Real-time Monitoring of Soil Water Content and Suction within a Slow Moving Landslide

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ABSTRACT
Loss of matric suction in the head scarp has the potential to trigger increased movement in metastable landslides. Measurements taken from in-place dielectric permittivity sensors installed in the head scarp and within the slide mass are analyzed based on temporal trends combined with weather station and displacement monitoring data. Fluctuations in the groundwater table due to changes in the river stage are considered in conjunction with changes in near surface matric suction. Determination of water content in the vadose zone is further correlated with the application of electrical resistivity tomography (ERT) to provide redundancy and develop a representative in-situ soil water characteristic curve for an active landslide. The research site, known as the Ripley Slide, is located about 8 kilometers south of Ashcroft, British Columbia and impacts this major railway corridor for both CP and CN along one of the busiest transportation routes in North America.

RÉSUMÉ
La perte d'aspiration matricielle dans l'escarpement de la tête a le potentiel de déclencher un mouvement accru dans les glissements de terrain métastables. Les mesures prises à partir des capteurs de permittivité diélectrique installés sur place dans l'escarpement de la tête et à l'intérieur de la masse coulissante sont analysées en fonction des tendances temporelles à partir des données de surveillance de la station météorologique et du déplacement. Les fluctuations de la nappe phréatique dues aux changements du niveau de la rivière sont considérées conjointement avec les changements dans la succion matricielle près de la surface. La détermination de la teneur en eau dans la zone vadose est en outre corrélée avec l'application de la tomographie par résistivité électrique (TRE) pour fournir une redondance et développer une courbe représentative de l'eau du sol in situ pour un glissement de terrain actif. Le site de recherche, connu sous le nom de Ripley Slide, est situé à environ 8 kilomètres au sud d'Ashcroft, en Colombie-Britannique et menace cet important corridor ferroviaire pour le CP et le CN le long d'une des voies de transport les plus achalandées en Amérique du Nord.

1 INTRODUCTION

The Thompson River valley south of Ashcroft, British Columbia serves as a major rail corridor for both of Canada's primary rail operators. The right of way for both Canadian Pacific (CP) and Canadian National (CN) traverses the Thompson River valley to create the vital link between sea ports on the west coast and the rest of Canada. The route is one of the heaviest trafficked rail corridors with up to 80 trains each day with some reaching 4.3 km in length. Steep valley walls along part of the Thompson River necessitate both rail companies share the corridor. The valley, comprised of glacial and post-glacial sediments, forms metastable slopes that present considerable challenges in terms of railway operations and maintenance. The movements of these slides require the railways to complete more frequent track maintenance involving track lifting and tamping of the rail beds (Eshraghian et al., 2008).

The entire Thompson River valley has a long history of landslides that have impacted the railway infrastructure since their construction (Stanton, 1898). A great deal of research has focused on understanding and analyzing the potential for future instabilities as well as establishing causation for slope movements. Previous research has investigated a variety of suspected causes such as irrigation on the upper terraces above the valley (Stanton, 1898); regional groundwater flow effects (Hodge and Freeze, 1977; Bishop, 2008); geologic controls exposed by the down-cutting Thompson River (Clague and Evans, 2003; Eshraghian et al., 2007); and elevated pore pressures along failure surfaces (Porter et al., 2002). More recently, the dynamic effects of river stage have been studied as a potential cause for variable rates of landslide movement for some of the failures (Eshraghian et al., 2008; Hendry et al., 2015).

A significant portion of the research has focused on contributing factors and data collected from the lower reaches of the slope to explain movement patterns and rates. There has yet to be an investigation on the contribution of soil suction above the ground water table on the stability of the slope.

A recently initiated investigation is characterizing the influence of the soil moisture deficit (SMD) and temporal changes in matric suction on the rate of movement. Instrumentation and monitoring of the matric suctions and additional laboratory characterization of the near surface soil has been undertaken as part of this study. Bulk soil samples recovered from boreholes, where the instrumentation was installed, have been used to determine soil water characteristic curves (SWCCs) and total suctions within the head scarp and slide mass. The field and laboratory data are used to evaluate temporal changes in both matric and osmotic suctions within the slide mass and head scarp. The results of the quantitative assessment are used to further assess the impact of unsaturated soil mechanics and how infiltration and deep percolation can affect the overall stability of a slope in an arid climate.

2 RESEARCH SITE

The Ripley Slide was selected to study the effects of fluctuations in the SMD on the movement of the slide mass as the conditions at the site have been well documented and heavily instrumented for both movement and pore-water pressure fluctuation. In 1951, Charles Ripley first noticed the Ripley Slide was shifting the fence alignment upslope of the CP tracks (Leonoff and Klohn Leonoff Ltd., 1994). The landslide became more evident around 2005 and as of 2015, the Ripley Slide had an approximate size of 1.0 x 10^6 m^3 (Hendry et al., 2015). In the last several years, the Ripley Slide has continued to move with rates that vary seasonally throughout the year.

The rail corridor includes three mainline tracks, one CN and two CP. The Ripley Slide affects three tracks upslope of the toe of the slide where it emerges within the Thompson River (Figure 1). The monitoring equipment that is currently in place and operational includes permanent and mobile GPS stations; piezometers; ShapeAccelArray (SAA) inclinometers; and corner reflectors for satellite-based interferometry. Ground-based LiDAR scans were completed in previous studies of the site (Bobrowsky et al., 2015). More recently, a weather station was installed and became operational in September 2016.

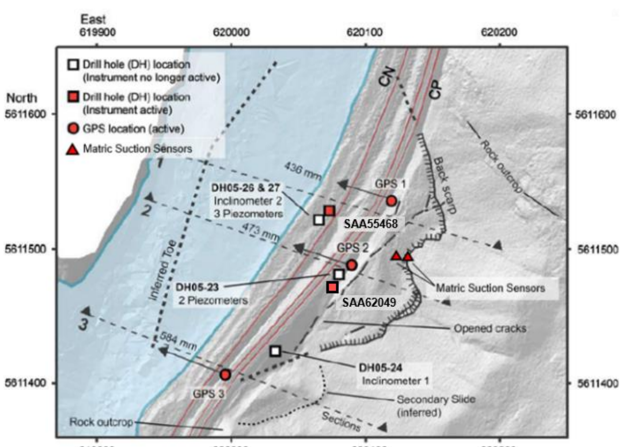

Figure 1. Extent of Ripley Slide (modified from Hendry et al., 2015 and Macciotta et al., 2014)

Surficial sediments were deposited over three separate glacial periods (Fulton and Smith, 1978). During the intervening periods, erosion and mass wasting has resulted in numerous unconformities (Clague and Evans, 2003). A detailed site investigation was carried out in 2015 and revised cross sections for the Ripley Slide were developed (Schafer, 2016). The investigation indicated signs of landslide retrogression whose shape and movement are influenced by the presence of subsurface andesite bedrock. Tension cracks exist within the unsaturated upper reaches of the landslide and form the current head scarp of the slide. The tension cracks are observed to act as snow catchments and intercept surface runoff moving down the valley slopes, resulting in higher rates of infiltration at the head scarp. This can contribute to deeper percolation of water and further loss of matric suction.

3 FIELD MONITORING

Recent additions to the well-established network of instrumentation present at the Ripley Slide occurred from September to November 2017. The primary focus of the current investigation is centred on stratigraphic and groundwater conditions upslope of the railway right of way. The research is focused on determining the temporal changes to the SMD within the head scarp and the slide mass. The effects of groundwater infiltration and percolation are monitored by use of two separate systems described herein.

3.1 Proactive Infrastructure Monitoring and Evaluation (PRIME) System

The PRIME system is an in-place electrical resistivity tomography (ERT) method developed by the British Geological Survey (BGS), now installed for testing at the Ripley Slide. The system uses ERT to monitor fluctuations in electrical resistivity of the overburden, which can then be directly related to the in-situ water content of the soils.

The application of an ERT system over a landslide presents several challenges. Variable displacement of the entire network causes distortion of electrical resistivity imagery and requires the use of methods based on geoelectrical measurements and data inversion (Wilkinson et al., 2015). Furthermore, the resistivity data must be correlated to known water content information to infer the changes in water content with depth over time. The PRIME system makes use of water content instrumentation to provide calibration parameters for the in-situ resistivity measurements.

In September 2017, representatives from the Geological Survey of Canada (GSC), University of Alberta (UofA), and the University of Saskatchewan (UofS) established the grid network for the PRIME system. The network for the ERT was determined based on the visible head scarps that appear upslope of the rail alignment. Resistivity probe cross-sections were stationed to intersect the slide mass and head scarp perpendicular to one another. The extent of the ERT survey was limited to 91 m parallel and 54 m perpendicular to the Thompson River

(Figure 2). As shown in Figure 3, the grid layout was hand excavated and covered following installation of the probes and the associated cabling. The lines were later armoured with small boulders to limit animal disturbance.

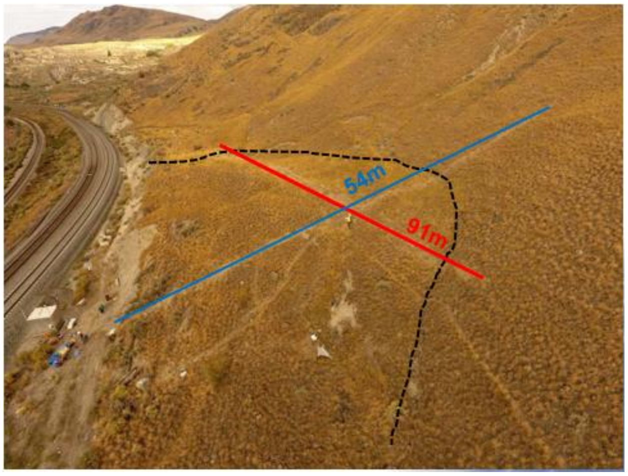

Figure 2. Extent of the ERT survey


Figure 3. Installation of ERT system

The ERT system provides the potential for rapid subsurface and subsurface resistivity characterization that can be used to estimate soil moisture and compared to suspected landslide triggering water content. Alarm levels could be based on water content exceeding the plastic limit along the failure surface (Gunn et al., 2015).

3.2 Matric Suction Monitoring

From a geotechnical perspective, variations in water content can have a significant impact on the amount of matric suction that can be generated in the soil. In theory, changes in the matric suction can affect slope movements and rates by altering the shear strength available in the unsaturated zone (Potts et al., 1997; Carse, 2014). A better understanding of the stabilizing effect provided by matric suction in the head scarp may offer further justification and explanation for the overall slope stability at the Ripley Slide. Furthermore, infiltration and deep percolation can provide an additional source of groundwater that can lead to increased pore pressure on the failure surface, reduced effective stress and slope movement (Vaughan and Walbancke, 1973).

Measurement of the in-situ matric suction was conducted using calibrated dielectric permittivity sensors. The sensors operate on the principle that the matric suction of the soil is in equilibrium with a porous ceramic disk surrounding the dielectric permittivity sensor inserted into the soil to a given depth. Therefore, it is important that the soil be in intimate contact with the ceramic disk to ensure equilibration. The water content is then converted to a matric suction using a well-defined SWCC for the ceramic disk (Decagon Devices, Inc. 2017).

In November 2017, one borehole was drilled within the head scarp and another within the slide mass. These locations are labeled with matric suction sensors in Figure 1. The boreholes were drilled to a depth of 2.7 m and 2.0 m below the ground surface within the slide mass and tension crack respectively. Borehole advancement using hand-drills was extremely difficult due to the highly heterogeneous soils (silt till). As a result, boreholes were terminated with auger refusal on coarse gravel or cobbles at the base of each hole. The location of the boreholes allowed for comparison of matric suction between the tension crack and a background reading for an intact point in the slide mass. The tension crack is known to collect and trap a portion of the available upstream surface water, either during spring melt or the occasional rainfall event, as it travels downslope towards the river. Trapped water in the tension cracks has a higher probability of contributing to deeper percolation in an area known to have high rates of evaporation and transpiration causing a net water deficit.

Data from the weather station provides the input associated with precipitation/snow melt whereas displacement monitoring is obtained from two SAAs located just east of the live rail beds and three GPS landslide monitoring stations located along the CP track and across the landslide. These data were then used to provide the input relating change in matric suction from atmospheric influences and slope movements.


Figure 4. Matric suction instrumentation relative locations on the landslide an in the head-scarp

4 LABORATORY CHARACTERIZATION

The geotechnical characterization for the shallow stratigraphy present upslope of the railway right of way was determined in the soils laboratory at the UofS. Samples were recovered during the hand augering in November 2017. A detailed characterization of the soil was carried out including:

- natural water content determination;
- total suction measurements using the chilled mirror hygrometer technique;
- grain size distribution via mechanical sieve and hydrometer methods (ASTM D1140-92 and ASTM D422-63);
- specific gravity testing (ASTM D854-92);
- Atterberg limits (ASTM D4318-95); and
- soil water characteristic curve analysis based on axis translation methods (ASTM D6836-02).

Natural water content was measured from sealed bag samples collected during the site investigation. The results are plotted in Figure 5. It is evident that the natural water content within the head scarp was approximately 5 to 10% higher when compared to the samples taken from the slide mass. This was attributed to an increased capture and storage of surface runoff within the head scarp due to the presence of the tension crack, and an interception of some of the surface runoff upslope of the head-scarp, as compared to the direct infiltration and minimal surface run off from the slide mass site.

Total suction was measured from the sealed bag samples soon after they were transported to the laboratory at the UofS. These measurements confirmed lower values of total suction in the head scarp relative to that of the slide mass, as was expected from field observations.

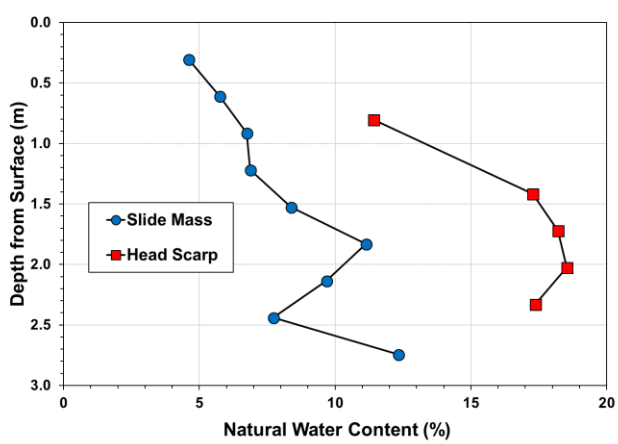

Figure 5. Natural water content variation with depth

Atterberg limits and grain size distribution established that the soil within the head scarp and the slide mass were composed of the same geologic materials.

The development of parameters for a soil water characteristic curve enabled the conversion of matric suction measurements to water content for soil around a given sensor. Additionally, in-situ water content for the soil will be compared to water content interpreted from the ERT system to develop a two-stage verification of water content and develop a system to rapidly identify potential impacts on slope stability.

5 DISCUSSION OF RESULTS

Unsaturated soil mechanics involving matric suction in the upper reaches of the landslide have the potential to influence the overall stability on a seasonal basis. Comparisons have been performed between the collected matric suction monitoring data and the existing displacement monitoring data. A series of trends were observed when analyzing the water content, displacement monitoring, matric suction, air temperature, and precipitation rate data.

5.1 Soil Characterization Analysis

The grain size distribution testing was conducted at regular intervals for both boreholes. The results from the mechanical sieving and hydrometer indicate a well-graded soil predominantly composed of a mixture of sand, silt, and clay with trace gravel and cobbles. Typically, around 60% of the samples tested passed the No. 200 sieve. Hydrometer testing indicated that most of the fines were silt sized particles. While there was no apparent trend in the percentage of fines by mass when plotted with depth, the percentage of clay in both boreholes was consistently less than 10%, excluding those samples taken at a depth of 1.7 m (Figure 6).

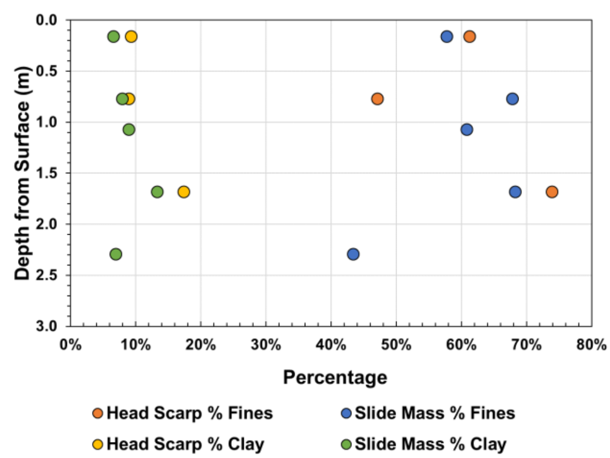

Figure 6. Fines and clay composition from head scarp and slide mass

Atterberg limit tests were carried out for one sample in each of the boreholes and the results were found to be similar between the two locations. The plastic limit varied between 19 and 22%, whereas the liquid limit ranged between 30 and 33%. These results indicate a reasonably low plasticity clay (CL). A laboratory hygrometer was used to determine the total suction for the samples recovered from the slide mass and within the head scarp and the results are shown in Figure 7.

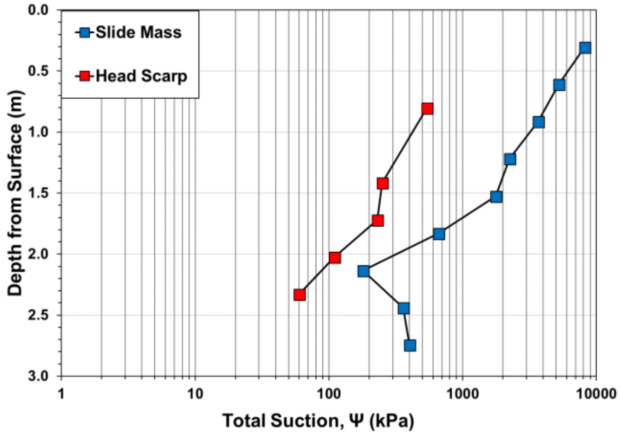

Figure 7. Total suction with depth

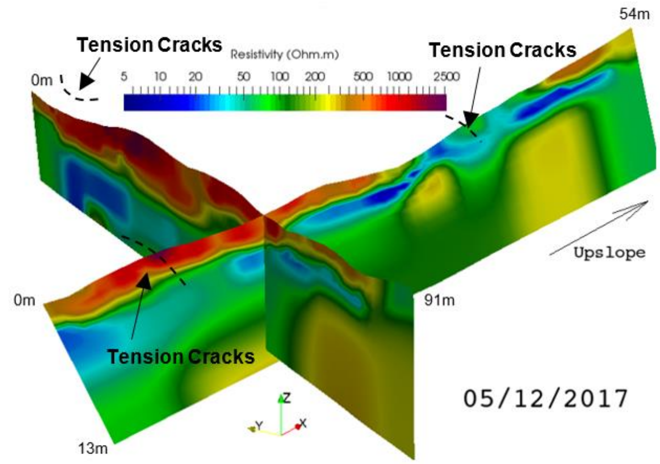

Figure 8a. Background survey of resistivity using ERT

Determination of a representative soil water characteristic curve (SWCC) for the site presents many challenges. Standard methods involving the axis translation method and the Tempe cell apparatus are currently being employed to develop a reasonable relationship between the water content and matric suction of the soil. The potential for osmotic suction indicates that measurements of total suction may not be equal to matric suction. Therefore, some form of axis translation method combined with an analysis of volume change effects (such as a shrinkage limit test) must be used to formulate an appropriate soil water characteristic curve relationship (Fredlund and Houston, 2013).

5.2 Comparison of Suspected Movement Controls

The location of the tension crack is such that any surface water that flows downslope over the Ripley Slide from upstream lands is captured in the tension cracks and stored for deep percolation or evaporation. While transpiration at the Ripley site varies throughout the year based on rainfall and drought experienced by the low vegetative cover of native grasses, transpiration is expected to be minimal relative to the evaporative component of the water balance during most of the year. The ensuing runoff collection can cause increased deep percolation and elevated pore-water pressures on the failure surface. Data collected from the ERT suggest widespread but shallow changes in water content may occur rapidly. The following set of figures shows the initial background survey data from December 5, 2017, followed by one such instance of rapid change in resistivity (indicating changing water content) occurring between February 6 and 13, 2018 (Figure 8a, b & c).

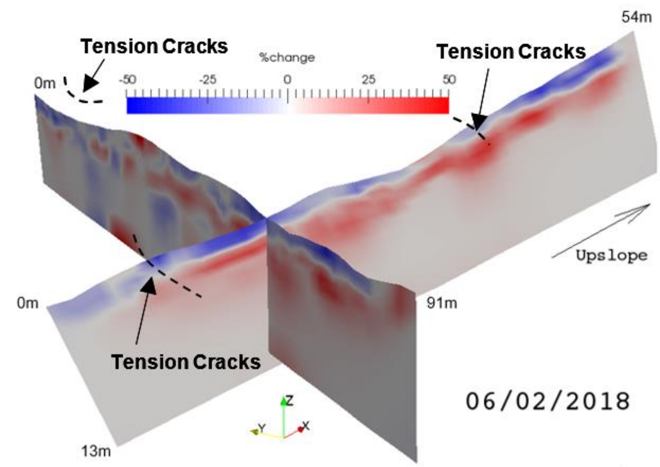

Figure 8b. Change in resistivity from December 5, 2017 to February 6, 2018

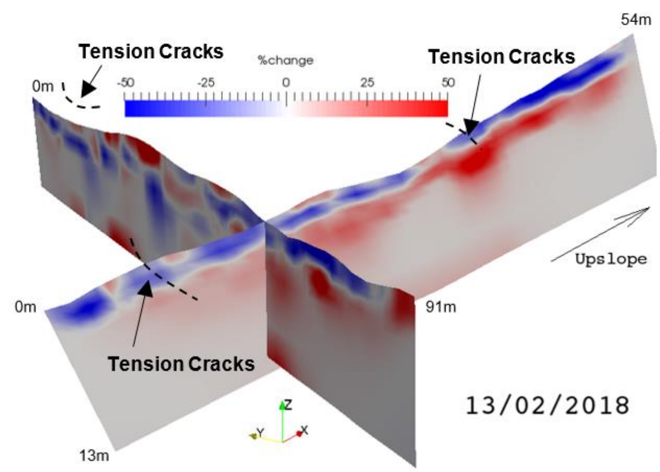

Figure 8c. Change in resistivity from December 5, 2017 to February 13, 2018

The soil water characteristic curve (SWCC) implies that increases in water content cause a loss of matric suction which aids in the temporary stabilization of the landslide. A preliminary SWCC is shown for the soil recovered from the unsaturated slide mass of the Ripley Slide. The figure indicates substantial losses in suction would occur due to changes in water content (Figure 9).

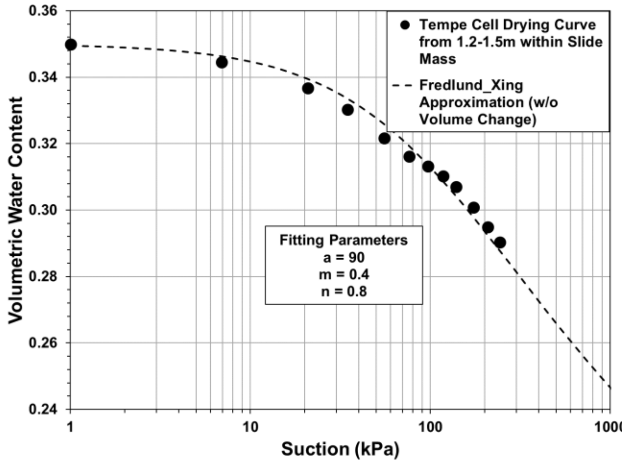

Figure 9. Preliminary SWCC for slide mass soil

The infiltration and rate of recharge into these tension cracks can cause a gradual loss in shear strength and results in changing rates of landslide movement. Infiltration can lead to rising water contents at depth further reducing the effective stress along the slide plane which can increase movement rates resulting in deeper tension cracks. The matric suction monitoring data suggest that the matric suction near the surface can change quickly with minor changes in the precipitation rate (Figure 10). During the same period, the matric suction in the slide mass is relatively unaffected (Figure 11). When compared with the recorded air temperature, the data confirm a loss of head scarp matric suction a few days after the temperature starts to reach daytime highs above 5°C (Figure 12).

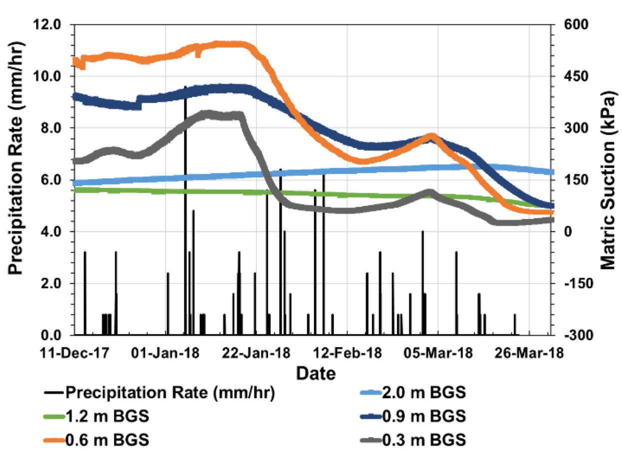

Figure 10. Variable measured matric suction in the head scarp with precipitation rate

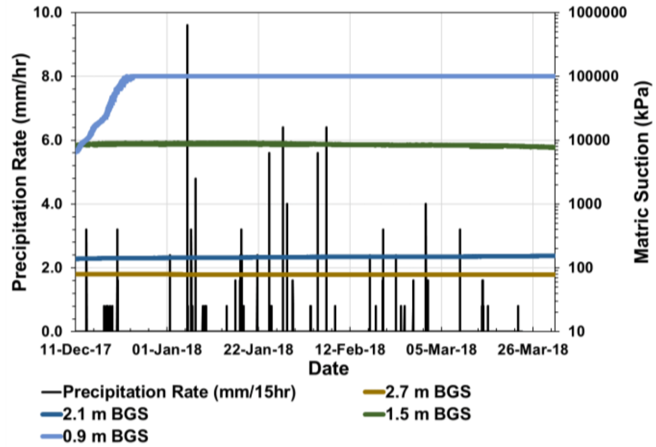

Figure 11. Constant measured matric suction in the slide mass with precipitation rate

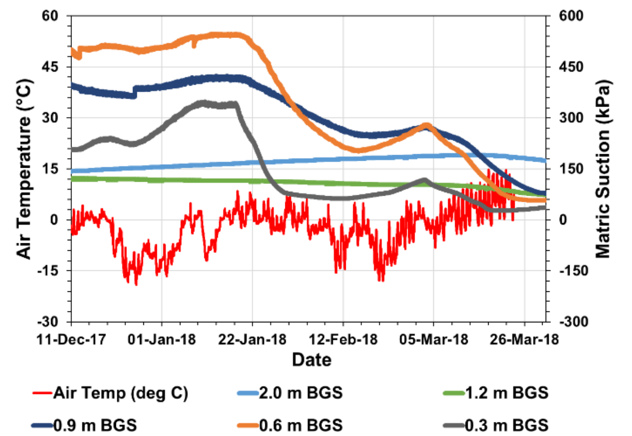

Figure 12. Head scarp measured matric suction and air temperature fluctuations

A weather station installed on site has been continuously tracking total precipitation, precipitation rate, and air temperature since late September 2016. The data collected during this period suggest that June to September are characterized by very low precipitation as expected for the Thompson River valley (Figure 13). During the summer, the rate of landslide movement tends to stagnate (Figure 14). Noteworthy is the contribution of changing river stage. When the precipitation levels are low (June and July), the Thompson River is subjected to spring freshet water levels shown to partially buttress the slope as well as reduce any artesian pressures acting on the slide plane. These additional factors likely contribute to the reduced movements. During the fall and winter months, the Thompson River level drops and the movements increase (Eshraghian et al., 2007; Hendry et al., 2015).

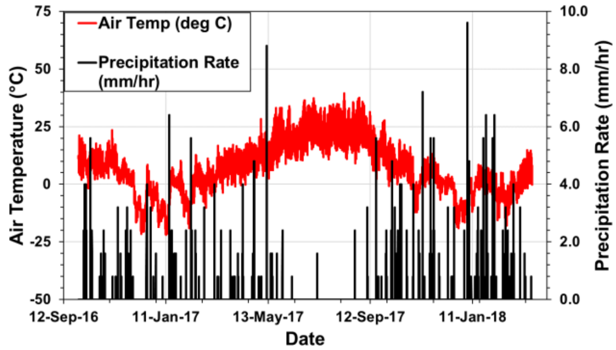

Figure 13. Change in air temperature and precipitation rate

A period of rapid landslide movement started in mid-February 2017 based on data from an SAA inclinometer located adjacent and upslope of the tracks near the centreline of the Ripley Slide (Figure 1). Displacement data at approximately 270 masl was associated with the highest rate of lateral movement (Figure 14). During the first few months of the year, the river level was at its lowest prior to spring runoff (Figure 15). At that point in time, the Ripley Slide is susceptible to any stability-altering changes that could trigger movement. The gradual lowering of the river level could provide an explanation for the accompanied gradual increase in movement starting in August 2017.

A buildup of frozen groundwater and snow combined with rising temperatures above 0°C and a minor rainfall event could have detrimental effects on the stability. A detailed analysis of the precipitation and temperature data reveals that there was a warming trend from sub-zero to above-zero temperatures and a spike in precipitation a few days prior to the movement in mid-February 2017. The delayed and extended duration of the movement could be related to the required time for infiltration entering the head scarp to cause a drop in matric suction within the unsaturated region of the landslide. Currently, the hydraulic conductivity of the soil is not known, but based on the Kozeny-Carman method described by Chapuis and Aubertin (2003), the permeability of the soil is predicted to be around 1.0 x 10^6 m/s. Therefore, we expect that if water is trapped within the head scarp, there is a high potential of infiltration to deeper horizons in the winter months when the air temperature is low, and evaporation is reduced.

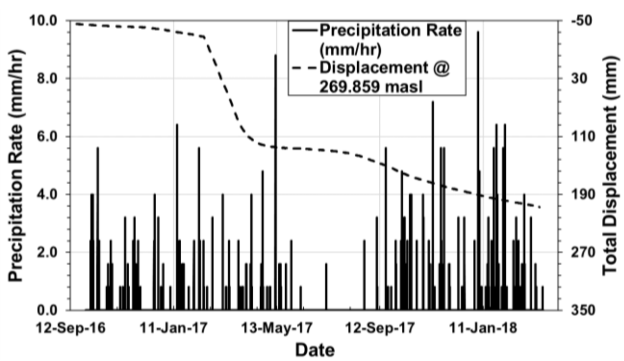

Figure 14. Change in precipitation rate and displacement

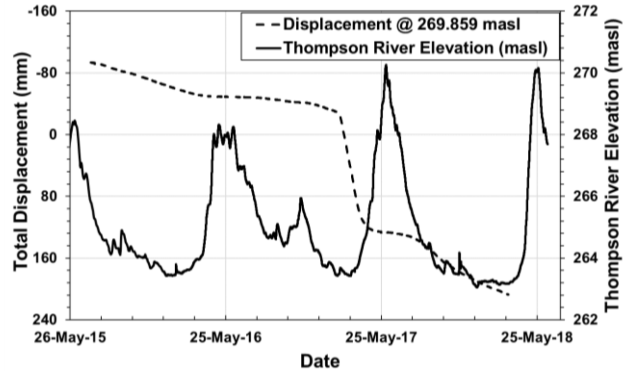

Figure 15. Change in river stage and displacement

The weather station, displacement monitoring, and matric suction instrumentation data continue to be collected and processed. The seasonal triggers and controlling factors that have been identified require more information over a longer time span to expand our conclusions.

6 CONCLUSION

This research introduces a new topic of discussion and potential controlling factor influencing landslide movement and rates of movement at the Ripley Slide south of Ashcroft, British Columbia. A cooperative effort is currently underway between the UofS, UofA, GSC, and the BGS that will further broaden our understanding of the numerous factors driving instabilities that are present within the Thompson River valley impacting the CP and CN railway corridor.

New instrumentation focused on soil matric suction and its effects on slope stability is underway. A detailed understanding of the meteorological and hydrological components of the study site are identified as important factors contributing to changes in the movement rate for the Ripley Slide.

By considering all the potential controlling factors, more detailed analysis and effective solutions may be developed to deal with problem areas that experience similar conditions. A comprehensive knowledge of a site requires a perceptive field monitoring plan and lab characterization followed by intense scrutiny and comparison of all factors that may be related to one another and have an impact on slope stability. The identification of these changes is vital to the maintenance of this major transportation corridor.

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