Variations in river level and their impact on slope stability at the Borden Bridge landslide

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ABSTRACT

Slope failures along the deeply incised river valleys are common throughout the prairies. These failures typically take the form of deep-seated, translational landslides that move predominately on either weak bentonite layers or pre-sheared Cretaceous shale bedrock layers. One of these landslides is at Borden Bridge, which is located on Highway No. 16 approximately 50 km west of Saskatoon. This paper presents a numerical evaluation of the potential role of the river level and the corresponding pore-water pressures within the clay shale on the rate of movement of the east bank of the Borden Bridge. Pore-water pressures and rates of movement modeled in the parametric analyses will be compared to those measured in the field. Though this work is preliminary, it will provide information regarding the role of river level fluctuations, the corresponding pore-water pressure response on the pre-sheared slide plane and the observed rate of movement of the Borden Bridge landslide.

RÉSUMÉ

Les ruptures de pente le long des vallées des rivières profondément incisées sont courantes dans toutes les Prairies. Ces défaillances prennent généralement la forme de glissements de translation profonds qui se déplacent principalement sur des couches de bentonite faibles ou sur des couches de substratum schisteux du Crétacé préchargées. L'un de ces glissements de terrain se trouve au pont Borden, qui est situé sur la route no 16, à environ 50 km à l'ouest de Saskatoon. Cet article présente une évaluation numérique du rôle potentiel du niveau de la rivière et des pressions interstitielles correspondantes dans le schiste argileux sur la vitesse de déplacement de la rive est du pont Borden. Les pressions interstitielles et les vitesses de déplacement modélisées dans les analyses paramétriques seront comparées à celles mesurées sur le terrain. Bien que ce travail soit préliminaire, il fournira de l'information sur le rôle des fluctuations du niveau de la rivière, la réponse de la pression interstitielle correspondante sur le plan de glissement pré-cisaillé et le taux de déplacement observé du glissement du pont Borden.

1 INTRODUCTION

Three bridges stand at the location where Highway No. 16 crosses the North Saskatchewan River near Borden, Saskatchewan. These three bridges have been constructed on historic landslide debris. The first bridge is a concrete bowstring arch bridge designed by C.J. Mackenzie. At the time of completion in 1937 it was one of the longest and last of its type constructed in Canada (Neufeld, 1984; Herrington, 2008). This bridge is now only open to foot traffic but widely recognized for its cultural significance and appealing design. To accommodate increasing vehicle size and traffic, two modern bridges have been constructed on the site. The second bridge was constructed approximately 70 m downstream of the first bridge in 1985. The second bridge currently hosts the west-bound traffic of Highway No. 16. The third and final bridge was constructed between the two previous bridges in 1997 and currently accommodates east-bound traffic. The bridges are shown below in Figure 1.

The landslide movement being considered within this paper is restricted to the east abutment. The west abutment is founded on a deep deposit of alluvial sand, and is considered stable.

The North Saskatchewan River Valley was formed during the Wisconsinan deglaciation. As glaciers retreated north-eastward, the channel was eroded as a spillway that flowed into Glacial Lake Saskatchewan approximately 12,000 years ago (Christiansen, 1979). In the years since deglaciation, the river valley has been further eroded and North Saskatchewan River Alluvium has been deposited. Radiocarbon dating of the alluvium at the Borden Bridges has been dated to between 2915 and 900 years before present (Christiansen, 1983).

A surficial cut through glacial till accommodates the approach through the east abutment. It has been widely reported that eastern valley walls in Saskatchewan host numerous retrogressive landslides (Haug et al., 1977; Clifton et al., 1981; Eckel, 1985). Eastern valley walls are host to such landslides due to the direction of glacial thrust. The site of the Borden Bridge is no exception, with landslides extending kilometers up and downstream from the site. Movement near the bridges is typical to that of a multiple retrogressive landslide. Such landslides frequently occur due to the rapid downcutting during and following deglaciation (Eckel, 1985).

During construction of the bridges toe berms were pushed into the river. The construction of the initial bridge involved narrowing the channel to reduce bridge length. While the berms placed during construction of the 1985 and 1997 structures were done in an effort to increase the factor of safety against instability (Panesar et al., 2014).

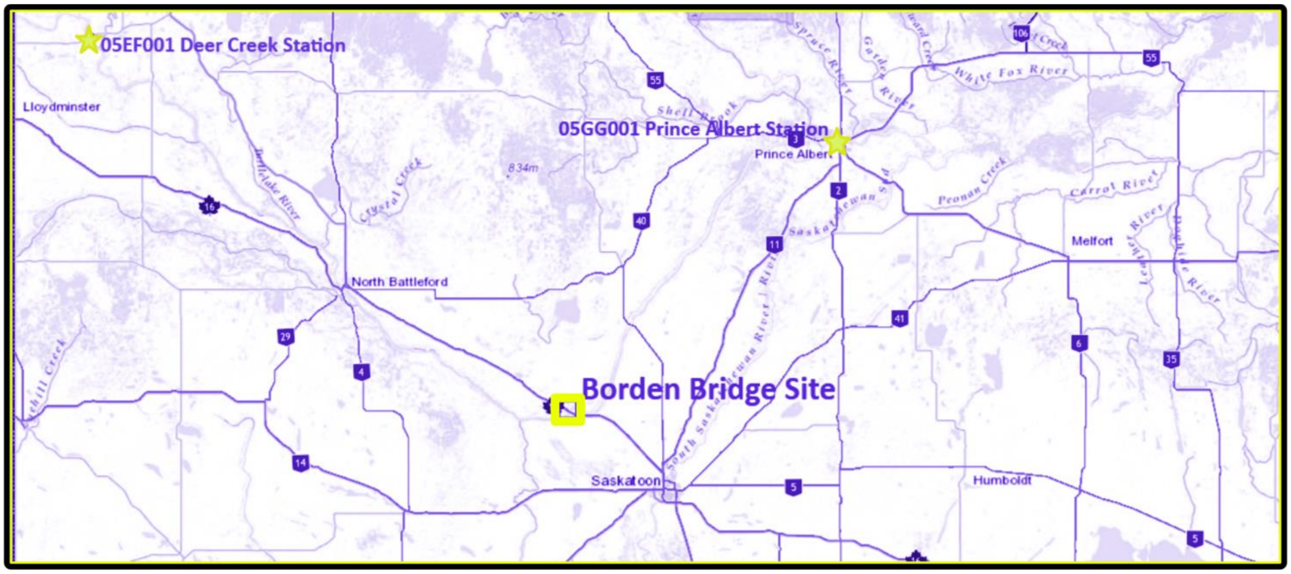

Figure 1. Location of study site and hydrometric stations nearby on the North Saskatchewan River (modified from Saskatchewan Ministry of Environment Sask Interactive Mapping, 2018)

However, it has recently been noted that erosion of the toe is occurring beneath the 1937 and 1997 bridges. Erosion beneath the east bound bridge between 1995 and 2013 has been measured from topographic and bathymetry surveys to be 6.2 m (Clifton Associates, 2014; Panesar et al., 2014). Toe erosion is a strong influencing factor in multiple retrogressive landslides (Sauer and Christiansen, 1987).

The Borden Bridge landslide is moving in a zone of high plasticity clay shales. This zone is a near horizontal surface, which is common to each of the blocks of the landslide. The Cretaceous shale underlying the Borden Bridge is contains highly smectitic layers created by volcanic ash deposits and consists of the Judith River Formation and the Lea Park Formation shales. These shales are a major factor in the extensive landslide topography of the region. The disturbed shale that composes the historic landslide debris at the Borden Bridges site has low strength properties and has been shown to exhibit residual behaviour (Clifton et al., 1995).

Increased rates of movement have been observed in the past ten years, and thus there is increased risk for the infrastructure at Borden Bridges. Highway No. 16 is a Trans-Canada highway, and is a critical transportation route for goods across the country. Identifying the triggering factors of movement at this landslide will better inform the Saskatchewan Ministry of Highways and Infrastructure during their risk analysis of the site. This study aims at identifying the impact that river level variations have on the movement of this landslide.

2 METHODOLOGY

The purpose of this paper will be to review and compile previous work carried out at the Borden Bridge site. The data will then be used to develop a series of Limit Equilibrium Analyses (LEA) to evaluate the role of the river stage on the subsurface pore-water pressure regime and the overall stability of the east bank of the Borden Bridge approaches.

The methodology for this study consisted of the following:

- synthesis of historic data collected during previous investigations of the Borden Bridges;
- review of regional geology and site characterization of similar sites;
- limit equilibrium analysis of the previously identified critical section to confirm soil strength properties;
- interpolation of river flow rate data from Deer Creek and Prince Albert; and
- finite element analysis of critical cross section with river fluctuation.

3 SITE HISTORY

The volume of previous geotechnical investigations at the Borden Bridge site has been significant. Numerous testholes have been advanced at the site, with upwards of one hundred holes drilled. Most of the investigations at the site of the Borden Bridges have been completed prior to and during the construction phases for each of the three structures.

The site of the initial Borden Bridge was constructed in the 1930's as a replacement to the Ceepee ferry, providing an integral link northwest to Edmonton. Herrington (2008) discusses the cultural significance of the 1937 bridge. Constructed as a part of a social program during The Great Depression it provided much needed income to area residents; it was on the basis of increased need for labour that the concrete structure was chosen over a steel structure. Wilson et al. (1989) discusses the 17 testholes completed by the Saskatchewan Department of Highways in early 1934 followed by 12 additional testholes drilled by the Department of Public Works of Canada during the summer of 1935. Despite the 29 testholes completed, there is no indication that the initial designers were aware the bridge was constructed on landslide debris (Wilson et al., 1989). Documents pertaining directly to the construction of the initial 1937 bridge were not available for this study. An improved alignment of the east approach was constructed in 1967. The fill placed in this realignment was found to not significantly impact the overall stability of the east abutment (Clifton Associates, 1982). By all accounts and documents the performance and stability of this bridge upon inspection was satisfactory until at least 1989 (Wilson et al., 1989).

It was during the investigations prior to the construction of the second bridge that the existence of subsurface landslide debris at the site was noted (Clifton Associates, 1982). Wilson et al. (1989) reported 70 test holes completed between August 1982 and July 1983 in preparation for the design and construction of the second bridge. Investigations were also carried out during the planning for the third bridge. Clifton Associates (1995) reported 17 testholes completed in 1994 and 13 completed in 1995 subsequent to the preparation of the geotechnical analysis for the third bridge. Comprehensive testing and analyses were carried out as part of these drilling programs. Routine testing and classification of samples as well as specialized testing including direct shear, triaxial shear, and consolidation tests were carried out on samples recovered from the drilling programs (Clifton Associates, 1983; Clifton Associates, 1995; and Wilson et al., 1989).

More recently a slope stability assessment was carried out by Clifton Associates in 2014. This report identified a critical cross section along the maximum displacement direction. It also identified that increased slope movement was observed with a general increase in piezometric heads between 0.4 m and 0.8 m, with a generally increasing trend since 2008 (Clifton Associates, 2014).

4 SITE GEOLOGY

4.1 Regional Geomorphology

The Borden Bridges are located within the Saskatchewan Rivers Plain. Typical landforms in the area include gently undulating and rolling till plains (Ellis and Clayton, 1970). The relief of the North Saskatchewan River Valley at the site of the Borden Bridges is approximately 50 m on the east slope. The North Saskatchewan River is a braided stream with shifting sandbars (Christiansen, 1983). The braiding and sandbars can be seen in Figure 2.

Multiple glaciations are responsible for the landforms in the region of the Borden Bridges. During the last deglaciation, approximately 12,000 years ago, the North Saskatchewan River Valley was incised into the glacial sediments and bedrock of the area (Christiansen, 1979). Entrapment of glacial melt water between the Eagle Hills Escarpment and the retreating glacier formed the valley in this region (Christiansen, 1983). The relatively shallow slope of the valley at this site, generally less than 10(H):1(V), is an indication of slumping of the valley walls (Clifton Associates, 1983). Such slumping has occurred as the levels of flow within the spillway dropped from those experienced during deglaciation.

Figure 2. Aerial image of Borden Bridge site and landforms (after Panesar et al., 2014)

4.2 Regional/Local Geology

The Cretaceous bedrock of the Lea Park Formation at the Borden Bridges is overlain by disturbed shale bedrock of the Judith River Formation and Quaternary glacial deposits of varying thickness, as well as postglacial surficial stratified drift (including North Saskatchewan River Alluvium). The glacial drift encountered at this site consists of Battleford Formation, Floral Formation, and Sutherland Group tills (Clifton Associates, 1995). As reported by Clifton Associates, the drift encountered near the two modern bridges riverward of the historic slump block is highly disturbed and variable. This disturbed till is colluvial in nature characterized by inclusions of softened shale, sand, gravel, boulders as well as wet and soft zones (Clifton Associates, 1983). The drift encountered near the abutment of the original bridge was noted as being very hard and less disturbed than that encountered further downstream. The Battleford Till at this site is very thin and oxidized. Christiansen (1968) described the Battleford Till, including the boulder pavement that is found beneath the unit. Locally, historic landslide debris, in the form of disturbed and brecciated clay shale overlies intact shales. The disturbed shale is characterized with slickensides, fractures, and interbedding of silt and sand. Within the river bed, a variable thickness of alluvial sand was deposited near the surface (Clifton Associates, 1995). The stratigraphy of the site can be characterized into five distinct units from the base unit to the ground surface as follows (Clifton Associates, 1995; Wilson et al., 1989):

- Sandy Clay Shale (Lea Park Formation);
- High Plasticity Clay Shale (Lea Park Formation);
- Disturbed Shale (Judith River Formation);
- Glacial Drift (Glacial Deposits); and
- Alluvial Sands (Postglacial Deposits).

4.3 Bedrock Geology

The bedrock underlying the glacial drift consists of two formations of the Upper Cretaceous period. The Lea Park Formation is overlain conformably by the Judith River Formation. As reported by Clifton Associates and Christiansen in studies of the region, The Lea Park Formation is marked by a high montmorillonite clay content, and high liquid limit. The Lea Park formation has an increasing sand content near its contact with the Judith River Formation. While the Judith River formation is marked by the interbedding of very fine to medium grained sand, silty sand, and sandstone. The Judith River Formation comprises the disturbed shale encountered at the Borden Bridges while the shear zone exists within Lea Park Formation (Christiansen, 1983; and Clifton Associates, 1995).

5 INSTRUMENTATION RECORD

Various instrumentation including piezometers and slope inclinometers have been installed and monitored since the 1980's. Additional instrumentation was installed in the fall of 2014 to replace some aged and sheared off instrumentation as well as increase coverage in areas of data gaps on the east abutment. In the fall of 2017, a weather station was installed on site to record barometric pressures, precipitation, wind, and temperature fluctuations.

5.1 Slope Inclinometers

Slope inclinometers have been utilized to determine the location of the slip surface at the site. The slip surface has been observed in the high plasticity clay shale between elevations 412 m and 415 m. Details about the slope inclinometers are provided in Table 1. Currently, monitoring of the slope inclinometers is completed twice a year.

Table 1. Landslide slip surface location

Slope Inclinometer Number	Elevation of Slip Surface (m)	Depth of Slip Surface (m)
SI002	412	37.0
SI003	414	41.0
SI004	413	35.5
SI006	414	36.5
SI007	413	36.5
SI008	415	35.0
SI501	412	33.0
SI502	413	33.0
SI504	413	45.0

[1]SI503, SI505, and SI506 currently do not show reliable data or apparent movement

5.2 Vibrating Wire Piezometers

Piezometer technology at the site has varied over the years. During the 2014 instrumentation program, six sets of vibrating wire piezometers were installed. Each set consists of three piezometers with varying tip elevations. An additional piezometer was installed adjacent to BH501 in September 2017. The intended use of this piezometer was to provide data on the river level. The instrument was installed in a test pit hydraulically connected to the river. Details of the piezometers are listed below in Table 2 and illustrated in Figure 3.

Figure 3. Layout of recent piezometers on east abutment

Table 2. Piezometer location and tip elevations

Piezometer Number	Location on Slope	Ground Elevation (m)	Tip Elevation (m)
PZ501-A	Toe	446.56	415.76
PZ501-B	Toe	446.56	421.86
PZ501-C	Toe	446.56	431.06
PZRiver	Toe	446.56	442.80
PZ502-A	Toe	446.33	407.03
PZ502-B	Toe	446.33	412.23
PZ502-C	Toe	446.33	431.43
PZ503-A	Middle	457.96	406.76
PZ503-B	Middle	457.96	410.76
PZ503-C	Middle	457.96	443.66
PZ504-A	Middle	458.31	408.01
PZ504-B	Middle	458.31	415.01
PZ504-C	Middle	458.31	451.61
PZ505-A	Upper	461.52	408.52
PZ505-B	Upper	461.52	428.32
PZ505-C	Upper	461.52	448.12
PZ506-A	Toe	449.66	412.61
PZ506-B	Toe	449.66	419.46
PZ506-C	Toe	449.66	443.56

[1]elevations reported as metres above sea level

5.3 Weather Station

The weather station has recently been installed at the site to best illustrate the local conditions. Prior to the installation of this instrument, weather data from Saskatoon had to be utilized in analysis. The weather station will allow a more accurate understanding of conditions at the site. Increased accuracy of rainfall data will also allow a comparison of pore-water pressures with the precipitation events in real time and the influence such weather events have on the river level.

5.4 Hydrometric Monitoring

A vibrating wire piezometer was installed in a hydraulically connected test pit to the river in the fall of 2017 to monitor river levels. Prior to this, Government of Canada Hydrometric Stations along the North Saskatchewan River on either side of the Borden Bridges at Deer Creek (05EF001) and Prince Albert (05GG001) may be used to interpolate river level values. There was a brief period of manual river level monitoring at the Borden Bridge site in the 1950's.

It can be shown that there is an approximate lag of five days between flows seen at Deer Creek and Prince Albert. Figure 4 below illustrates recorded flows at the two stations as well as the adjusted Prince Albert flow. The adjusted Prince Albert flow illustrates Prince Albert flows set back five days in time. Flows at Borden then can be estimated at a three day lag following flows at Deer Creek. The Borden Bridges are located at approximately three fifths of the flow path between Deer Creek and Prince Albert along the North Saskatchewan River Valley. Small variances in the flow rate between the two stations may be attributed to the varying terrain and precipitation events.

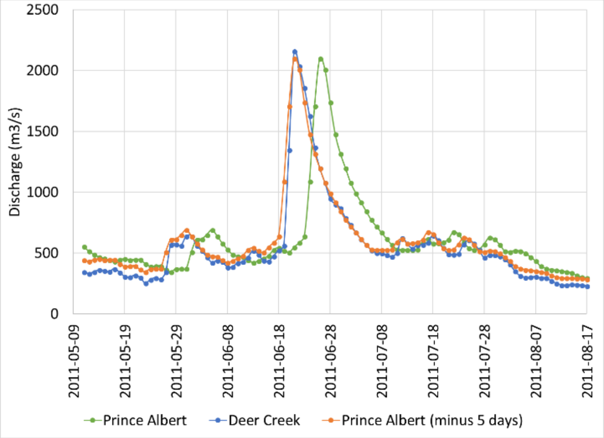

Figure 4. Measured flow rates at Prince Albert and Deer Creek Stations and adjusted Prince Albert flows to illustrate the lag between peak flows at the stations. (data from Environment and Climate Change Canada Historical Hydrometric Data)

The newly installed piezometer adjacent to the river, described above in Section 5.2, has only monitored winter conditions. Winter conditions pose challenges in water level monitoring due to freezing effects. Additionally, winter flow conditions often do not experience the variation seen during spring runoff or major precipitation events. Once such events have been recorded, river levels at Borden can be more accurately correlated to river levels at Prince Albert and Deer Creek. The available historical hydrometric data then can be modeled against the pore-water pressures and slope movements observed at the Borden Bridge site. Available river level piezometer and precipitation records are provided in Figure 5.

Piezometric readings from PZ501, precipitation record, and the PZRiver readings between fall 2017 and spring 2018 are combined in Figure 6 below. There is no visible indication that river level is impacting groundwater levels. However, the period of data available is through the winter months. During the majority of this period the ground surface and river level would have likely been frozen.

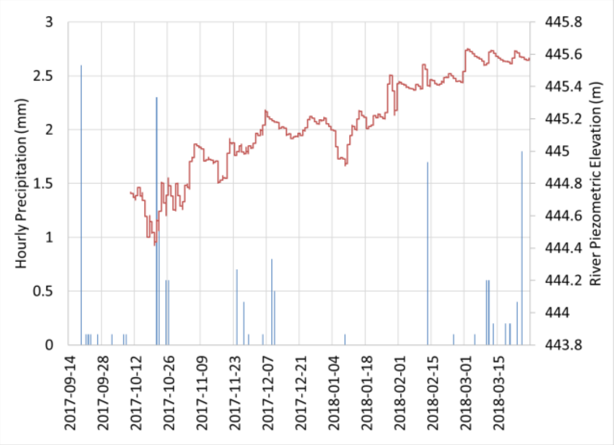

Figure 5. Precipitation and river level readings (from PZRiver) from fall 2017 to spring 2018

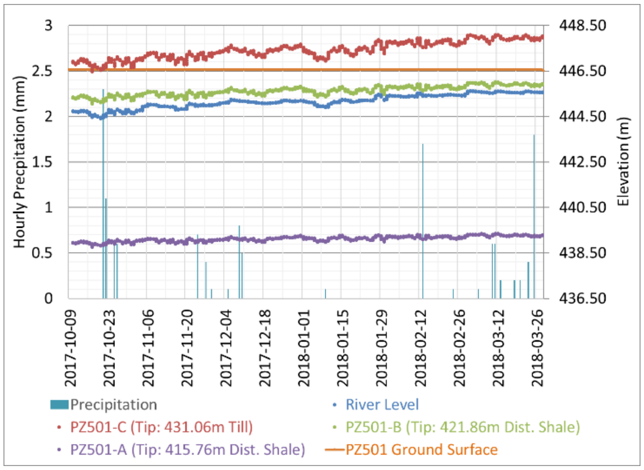

Figure 6. Piezometric readings near toe of slope with hourly precipitation and river levels read from PZRiver from fall 2017 to spring 2018

6 MODELLING

6.1 Historical Models

The stability of the Borden Bridges has historically been modelled utilizing the limit equilibrium method. In practice, the limit equilibrium method is the most common form of analysis. The limit equilibrium method is a static analysis of the stability of the slope. The current study has been completed with numerical modelling software using the limit equilibrium method for slope stability and finite element analysis for groundwater conditions.

The first available stability analysis was completed by Clifton Associates for the Saskatchewan Department of

Highways in 1982, as part of the preliminary geotechnical analysis of the site. This was followed by further investigation and analyses in 1983 in preparation for construction of the 1985 bridge. The existence of a shear zone at the high plasticity contact between the disturbed Judith River Formation Shale and the intact Lea Park Shale was recognized and identified as the most likely shear surface in these analyses. Conditions prior to construction of the 1985 bridge indicated a critical factor of safety of 1.02 with construction of the new grade line expected to increase this to 1.35. In this analysis an increase in piezometric head by 5 m was shown to only decrease the factor of safety by 9%, thus the slope was considered to be not sensitive to piezometric variations (Clifton Associates, 1983).

Another back analysis was completed in 1995 in preparation for construction of the third bridge. Numerical methods were used in this analysis. The design shear plane parameters were reported by Clifton Associates (1995) as ϕ’ of 6.5° and c’ of 2 kPa at limit equilibrium.

Following several years of increased precipitation and movement observed at the Borden Bridge landslide, another stability analysis was carried out in 2014. This analysis identified a critical cross section in the direction of observed movement north-west cutting across the bridge alignments. This analysis reported reduced shear strength parameters from the 1995 analysis to ϕ ’ of 5.4° and c’ of 0 kPa. Strength parameters of the disturbed shale unit were also reported to be reduced (Clifton Associates, 2014; Panesar et al., 2014). This reduction in strength parameters in the most recent back analysis was suggested to be due to multiple factors. Clifton Associates (2014) suggested these factors as updated topography and bathymetry, the 1997 alignment shifted location, increase in piezometric head, reduced shear strength values obtained from back analysis, and optimization techniques used by the more recent software.

6.2 Method of Analysis

SLOPE/W and SEEP/W programs by GEOSLOPE International Ltd. were used for this study. An initial slope stability analysis was carried out utilizing SLOPE/W to locate a critical slip surface. SEEP/W was then used to analyze time steps of varying river levels. This seepage analysis was then utilized as the parent piezometric condition for a second SLOPE/W analysis along the critical slip. The stability analysis used the Morgenstern-Price method of analysis with a half-sine side force function. Mohr-Coulomb material models were applied to all materials, with the input properties listed in Table 3. Block specified analysis was utilized to best describe the translational failure that is observed at the Borden Bridges. The slip surface was optimized by the software program to a more realistic slip surface.

The volumetric water content functions and hydraulic conductivity functions have been estimated for this preliminary analysis. Isotropic flow conditions were also assumed.

6.3 Material Properties

Translational failure in weak clay shales is common to the Saskatchewan River Valleys. Material properties obtained from laboratory and back analyses reported for similar slides including the Maymont, Denholm, and Petrofka slides have been assembled. The data from the other sites in similar geological settings were used in addition to the previously back-analyzed values and laboratory results from the Borden Bridge site. Table 3 outlines the material parameters used in this analysis.

Table 3. Analysis material properties

Material	Unit Weight, γ (kN/m^3)	Cohesion, c’ (kPa)	Effective Friction Angle, ϕ’ (°)	Saturated Hydraulic Conductivity, K (m/s)
Alluvial Sand	19.4	0	30	4 x10^{-3}
Disturbed Shale	19.8	4	8.7	10^{-9}
High Plasticity Clay Shale	19.9	0	5.5	10^{-9}
Sandy Clay Shale	20	10	35	10^{-9}
Till	21.8	7	25	10^{-10}

6.4 Hydraulic Conditions

Average readings between 2014 and 2018 for piezometers PZ505, PZ504, PZ502, and PZ501 were incorporated in the numerical models.

River level variations were incorporated into a seepage model utilizing a changing head boundary condition along the river basin.

6.5 Stratigraphic Profile

The cross section was taken, similar to that of Clifton Associates (2014) analysis in the direction of observed movement. The profile is shown below in Figure 7.

6.6 Modelling Results

6.6.1 Stability Model Results

The results of the stability analysis indicated that the landslide at the Borden Bridges had a low factor of safety equal to approximately 1.06. This agrees with the observed movements in the slope inclinometers. The optimized slip surface of the landslide is shown in Figure 8. This model used a river level elevation of 443.05 m, from September 2011.

6.6.2 River Level and Pore-water Pressure Comparison

Observed river levels and pore-water pressure conditions along the slip surface were compared. One comparison is shown above in Figure 6. Currently there is no clear pattern between river level increases and pore-water pressures

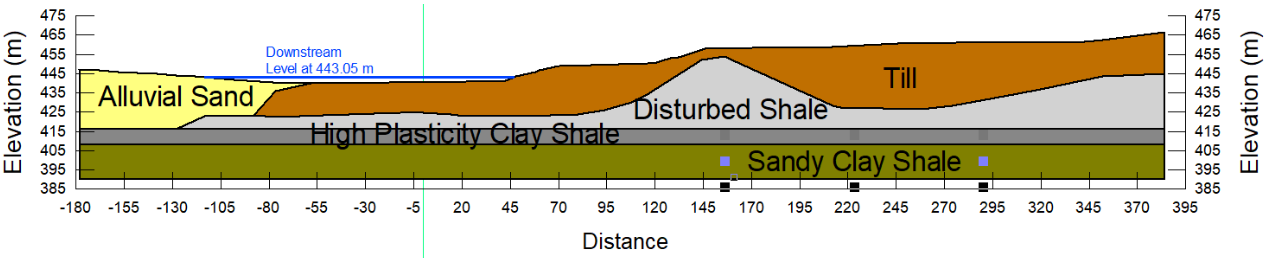

Figure 7. Stratigraphic cross section utilized in finite element analysis

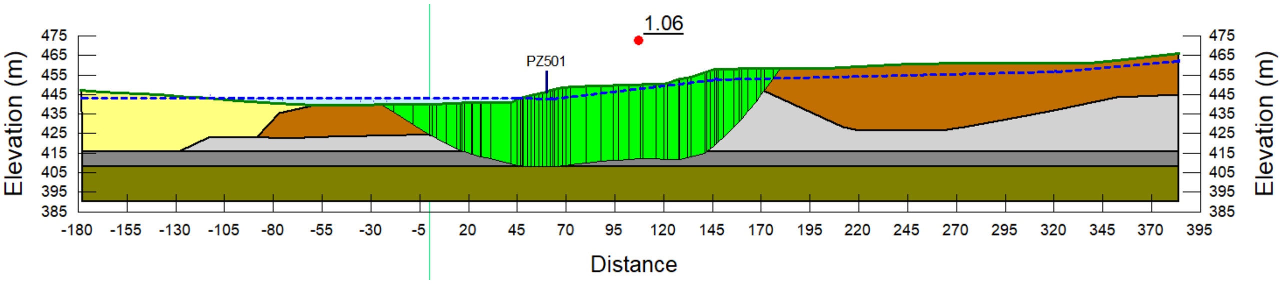

Figure 8. Optimized slip surface with a factor of safety of 1.06

measured along the slip surface. This may be due to the river level records consisting almost exclusively of winter flow levels and the associated freezing effects of the season.

6.6.3 River Level and Factor of Safety Analysis

The river level data from PZRiver was utilized in a stepped seepage analysis with the resulting pore-water pressures used in a stability analysis. The results from this analysis are shown in Figure 9. It is indicated that the factor of safety of the slope is significantly influenced by river level variations. The pore-water pressure response to variations in river level indicated that the till unit responded rapidly to changes, while all underlying shales responded only to large variations and not immediately.

The results of this analysis are preliminary, as the available data was during freezing periods and do not illustrate extreme flows that may be experienced during runoff and extreme precipitation events.

To illustrate potential extreme river level fluctuations, a second analysis was carried out. This analysis utilized river level data from the Prince Albert hydrometric station. It was assumed that Borden would experience the flows two days prior to that of Prince Albert. River elevations for this analysis were calculated based on the river elevation at Prince Albert on September 3, 2011. On September 1, 2011 a survey was carried out at the Borden Bridges where river elevation is known. A change in the Prince Albert levels between that date and the following dates was applied to the known elevation at the study site to provide river level estimates. Utilizing this estimation, river levels between 2012 and 2015 had a minimum and maximum elevations of 441.212 m and 446.696 m. The results of this estimated analysis is provided in Figure 10. Once the river level falls below an elevation of 443.0 masl, the factor of safety drops to 1.

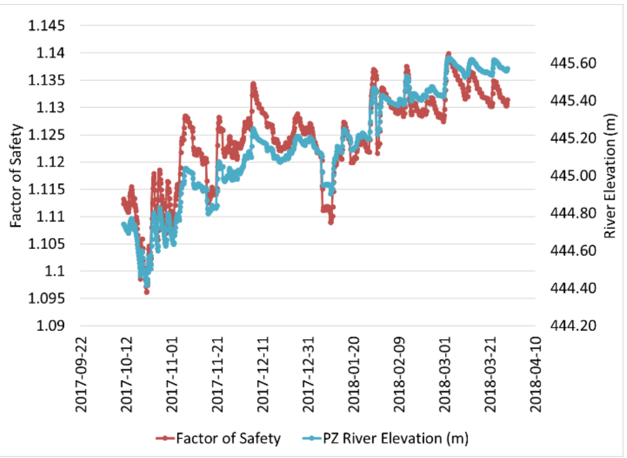

Figure 9. River level variations and associated critical slip surface factor of safety.

Figure 10. Estimated river level variations and associated critical slip surface factor of safety (null readings omitted)

7 CONCLUSIONS

This paper provides a starting point for the analysis of slope stability with respect to observed river level variations at the Borden Bridges. River levels are shown to impact the factor of safety of the slope. The influence of river level variation on pore-water pressures experienced in the shear zone have yet to be confirmed. However, this work is only preliminary. As data regarding spring and summer flow levels becomes available further analyses will be completed. Recommendations for future work include:

- Installation of a river level piezometer located in the alluvial sand along the west embankment to ensure the piezometric levels reflect river level;
- Analyze the impact of spring run off and summer precipitation event river fluctuations on the pore-water pressures experienced in the slope and the stability of the slope;
- Analyze the impact of dry year, low river levels, on the stability of the Borden Bridges;
- Utilize river level piezometer data at Borden to calibrate historical records at Deer Creek and Prince Albert for interpolation of historic river levels;
- Increase monitoring frequency for slope inclinometers and analyze rate of movement with respect to river level fluctuations; and
- Analyze potential strain softening of the shear zone caused by river level fluctuations.

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