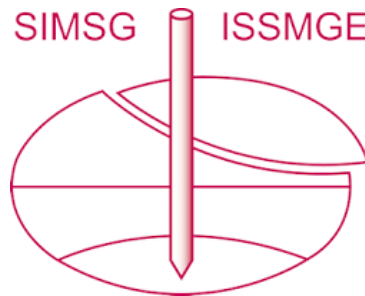


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The paper was published in the proceedings of the 7th International Young Geotechnical Engineers Conference and was edited by Brendan Scott. The conference was held from April 29th to May 1st 2022 in Sydney, Australia.

Horizontal directional drilling ground heave during watermain installation beneath a dike

Du forage directionnel horizontal et un soulèvement de terrain pendant l'installation d'une conduite principale sous une digue

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ABSTRACT: A watermain was installed beneath a dike that provides flood protection to a low-lying community in southern Manitoba, Canada using horizontal directional drilling. During installation, surficial cracking and heaving of up to 0.9 m occurred on the wet side of the dike, prompting concerns regarding the impact of the installation on the integrity of the community's flood protection system. A sub-surface investigation was undertaken at the heaved location, and finite element seepage modelling was completed to develop a repair detail to restore the dike to pre-construction conditions. The repair involved replacing the cracked and heaved material within 1.5 m of ground surface with compacted high plasticity clay. The modelled seepage rate prior to the repair through the dike and foundation were 0.17 L/d/m and 5.82 L/d/m, respectively. Following the repair, modelling showed seepage through the dike was reduced to pre-failure conditions (0.01 L/d/m). The repair work was both urgent and challenging considering it had to be completed in winter prior to the spring melt and associated flooding.

RÉSUMÉ : Une conduite principale était installée sous une digue utiliser pour protéger une communauté de faible altitude, au sud du Manitoba, Canada, contre les inondations. La conduite utilisait du forage directionnel horizontal. Pendant l'installation il y a eu de la fissuration superficielle et un soulèvement jusqu'à 0,9 m sur le côté trempé de la digue, sollicitant des inquiétudes sur l'impacte de l'installation et l'intégrité des mesures de protection contre les inondations. Une investigation de subsurface a eu lieu à l'endroit du soulèvement. Un élément fini d'infiltration a été complété pour développer un détail de réparation pour restaurer le site aux conditions avant la construction. Le réparage était urgent et compliquer parce qu'il avait besoin d'être complété pendant l'hiver avant la fonte printanière et les inondations.

KEYWORDS: HDD, heave, seepage modelling, compaction

1 INTRODUCTION

In early December 2019, an encasement pipe for a new watermain was being installed beneath a dike that provides flood protection to a low-lying community in southern Manitoba, Canada. The pipe was being installed using horizontal directional drilling (HDD) trenchless methods to avoid an open cut through the dike.

The encasement was a 550 mm diameter DR11 high density polyethylene (HDPE) pipe which was being pulled through a tunnel that had been reamed to 760 mm diameter. A bentonite grout slurry (drill fluid) was pumped through the tunnel to minimize sloughing/caving and lubricate the encasement pipe to ease installation.

The sending and receiving pits were 125 m apart, and for reference have been assigned stationing of 0+000 (upstream side of dike) and 0+125 m (downstream side of dike), respectively. The dike footprint lies between Sta. 0+063 and 0+113 m. The design installation depth varied along the alignment from as shallow as approximately 3.5 m at Sta. 0+025 up to approximately 9 m below the dike. Figure 1 shows a cross-sectional view of the project area between the sending and

receiving pits.

The site is located in a geographic area of Manitoba known as the Red River Valley, which is broadly characterized by surficial deposits of high plasticity lacustrine clay underlain by silt till and bedrock. The pipe was installed within the clay, which at this site is greater than 30 m thick.

2 INSTALLATION

The encasement pipe installation was completed in two attempts, 8 days apart.

2.1 First Installation Attempt

As the encasement pipe was being pulled through the reamed tunnel, surficial cracks developed along the alignment from Sta. 0+054 to 0+066; installation was halted as soon as the cracks were detected with the leading edge of the encasement pipe at Sta. 0+085. The encasement pipe was removed, and it was at this stage that geotechnical engineers were retained to establish the cause of the surficial cracking to mitigate further damage and the

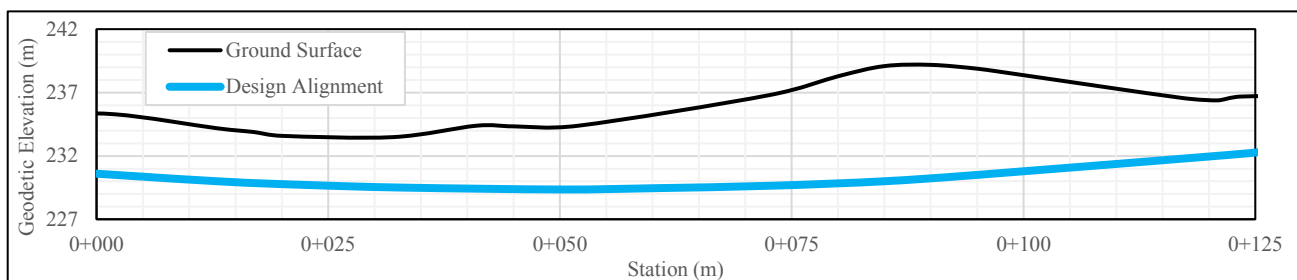


Figure 1. Installation cross-section

implications of the cracking, particularly relative to the performance of the dike.

On December 4, the crack was about 15 m long and approximately 75 mm wide at its widest point near the center (Figure 2). According to the contractor, when the cracking occurred the pipe was being pulled through at a rate of approximately 1.5 m per hour, and there was no notable loss of drill fluid or changes in fluid pressure during the installation, and no drill fluid was observed in the cracks.

The primary concern at this time was related to the extent and severity of the disturbed ground due to the installation, and the impact it may have on the performance of the dike; specifically, the potential for increased seepage within the disturbed ground, or worse, the potential for a hydraulic connection between the reamed hole and the outside of the encasement pipe (open flow).

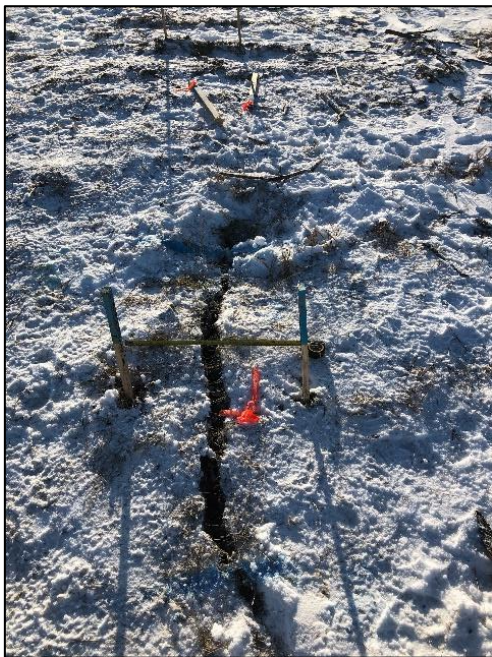


Figure 2. Original crack approximately 75 mm at its widest point

A seepage analysis (described in detail later) was conducted using the design pipe profile and conservative estimates of the sub-surface extent of the cracking to predict the future performance of the dike and model crack repairs.

Recommendations were provided to closely monitor the crack and fluid pressure for the remainder of the installation to prevent further disturbance and identify and address the cause of further disturbance (if observed).

2.2 Second Installation Attempt

The second attempt at installing the encasement pipe was undertaken on December 12. The previously reamed hole was reamed several more times prior to encasement pipe installation.

This time, the encasement pipe was fully installed at a rate of approximately 50 m per hour, and additional ground disturbance occurred beyond the initial surficial cracked area. The ground heaved forming a 13 m long, 0.9 m tall hump between Sta. 0+034 and 0+047 and the surficial cracking spread from Sta. 0+026 to 0+075 (Figure 3).

3 SITE INVESTIGATION

Following encasement pipe installation, the as-built location of the pipe was surveyed, and a sub-surface investigation was completed on December 20 to determine the extent of cracking with depth and confirm the presence of drill fluid. The

investigation consisted of excavating a test trench along the crack, starting in the middle of the heaved area to approximately 5 m south of the crack.

Approximately 1.1 to 1.5 m of brown, high plasticity silty clay was encountered above the drill fluid at the hump location, which thickened to approximately 1.5 to 2.1 m just south of the heaved area.

The pipe was encountered at a depth of 1.5 m below original grade, which is 1.3 m shallower than the design depth at this location. The drill fluid was under pressure as it flowed up into the excavation once it was exposed and rose to approximately 1 m below original grade.

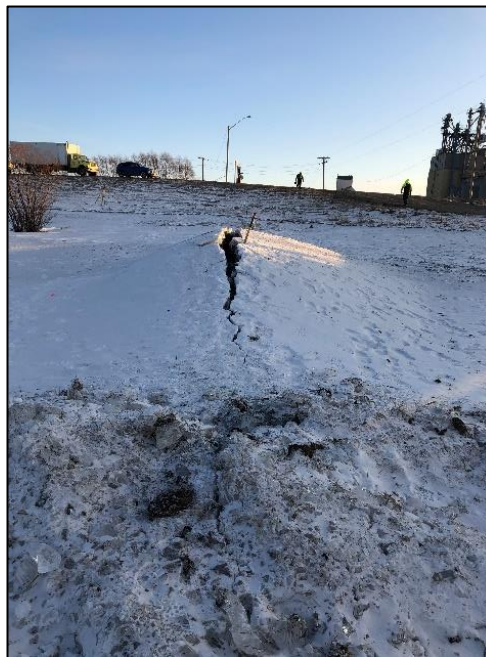


Figure 3. 0.9 m high heaved area after installation attempt 2 with the dike in the background.

4 HEAVING MECHANISM

Heaving in HDD installations occurs as a result of annular pressure exceeding the capacity of the overlying soil to resist it. The pressure is a function of a variety of factors including (but not necessarily limited to) installation depth, drill fluid properties, in-situ soil properties, pump rate, pipe and annulus dimensions, and installation rate (Latorre et. al, 2002, Suleiman et. al, 2010). Many of these factors relate to and affect one another. For example, the in-situ soil properties will affect the drill fluid viscosity required to create a filter cake around the annulus along with the properties of the drill fluid as it recirculates and removes cuttings from the tunnel. This in turn affects the pressure required to pump the drill fluid and the permissible pullback rate required to limit drill fluid displacement and associated pressure increases to below design thresholds.

The multi-variable nature of this problem requires quantitative installation data to reasonably identify the specific cause(s) of the ground disturbance observed during the encasement pipe installation. Without being on site to observe and document either installation attempt, there is simply not enough information available to conduct a forensic analysis of the specific factors leading to the surficial heave.

However, one measurable deviation from the design is the installation depth, which was observed to be 1.3 m shallower than designed where the ground heaved at Sta. 0+040. While it is unclear whether a greater embedment depth would have prevented ground disturbance entirely, the shallow installation

depth was undoubtedly a contributing factor.

5 SEEPAGE ANALYSIS

A seepage analysis was conducted to estimate the pre-construction groundwater flow regime through and beneath the dike (dike foundation), predict the potential increase in groundwater flow resulting from the disturbed ground under several scenarios, and design a repair detail with the intent of re-establishing pre-construction conditions. The analysis approach was generally conservative in nature given the limited amount of information available and the high consequence associated with a breach of the dike, which is classified as critical infrastructure.

The seepage analysis was conducted using the GeoStudio 2016 software package (Geo-Slope International Ltd.). Groundwater (seepage) conditions were modelled using finite element methods to determine groundwater levels, seepage rates and hydraulic gradients.

5.1 Model Geometry

The original model geometry was based on the design encasement pipe alignment and was undertaken after the first installation attempt. However, following the increased surficial damage and alignment deviations, the model geometry was modified to reflect the final site conditions using the as-built pipe profile, sending/receiving pit locations and ground surface profile.

Conservative estimates were made of features not visible at ground surface including the extent of disturbed ground and drill fluid around the encasement pipe annulus. The extent of the disturbed ground was assumed to extend laterally from the start of the surficial cracking down to the top of the encasement pipe. The area where the ground heaved from Sta. 0+034 and 0+047 was assumed to be heavily disturbed from ground surface down to the top of the encasement pipe.

The encasement pipe itself was omitted from the analysis, and the reamed pipe opening along the alignment was modelled as one region, referred to as the pipe cavity. Drill fluid was assumed to be present within the low point of the pipe profile (below Elev. 230.5 m) at the request of the client. The remaining portion of the pipe cavity was assumed to be open; this is a conservative approach that effectively reduced the seepage path for groundwater moving through the drill fluid in the pipe annulus.

5.2 Material Properties

Based on the limited sub-surface information available, estimates of hydraulic conductivity (k) for each material unit used in the analysis tended to be conservative. Table 1 summarizes the material properties used in the seepage analysis. All materials were modelled assuming fully saturated conditions.

The conductivity of the intact dike and foundation soil was assumed to be 1×10^{-9} m/s which is a typical value for compacted high plasticity clay in the Red River Valley. The conductivity of the disturbed zone associated with the cracked clay was increased by two orders of magnitude. This is to simulate the potential for more seepage across this disturbed zone and assumes the

“cracking” of the ground would be substantial enough to be somewhat inter-connected across the entire length of the zone. This higher conductivity value was also assumed for the clay used to backfill the pits to account for being placed in the winter. The soil beneath the heaved ground to the top of the pipe is assumed to be at a hydraulic conductivity of 1×10^{-2} m/s to account for the ground likely being highly disturbed. The pipe cavity in the model was assumed to essentially have open pipe flow in terms of the hydraulic conductivity assigned (0.1 m/s).

Table 1. Seepage Model Material Properties

Material	Hydraulic Conductivity, k (m/s)
In-Situ Clay	1×10^{-9}
Cracked Clay	1×10^{-7}
Heaved Clay	1×10^{-2}
Pipe Cavity	1×10^{-1}
Clay Fill – Pit Backfill	1×10^{-7}
Clay Fill – Crack Repair	1×10^{-10} to 1×10^{-8}
Drill Fluid (Bentonite Grout)	1×10^{-9} to 1×10^{-8}

A clay blanket (surficial layer of compacted clay) was analyzed as a seepage mitigation measure, the strategy being to repair the existing cracked and disturbed ground to prevent limit seepage down into potentially disturbed material beneath. The conductivity of the clay blanket was varied between 1×10^{-8} and 1×10^{-10} m/s to represent conductivity values achievable in the field, with the lower end of the range likely only achievable in summer construction conditions.

5.3 Boundary Conditions

A total head boundary condition of 238.5 m was assigned to the ground surface on the north (wet) side of the dike to simulate the design flood event (assumed to be 0.6 m below the top of the dike). On the dry side, a drainage condition (zero total flux) was applied from the crest of the dike (Sta. 0+091) to just past the exit pit (Sta. 0+132). No flow was permitted in or out of the model domain.

Flux boundaries were drawn within the dike and from the dike crest to the bottom of the model domain to determine the flow per metre through and under the dike. Figure 4 shows the model regions, boundary conditions and mesh of 1 m triangular elements.

5.4 Cases Analyzed

Six cases were analyzed to represent the pre-construction condition, post-construction condition, and repairs:

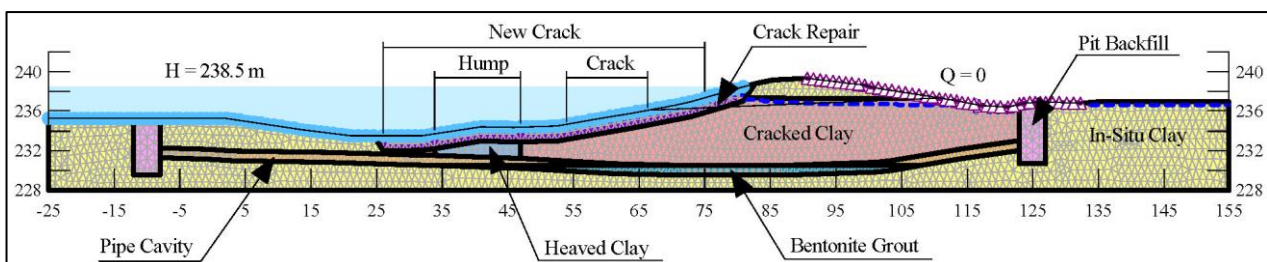


Figure 4. Model Setup

5.4.1 Case 1: Pre-construction condition

This case was used as a baseline to compare with subsequent model runs. Only one material, in-situ clay, was used for both the dike and dike foundation soils.

5.4.2 Cases 2 and 3: Post-construction, pre-repair condition

These cases represent estimates of the groundwater regime present after encasement pipe installation. They include zones of cracked and heaved clay, the pipe cavity and backfilled sending/receiving pits. To explore the sensitivity of the model to drill fluid hydraulic conductivity, Case 2 assumes drill fluid in the pipe cavity with $k = 1 \times 10^{-9}$ m/s, and Case 3 assumes a higher permeability drill fluid with $k = 1 \times 10^{-8}$ m/s. The drill fluid, which was observed to be high slump and low viscosity, was modelled within the pipe cavity to completely fill the cavity at the lowest point and extend out horizontally within the cavity.

5.4.3 Cases 4 to 6: Post-repair condition

A 1.5 m thick clay blanket was modelled at ground surface to seal off the zones of cracked and heaved clay at surface. At the time of the analysis, there was uncertainty relative to whether the repair would be undertaken in the winter (before the spring flood) or summer, and therefore uncertainty relative to the level of compaction that could be achieved. Cases 4, 5 and 6 model clay blankets with hydraulic conductivities of 1×10^{-8} , 1×10^{-9} and 1×10^{-10} m/s, respectively to explore the potential effectiveness of a poorly to well-compacted clay blanket. The drill fluid in the pipe cavity was modelled with a hydraulic conductivity of 1×10^{-8} m/s for cases 4-6.

5.5 Model Results

The pre-construction analysis (Case 1) estimates a combined seepage through and beneath the dike of 0.04 L/d per metre of dike (L/d/m), which includes 0.01 L/d/m through the dike. For all cases, the majority of the flow is through the foundation soil (beneath the dike).

In the post-construction analysis (Cases 2 and 3), 0.16 to 0.17 L/d/m of flow through the dike, and a combined total of 5.82 to 5.90 L/d/m through and under the dike was predicted. This amounts to approximately 190 times more flow through the foundation and 20 times more flow through the dike relative to the estimate of pre-construction conditions. Increasing the drill fluid hydraulic conductivity by 1 order of magnitude from Case 2 to 3 increases the total seepage rate by 1% (0.08 L/d/m).

Constructing a clay blanket (Case 4 to 6) reduces seepage through the foundation, especially when compacted to achieve lower hydraulic conductivities (about 40% reduction) and reduces seepage through the dike to pre-construction conditions. Results are summarized in Table 2.

Table 2. Seepage Analysis Results

Case	Seepage per metre of dike per day (L)		
	Foundation + Dike	Dike	Foundation
1	0.04	0.01	0.03
2	5.82	0.17	5.66
3	5.90	0.16	5.73
4	5.61	0.01	5.60
5	3.95	0.01	3.95
6	3.52	0.01	3.51

6 REPAIR

Based on the seepage analysis and discussions with the owner and client, a clay blanket repair was initiated to return seepage through the dike to pre-construction conditions. It was understood that the model would never show seepage through the foundation soil returned to pre-construction conditions due to the reduced seepage path in the model associated with limiting the bentonite grout to the low point in the pipe cavity. With limited information regarding the level of sub-surface disturbance and presence of bentonite grout throughout the pipe cavity, the conservative assessment of foundation seepage was accepted as an upper bound of the foundation seepage that may occur.

The repair was completed over the last week of March 2020, which included sourcing appropriate clay blanket material, removing disturbed material within the cracked and heaved areas, placing and compacting the clay blanket, and armoring the clay blanket with riprap to prevent erosion of the unvegetated upstream dike slope. While winter construction was not ideal, it was decided that a lower quality repair constructed immediately would be better than no repair in the event spring flooding inundated the site and potentially compromised perimeter dike. Figure 5 shows an aerial view of the site after the repair was complete.

6.1 Material Properties

The clay blanket specification required highly plastic clay fill be compacted in 150 mm lifts to 95% of the standard proctor maximum dry density (SPMDD) within 2% of the optimum moisture content, or to the maximum achievable level in consideration of adverse field conditions (e.g. winter construction).

Clay borrow was sourced nearby with the following properties summarized in Table 3.

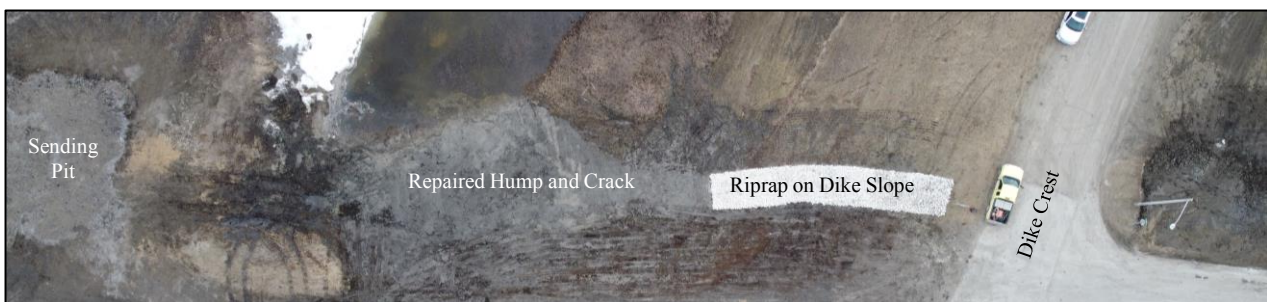


Figure 5. Post-Repair Photo

Table 3. Clay Borrow Properties

Property	Value
Liquid Limit	92
Plastic Limit	27
Plasticity Index	65
Clay Content (%)	80
Silt Content (%)	19
In-situ Moisture Content (%)	50.0 to 58.6
Optimum Moisture Content (%)	32
SPMDD (kg/m ³)	1337

The most significant challenge in using this material was the in-situ moisture content, which was well above optimum. Due to the winter construction, it was not feasible to dry the material, so it was placed and compacted at its in-situ moisture content. At this moisture content the clay was too wet and soft to effectively compact using a pad foot compactor, so the maximum practicable level of compaction was achieved by track-packing 75 to 100 mm thick lifts with a skid steer. Field density tests were conducted daily, with an average SPMDD of 81% and moisture content of 55%, which did not meet the project compaction specification; however, due to the high plasticity and clay content of the material it was suspected that the material would fall within modelled design range of hydraulic conductivity.

Flexible wall permeability testing on a Shelby tube sample obtained from the compacted clay blanket (80% SPMDD) yielded a hydraulic conductivity, $k = 9.67 \times 10^{-11}$ m/s.

A sample of the drill fluid that was allowed to cure in open air conditions was also tested, and yielded a hydraulic conductivity, $k = 4.96 \times 10^{-10}$ m/s, which is lower than the modelled drill fluid hydraulic conductivity. As shown in Figure 6, the sample which had originally filled the Shelby tube, experienced shrinkage upon curing; this likely represents an upper bound of shrinkage because it cured in an open-air environment. The hydraulic conductivity was not altered in the model to account for the possibility that some shrinkage in the field may result in a higher hydraulic conductivity; this potential reduction was deemed to have already been captured by the limited extent of bentonite grout within the pipe cavity.



Figure 6. Cured grout sample showing a reduction in volume occurs during curing.

7 CONCLUSIONS

The cracking and ground heave that occurred during the encasement pipe installation is a reminder that even in ostensibly ideal soil conditions for HDD, a perfect installation is never guaranteed. Annular pressure increases beyond what was planned for can occur during installation due to many interrelated factors including drill fluid properties, in-situ soil properties, pump rate, and installation rate. Pressures and drill fluid should be monitored closely throughout installation to permit adjustments to the installation procedure be made in real time if necessary. Maintaining the design ground cover is critical, and adjustments to installation pressures must be made if deviations from the design profile occur.

A finite element seepage analysis was used to develop a repair detail to return flow through the dike to pre-construction conditions. The model assumptions were intentionally conservative to account for the uncertainty in the extent of sub-surface disturbance and the conditions within the reamed tunnel surrounding the encasement pipe and due to the critical nature of the infrastructure at risk.

The high plasticity clay used in the repair was much wetter than optimum, and as a result could not be compacted beyond 85% SPMDD. However, testing confirmed the material still had an acceptably low hydraulic conductivity. In urgent situations where hydraulic conductivity is the most important design value, compaction specifications can be relaxed when using this type of material.

8 ACKNOWLEDGEMENTS

I'd like to acknowledge the contributions of my colleagues Nelson Ferreira and Reinhardt Van Rensburg, who were both intimately involved with the planning, implementation and reporting for this project.

I'd also like to thank our client and the owner for allowing me to write this paper and supporting international exposure to local engineering practice.

Thanks to Kent Bannister and James Blatz for nominating me to attend this conference, and to the Canadian Geotechnical Society for the honour to represent Canada as a delegate at this event.

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