Case Study: Remediation of a Riverbank Slope Failure in the Canadian Prairies

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ABSTRACT
A major pipeline crossing of the Souris River in southern Manitoba was undergoing a retrogressive slope failure within the limits of the pipeline corridor. A geotechnical investigation was carried out to assess the subsurface conditions in the slope and mechanism of the slope failure to develop a suitable remediation strategy. Activities included topographical and bathymetric surveys, pipeline surveys, borehole drilling using auger and bedrock coring techniques, and installation of instrumentation such as vibrating wire piezometers and slope inclinometers.

The selection of the borehole locations was a challenge due to the many on site constrains such as poor access for the drill rigs, safety concerns on the failed slope, and the presence of five active pipelines within the corridor. To gain critical subsurface information on the failed slope and within the river channel, geophysical surveys were also carried out such as seismic refraction imaging and multi-channel analysis of surface waves. By combining the results of the boreholes and instrumentation with the geophysical survey results, an interpretation of the failure mechanism was completed that allowed the remediation design and construction to proceed.

The remediation strategy consisted of addressing a weak toe condition, rebuilding the riverbank using imported fills, providing drainage within the remediated slope, and protecting the final remediated surface with a rip rap armor layer, topsoil and hydroseed, and erosion control blankets on the upper portion of the slope. The observational approach was successfully applied during the construction process so that confirmation of important design elements and changes to the design could be made quickly in the field by geotechnical personnel. Construction of the remediation was completed in the fall of 2016.

RÉSUMÉ
Un pipeline majeur traversant la rivière Souris dans le sud du Manitoba subissait une rupture de pente rétrograde dans les limites du corridor du pipeline. Une étude géotechnique a été réalisée pour évaluer les conditions souterraines dans la pente et le mécanisme de rupture de la pente afin de développer une stratégie de réparation appropriée. Les activités comprenaient des levés topographique et bathymétrique, des levés de pipelines, des forages utilisant des techniques de forage à la tarière et au roc, et l'installation d'instruments tels que des piézomètres à fil vibrant et des inclinomètres de pente.

La sélection des emplacements de forage était un défi en raison des nombreuses contraintes sur le site, comme un mauvais accès pour l'équipement de forage, des problèmes de sécurité sur la pente défaillante, et la présence de cinq pipelines actifs dans le corridor. Pour obtenir des informations critiques souterraines de la pente ratée et dans le chenal de la rivière, des levés géophysiques ont également été effectués, tels que l'imagerie de réfraction sismique et l'analyse multicanal des ondes de surface. En combinant les résultats des forages et de l'instrumentation avec les résultats de l'étude géophysique, une interprétation du mécanisme de défaillance a été réalisée, ce qui a permis la conception de réparation et la construction à procéder.

La stratégie de réparation consistait à réparer le pied de la pente, reconstruire la berge en utilisant des matériaux importés, assurer le drainage dans la pente et protéger la surface réparée finale avec une couche d'armure en enrochement, de la terre végétale et des couvertures hydrosolubles sur la partie supérieure de la pente. L'approche par observation a été appliquée avec succès au cours du processus de construction, de sorte que la confirmation des éléments de conception importants et des modifications à la conception pouvait être effectuée rapidement sur le terrain par le personnel géotechnique. La construction de réparation a été achevée à l'automne 2016.

Introduction

This case study involves the geotechnical assessment, design and construction to address a riverbank slope failure that occurred within a major active pipeline right of way (ROW) crossing of the Souris River in southern Manitoba, Canada. The site location, and a photo of the riverbank slope failure are shown on Figures 1 and 2.

Geotechnical investigations were completed by Stantec to assess the subsurface conditions and mechanism of the slope failure. Once the failure mechanism was understood then a suitable remediation strategy was developed. Geotechnical activities included review of background information, topographical and bathymetric surveys, pipeline surveys, borehole drilling using auger and bedrock coring techniques, and installation and monitoring of instrumentation including vibrating wire (VW) piezometers and slope inclinometers (SI's).

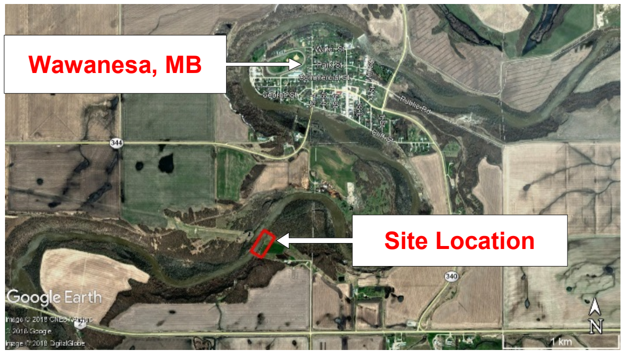

Figure 1. Site Location: Souris River pipeline crossing (North is up and river flow in a northerly direction)

Figure 2. Riverbank slope failure, January 2016
(East bank of Souris River looking north or downstream)

The selection of the borehole locations was a challenge due to the many on site constrains such as poor access for the drill rigs, safety concerns on the failed slope, and the presence of active pipelines within the corridor. To gain critical subsurface information within the failed riverbank slope and within the river channel, geophysical surveys including seismic refraction imaging and multi-channel analysis of surface waves were also carried out. By combining the results of the boreholes and instrumentation readings with the geophysical survey results, an interpretation of the failure mechanism was developed that allowed the remediation design and construction to proceed.

At the construction stage, there were several critical geotechnical unknowns that remained that needed to be confirmed during construction by geotechnical personnel. Since the project had full-time geotechnical presence during construction, an "observational approach" was used. The observational approach allowed several design modifications to occur in the field based on actual conditions observed during the construction process. A major construction challenge included the location of the slope failure within the river channel that required a significant temporary cofferdam structure to be erected so that the work could be carried out in the dry. The presence of active pipelines in and around the remediation works was also a challenge.

The remediation strategy consisted of addressing a weak toe condition, rebuilding the riverbank using imported fills, providing proper drainage within the remediated slope and protecting the final remediated surface with a rip rap armor layer below the design flood level together with erosion control blankets, topsoil and hydroseed on the upper slope. A permanent drainage swale was added at the top of the remediated slope to direct surface water to the river away from the remediated surfaces. Construction of the remediation was completed in the fall of 2016. Based on observations and instrumentation readings over 2017 and 2018, the remediation strategy is performing as designed.

Site Description

The existing ROW crosses the Souris River approximately 1.5 km south of the municipality of Wawanesa, Manitoba as shown on Figure 1. The ROW contains five active pipelines that were originally installed using the "open-cut method" of construction. The pipelines ranged from 508 mm to 914 mm in diameter and were installed at various times over the period from 1950 to 1998.

As shown on Figure 2, the slope failure occurred on the east bank of the Souris River within the ROW. Figure 3 shows a modeled cross-section through the center of the failure. Figure 3 also shows the location of a "low-density" area at the toe of the slope at the river edge that was identified by the geophysical survey as a "bedrock anomaly". As described in more detail below, this low-density area was identified as a weak toe condition and considered as a major contributing factor to the slope failure mechanism.

Geology, Terrain and Historical Air Photo Review

A geology, terrain and air photo review of the site and surrounding area was conducted by Stantec in 2014. Highlights from the review are presented below:

- A review of the background information showed the underlying bedrock is bentonitic shale of the Riding Mountain Formation (Halstead, 1960, Klassen et al. 1970).
- The regional surficial geology mapping identified alluvial sediments (sand, gravel, silt and clay) within the Souris River valley, a former meltwater channel, dissected into clay, silt and sand deposits of glacial Lake Aggasiz (Matile and Keller, 2004).
- Surficial deposits in the Wawanesa, MB area are known to consist predominantly of loam to silty clay loam lacustrine deposits, overlying glacial till at depths of approximately 1 to 3 m.
- Down-cutting and bank erosion specifically along meander bends of the Souris River has formed over-steepened banks, resulting in numerous large slope failures (relict and recent).

- It appeared that the cleared land to the south of the ROW and upslope to the east of the riverbank slope failure is on a large relict slope failure. This old regional slope failure appeared to be dormant, with no signs of recent activity.

Before the most recent slope failure event that occurred in 2010, the site had experienced at least two slope failure events (before 1947, prior to development of the pipeline crossing, and in 1999, following the installation of the last open cut pipeline). As of 2013, the riverbank slope failure had continued to retrogress upslope and extend across-slope, past the other pipelines. In 2016, the slope failure area appeared to have grown in horizontal extent and crossed all pipelines.

Subsurface Conditions

A total of ten (10) boreholes were drilled in 2014 and 2016. The locations of the boreholes were selected considering the proximity to the failure, the presence of active pipelines, and overall site access. The 2014 boreholes were drilled at the crest of the slope near the slope failure. The 2016 boreholes specifically targeted the areas in and around the slope failure. Borehole BH 16-01 was drilled at the top of the crest just outside of the failure, and BH16-02 was drilled mid-slope within the slope failure. A third borehole was also attempted at the toe of the slope in the area that was identified as a possible low-density area (bedrock anomaly) by the geophysical survey, but for safety reasons, this borehole was not drilled.

In general, the stratigraphic sequence encountered in the boreholes consisted of topsoil overlying fill over high plastic clay over discontinuous sand layers over clay till underlain by high plastic clay shale bedrock. The bedrock was typically weathered in the upper 0.5 m to 1 m and then became more competent with depth. The depth to the clay shale bedrock in the boreholes outside of the failure area varied from 4 m to 8 m below grade.

In general, groundwater levels measured from standpipes and VW piezometers varied from 2.9 m to 5 m below ground surface and several locations were dry. As stated below the highest groundwater level reading was within the slope failure at a depth of 2.9 m below grade.

Borehole BH16-02 was drilled to a depth of 9.7 m within the center and at mid-slope within the slope failure. The stratigraphic sequence encountered in BH16-02 consisted of 3.8 m of fill overlying clay shale bedrock. Figure 3 shows the approximate location of BH16-02.

Geotechnical Instrumentation

VW piezometers and SI casings were installed in selected boreholes. In BH16-01, located just outside of the slope failure, included an SI casing to a depth of 10.9 m and one VW piezometer at a depth of 3.1 m below grade.

In BH16-02, located within the slope failure, an SI casing was installed to full depth into the bedrock, and a VW piezometer installed at a depth of 3.8 m at the base of the drainage layer and at the overburden/bedrock transition.

The highest groundwater level measured in the piezometers was in March 2016 in BH16-02 at a depth of 2.9 m below grade (elevation 355.3 m).

Over the period from fall 2014 to spring 2016, lateral displacements measured in the 2014 boreholes ranged from 5 mm to 20 mm and the displacements were all within the overburden above the bedrock. In BH 16-02 mid-slope within the slope failure, lateral displacements were measured to be up to 35 mm over a period of four months in 2016. The lateral displacements were measured to be as deep as elevation 353.2 m, in the transition from overburden to bedrock as shown on Figure 4.

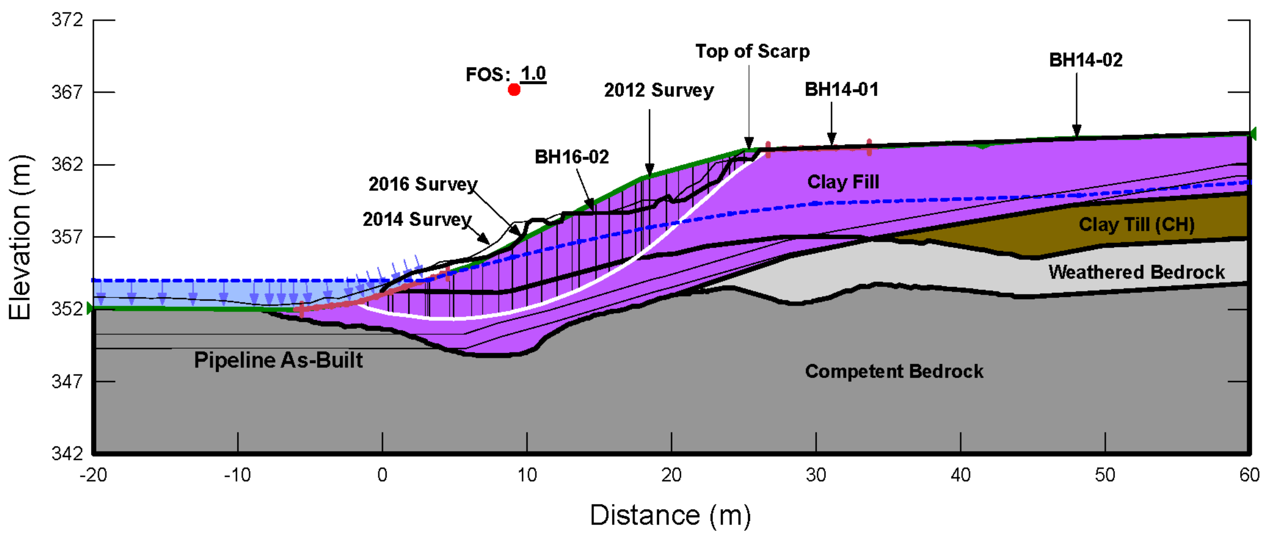

Figure 3. Cross-section through riverbank slope failure

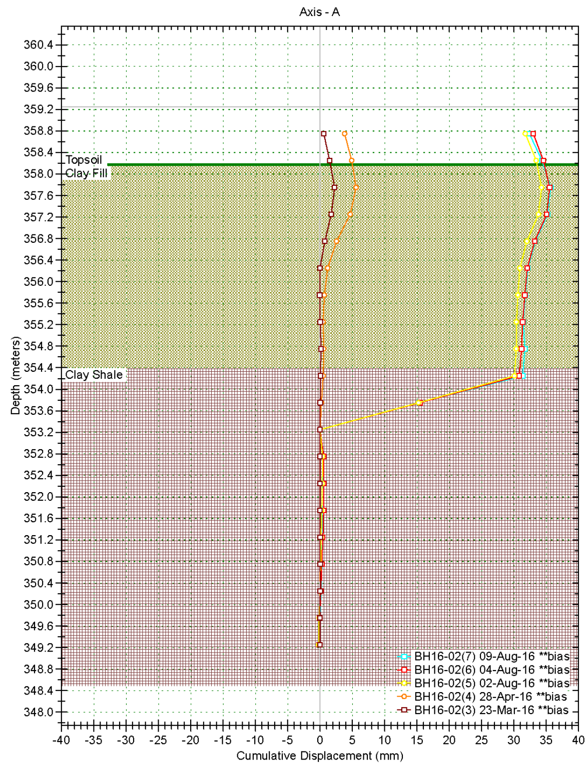

Figure 4. Cumulative lateral displacement data plotted with depth in BH-16-02.

Geophysical Survey

DMT Geosciences Ltd. (DMT) was subcontracted by Stantec in 2016 to undertake a geophysical survey at the site to assess the overburden/bedrock contact zone between boreholes and areas outside of the borehole locations. They also attempted to delineate the weathered bedrock and competent bedrock surfaces. A summary of the geophysical survey is provided below:

- There appeared to be good correlation between the borehole data and the geophysical survey results in terms of the overburden/bedrock contact elevations.
- The interpreted competent bedrock surface appeared to be consistent with the base of the pipeline trenches or the surface of "undisturbed bedrock". This competent bedrock or "undisturbed bedrock" surface was important because the riverbank slope failure movements appeared to be above this surface. The slope failure appeared to be sliding on the contact between the overburden/competent bedrock surface and/or the weathered bedrock/competent bedrock surface.
- A bedrock anomaly feature, consisting of an area with lower bedrock elevation, was identified at the toe of the riverbank slope failure as shown on Figure 5. This bedrock anomaly was a depressional feature of the bedrock surface at the toe of the slope. As described in more detail below, the anomaly appeared to be an area of possible bedrock disturbance by mechanical excavation during the installation of the 1998 pipeline.

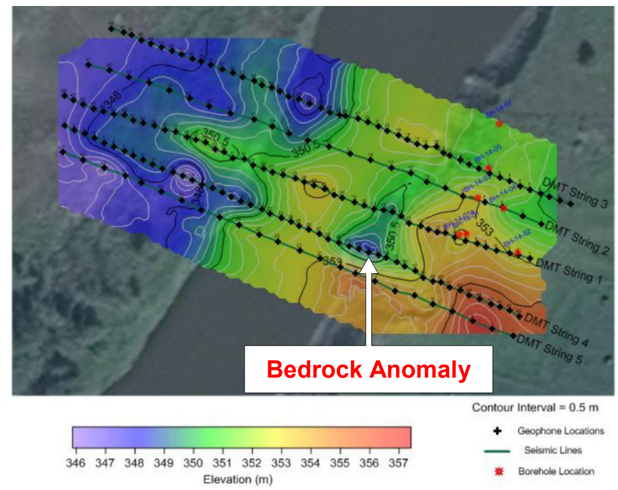

Figure 5. Interpreted competent bedrock surface from geophysical survey showing the "bedrock anomaly"

Background Review - Construction Photos

A review of several 1998/1999 pipeline construction photos showed the equipment and exposed soil and bedrock conditions during pipeline construction. These available construction photos provided additional information to help explain the possible presence of a low-density area at the toe of the slope and help explain the mechanism of the riverbank slope failure.

Based on the review of the 1998/1999 photos, Stantec was able to correlate the possible bedrock anomaly location identified in the 2016 geophysical survey with the location of the excavation of the pipeline trench. The area of the open cut trench at the toe of the slope also appeared to correlate well with the location of the slope failure that started in 1999 after installation of the pipeline.

The hypothesis is that the relatively deep excavation in the river channel as shown on Figure 6 resulted in removal of the natural bedrock toe support at this location. The bedrock removal by mechanical excavation may have resulted in a weak toe condition at this location. The bedrock excavation at the toe of the slope also appeared to have been relatively wide at the river edge. This weak condition at the toe of the slope may have been more susceptible to wash out and disturbance by the flow and energy of the river as compared to the surrounding bedrock. Also, there is indication that the failure slip plane is consistent with the elevation of the working platform on bedrock as shown on Figure 6. The above explanation is considered a major contributing factor to the riverbank slope failure. Also, there is indication of backfill placement in the winter during the original construction in 1998/1999, which can often be problematic for fine grained soils.

We understand that the riverbank slope was repaired in 1999 using perforated drains installed in the slope. We understand that the riverbank slope was inactive, with no apparent slope movements, over the period from 1999 to 2010. The slope failure was re-activated at the same location in 2010 and continued to retrogress until 2016. It is possible that the slope failure was re-activated in 2010 due to gradual river erosion of the toe combined with plugging of the drains.

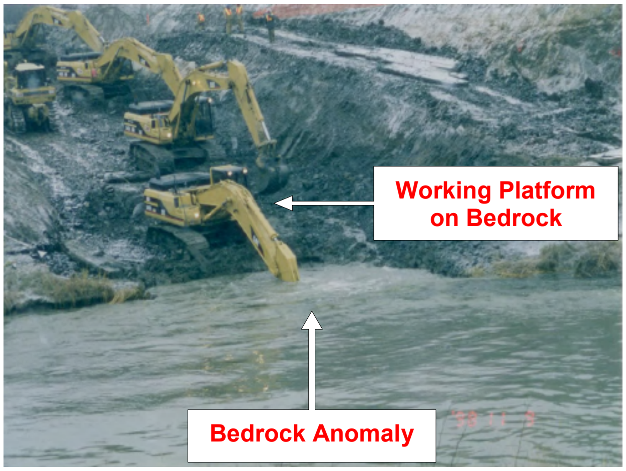

Figure 6. Construction of pipeline in 1998/1999 and possible bedrock anomaly

Slope Stability Analysis

Slope stability and seepage analysis were conducted using the available soil and bedrock information, groundwater information, topographical survey data, geophysical survey data, and as-built survey data of the most recent pipeline installation in 1998. The analyses were carried out using the commercial software Slope/W and Seep/W by GeoStudio. The Morgenstern-Price method was used for the slope stability analysis.

A traditional back analysis method was used to model the failure condition as shown in Figure 3. This back analysis was carried out to estimate the soil and bedrock strength parameters for a state of failure at a factor of safety of near unity. Based on the results of the back analysis, the effective strength soil parameters were assessed as shown in Table 1.

Table 1. Back Analyzed Effective Strength Soil Parameters

Material	Unit Weight (kN/m^3)	Effective Friction Angle (degrees)	Apparent Cohesion (kPa)
Clay Fill	19	24	2
Clay Till	19.5	25	5
Clay Shale (weathered)	20	25	5
Clay Shale (competent)	impenetrable		

For construction of the remediation, a minimum factor of safety of 1.3 was selected for the short-term condition of the excavation slopes using a total stress (undriened) analysis. Based on the analysis results a maximum slope angle of 2H:1V for the excavation slopes satisfied this criterion. For the final remediated slope, a minimum factor of safety of 1.5 was established for the long-term condition using effective stress (drained) analysis.

As stated above, the slip surface at the SI location installed in BH16-02 was measured to be in the general vicinity of the overburden/bedrock transition. The position of the circular slip surface is consistent with the analyzed slip surface as shown in Figure 3.

Mechanism of Slope Failure

The mechanism of the 2010 riverbank slope failure appeared to be due to a combination of the following factors:

- The apparent removal of the natural bedrock toe support by mechanical excavation during the pipeline installation in 1998/1999 is considered a major contributing factor to the slope failure mechanism. This removal of the bedrock toe support resulted in a weak toe condition that is consistent with the bedrock anomaly identified in the geophysical survey.
- The east riverbank slope is also located at the outside bend of a meander where there was no toe protection, so this is also considered to be a contributing factor to the slope failure mechanism. Lateral toe erosion has resulted in over-steepening of the east riverbank slopes.
- In 1998/1999, there is evidence that the slope was re-instated by placing and compacting fine grained soils in winter presumably in frozen conditions. Therefore, upon thawing in spring 1999, the fine-grained soils would have been in a potentially weakened condition, which may have also contributed to the slope failure.
- Rapid drawdown conditions within the riverbank slopes after a flooding event may have also been a contributing factor to the slope failure or it may have compounded an already weak slope condition.
- The surface drainage of the area upslope of the riverbank crest also appeared to be directed north and west towards the subject riverbank slope failure area. Once the slope failure started to occur in 2010, the additional surface water flow would have compounded the instabilities due to water entering tension cracks and saturation of the failed mass.

All evidence suggested that the slope failure was relatively shallow, and the slip surface was at the contact between the overburden/bedrock surface along the original working platform of the 1998/1999 pipeline construction as shown on Figure 6.

Remediation Design

Based on the results of the geotechnical assessment and slope stability analysis, Stantec developed a detailed design of the remediation strategy and developed Issued for Construction (IFC) drawings and technical specifications for the project. The overall remediation strategy included input from Stantec's geotechnical, hydrotechnical and civil engineering groups. In general, from a geotechnical perspective, the purpose of the remediation design was three (3) fold:

- Repair the slope failure area by removal of failed mass and replacement with engineered fill, and overall slope flattening to achieve a stable slope.
- Provide a minimum of 1.2 m depth of cover above the top of the pipelines.
- Provide proper erosion protection within the river channel using rock rip rap, and topsoil, hydroseed and erosion control blankets on the upper slope.

A typical cross-section showing the remediation design is shown on Figure 7. Other design highlights included:

- The final remediated/recontoured slope was constructed to 2.5H:1V.
- A 500 mm thick blanket stone drainage layer to drain any seepage down to the toe of the slope, where the drain becomes 700 mm thick.
- The requirement for on-going site review at strategic locations and various stages of construction by the geotechnical engineer using the “observational approach”. The observational approach was considered an important part of the design process, as several unknowns still remained regarding the subsurface conditions, especially at the toe of the slope, in the riverbed area, and surrounding the pipelines. Therefore, the various design assumptions needed to be confirmed in the field or changes made based on actual conditions observed during the construction process.
- It was unknown if the pipeline trenches below the temporary cofferdam would result in significant seepage.
- The geotechnical design assumed that all pipelines and pipeline bedding would be subject to site review to confirm the suitability of the backfill underlying and surrounding the pipelines.
- A geophysical survey and/or test pitting or probing program was planned to assess and further delineate the bedrock anomaly.
- The geotechnical design assumed a 600 mm separation between the blanket stone drain backfill and the outside of the pipelines. This 600 mm separation needed to be confirmed and possibly modified in the field based on the actual subsurface conditions and bedding conditions surrounding the pipelines.
- It was envisioned that the possible bedrock anomaly (i.e. lower density material) would consist of disturbed backfill and/or riverbed materials and/or sediment, which needed to be completely removed and replaced with a competent engineered material (i.e. fillcrete or granular fill)
- A temporary diversion berm and a permanent swale was included in the design to take collected surface water north of the remediated slope to a permanent rock rip rap swale to the river.
- A review of potential risks and the development of contingency plans to address these risks were completed as part of the design process in consultation with the owner, construction contactor, and geotechnical design engineer.

Construction Review and Observations

Stantec carried out Quality Assurance (QA) monitoring, materials testing and geotechnical review during construction of the riverbank remediation. The stages of construction and important observations that were made included:

- A temporary Portadam structure was erected and pumping of water from within the dam was established so that construction could be carried out in the dry as shown on Figure 8.
- Seepage through the existing open cut pipeline trenches below the dam was able to be controlled by traditional pumping methods.
- Removal of the failed mass using mechanical excavation was carried out down to competent materials. This removal included pre-sheared bedrock wedges down to competent bedrock as shown on Figure 9. Competent bedrock was found to be shallower in the slope and at the toe of the slope, as compared to the original design assumption.
- The original design assumed there was a high probability of a low-density infill referred to as the bedrock anomaly that had resulted in a weak toe condition. It was confirmed that the bedrock anomaly did in fact exist and consisted of a soft clay infill. The soft clay infill was removed and replaced with imported free draining granular materials wrapped in non-woven geotextile as shown on Figure 10. The bedrock anomaly crossed over two pipelines.

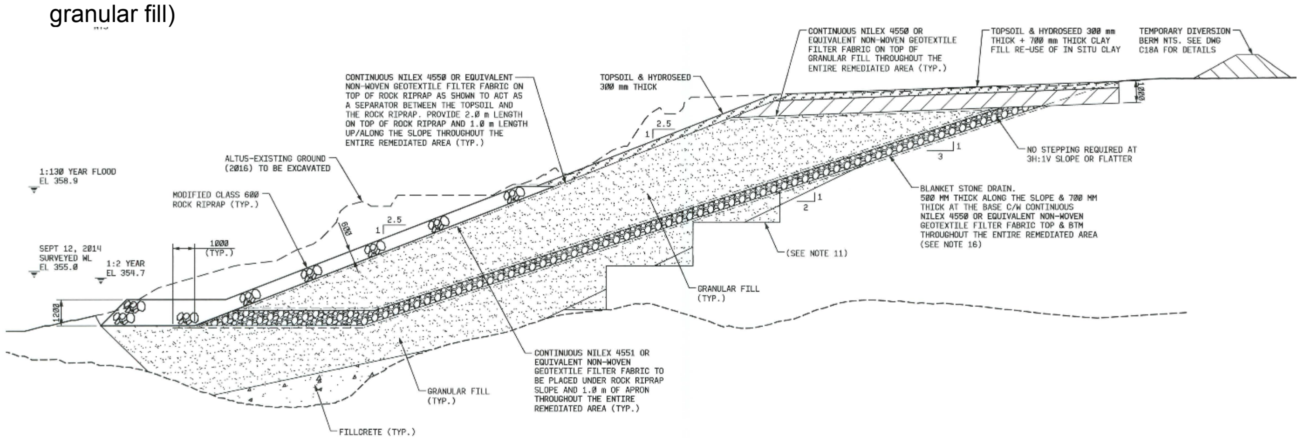

Figure 7: Typical section of remediation design

Figure 8. Temporary Portadam structure to allow the remediation to be carried out in the dry.

Figure 9. Removal of disturbed and pre-sheared bedrock down to competent bedrock using a tracked excavator.

- The existing geotechnical instrumentation was decommissioned.
- Due to the soft clay infill that extended into the river, a decision was made by the geotechnical engineer to extend the rock rip rap apron layer out into the river by an additional 3 m up to the inside edge of the Portadam.
- The use of geophysical survey techniques, as was originally planned, was not required because the soft clay infill was able to be removed using excavation techniques.
- It was observed that the slope failure was relatively shallow as the depth to competent bedrock was relatively shallow in the slope and at the river bottom. There was no indication that the slope failure slip plane intersected the pipelines.

Figure 10. Remote control compactor compacting granular backfill after removal of soft clay infill in the bedrock anomaly at the river bottom near the toe of the slope

- The conditions of the riverbed consisted of a relatively thin layer of gravel and sand overlying clay shale bedrock. The riverbed materials also consisted of flat platy gravel size particles along with sand and fine-grained materials.
- Based on observations from within the Portadam, there were no exposed pipelines identified.
- Base preparation below the proposed rock rip rap layer in the river channel assumed a competent subgrade condition. Base preparation consisted of removal of softened soils and softened clay shale bedrock down to competent bedrock followed by the placement of nonwoven geotextile followed by rip rap.
- A layer of non-woven geotextile was placed directly on the prepared subgrade followed by the placement of imported blanket stone drain materials. The drain materials were placed in 300 mm lifts and compacted with a minimum of 3 to 6 passes by a vibratory drum roller. The drain was fully wrapped with non-woven geotextile.
- Imported granular fill was placed and compacted in 300 mm thick lifts to 98 percent Standard Proctor maximum dry density, SPMDD (ASTM D698) over the drainage layer to the underside of the rip rap and topsoil layers.
- Local and imported clay fill was used for the clay cap layer at the top of the remediated slope. The clay fill was compacted using a sheep foot roller to a minimum 98 percent of the SPMDD.
- A 600 mm rip rap material was used for the riverbank armoring. A 200 mm rip rap material was used for the permanent swale at the top of the slope.
- Due to the large volumes of materials removed and replaced, as well as changes that were made during construction using the observational approach, it was important to maintain a detailed survey of the various layers, and 3D laser scans of the pre and post construction surfaces were developed as shown on Figures 11 and 12.

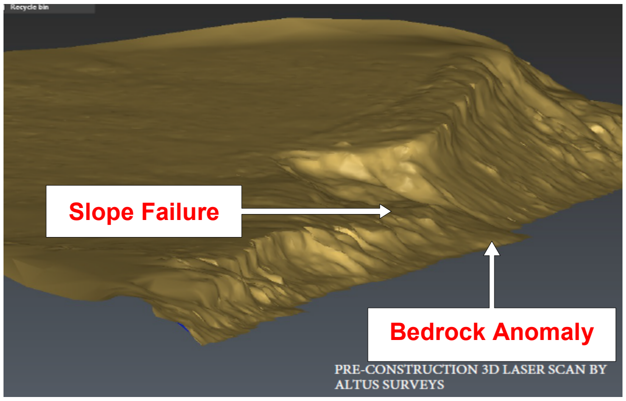

Figure 11. Pre-construction 3D laser scan showing site conditions and riverbank slope failure before remediation

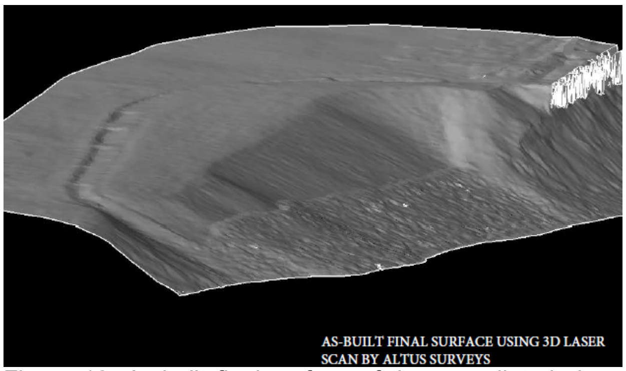

Figure 12. As-built final surface of the remediated slope using 3D laser scan

- An important design element included addressing surface erosion and minimizing overland flow by constructing a cutoff swale and directing the collected water to the river
- Erosion control on the final surfaces that were 2.5H:1V or flatter was accomplished using topsoil and hydroseed. On steeper slope sections especially at the transitions between the natural slopes and the remediated slopes, erosion control blankets as shown on Figure 12 were used in combination with topsoil and hydroseed to allow the vegetation to take hold.
- New geotechnical instrumentation was installed to monitor the performance of the remediated slope. An SI was installed into the competent bedrock. Two VW piezometers, one at the base of the drain and the second in the underlying bedrock were installed in BH16-03 at the location shown on Figure 13.
- Overall the design assumption concerning the mechanism of the slope failure was confirmed during construction of the remediation as there was in fact a soft clay infill surrounding a pipeline. The pipeline trench was also relatively wide at the toe of the slope and became narrower up the slope.
- Competent bedrock was found to be shallower in the slope and at the base of the river channel than what was assumed in the original design. Given that the design was based on the observational approach it was decided to not over-excavate competent bedrock in the slope to avoid disturbing the slope as much as possible given the proximity to active pipelines.

Figure 13. Final as-built remediated surface on November, 2016 (view looking north).

Stability Analysis of Remediated Slope

A slope stability analysis was carried out for several as-built cross-sections including a section through the zone of the bedrock anomaly as shown on Figure 14. The factor of safety for the remediated slope sections ranged from 1.5 to 1.8 and met the required factor of safety of 1.5 for the long-term condition.

Performance of Remediation Strategy

On March 28, 2018 Stantec returned to the site to observe the conditions across the remediated slope and to take SI and VW piezometer readings. As shown on Figure 15, the remediated slope is meeting the original design intent with no apparent erosion or slope instabilities observed.

Results of the VW wire piezometer instrumentation in the remediated slope on March 28, 2018 shows that the slope drain is in a dry condition. Unfortunately, the SI was frozen and lateral displacements were not able to be taken.

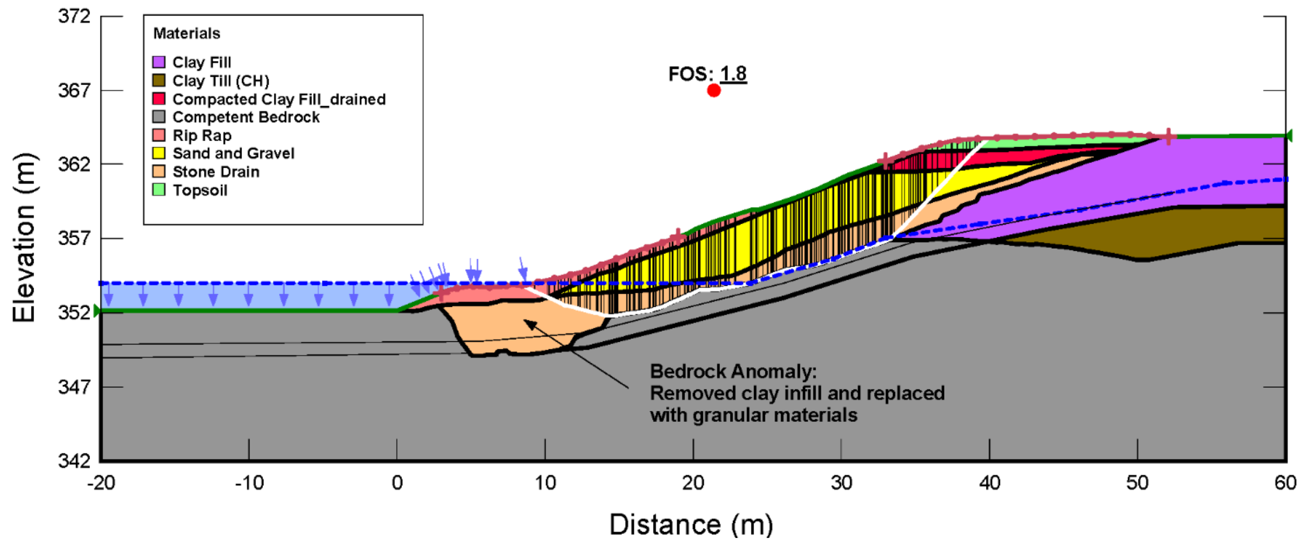

Figure 14. Slope stability analysis of the remediated slope.


Figure 15. Final Remediated Surface 16 months after construction, March 2018 (view looking north).

Conclusions

This case study reviewed the investigation methods, design details and construction process to remediate the failed riverbank slope. The following conclusions are made:

- The riverbank slope failure was successfully remediated over the fall 2016. The remediated slope appears to be performing and meeting the original design intent based on observations 16 months after construction.
- The use of traditional geotechnical borehole exploration and instrumentation combined with geophysical survey techniques was critical to understanding the failure mechanism of the riverbank slope. Once the failure mechanism was understood, the remediation design was able to proceed to construction even though several unknowns still existed.
- The authors cannot over emphasize the importance of the observational approach during construction that was applied for the project. This application was a very important element of the design given the many unknowns and risks that existed during the construction process. These design unknowns were identified/confirmed during construction and design changes were made in the field based on actual observations made by the pipeline owner, and the geotechnical engineer.
- Several design and construction contingencies were developed before construction began to address the unknowns and the potential risks that could be encountered during construction. Having these contingencies in place within the observational approach framework was also a critical and part of the design process.
- Having full-time support by geotechnical personnel during construction allowed the construction process to proceed and design decisions to be made quickly in the field during the construction process.

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