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POST-INSTALLATION GEOTECHNICAL ISSUES ASSOCIATED WITH LARGE-SCALE HDD CROSSINGS

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ABSTRACT

Horizontal Directional Drilling (HDD) is increasingly being used as a technique to install pipelines through challenging conditions. With this increased use, several post-installation geotechnical issues have, quite literally, surfaced, often many months or years following the original installation. These issues include sinkhole development around the entry/exit points for the HDD operations and settlement of the surface above the HDD bore path. Both can be attributed to two major factors, those involving unfavourable ground conditions and those involving problematic installation procedures. Several examples of each of these factors are described along with mitigation measures designed to prevent both sinkhole and settlement from occurring following HDD installation. Case histories from two large HDD crossings are subsequently presented which illustrate the potential magnitude of these issues and the steps that are often required for repair; the first from a crossing of the Fraser River outside of Vancouver, Canada, and the second from a crossing of a major river in north-central Argentina. In both of these cases, large sinkholes formed behind the HDD exit points, resulting in property damage and possibly threatening neighbouring utilities. Site investigation and design techniques implemented to minimise the potential for sinkhole development and settlement are discussed, and several remediation options used in the case histories are presented.

Keywords: Horizontal, Directional, Drilling, HDD, Sinkholes, Settlement, Geotechnical, Soils

INTRODUCTION

Horizontal directional drilling (HDD) has become an increasingly common technique for pipeline crossings, be they beneath rivers, through mountains, or below urban infrastructure. In the last few years, several post-installation geotechnical issues associated with large-scale HDD crossings have, quite literally, surfaced. These include sinkhole development around the entry/exit points for the HDD operations and settlement of the surface above the HDD bore path; issues that not only affect people and surface structures, but can place unplanned stresses on the pipeline itself. This paper will present some of the contributing factors to these geotechnical issues, some mitigation options, and finally two case histories where these issues have either occurred or been prevented.

POTENTIAL LONG-TERM EFFECTS OF HDD

The horizontal directional drilling technique has advanced significantly from its “pioneering” days in the 1970s and 1980s. Improvements to borepath guidance have been likened to those used by modern militaries, where the difference between the intended and actual drill bit emergence locations are often within 1m after drilling more than 2km. Similarly, the science behind mud mixtures has advanced significantly with new additives being mixed with the traditional muds to vary viscosity, density and to prevent loss through porous materials. However, almost all of the advances over the years have developed to assist in the installation phase of the HDD project with little emphasis on the long-term performance of the crossing once the installation has been completed.

Recognising the potential long-term effects of an HDD operation after a successful installation is critical given the increased use of HDD in urban environments and the further difficulties associated with repairing a pipeline installed by HDD compared with the shallower, conventional cut-and-cover methods. Two forms of post-installation geotechnical issues associated with large-scale HDD crossings are localised sinkholes and settlement above the installed pipeline.

SINKHOLES

Sinkholes occur when subsurface soil or rock is lost through either dissolution (typical of the method by which limestone caves are formed) or by mechanical processes (such as erosion or scour). This second process accounts for sinkholes associated with HDD through the act of drilling and removal of the waste cuttings, as the borepath itself acts as a cavity into which overlying materials are able to collapse. This collapse occurs locally, either partially or completely filling the borepath over a limited length with a volume of material from the surrounding native soil. Depending upon the diameter of the borepath and if the collapse occurs prior to or following installation of the new pipeline within the borepath, this volume can be relatively large.

In dense soils, arching or bulking of surrounding sands or silts, or swelling of clays, may replace this lost volume, thereby effectively filling in the sinkhole, and preventing its appearance at the surface.

In situations where the overlying materials are in a loose state, or there is insufficient capacity in the soils to bulk or swell to the required volume, this collapse is able to propagate to the surface over time, forming a "chimney-like" depression, as illustrated in Figure 1. This upward propagating collapse may be an actual void, where material physically drops into a cavity, or it may be a zone of soil that is made looser compared to its surrounding materials. This becomes a post-installation issue because, while the initial collapse into the borepath can occur during the HDD operations, propagation to the surface can take several weeks or months following the pipe installation.

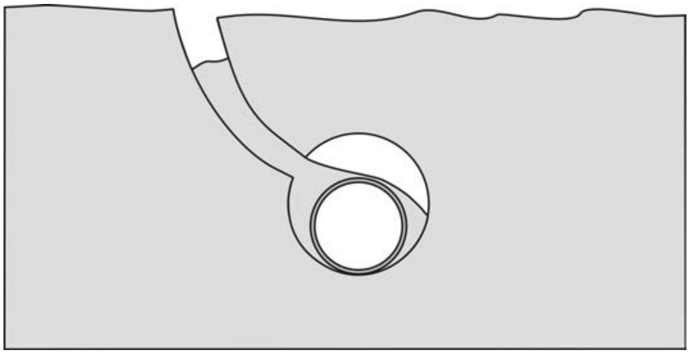

Figure 1. Schematic illustration of a cavity collapse triggering development of a sinkhole.

SETTLEMENT

Settlement of the ground surface above the path of the HDD occurs under much the same circumstances as those leading to the formation of sinkholes, namely from a lack of wall support, resulting in a collapse of the overlying materials into the borepath. In contrast, however, to the mechanism leading to the development of sinkholes, in which individual collapses are transmitted to the surface forming localised features, settlement occurs as a result of a progressive relaxation of the soil into the borepath along the entire length of the bore, as illustrated in Figure 2. This relaxation follows a similar mechanism as witnessed following tunnelling operations, where a broad trough-shaped depression is observed at the surface following the path of the tunnel bore.

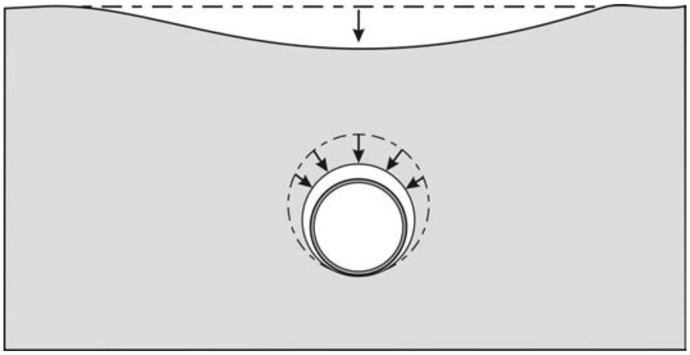

Figure 2. Schematic illustration of closure of the borehole wall resulting in development of a settlement trough.

Unlike in the formation of sinkholes, where the availability of a collapsible annular space and occurrence of overlying loose materials are the governing factors, creation of settlement troughs above an HDD bore appears to be a complex phenomenon involving additional factors. Ariaratnam [1] investigated the closure of the annular space around pipelines using pipe segments of up to 12 inches (305mm) in nominal diameter bored through both sands and clays. While not the objective of this investigation, Ariaratnam noted that no appreciable ground surface settlement above the borepath was observed. In contrast, however, are the settlement troughs observed above many shallow small diameter tunnels. It is likely, therefore, that one significant factor governing the formation of settlement troughs in HDD installations is the depth of cover to bore diameter ratio, H/D. In Ariaratnam's experiments, this H/D ratio was relatively large compared with many tunnels. With the advance of HDD technology over the recent years, the diameter of installed pipes has increased dramatically. The installation of 48-inch (1220mm) nominal diameter pipelines are now common, and the H/D ratio is gradually dropping to where it resembles that of a small tunnel, especially in sections where the borepath rises as it approaches the entry and exit points. In these locations, shallow settlement troughs have been detected, as noted at one of the locations discussed in the case histories.

TRIGGERING FACTORS RELATING TO UNFAVOURABLE GROUND CONDITIONS

Arguably, the most significant factor contributing to the development of sinkholes or settlement is unfavourable ground conditions. While not an exhaustive list, the following ground conditions individually or in combination can lead to such developments.

Loose Soils (Sand/Silt/Gravel)

Loose (low density) soils are the proverbial 'bad guys' when soil mobility or collapse is concerned. These soils often exist in highly unstable configurations, laid down in nature grain by grain to form a house of cards, where the displacement of only a small amount of soil at the bottom of a deposit can cause a collapse into a denser state of the whole column of soil. From the perspective of the mechanism driving sinkhole migration, while the propensity to collapse may initially trigger the mechanism, more importantly, the limited lateral stress developed by the loose soil is unable to prevent the vertical propagation of this collapse, as would typically be the case in denser materials.

Compressible Ground (Peat/Clay)

Akin to the ability of loose soils to contribute to the development of sinkholes, the presence of compressible ground plays a significant role in the development of settlement troughs above HDD borepaths. As described by Lee et al. [2], for the soil movements around tunnels in soft soils, "[the] inward soil movement due to the stress released by tunnelling inevitably causes ground movement around a tunnel". When such movements occur, their expression at the surface becomes a function of the stiffness of the overlying soils. Highly compressible materials such as peat and soft clays, with their low stiffness, typically show dramatically greater surface settlements than more brittle granular soils, as described by Peck [3].

Fluctuating Water Tables & Tides

Fluctuation of the local water table can play a significant role in initiating the collapse of soils into cavities through two main processes; by varying the weight of overlying soils, and by progressively washing or 'pumping' of the soils. Soils located below the water table have an apparent weight less than those above the water table in much the same way as one's weight is less when in a swimming pool. This difference in the buoyant weight of a soil compared to its non-submerged, but still saturated, weight becomes crucial when the water table fluctuates. As the water table drops, the weight of the soil overlying the pipeline, and any cavity that may be present near it, increases. This increase in weight can potentially fail the arching that may have been keeping a cavity open and thus initiating sinkhole development.

In tidal areas, the cyclical rise and drop of the local water table has the ability to wash fine particles from a soil's matrix. In well graded soils, where particles of many sizes are present, fine particles play two important roles in preventing collapse. Firstly they can form the cohesive bonding seen in clays, and secondly, they fill in the gaps between larger particles, effectively locking these larger particles in place. However, when the water table continuously fluctuates, the intake and egress of water into a soil column can, over time, wash these fine fractions from a soil, leaving only the larger particles behind. With the finer particles absent, the larger particles are more easily able to shift, and hence, collapse into underlying cavities.

High Conductivity Soils

Loss of circulation during drilling is a problem when the hydraulic conductivity (permeability) of the surrounding soil is sufficiently high, and the viscosity of the drilling fluid low enough, that the drilling fluid is capable of flowing into the permeable soil, as described by Barlow and Cavers [4]. Following pipe installation, these high conductivity soils can pose an additional problem. When layers of high conductivity soils occur beneath those containing fines, the act of drilling through these layers can provide an increase in the hydraulic connection between them, especially when the borehole annulus remains open. If excessive surface water runoff into the borehole occurs, or if the groundwater flow gradient is high, the fine-grained soils in the overlying layer can, over time, migrate down the borehole and into the high conductivity soils. This migration of fine soils from along the borepath can result in an excessive loss of material and development of a cavity, with a subsequent progression into sinkholes or settlement.

TRIGGERING FACTORS RELATING TO INSTALLATION METHODS

Besides the condition of the subsurface soils, situations that arise as a direct result of the HDD installation process can also trigger development of geotechnical issues after installation. Again this list of installation related conditions is not intended to be exhaustive, but rather to highlight some of the possible situations that may arise.

Excessive Annulus Size

As part of the HDD design process, HDD teams are typically forced to balance the added costs of drilling an excessively large borehole against the increased difficulties of pulling the product pipe through too small an aperture, and the possibility of locking the pipe in place. This balance governs the selection of an appropriate annulus size between the borehole and the product pipe. To assist in this balancing act, the Directional Crossing Contractors Association (DCCA) provides a published set of guidelines that includes a recommendation for selecting a reasonable borehole annulus size [5,6]. Their recommendation is that the final bore should be at least 1.5 times the size of the outside diameter of the product line [5]. Unfortunately, in many HDD cases, the installed pipe rests on the invert of the borepath, and as the increased capabilities of HDD have allowed larger diameter pipes of 48-inches (1210mm) and beyond to be installed, often the size of this annular space can exceed 24-inches (610mm), all occurring above the installed pipe. These large spaces provide ample volume to act as locations where unstable soils can collapse, initiating sinkhole and settlement in the soils above.

Difference in Entry/Exit Point Elevation

Under conditions of equal elevation, drilling mud typically provides support to prevent collapse and ravelling of soils into the borehole and into the stream of circulating drill cuttings. When differences in the entry and exit point elevations occur, however, the borehole behind the higher of the entry or exit points will be left unsupported as the mud attempts to achieve hydraulic equilibrium at the elevation of the lower point. The inline distance over which the borehole remains unsupported, especially at fairly flat entry and exit approach angles, can be extensive, and when ravelling occurs in loose soils, large voids can form, and over time sinkholes can develop.

Excessive Washing (Stationary Circulation)
During both the drilling and reaming stages of a project, there may be situations that occur which require that advancement of the borepath or the reaming process be halted. During these times, the HDD operator has the option of continuing to circulate the drilling mud and to remove suspended cuttings or to stop circulation completely. Should circulation continue without advancement of the cutting head, in loose soils, the jetting action at the head can wash or erode the borehole wall resulting over time in a loss of material. During installation, the area where this lost material originates will typically be supported by the drilling mud, however, if the drilling mud disappears over time (deflocculates) or if the washing is excessive enough that ravelling occurs above the hydrostatic equilibrium, then unsupported voids can form, leading to sinkhole development.

Excessive Circulating Pressure Scouring the Borepath
Similar to excessive washing, when the cutting head is stationary, if the advancing head has excessive circulating pressure, the action of the jets can scour the borehole walls. If the drilling mud deflocculates over time, these overly scoured zones can increase the effective size of the annulus beyond that which was the final reamed diameter. This results in the same triggering mechanism as found with an excessive annulus size, and can lead to sinkhole development if the scouring is local or settlement if the scouring occurs over a large portion of the borepath.

MITIGATION METHODS

The easiest mitigation method is foresight. Conducting an initial geotechnical investigation that allows for the identification of, or even suspicion of, unfavourable ground conditions prior to construction allows the owner and designer to take steps to handle such conditions before they can trigger sinkhole development or large-scale settlement. When loose soils prone to these forms of movement are found, such measures, many of which can be applied before the installation is completed, can include the following:

1. Stabilising the borepath wall with casing until a transition is made into competent materials. Clearly, this method is only appropriate near to the entry and exit points, however, it is at these points that the H/D ratio is smallest, and hence, the pipeline most susceptible to many of the triggering mechanisms described above.

2. Filling the annulus with cementatious grout. This measure is designed to provide permanent support to borehole walls, regardless of the size of the annular space. While relatively inexpensive, using this method requires, however, that an important design decision and commitment be made. If the borepath is to be filled with a delayed-setting cementatious grout prior to pullback, then this method will guarantee completely filling the annular space. Should a problem occur during pullback, then a delay may result in the grout setting and pipeline being sealed in place or the borepath grouted closed. If the grout is injected following installation of the pipe, ensuring that the annulus is fully filled over the entire length of the borepath may be difficult.

3. Compensating for differences in elevation head by varying the mud pit elevations. In locations where the difference in mud pit elevations are relatively small (i.e. less than approximately 10m) it may be feasible to either raise or lower the mud pit elevation accordingly to achieve hydrostatic equilibrium between the entry and exit points, and thus to prevent any part of the borepath from being unsupported. Care should be taken, however, that hydrofracture (loss of fluid containment) does not occur due to great a difference between the elevated pressure head and the resistive pressures that can be supplied by the overlying soils near to the lower of the entry or exit points.

4. Balancing the drill advancement and the circulation rates to prevent scour, and minimising circulation when stationary in sensitive materials. Through monitoring of the quantity and density of mud returns it is possible to establish if either mud loss is occurring, indicating high conductivity materials, or if volumes of material greater than that of the advanced borepath are being returned, indicating that scour is occurring. While this is common practice for almost all drillers, its objective is not to improve the drilling efficiency, but rather to identify and quantify the size of voids that may be forming. Once these measurements have been performed, adjustments to the mud mixture and circulation rates can be made, thus preventing further loss of material.

CASE HISTORY: FRASER RIVER, CANADA

Terasen Pipelines (Trans Mountain) Inc. (Terasen), formerly known as Trans Mountain Pipe Line Company Ltd. (TMPL), owns and operates an 1146 km, 610mm diameter crude oil and refined products transportation pipeline between Edmonton, Alberta and Burnaby, British Columbia. In September 2003, Terasen replaced their existing trenched and covered pipeline crossing of the Fraser River, outside of Vancouver, B.C., with one installed using horizontal directional drilling.

The total length of this crossing was 1293m, through which a 24-inch (610mm) pipe was installed into a 38-inch (965mm) reamed borehole. The HDD entry point was located on the south side of the river, approximately 250m back from the bank and within the limits of the City of Surrey. One of the significant features of this crossing is that between the entry point and the river bank is CN Rail's Thornton Yard. This yard is the westernmost terminus of CN Rail's national operations, with more than 50 parallel pairs of shunting rails and continuous track operation; beneath which the HDD would pass at a relatively shallow H/D ratio. The HDD exit point was located approximately 450m back from the north river bank and within the City of Coquitlam. This location has historically been the site of heavy commercial and light industrial operations, including lumber mills and landfill sites. Currently, the location is dominated by warehouse style large commercial buildings.

Prior to conducting the HDD, BGC Engineering Inc. (BGC) was retained as consulting geotechnical engineers to carry out a detailed site investigation for the proposed crossing. This investigation covered the land on both sides of the Fraser River and within the river itself. The investigation involved both onshore and offshore rotary drilling as well as onshore cone penetration testing. Both the gradational sizing of the soils as well as the penetration resistance was assessed at 15 locations along the intended borepath. Following the field investigation, a detailed stratigraphic interpretation of the materials beneath the river and below either bank was developed (Fig. 3), providing the HDD designers with a cross-section for use in planning the optimal borepath route through various units.

Having taken into account the soils identified from the geotechnical investigation, and adopting the recommendation for casing the entry point down to a depth of 15m, during the September 2003 HDD installation process, only a few challenges were encountered, and the installed pipeline was tested and put into service Some of the difficulties during installation included the temporary loss of the guidance signal near the HDD exit point due to a broken wire at the drill head, resulting in the complete extraction or “tripping” of the drill pipe, and some loss of fluid when a permeable gravel deposit was crossed. Shortly after completion of the HDD installation, CN Rail reported that maximum settlement in the region of 30mm had been noted through their yard along the borepath, forming a broad trough shape. These values correlated well with the settlement calculations estimated prior to construction.

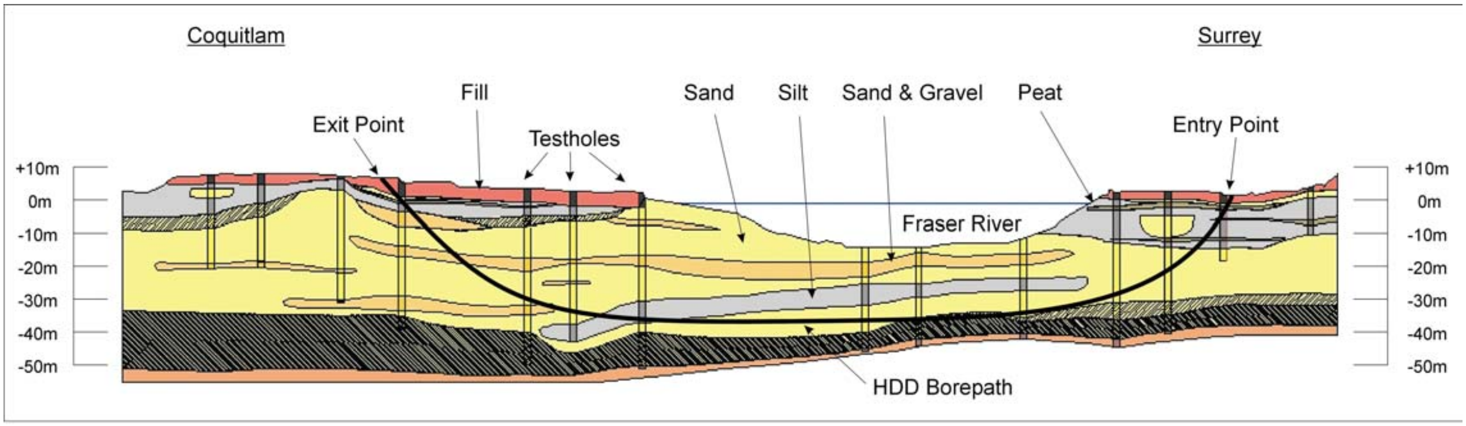

Figure 3. Schematic illustration of the Terasen Fraser HDD Crossing. Note 5x vertical exaggeration.

The results from the geotechnical investigation indicated that the crossing location was the site of sediment deposition by the Fraser, and that several interbedded layers of sands, silts and gravels were present. On the inside bank of the river (within the CN Rail yard), thick deposits of peat were also found, consistent with a lowland overbank flood depositional environment. Across the majority of the test sites, the soils were determined to be loose to very loose (SPT blow counts less than approximately 10) over the top 10 – 12m before more dense materials were encountered. Due to the presence of the Fraser River and proximity to the Pacific Ocean, a relatively high water table was also encountered, and which was subject to some tidal fluctuation.

Given the loose sands and peats found along the south bank of the river, and the low tolerance to settlement of the heavily loaded rail tracks running through the CN Rail yard, BGC conducted as part of the design process an assessment of the potential impact of running the HDD beneath the yard. This assessment included using the method by Lee et al. [2] for assessing soft soil movements around tunnels. BGC’s recommendation to Terasen was that the initial entry run of the HDD be cased down to a depth of 15m, thereby keeping the settlement over the yard to less than 34mm, a value deemed acceptable by CN Rail.

In October 2003, following heavy rainfall and localised flooding, over a period of four weeks, three sinkholes opened up just short of the exit point, on either side of the intersection of two heavily trafficked roads, and posing concern to the City of Coquitlam for both the road and underground services in the immediate vicinity of the sinkholes. These sinkholes were either directly over or within 4m of the newly installed pipeline, and ranged in size up to 4m in diameter and 2m deep; depths similar to that of the local water table.

Figure 4. Photograph of a sinkhole in Coquitlam, B.C.

Figure 5. Photograph illustrating the vertical nature of the sinkholes observed in Coquitlam, B.C.

Several possible mechanisms for the formation of these sinkholes have been developed, including:

1. That over the month following installation, the bentonite mud left in the borehole following pullback deflocculated, leaving the large annulus unsupported and the loose soils to collapse into the annulus.

2. That circulation may have been allowed to continue during the time when the source of the problem for the loss of the guidance signal was being discovered. At this time, the HDD was relatively shallow and close to the exit point with the stationary jetting resulting in a loss of some of the loose overburden material.

3. That with the large rainfall, increased surface water runoff and groundwater flow may have infiltrated the borepath, washing the bentonite mud into the coarse granular layer noted to have caused a loss of circulation during the drilling, and leaving the annulus unsupported.

At Terasen's request, in December 2003, BGC initiated an investigation and ground improvement program. The investigation phase of the program included exposing the pipeline towards the exit point in a large excavation and observing the condition of the pipeline and original HDD bored annulus. From this excavation little evidence was apparent of any bentonite mud remaining in the borehole annulus, supporting several of the possible triggering mechanisms described above.

Following these observations, a two-stage mitigation plan was developed by BGC in conjunction with Terasen and the City of Coquitlam, in which, for the first stage, a light-weight flowable fill mixture was injected from a distance back towards the river side of the sinkholes in an attempt to fill any remaining void space in the annulus along the pipe. This was intended to prevent any unsupported sections of borehole along the pipe from collapsing in the future. This first stage was successfully completed by utilising PVC pipe, which was required due to its limited abrasive and puncture potential against the new pipeline. Through a combination of jetting, vacuuming and top-hammering, the PVC pipe was installed down to the depth of the annulus over the centreline of the pipe, after which the flowable fill was pumped under controlled volumes and pressure into the annulus. Pumping continued until the flowable fill was observed entering the excavation at the exit point, thus ensuring that the annulus was completely filled.

The second stage of the ground improvement program consisted of compaction grouting the soils overlying the pipeline in an attempt to stiffen any areas where voids may have started migrating to the surface. This stage also utilised PVC pipe to protect the new pipeline. As for the first stage, the PVC pipe was installed down to the depth of the pipeline, although for this stage, installation was made in parallel holes to either side of the pipeline. Once installed, measured volumes of compaction grout were injected at a controlled pressure as the PVC pipe was extracted. Injection was stopped prior to reaching the surface to prevent jacking of the ground surface.

In summary of this case history, Terasen conducted a detailed geotechnical investigation in an attempt to ascertain the subsurface soil conditions for HDD. The insight gained from this investigation allowed for mitigative steps to be taken to minimise long-term settlement in an area where large settlements could not be tolerated. A series of sinkholes also developed post-installation due to unforeseen circumstances, and mitigative steps were taken to prevent their future development.

CASE HISTORY: NORTH-CENTRAL ARGENTINA

In 2001, BGC was retained to undertake a natural hazard and risk assessment of a 20-inch (508mm) diameter gas pipeline in north-central Argentina, which had been constructed in 1997-98. As part of this assessment project, a field inspection with an owner representative was undertaken at one of several river crossings. At that time, the owner representative remarked that the crossing had been constructed using HDD, and that a calliper pig had encountered an obstruction a year after construction; the cause of which had remained unexplained.

Figure 6 provides a schematic illustration of the crossing, and shows the completed path of the HDD. From an entry point at the top of the left (north) valley slope, the HDD descended beneath the slope and then the river to the exit point on the far (south) bank of an alluvial river terrace. As a result of the geometry of this crossing, an elevation difference on the order of 50m occurs between the entry and exit points, leaving most of the drill path beneath the left valley slope above the hydraulic equalization level, which was controlled by the exit point mud pit. This portion of the bore, about 260m long at an 11 degree downward incline, was, therefore, unsupported during the drilling and reaming passes.

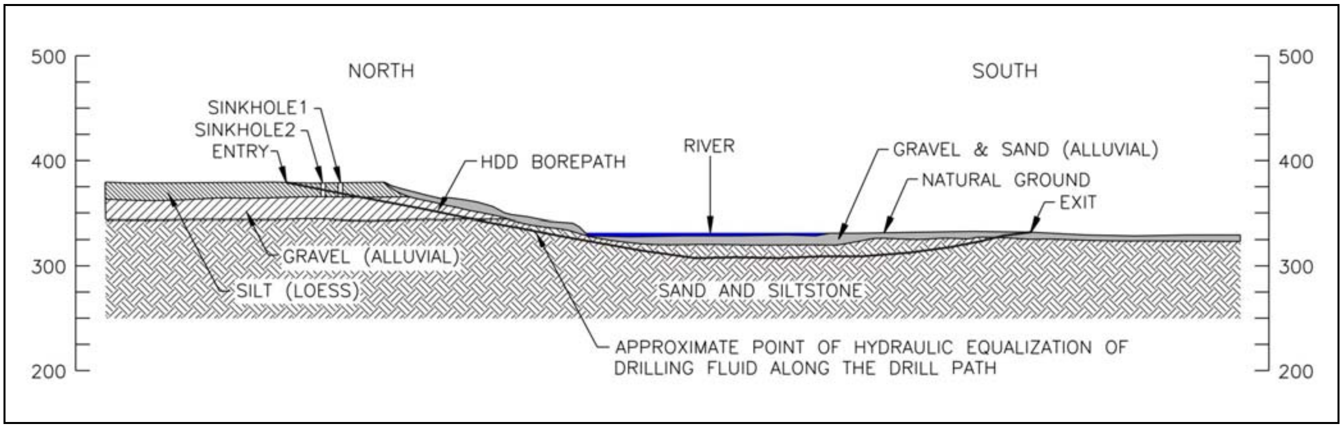

Figure 6. Schematic illustration of the North-Central Argentina HDD Crossing. Note 3x vertical exaggeration.

The stratigraphy of the left valley slope comprises a thick blanket of loess (i.e. wind blown sandy silt) overlaying alluvial cobble gravel with sand lenses. Figure 7 shows these two units in outcrop at a nearby natural exposure. The gravel unit, in turn, rests on very to extremely weak and subvertically dipping sedimentary rocks comprising sandstones, siltstones and limited claystones.

Figure 7. Wind blown sandy silt (loess) overlaying cobble gravel with sand lenses at a tributary valley near to the crossing.

Shortly after completion of the drilling and reaming activities in December 1998, the owner representative reported that two sinkholes had developed near the entry point at the top of the slope, as shown in Figure 6. At the time of construction, sinkhole #1 was 1 m in diameter, and its depth could not be determined because of the danger of collapse as the feature was approached. Sinkhole #2 was about 5m in diameter and 4m deep. These sinkholes were noted by the contractor and construction subsequently continued with pull-back of the pipeline.

Once the pipeline installation was successfully completed, the sinkholes were backfilled by the contractor using local sandy fill with gravel and cobbles. Many loads were end dumped near the features and pushed into the sinkholes with a crawler tractor.

The subsided surface expressions of the filled sinkholes more than two years later are illustrated in Figure 8. This southward view along the surface trace of the drill path shows one of the authors standing in sinkhole #2. The individual in the background is standing in the centre of sinkhole #1. The diameter of both sinkholes expanded during backfilling, indicating that the cavities were substantially larger than initially appeared at the ground surface.

Figure 8. Surface expression of Sinkhole #2 (foreground) and Sinkhole #1 (beneath background individual) two years after construction.

The act of simple backfilling with the pipeline already installed almost certainly caused high bending strains where the fill material loaded the pipeline section that was spanning the bottom of each sinkhole. Excessive curvature, including strains that may be approaching yield, wrinkles and ovalities may all be present, and is likely the root cause of the calliper pig becoming stuck. In addition, impact loading caused by the cobbles being dropped onto the unsupported pipe may have caused coating damage and dents.

Examining the construction history indicates that the sinkholes likely resulted from collapse and loss of ground where the unsupported HDD path passed through the cobble gravel and its contact with the overlying loess. The borehole annulus has likely enlarged laterally in the cobble gravel and this resulted in a collapse propagating vertically into the loess until the resulting 'chimney' extended to the ground surface.

Two potential construction problems were foreseeable when the loess and cobble gravel materials were left unsupported:

1. Neither soil has any significant natural cohesion, hence they would collapse into the unsupported annulus. The likelihood of collapse would increase with the diameter of the borepath. The presence of a water table would accelerate the rate and extent of collapse. In the absence of a water table, suction pressures in the silt would limit the nature and extent of collapse, but suction pressures would have little affect on the cobble gravel.

2. As the bit and reamer pass through the unsupported zone, the spraying affect of slurry discharge and the washing affect as it flows downward toward the hydrostatic equalization elevation (which is the approximate level at the right bank exit point of the drill) would erode material from the unsupported walls of the opening.

In summary of this case history, unfavourable geometry required that a large section of the HDD borepath would remain unsupported in loose soils. Unfortunately for the contractor (and eventually for the owner), no definitive steps were reported to have been taken to prevent excessive scour and erosion from occurring along the unsupported section of the borepath, and subsequently collapse occurred which likely led to the formation of sinkholes. An ineffective ground improvement program was undertaken by the contractor, which has likely led to further stress and damage occurring to the pipeline.

CONCLUSIONS

This paper has attempted to highlight some of the potential triggering factors that may lead to development of two of the most common post-installation geotechnical issues for HDD, sinkholes and settlement above the borepath. These triggering factors were divided into two main categories, those relating to unfavourable ground conditions and those relating to installation methods.

As unfavourable ground conditions, the presence of loose soils, compressible ground, fluctuating water tables and tides, and high conductivity soils were discussed. As triggering conditions related to installation methods, excessive annulus size, the difference in entry/exit point elevation, excessive washing, and excessive circulating pressure were also discussed. While any of these factors can on their own lead to development of sinkholes or settlement, the presence of loose soils with any other factor appears to most readily promote these features, as was seen in the two case histories presented.

Identifying the existence of any of these triggering factors as early as possible in the construction process, or ideally in the design stage, will allow for mitigative measures to be implemented and minimising the potential for either sinkholes to develop or settlement to occur.

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