Vibration Induced Settlement of a 13.5 metre Railway Embankment (Paper ID 989)

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ABSTRACT
TransCanada Pipelines is constructing two adjacent tank farms in central Alberta, Canada. Separating the two tank farms is a railway spur line on a 13.5 metre high railway embankment. Six interconnecting pipelines were required to cross the embankment in very close proximity. A narrow right-of-way, shallow groundwater, fine sandy soil conditions, site specific obstacles, unknowns in the embankment and very specific railway requirements created some difficult challenges for a multiple trenchless crossing solution. After a review of the available trenchless options, the guided slip bore technology was selected as it provided solutions to most of the constraints. A unique application of this technology was adopted to mitigate issues associated with saturated sand in the embankment foundation and railway requirements. Of primary concern to Canadian Pacific Railway (CPR) was the potential for vibration induced settlement as a result of the construction methodology chosen. Prior to providing the needed crossing agreement CPR set a number of requirements for settlement monitoring of the embankment. This paper provides an overview of the case history, including the results of the monitoring program and discussion of the issues related to embankment settlement.

PRESENTACIONES TÉCNICAS
TransCanada Pipelines está construyendo dos grupos de tanques para el almacenamiento comercial de petróleo (gas) en la región central de Alberta, Canadá. Separando los dos grupos de tanques se encuentra una pequeña vía de ferrocarril la cual está sobre un terraplén 13.5m de alto. La obra incluye la construcción de seis ductos de interconexión a través de este terraplén. Sin embargo, las condiciones encontradas en campo como el nivel freático superficial, suelo arenoso fino, desconocimiento de las propiedades del terraplén y requisitos específicos de la vía del ferrocarril, crearon grandes desafíos para proporcionar una solución de cruzamientos múltiples sin uso de zanjas. Después de una revisión de las soluciones disponibles se selecciono la tecnología de perforación dirigida (guided slip bore), ya que eta proporcionaba las repuestas para la mayoría de las limitaciones encontradas en el sitio. La principal preocupación de la compañía Canadian Pacific Railway (CPR), era los posibles asentamientos por vibración del terraplén como resultado de la metodología de construcción seleccionada. Previo al otorgamiento del contrato de construcción, CPR estableció un número de requisitos para el monitoreo de asentamientos en el terraplén. Este artículo presenta un resumen de este caso, incluyendo los resultados del programa de monitoreo y una discusión de asentamientos en el terraplén.

1 INTRODUCTION

Hardisty is a central distribution point for shipping (by pipeline) of petroleum products in Alberta. A number of terminal operators have extensive facilities here. As seen in Figure 1, Hardisty is 450 km due south of Fort McMurray, 180 km southeast of Edmonton and 260 km northeast of Calgary. TransCanada Pipelines is one of the operators that have terminal facilities in Hardisty. TransCanada has two terminals (A & B) at Hardisty. Terminal A feeds their Keystone pipeline which transports oil across to Manitoba and then south into the United States. Upon completion of the final portion of Keystone, the pipeline system will ultimately comprise 6034 km of large diameter pipeline starting at Hardisty and extending to the US Gulf Coast.

Terminal A is separated from Terminal B by a 13.5 m high embankment supporting the Canadian Pacific Railway (CPR). The terminals require interconnecting pipelines comprised of four NPS (Nominal Pipe Size) 36 inch process pipelines, one NPS 30 inch casing to house a 20 inch firewater line and a communication line, and one NPS 6 inch casing to house additional redundant communication lines.

The embankment was built to accommodate railway grade requirements as the alignment crosses the Battle River valley. In order to climb out of the valley and keep within grade limits, the railway constructed a large sweeping curve as seen in Figure 2. The valley is approximately 110 m deep and the curved alignment required an extensive fill operation that resulted in the high embankment that supports the railway. This embankment was probably constructed in the mid 1900s and no information was available from construction of the railway. A number of geotechnical drilling investigations (see references) were conducted to characterize subsoil conditions along the approaches to the embankment, and directly through the embankment fill from track level. A geophysical survey was also conducted on the embankment fill using Ground Penetrating Radar (GPR) to try to determine if there was anything in the embankment that would cause problems with the pipeline installations.

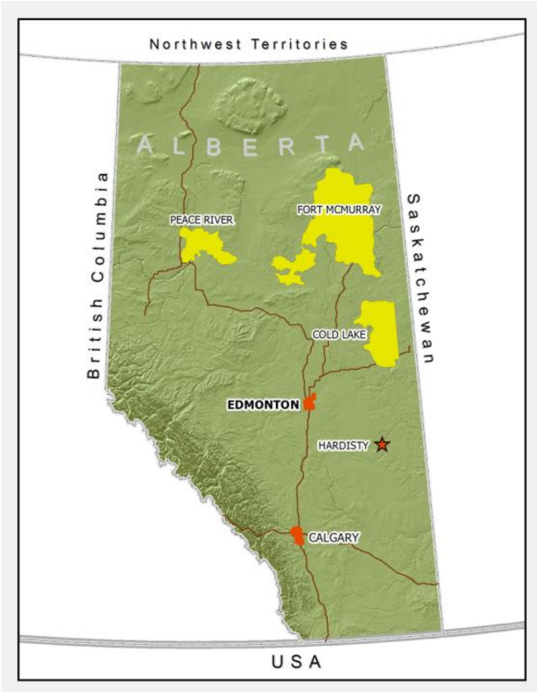

Figure 1. Location of Hardisty. Note Athabasca Oil Sand deposits (yellow).

2 SUBSURFACE CONDITIONS

The various geotechnical investigations (Coffey 2009 and 2010) determined that the in situ soil conditions below the railway embankment comprised an average 10 m thick layer of loose to compact fine grained sand, with an average SPT N value of 14 (uncorrected). The sand was overlying low to medium plastic, firm to stiff silty clay till with a trace of sand and gravel. The water table was encountered approximately 1 m below grade in the fine uniform sand deposit underlying the embankment. A cross sectional view of the embankment is provided in Figure 3.

The 13.5 m high embankment was mainly comprised of loose sand fill. Discounting the top and bottom two m of the embankment, the N values from SPT tests ranged between 3 and 11 (uncorrected) with an average value of 5.7. The upper 2 m of the fill had higher densities, likely related to compaction of the top of the embankment, and the effects of train traffic. The lower 2 m of the embankment also had higher density, possibly related to original construction.

In addition to drilling, a GPR survey was carried out on the embankment to determine if there was rock or other foreign material that could negatively impact the construction methodologies for the crossing. Nothing was detected in the GPR soundings that would hinder pipeline installations.

Figure 2. CPR embankment in area of crossing.

3 DESIGN

During the initial stage of the design process, consideration was given to the use of Horizontal Directional Drilling (HDD) to install the pipelines in native ground below the embankment. This is a well accepted technology for this type of crossing and is an accepted technology by CPR. However a number of factors with the proposed installations made the conditions unsuitable for HDD. The key issue was the tight spacing of the five pipelines that had to fit into a 15 m wide right-of-way (ROW). Given the pipeline diameters, and the need to open a hole 20 to 40 percent larger than the pipeline, the horizontal spacing between successive HDD borehole walls would have been in the order of 1.3 m. There was a

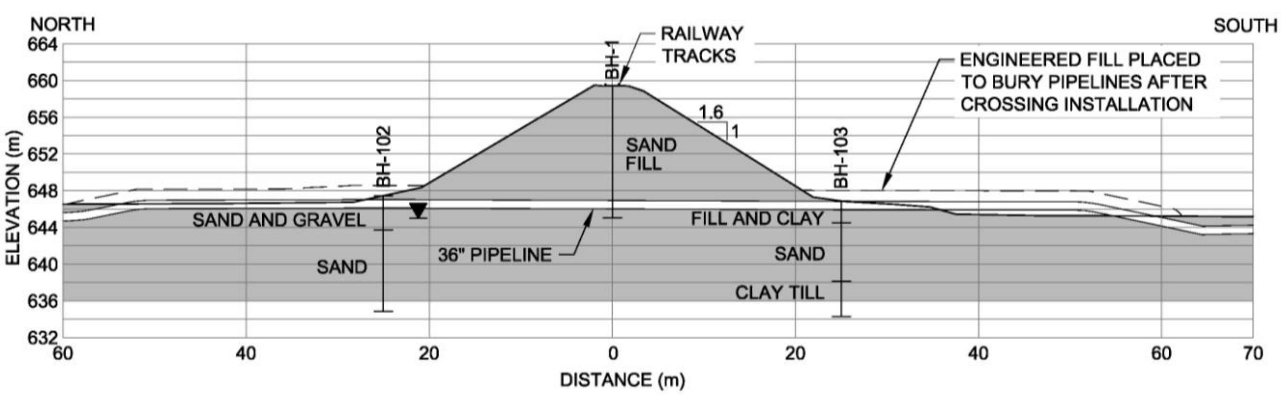

Figure 3. Cross section of railway embankment showing soil conditions and pipeline alignment

very high potential that the drilling mud would hydraulically fracture the bridge between HDD boreholes leading to interference between installations and likely loss of ground. In addition, the loose, saturated silty sand would have been prone to collapse into the HDD borehole and associated loss of ground even if the spacings were larger and there was no potential for cross connection between successive holes.

In the end, the relatively new Guided Slip Bore technique was adopted as it was considered to be an effective method to mitigate loss of ground and settlement concerns for the tightly spaced installations. In addition, to avoid constructing in saturated conditions, it was decided to employ the unusual solution of installing the crossings at ground surface, through the lower section of the embankment and subsequently burying the above-ground pipeline sections, rather than advancing the bores from excavated pits in the in situ sand below the embankment. The position of the pipelines in relation to the embankment is shown on the cross section on Figure 3. This unusual solution required an observational approach to construction, where a rigorous monitoring program was followed to ensure that any unacceptable ground deformations or embankment side slope movements in the loose sand fill were detected at initial onset so that corrective actions could be taken. The details of the Guided Slip Bore technique, and the monitoring system that was adopted are outlined later in the paper.

4 CPR CROSSING REQUIREMENTS

The CPR has considerable experience in dealing with foreign utility crossings below their track. They have developed well established criteria that are outlined in CPR (2007) and CPR (2009). The key issues with this particular crossing were to ensure that:

1. The stability of the 13.5 m high, steep side slopes in the loose sand embankment was not compromised;
2. Under no circumstances would slope movement propagate to the top of the embankment and lead to differential track movement;
3. Loss of ground related to the installation technique would not lead to unacceptable track settlements; and
4. Densification of the overall embankment from equipment vibration would not lead to unacceptable track settlements.

A few of the relevant design requirements of CPR (2007) are listed below for the crossing:

a) No casing is required for oil & gas pipelines crossings
b) Minimum cover depth below the base of the rail is 3.05 m within 7 m of the centre of the outside rail measured at right angles to the centre-line of the track.
c) Minimum cover depth under bottom of ditch is 1.83 m within railway ROW.
d) Conduits over 4 inch diameter are required to be made of steel, HDPE is not permitted.
e) A site specific geotechnical investigation is mandatory as required in the CPR protocol for pipe sizes of 30 inch or more.

5 GUIDED SLIP BORE TECHNIQUE

The contractor utilized the Guided Slip Bore technology to bore all the crossings. A more conventional slip bore methodology involves driving a casing the length of a crossing, without explicit steering capability. Accuracy is limited and as a result the length of bore that would utilize a conventional slip bore method is relatively short. However, with the advent of the ‘guided’ slip bore, the accuracy and therefore the length of crossing is increased. First, a 6 inch pilot hole is drilled through the crossing. The contractor utilized an Akkerman 240A guided boring unit that was mounted on rails to advance the pilot hole through the embankment. A photo of the guided boring unit is provided on Figure 4, where it is preparing to drill the 6 inch pilot hole for the third installation, immediately beside the initial two installed pipelines. The alignment tolerance was plus/minus 50 mm, which was easily met with the laser guided system.

Figure 4. Bore rig preparing to install 6 inch pilot hole beside first two installed pipelines.

Once the pilot hole was complete the driving shoe or “spider”, was welded to a section of casing pipe and connected to the drill steel at the leading edge. Figure 5 shows a photograph of the spider attaching the 30 inch casing pipe with the pilot hole drill pipe for the first installation. A 24 inch pneumatic hammer proceeded to drive the casing in from rig side. The drill pipe was then removed piece by piece as the casing penetrated the soil. The spider allows the majority of the soil to enter into the casing during the initial portion of each advance. However, as soil accumulates during the advance, a plug is established within the casing, and a greater proportion of the soil is displaced around the casing. As this happens the hammering is harder, resulting in increased vibration levels. Typically, the casing is driven until the advance rate is slowed to a point where the soil inside the casing needs to be removed by augering. This was typically done every 15 m when an additional section of pipe was added to the casing. Once the soil is extracted by augering, additional casing is welded on and hammering resumes. Once the temporary casing is through the embankment, the hammer is reversed and the casing is hammered back, bringing the product pipe through the embankment.

Figure 5. “Spider” attachment connecting 30 inch casing for first Installation to 6 inch pilot string, protruding from embankment.

Figure 6 shows a view of the embankment looking north, as the pneumatic hammer is installing the casing for the

fifth and final pipeline.

6 MITIGATIVE MEASURES

Constraints were imposed on the construction operation to control the risk of loss of ground. Two of the common sources of loss of ground during slip bore operations that produce ground settlement are over-excavation of the bore to form a gap between the ultimate product pipe and the borehole wall; and slumping or flow of overlying material into the front of the casing as it advances that can produce voids that propagate to surface as settlement or sinkholes.

The potential for loss of soil into the open end of the advancing casing was controlled by leaving a minimum soil plug inside the casing of 3 m (approximately 3.5 pipe diameters) each time the soil was augured out. The effect of leaving a plug of this size would lead to a net outward displacement of soil, as the volume of soil entering the casing would be less than the displaced volume, due to the frictional resistance between the soil plug and the inside walls of the casing. This resistance would increase as the advance proceeded and soil accumulated in the casing.

The potential for a gap between the product pipeline and the borehole wall was virtually eliminated with the guided bore methodology that was employed. The initial 6 inch drill pipe for the pilot hole was advanced without the removal of any soil, which would have displaced soil to produce a combination of heave and soil densification. As mentioned above, the advance of the casing would have also led to a net displacement. The product pipeline that then followed the casing was the same diameter as the casing, avoiding the creation of an annular space.

The remaining issue that could not be mitigated to the same level was the potential for densification of the loose fill that formed the overall embankment associated with the vibration from the pneumatic hammer. It was agreed that an observational approach would be adopted to address this issue, where embankment stability, ground deformation and vibrations would be closely monitored and corrective actions implemented if necessary to ensure that unacceptable deformations did not occur. The monitoring program is outlined in the following section.

7 CONSTRUCTION MONITORING

7.1 Monitoring System

The monitoring program consisted of the following elements:

1. Surveying of 15 surface settlement monuments at track level at 7 locations along the track, spanning a 40 m distance that was centered above the 15 m wide pipeline ROW;
2. Surveying of deep downhole settlement monuments installed at depths of 3.5 m and 11 m directly below the track, or 9 m and 1.5 m above top of pipeline, respectively.
3. Surveying of surface settlement monuments directly above the pipelines along the embankment side slopes.
4. Close visual observation of the embankment side slopes during the advancement of the casing and product pipes.
5. Surface vibration monitoring at various locations along the embankment slopes during the installations in the event that settlements were unacceptable and vibration limits were required.

The elements of the instrumentation program are illustrated schematically on the cross section on Figure 7.

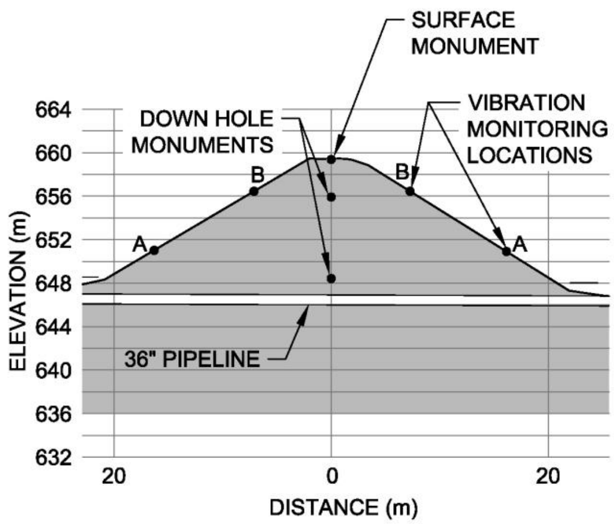

Figure 7. Embankment cross section showing position of monitoring system components.

7.2 Settlement at Track Level

The progressive ground settlement measured at track level for each of the 7 monitoring stations throughout the duration of the 5 installations is plotted versus time on Figure 8. Also indicated on the figure are the time intervals for the initial casing advance and product pipeline installation for each crossing.

The surface settlement trough measured along the track at the completion of each installation is shown on Figure 9. The maximum settlement is plotted for each of the pipeline installations on Figure 10.

The following observations are made from the settlement data:

- The maximum settlement per individual pipeline installation ranged from 5 to 11 mm, with an average maximum of 9 mm per installation. The maximum settlement was generally centered above the active installation.
- The total cumulative settlement at the end of the 5 installations was 40 mm at the maximum point.
- The settlement that occurred during the casing advance was on average 3.6 times larger than the settlement during advance of the product pipelines for the last two installations. The frequency of surveying of the monuments did not allow quantification of the difference between settlements during casing and pipeline advance for the first three pipelines.
- The magnitude of settlement for each successive pipeline installation did not decrease with time. The magnitude of settlement was directly related to pipeline diameter, where the maximum settlement for the 30 inch pipeline was 5 mm; and the settlement for the final 4 36 inch installations averaged 10 mm.

7.3 Settlement at Depth

Two survey monuments were installed to allow measurement of settlement at depth within the embankment fill. Figure 11 shows the settlement versus time profile for the two sub-surface installations compared to surface settlement measurements at track level at the two monuments that were in the area above the deep monuments. There was a general trend of settlement reducing with depth in the embankment. The deepest sub-surface monument that was 1.5 m above pipeline level and 11 m below track level showed the approximately 8 mm less settlement than the monument that was only 3.5 m below track level. The surface settlement at the closest monitoring station at track level had the same approximate settlement as the shallow, 3.5 m sub-surface monument.

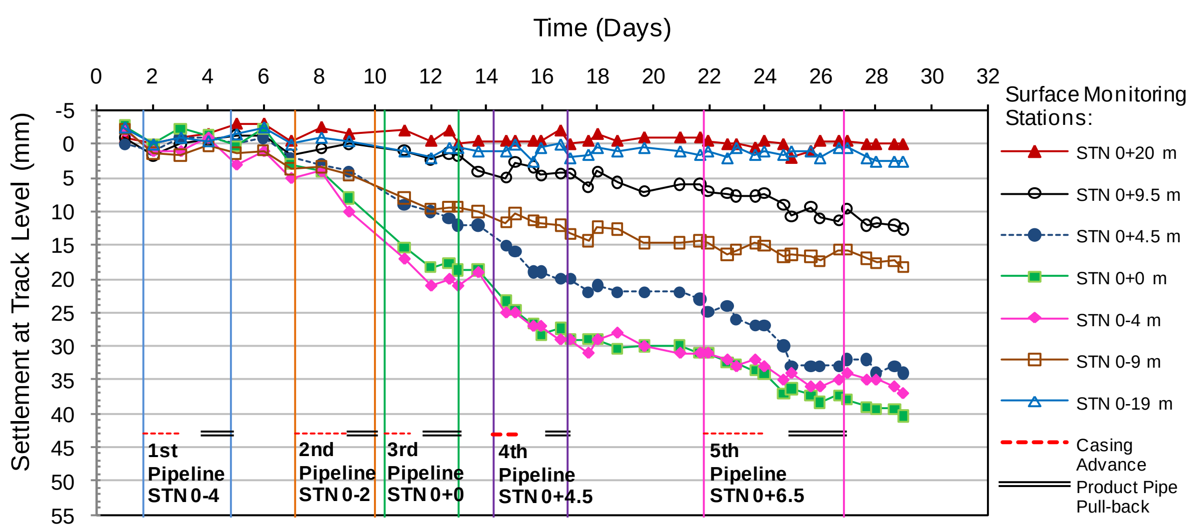

Figure 8. Ground settlement versus time for survey stations along top of railway embankment.

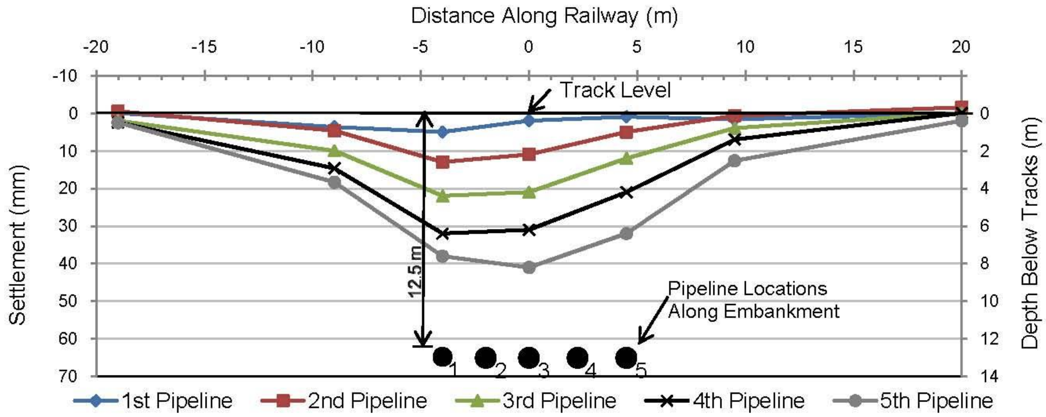

Figure 9. Ground settlement profile at track level along railway at the end of each pipeline installation.

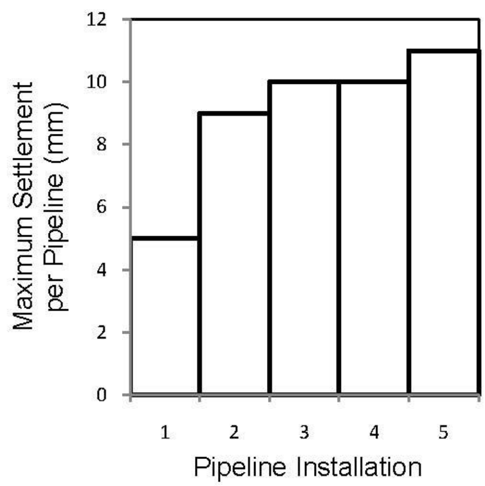

Figure 10. Maximum settlement at track level for each pipeline installation.

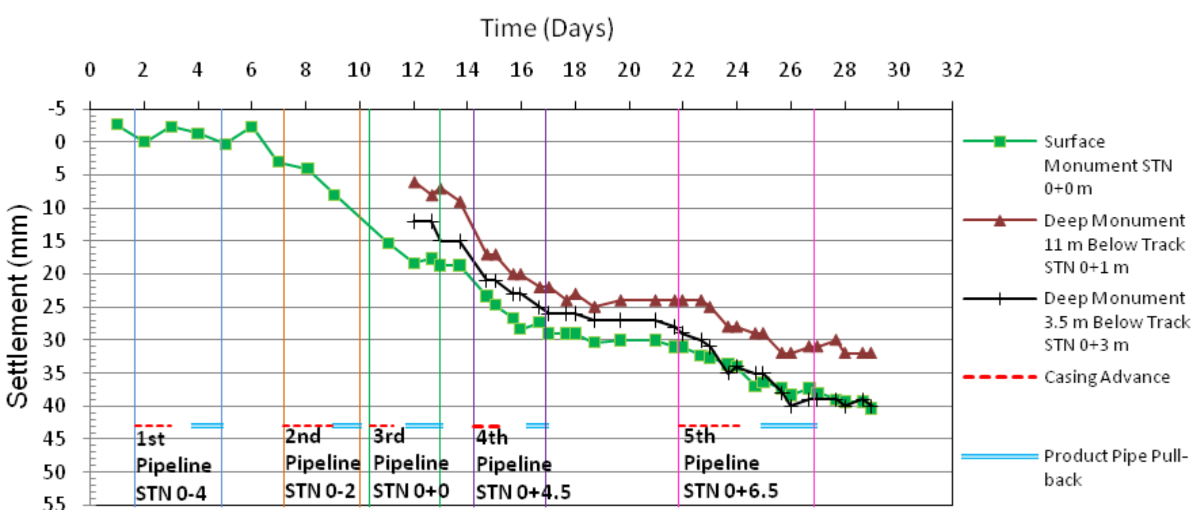

Figure 11: Ground settlement versus time for survey monuments at depth in embankment

The magnitude of ground vibrations measured by the unit for any given installation was found to vary over two orders of magnitude depending on the proximity of the unit to the leading end of the casing, and the quantity of accumulated soil that was present inside the casing at the time of the measurement. The highest ground vibrations and associated settlement happened during the casing advance, when the hole was opened from the 6 inch pilot hole to the full diameter of the casing and ultimate product pipeline. There was a definite increase in ground vibration as the casing filled with soil during the advance, and an increasing proportion of the soil was displaced around the advancing casing, rather than entering the casing. The casing advance rates would decrease as the casing filled with soil and more of the energy was consumed overcoming the soil friction on the casing and pushing the soil bulb ahead of the casing.

Given the large size of the embankment, and the constantly changing position of the leading edge of the casing, where the largest vibrations were focused, it was not possible to establish surface monitoring locations that could effectively track the relevant vibrations over the approximate 60 m length of advance. Monitoring locations on the embankment side slope, in close proximity to the casing would measure relatively high vibrations when the casing was entering or exiting the embankment and the unit was relatively close to the advancing edge. The monitoring unit detected peak particle velocities in range of 30 to 40 mm/sec in these cases. As the casing got further into the embankment, and into the most relevant zone below the tracks, measured vibrations would drop off due to the increased distance to the leading edge of the casing. Vibrations attenuated significantly as the unit was repositioned higher up on the slope in an attempt to track the leading edge, due to the increased distance.

After some initial experimentation, the unit was generally positioned within the middle third of the side slope, either in Position A or B, as indicated on Figure 7. Vibrations that occurred during the installation of the product pipeline behind the casing were generally below the detection limit of the monitoring equipment. It is of interest to note that vibrations induced by train traffic were in the order of 3 mm/sec when the unit was 3 m below track level. This is about 10 times smaller than the velocities quoted above when the unit was the same approximate distance from the front of the casing.

7.4 Visual Monitoring

Careful visual monitoring was conducted of the embankment side slopes during all stages of the pipeline installations to ensure that any potential slope instabilities were detected at initial onset, before progressing to the top of the slope. Despite the steep inclination of the slopes (1.6H:1V) and the loose condition of the sand fill, the slopes performed well during all installations. The only visually detectible movements were at the exit point where the head of the casing emerged from the embankment. The displacement of a bulb of soil ahead of the casing caused localized movements as the casing head broke through.

8 DISCUSSION

The most common source of settlement for pipeline crossings installed by the slip bore method is usually associated with over-excavation of soil along the bore path from soil slumping or flowing into the open end of the advancing casing from above. This mechanism was effectively eliminated for the five pipeline crossings through the railway embankment by keeping the bore path in unsaturated sand fill above the phreatic surface; and by keeping a minimum 3 m long plug of soil in the casing at the advancing face.

The key remaining issue at this site was the potential for the loose sand that comprised a majority of the 13.5 m high embankment to densify under equipment vibration during casing advance to produce settlement at track level. The monitoring data showed a pattern of settlement that is consistent with sand densification, but at magnitudes that were small compared to the substantial thickness of loose sand and that did not pose a problem to the railway company. The settlement that was measured at depth in the embankment fill, just above pipeline level was smaller than the settlement measured in the upper section of the embankment and at track level. This pattern of increasing settlement with height above the pipeline is opposite to the normal pattern where settlement is induced by over-excavation along the bore path, yielding movements that are highest in the near vicinity of the casing. The loss of ground at the casing produces settlement in the overlying soil, where the width of the settlement trough increases with height above the pipe, and the settlement magnitude decreases. This is especially true in sand fill that would not tend to form a chimney. The observed pattern of larger vertical displacements occurring higher up in the embankment is supportive of the sand densification mechanism, where settlement magnitudes would be expected to increase with height in the embankment.

While the overall embankment settlements were quite small, it is of interest to note that the four 36 inch installations were consistently about double the settlement of the 30 inch installation. The main sources of resistance to casing advance are as follows:

- Soil traction on exterior of casing, that would increase with embankment penetration;
- Soil traction on interior of casing, that would increase with soil accumulation between auguring intervals; and
- Displacement of the soil bulb around, and in front of the advancing casing for the proportion of soil that does not enter the casing.

Given that 80 percent of the settlement generally occurred during casing advance, it would appear that displacement of the soil at the leading edge of the casing dominates the resistance and hence the required energy and vibrations. The 36 inch casing has a cross sectional area that is 44 percent larger than a 30 inch casing, which would likely have been the main factor driving higher resistance and higher settlement. The 20 percent higher shaft surface area between the 36 and 30 inch casings would have also been a factor at increasing driving resistance, but was likely secondary, given that so little settlement occurred during product pipeline advance, with the full 60 m of pipe in the embankment for the entire duration.

9 CONCLUSIONS

The main conclusions from the observations taken during the pipeline installations are as follows:

1. The guided slip bore method was found to be an effective means of limiting settlement in a challenging setting, with five closely spaced pipelines in a loose sand embankment. The ability to tightly control both the pipe alignment and the potential for loss of ground into the borehole made the method superior to directional drill alternatives for this case.
2. Maintaining a minimum soil plug inside the advancing casing of at least 3.5 pipeline diameters was effective at controlling loss of ground at the leading edge of the casing.
3. The 36 inch installations yielding twice as much settlement as the 30 inch installation is considered to be dominantly related to the increased vibrational effects associated with advancing pipe with a 44 percent larger end area.
4. Monitoring vibrations at the ground surface was not an effective tool for enforcing threshold criteria to control settlement, as the highest vibrations were focused at the leading edge of the casing, which was constantly changing position. A more sophisticated system would be required to monitor vibrations near the leading edge of the casing.

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