth, there have been an increased number of contractors utilizing this methodology, and an increased number of incidents where surface heave from an installation has damaged existing surface and subsurface structures. According to a survey conducted by Allouche et al. (2000), 89% of the contractors surveyed were involved in utility installation and 74% in municipal applications. With almost three quarters of all directional drilling contractors involved in municipal applications, there is an increased possibility of contractors drilling within the vicinity of engineered surface or subsurface structures. Ground disturbance resulting from these installations may occur during the initial pilot bore, prereaming, or the final backream where the product pipe is installed. It is during the reaming and product installation phase where most ground movements occur, due to the action of the reamer either removing soil cuttings or displacing the soil during pullback. Ground movements are becoming a greater concern for municipalities and contractors as horizontal drilling utilization increases and underground right of ways become increasingly crowded. For example, as a result of increased number of incidents involving contractors that have humped roadways, in January of 2000, the City of Santa Clara, Calif., placed a moratorium preventing the use of horizontal directional drilling. It is anticipated that through this research, an understanding of how construction techniques affect the development of ground displacements may be developed, and practitioners of this technology can better plan and implement solutions to minimize the magnitude of ground movements associated with a particular installation.

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Horizontal Directional Drilling

Horizontal directional drilling technology evolved from the merging of oil field and water well drilling technologies. The main advantage of this technology over conventional pipe installation techniques is that HDD is a trenchless method, meaning that it requires a minimal amount of excavation to complete an installation. This technique allows for flexibility in the installation of the pipe, as the borepath may be curved or straight, with the path changing direction and depth during installation to avoid surface and subsurface obstacles. First employed in 1971 for a river crossing near Watsonville, Calif., the horizontal directional drill-

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ing industry has grown to encompass 17 manufacturers and several thousand rigs operated by several hundred contractors (Allouche et al. 2000). Directional drilling has been utilized in several industries, first in the oil and gas industries in the early 1980s, then expanded to include utility installation, environmental remediation, and the installation of gravity sewers and forcemains (Allouche et al. 2000).

The installation of pipe and conduit utilizing directional drilling is typically completed in a two-phase operation including the drilling of a pilot hole and its subsequent reaming to install the product pipe (Bennett et al. 2001). Installation of conduit and pipe is conducted from the surface, and commences with the boring of a pilot bore along the path of installation. The pilot bore is launched from the surface at an angle between 8 and 16°, and then gradually becomes horizontal when the required depth is reached. The bore can be steered and tracked from the surface using a walk over or wire line locator system to direct the bore to the exit location (Ariaratnam and Allouche 2000). Once the drill string reaches the surface at the exit location, a reamer is attached to the drill string and pulled back to the entry point. This process enlarges the borehole for the installation of the product line. To achieve the appropriate bore size it may be necessary to perform several reaming operations. Generally, all reams prior to the actual product installation are referred to as prereams, and the final ream to which the product pipe is attached is refereed to as the backream. The product line is installed once the borehole is enlarged to a diameter that is generally 1.5 times the outside diameter of the product pipe or conduit (Bennett et al. 2001; Lueke et al. 2001). More detailed descriptions of the HDD process may be found in Ariaratnam and Allouche (2000), Bennett et al. (2001), Allouche et al. (2000), and Knight et al. (2001).

Surface Heave Factors

The main objective of this research was to study and gain a better understanding of the effects that various construction-related factors have on the development of surface heave during a horizontal directionally drilled installation. The first step toward this goal was to identify the factors that may influence ground movements, and then devise a field based experimental program to measure the effects of these factors. The identified factors include: (1) annular space, (2) backream rate, (3) borehole pressure, (4) depth of cover, (5) reamer type, (6) reamer diameter, (7) soil composition, and (8) soil density.

Identifying and understanding the influence of potential surface heave contributing factors is important to industry practitioners in reducing risks associated with directional drilling installations. The methodology presented in this paper, using field based experimental design, enables both practitioners and researchers to gain a better understanding of the mechanisms that may cause surface heave during this trenchless construction method. This information is particularly important when drilling under paved roads and highways where public safety could be compromised.

Annular Space

The annular space is the area that is created between the drill stem or product pipe and the wall of the borehole. This space provides a route for drilling fluid mixed with native soil cuttings (i.e., slurry) to circulate back to the entry or exit locations. Good practices recommend that the diameter of the borehole be 1.5 times that of the product pipe (Bennett et al. 2001). If circulation is lost, soil cuttings may remain in the bore and cause overpressurizing of the borehole, thereby contributing to the displacement of soil and surface heave, and possibly causing inadvertent returns (Lueke and Ariaratnam 2002).

Backream Rate

During the installation phase, the speed at which the reamer is pulled toward the drill rig through the borehole is commonly referred to as the backream rate. The maximum backream rate is a function of the borehole diameter, drilling mud pump capacity and efficiency, drilling fluid viscosity, and a flow factor. The flow factor is a multiplier applied to the volume of the borehole to estimate the amount of drilling fluid required to effectively transport cuttings from the bore to the surface (Bennett et al. 2001). Typically, the backream rate is measured in terms of the length of time required to pull one section of drill pipe or stem.

Borehole Pressure

Borehole pressure refers to the fluidic pressure developed in the borehole as a result of the drilling process. At the time of this research, there are no readily available methods to measure the actual pressures in the borehole. Subsequently, it was decided that the drilling fluid flow rate be measured instead of borehole pressure. Flow rate provides a measure of the volume of drilling fluid pumped into the borehole during the installation, and could be measured by installing an inline flow meter after the mud pump on the drilling rig.

Depth of Cover

Depth of cover refers to the distance between the surface and the outside diameter of the product pipe. The amount of soil between the pipe and the surface has a direct influence on the expected amount of surface heave. The greater the cover, the less risk of surface heave occurring due to increasing over burden pressure and arching occurring in the soil matrix.

Reamer Type

There are various types of reamers utilized in directional drilling. The selection of a suitable reamer is generally based on the composition and nature of the soil formation where the installation is occurring. Reamers are typically classified into three main categories: (1) compaction, (2) mixing, and (3) all-purpose. In this research, a spiral (compaction) and a fluted (all-purpose) reamer were utilized. The behavior of the reamer within a specific soil medium determines the potential of ground displacements in the vicinity of the borehole (Lueke and Ariaratnam 2002).

Reamer Diameter

Reamer diameter refers to the largest diameter bore that the reamer cuts into the soil medium during reaming. The ratio between the diameter of the bore and depth of cover may have an influence on the magnitude of surface heave exhibited on a given installation.

Soil Composition

Soil composition refers to the classification of the soil by its material characteristics. This classification is made utilizing particle

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size distribution and plasticity. The composition of the soil determines its behavior during an induced strain event.

Soil Density

Soil density is simply defined as the ratio of mass to unit volume of the soil. The density of the soil may relate to the ease of compaction or dislodging of the soil during the reaming phase of the installation.

Experimental Design

Surface heave exhibited during a horizontal directionally drilled installation is the output response of a system affected by the aforementioned factors. Typically, in the investigation of the effects of one or more variables on the response of a system, a factorial design is utilized (Finney 1955). In a general factorial design, a fixed number of levels are selected for each of the factors that are under investigation (Box et al. 1978). An experiment is then conducted with all possible combinations of factors at their various levels. This factorial design considers the interaction effects between the factors with relatively few observations, and the data collected is suitable for the development of models to explain the observed behavior of the response in question. The following sections briefly describe the design of the field experiment, further discussion can be found in Lueke and Ariaratnam (2003).

Analytical Hierarchy Process

To conduct a field examination utilizing all eight factors would require 256 observations, assuming 2 levels per factor. This number of observations would exceed the available resources for this research. The analytical hierarchy process (AHP) was utilized to select factors for inclusion in the experiment. The AHP is a multicriteria decision-making approach that was developed by Saaty in the 1970s as a method to aid decision makers in the solving of complex problems (Saaty 1980; Triantaphyllou and Mann 1995). The process is commonly conducted utilizing the direct questioning of people who may or may not be experts in the problem, but who at least are familiar with the problem. This process would rank the factors in their perceived order of importance towards the development of surface heave.

Ten industry experts were solicited from the areas of contracting, consulting, manufacturing, and academia, with each respondent answering a questionnaire based on the pair wise comparison of each identified drilling factor. The respondents were asked to assess the relative importance each factor to another for every possible combination of factors using a predetermined scale. The average results from all respondents are presented in Table 1. Borehole pressure was found to be the factor perceived to contribute the most to surface heave, while the factor thought to contribute the least was reamer diameter. Details of this analysis can be found in Lueke and Ariaratnam (2003).

Selecting Factor Levels

To assist in limiting the number of factors investigated, the study was limited to one site, that being the Univ. of Alberta Research Farms. Soil density and soil composition factors were eliminated from the examination as these factors were relatively constant across the site. The elimination of soil considerations allowed the investigation to focus primarily on construction factors. Based on the results of the AHP; borehole pressure, depth of cover, and backream rate were included in the experimental design due to their high ranking. Of the three remaining factors; annular space, reamer type, and reamer diameter; reamer type was selected to be included in the study. The reamer type was selected to obtain data relating to the rig operational pressures and ground movements to contribute to future research. Using the two level factorial design, with each of the four factors examined at two levels, 16 observations were required to achieve all possible combinations ($2\times2\times2\times2=16$).

Factor levels were determined from previous field experimentation as well as the limitations of the drilling equipment utilized (Ariaratnam et al. 2000). It was decided to use a 200 mm diameter pipe, as this represented a typical size of product pipe used in practice (Allouche et al. 2000). The depth of installation was set at 900 and 1200 mm below the surface to simulate shallow utility installation. For reamers, a spiral compactor reamer and a fluted reamer were selected. These were best suited for the soil conditions found at the field site and typical of the type of tooling that an HDD contractor would use under the field conditions found at the University of Alberta Farm site. With borehole pressure being difficult to measure, mud flow was used as a substitute and set at 50 and 100 L/min, adjusted for altitude. And lastly, backream rate was set at the maximum (2 min/rod or 1.524 m/min) and minimum (6 min/rod or 0.508 m/min) pullback rates that the drilling rig could maintain.

Table 1. Relative Factor Weight

Factor	Weight
Borehole pressure	0.182
Depth of cover	0.165
Backream rate	0.148
Soil density	0.139
Soil composition	0.106
Annular space	0.099
Reamer type	0.088
Reamer diameter	0.071

Field Investigation

To further minimize the number of installations required in the experimental procedure, an innovative method of borepath design was considered. If a factor could be included in the actual bore profile, the number of installations would be reduced by half. One factor that was included in the bore profile was the depth of cover, as it could be varied along the borepath. To further reduce the number of installations, each bore was designed in a mirror image such that during the backream the first half could be performed with a low mud flow rate and the second half with the higher flow rate. By the inclusion of these factors in the design of the borepath, the number of installations was reduced from sixteen to four, effectively reducing the number of installations to a manageable level, while still maintaining experimental integrity. The final borepath design is shown in Fig. 1. The borepath is approximately 86.5 m in length, with four measurement locations along its length. Each measuring location was composed of five surface points that provided vertical heave measurements above the center line of the installation as well as two points to the left and right separated by 200 mm perpendicular to the borepath. A total of four installations were conducted utilizing this borepath; par-

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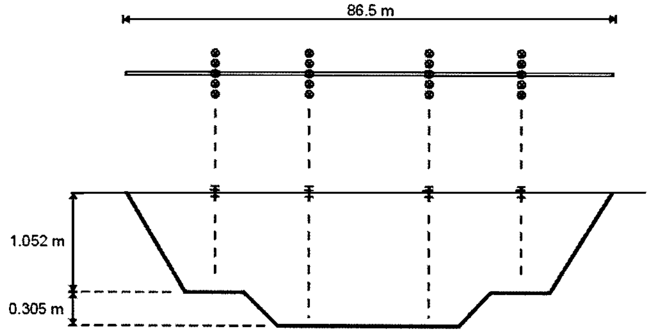

Fig. 1. Borepath design

allel to each other with a 5 m separation between each installation to minimize displacement contamination. Each borepath was drilled utilizing similar techniques according to HDD best practices (Bennett et al. 2001), with specifically assigned levels to each section of the path to obtain every possible combination of factor levels. Installations were conducted utilizing the Vermeer D24×40A Navigator horizontal directional drill, by a contractor that was experienced working with the soil conditions found at the test site. Installations were completed over two days in summer of 2001, at the Univ. of Alberta Research Farm. Soil composition of the upper 4 m at this site consists of a uniform lacustrine Lake Edmonton Clay with a unit weight of approximately 18 kN/m^3 (Zhang 1999).

Ground Movement Results

Ground movements were recorded after the drilling and backreaming phase of each installation. The layout devised in the experimental design allowed for the comparison of ground movements resulting from all combinations of factors studied. From the installations, it was discovered that, in all cases, surface heave was exhibited after both the drilling and reaming phases. Ground movements during the drilling phase of the installation ranged between 0 and 1 mm, while for the reaming phase, vertical ground displacement were measured between 2 and 6 mm. The following sections discuss results by factor examined during the field installations.

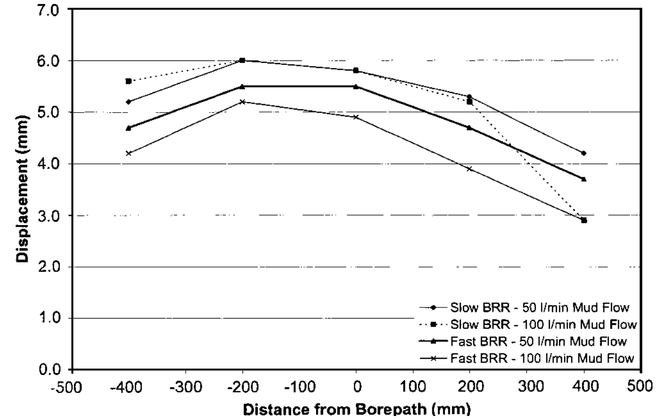

Fig. 3. Displacements from 900 mm depth with spiral reamer

Backream Rate

As previously discussed, backream rate refers to the speed at which the reamer is pulled through the borehole to the drill rig, measured in time required to pull one length of drill stem or rod. For this investigation the backream rate was set, by default of the machine's operating envelope, to have a slow pullback rate of 6 min/rod (0.508 m/min), and a fast pullback rate of 2 min/rod (1.524 m/min). Figs. 2–5 illustrate the displacements recorded for different backream rates and mud flow, compared by depth and reamer type. Each figure indicates the vertical surface displacement exhibited for both slow and fast backream rates with mud flow above the centerline of the pipe and at the two locations perpendicular to the installation. Two monitoring points on each side of the borepath, located in multiples of the pipe diameter to the left and right of the borepath, were at 200 and 400 mm.

Results from the field installations conducted at 900 mm depths indicate that the slower backream rate of 6 min/rod (0.508 m/min) induces greater surface heave than those conducted with the fast backream rate of 2 min/rod (1.524 m/min). For installations with the fluted reamer, the difference in heave magnitude between the slow and fast backream rates was almost 2 mm. Alternatively, for installations performed with the spiral reamer, the difference between the slow and fast backream rates was only 0.3–1.0 mm depending on mud flow rate. Installations at the 1,200 mm depth behaved slightly different. For the installations conducted with the fluted reamer, there was a reversal in that the faster backream rates produced greater surface heave than

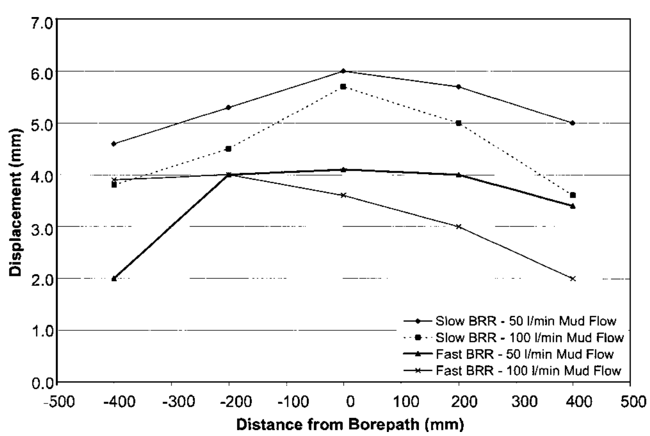

Fig. 2. Displacements from 900 mm depth with fluted reamer

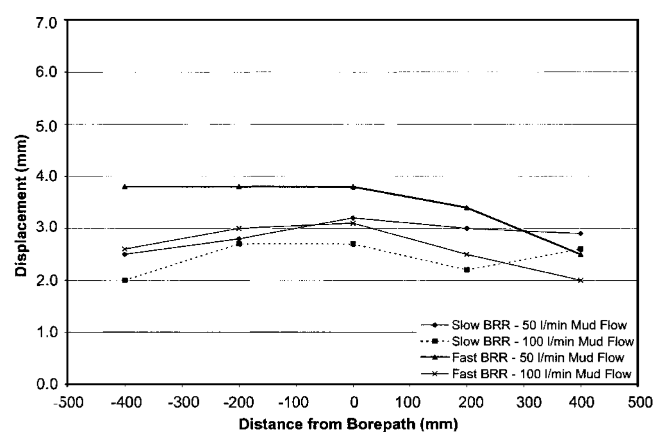

Fig. 4. Displacements from 1,200 mm depth with fluted reamer

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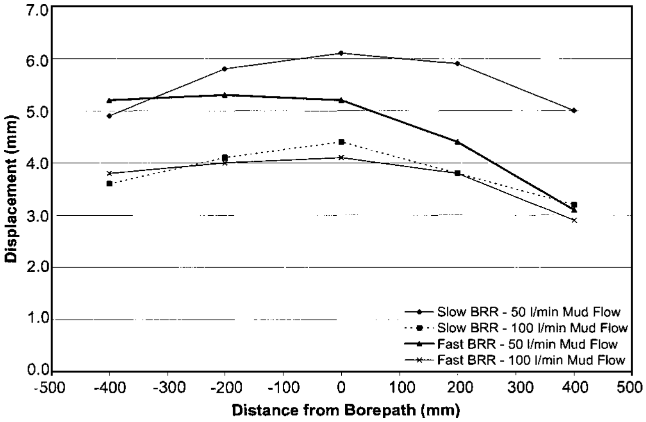

Fig. 5. Displacements from 1,200 mm depth with spiral reamer

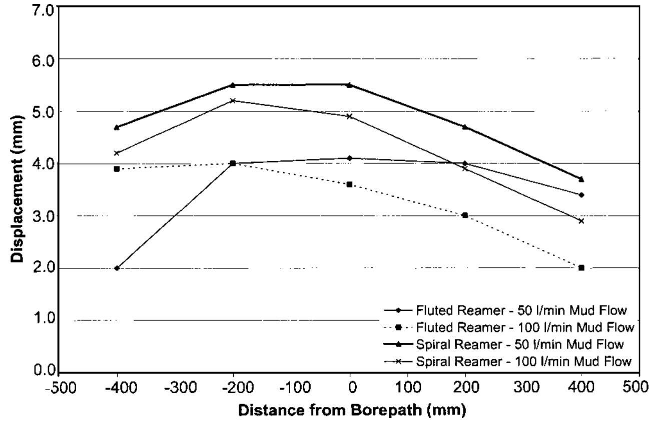

Fig. 7. Displacements from 900 mm depth with fast backream rate

the slower backream rate regardless of mud flow. The differences between heave magnitudes are between 0.5 and 0.7 mm when comparing backream rate and the associated mud flow. However, the spiral reamer at 1,200 mm behaved as the other installations conducted at 900 mm, with the slower backream rate producing greater surface heave than the faster rate. Additionally, there was a consistent pattern of lower flow rates being associated with greater surface heave, when comparing data series with the same backream rate and depth of installation.

The observed results are opposite to what may be expected. Intuitively, slower backream rates may be associated with less ground disturbance as there would be an increased volume of drilling fluid to sweep cuttings out of the bore, thereby reducing the volume of soil that may be displaced into the surrounding soil stratum. However, the only observation that demonstrated this premise was that of the fluted reamer at the 1,200 mm depth, otherwise the ground displacements were less with the faster backream rate. This would suggest that the mechanism at work might be related to the volume of drilling fluid in the bore, or the borehole pressure. With the slower backream rate there would be a greater volume of drilling fluid pumped into the bore, and in combination with the piston action of the reamer in the borehole, may result in greater surface heave for these installations.

Reamer Type

Fluted and spiral compactor reamers were used for the field installation as previously discussed. Each reamer was used for two boreholes, with similar installation procedures to provide a comparison of the behavior of each reamer. Unlike the backream rate and mud flow factors that could be varied during an installation, the reamer type had to be selected prior to the installation commencing, as this factor was borehole specific. Figs. 6–9 illustrate the results from the four installations by depth and backream rate. The mud flow for a particular installation is identified with the particular reamer type.

The results reveal two patterns that are consistent through most of the installations. First, the spiral compactor reamer induces greater surface displacements than the fluted reamer for depth and mud flow rates. And second, the low mud flow rate for any given combination of factor levels produced greater surface heave than the higher mud flow rate installations for both reamer types. These patterns were consistent for the installations conducted at the 1,200 and for the 900 mm depth installation with the fast backream rate. The installations conducted at the 900 mm depth with the slower backream had relatively the same amount of surface heave for either reamer type and mud flow rate, with all four installations having a maximum displacement within half a millimeter of each other. For all other installations, the difference between the fluted and spiral compactor reamer displacements was much greater, up to approximately 3 mm.

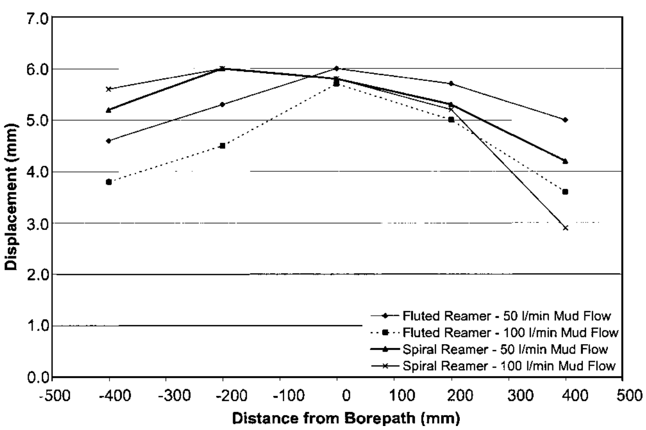

Fig. 6. Displacements from 900 mm depth with slow backream rate

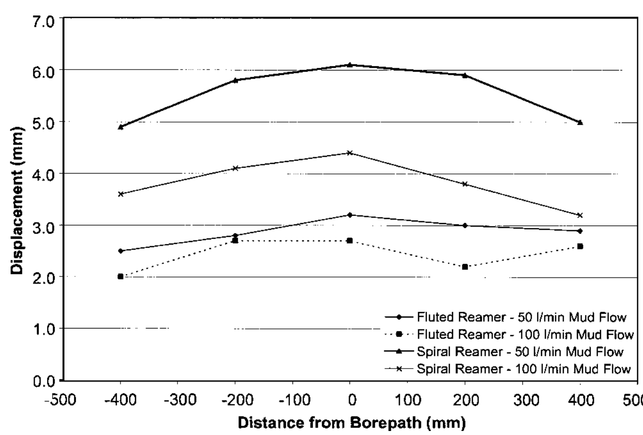

Fig. 8. Displacements from 1,200 mm depth with slow backream rate

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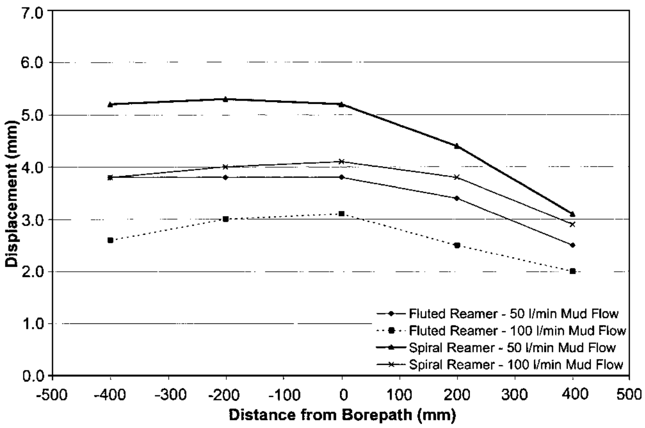

Fig. 9. Displacements from 1,200 mm depth with fast backream rate

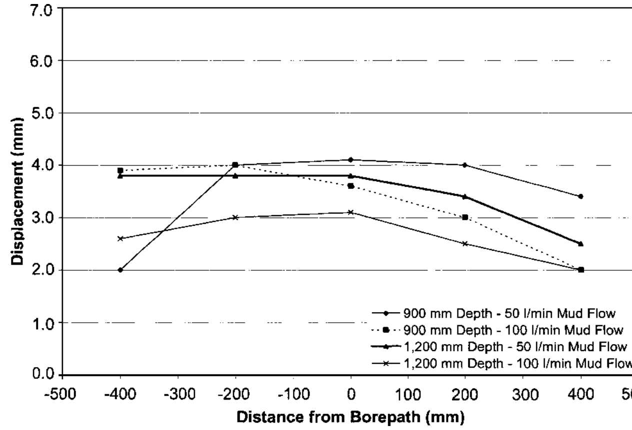

Fig. 11. Displacements from fluted reamer with fast backream rate

The greater surface heave exhibited in the installations conducted with the spiral compactor reamer may be accounted for by the design of the reamer itself. As opposed to the fluted reamer, which has slots curved around the circumference of the tool to provide a passage way for cuttings and drilling fluid to flow from the front to the back of the reamer, the spiral compactor has an expanding screw like configuration. The configuration of the spiral reamer does not allow for the transfer of material from the cutting face to the trailing face of the reamer. As a result, that material is compacted into the surrounding soil from the rotation of the reamer as it passes through the ground. If this material is not removed or transported to the entrance or exit pit, its volume will compact into the soil, thereby creating greater surface heave than if it were removed. Again, the lower mud flow application rate created greater surface displacements than those installations conducted with the higher application rate. This pattern is also demonstrated in the different reamer types, as ground movements for installations conducted with either reamer type are greater with the lower mud flow rate, when compared to the same installation conducted with the same reamer with a higher mud application rate. These patterns may be related to borehole cleaning and soil cutting transportation effectiveness.

Depth of Cover

The depth of cover factor levels was set to be 900 and 1,200 mm. Depth of cover refers to the distance between the surface and the borepath at which drilling and reaming were conducted. In general, HDD installations of this diameter are typically not conducted at this shallow of a depth; however, for the purpose of this investigation it was necessary to have some discernable surface heave. Subsequently, the slightly shallower cover depths were chosen to provide a comparison of the effect of the various factors on surface heave during a horizontal directionally drilled installation. Figs. 10–13 compare the effects of installation depths and mud flow rate to the magnitude of surface displacement developed during the reaming phase of the installation. There is a figure for each reamer type in combination with each backream rate, with surface heave indicated at locations above the borepath and laterally from the borepath.

In general, the data indicates that installations conducted at shallower depths induce greater surface heave than those conducted at deeper depths. For most installations, surface heave for the shallow installations were greater than the deeper installations when comparing installations with similar mud application rates. Additionally, for any given installation, lower mud flow rates produced greater surface heave when comparing results from the same installation depth, reamer, and backream rate. When considering the effect of the backream rate, a smaller spread was observed between the maximum and minimum surface heave values for installations conducted with the fast backream rate when comparing similar reamers. Additionally, there is less surface heave for installations conducted with a fast backream rate and similar reamers. This pattern is not as evident for the installations con-

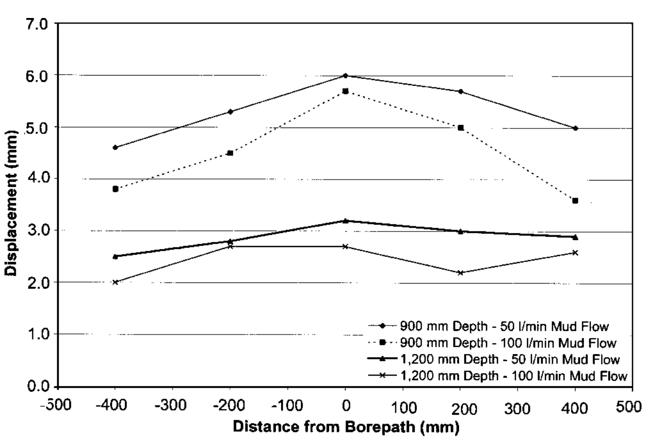

Fig. 10. Displacements from fluted reamer with slow backream rate

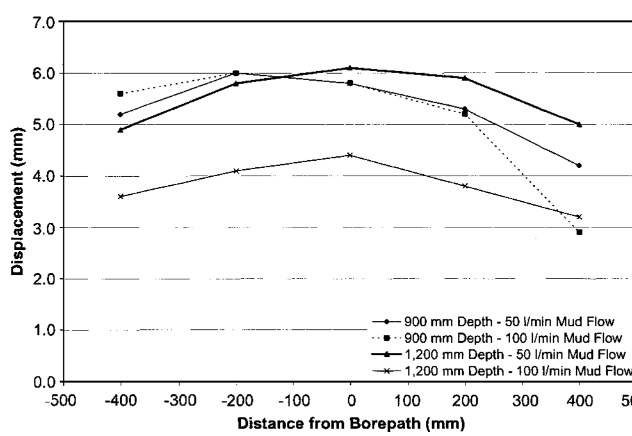

Fig. 12. Displacements from spiral reamer with slow backream rate

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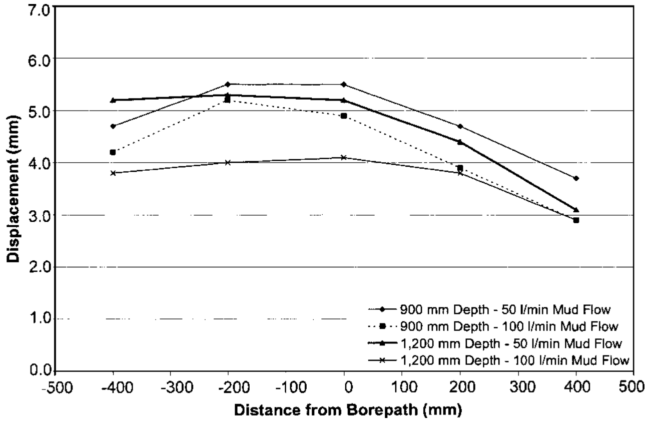

Fig. 13. Displacements from spiral reamer with fast backream rate

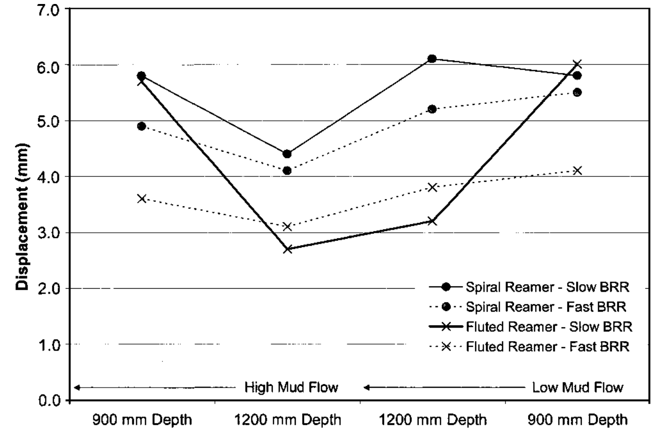

Fig. 14. Summary of centerline displacements by borepath

ducted with the spiral reamer and a slow backream rate, as there was not as great of a difference in the surface displacements between the two installation depths.

Intuition suggests that deeper installations would produce less surface heave than those conducted at shallower depths. This is due to the effect of soil arching on deeper installations, and the ratio of the change in borehole diameter (or soil displaced) to the depth of the installation being smaller. At deeper depths, there is a greater volume of soil to absorb the effects of displaced soil cuttings and dissipate the volume change. As the depth of cover increases, the magnitude of surface displacements decreases. This is particularly evident when comparing Figs. 2 and 4. Though the data collected examining the depth of cover appears to be intuitive, the data collected are essential to not only prove this assumption by to provide the data sets required to fully examine the system for modeling purposes.

Mud Flow

The rate at which drilling fluid is injected into the bore during the pullback is referred to as the mud flow. Mud flows were varied between the two predetermined levels during the reaming phase of the installation. Low flow was measured to be 50 L/min, while high flow was 100 L/min. In Figs. 2–13, each result is plotted with reference to mud flow. In general, the low flow rate level produced the greatest displacement in almost all situations and consistently had larger displacements than those installations performed with the higher flow rate. The only exception is illustrated in Fig. 3 at the 900 mm depth with a spiral reamer pulled at a slower backream rate. In this situation, the maximum surface heave was the same for both mud flow levels. As there appears to be no correlation between installation parameters, this may be accounted for by normal natural experimental variation.

The observed behavior may be explained through the process of cuttings transport and borehole cleaning efficiency. During the reaming phase of the installation, the reamer cuts or displaces the soil along the borepath in an effort to provide sufficient space for the product pipe. The method in which the borehole is enlarged depends primarily on the type of reamer, though, in most situations, cuttings from the soil formation are produced and remain in the borehole unless removed. Cutting removal is accomplished by displacing the cuttings that are produced with an equal or greater volume of drilling fluid to provide the transport mechanism. The volume of drilling fluid required to flush the borehole and transport the cuttings is dependant on the nature and consistency of the soil formation.

For these installations, HDD best practices indicate that a volume three to five times that of the volume of bore produced is required for adequate borehole cleaning and cuttings transport (Bennett et al. 2001). With the 300 mm diameter bore (i.e., 1.5 times the product pipe diameter), its cross-sectional area is approximately 700 cm^2, and using the length of the rods (3.048 m) to calculate the volume of the borehole, approximately 215 L of soil would have to be removed per section of rod. Using a clean out factor of 4, the total volume of drilling fluid required to provide adequate borehole cleaning is approximately 860 L.

Based on the results of the research, the larger displacements associated with the lower flow rate may be explained by the displacement of materials left in the borehole as a result of inadequate cleaning and cuttings transport. This is supported by the smaller displacements recorded at the points where a higher mud flow rate was utilized, perhaps doubling the effectiveness of cuttings transport and borehole cleaning.

Centerline Heave Observations

Centerline heave observations are plotted for all installations by reamer and backream rate, organized by depth and mud flow rate in Fig. 14. Each line represents a borepath used during the field investigation. This figure provides an overview of all observations and allows some general trends to be observed and reconfirmed from previous discussions:

1. There is an inverse relationship between surface heave and mud flow rate;
2. There is an inverse relationship between surface heave and depth of cover;
3. Generally, the spiral reamer created greater surface heave;
4. Reamers may behave differently depending on installation practices; and
5. Depth of cover determines the order of magnitude of displacements when all other factors are equal, suggesting depth of installation to be a major factor in the development of surface heave on HDD installations.

Conclusions

This paper presented an analysis of several factors that contribute to the development of surface heave during horizontal directional

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drilling installations. These include: (1) mud flow; (2) backream rate; (3) reamer type; and (4) depth of cover. A full factorial experiment was designed and implemented based on these contributing factors. From this study the following conclusions can be drawn:

1. Low drilling fluid application rates, or mud flow, produced greater surface displacement with almost all combinations of factor levels, and had larger displacements than those installations conducted with the higher flow rate. There is an inverse relationship between mud flow and surface heave.
2. Installations conducted at the 900 mm depth with the slower backream rate had greater surface displacements than those conducted at the faster backream rate. With increasing depth, the difference between the magnitudes of displacements exhibited between the slow and faster backream rate diminished. An exception to this pattern was the 1,200 mm deep installation utilizing the fluted reamer, as it produced greater surface heave at the faster backream rate.
3. Regardless of depth and mud flow rate, the spiral compactor type reamer generally induced greater surface displacements than the fluted reamer.
4. In general, shallow installations produce greater surface heave than deeper installations. For installations conducted with a slow backream rate, the difference between the magnitude of the installations at 900 and 1,200 mm depths were smaller than those installed with the faster backream rate. There is an inverse relationship between surface heave and depth of cover.
5. Reamers may behave differently depending on drilling practices utilized.

The findings presented in the research indicate the major trends in surface heave development associated with various construction practices in horizontal directional drilling, in the particular soil found at the Univ. of Alberta Research Farm. It also sets a framework from which future research may be conducted to examine surface heave development in other soil compositions, as well as the development of a model to examine the interaction effects of the various drilling techniques to minimize the magnitude of surface heave on directional crossings.

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