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Novel techniques to monitor changes in near-surface water content for a slow-moving retrogressive landslide in British Columbia, Canada

Kelvin Sattler & David Elwood
Dept. of Civil, Geological & Environmental Engineering, University of Saskatchewan, Canada, kelvin.sattler@usask.ca

Michael T. Hendry
Dept. of Civil & Environmental Engineering, University of Alberta, Canada

David Huntley
Geological Survey of Canada, Canada

Jessica Holmes, Jonathan Chambers, Paul B. Wilkinson & Philip I. Meldrum
British Geological Survey, United Kingdom

Shane Donohue
Dept. of Civil Engineering, University College Dublin, Ireland

Wayne Clifton
Clifton Engineering Group, Canada

ABSTRACT: Negative pore-water pressure variations are measured using a combination of commercial and custom-built dataloggers across a semi-arid, slow-moving, retrogressive landslide near Ashcroft, British Columbia, Canada. The landslide intersects a key rail corridor that is shared by both of Canada's chief railway operators and provides a vital link from the Port of Vancouver in the west, to the rest of Canada. This study investigates the seasonal and multiyear variations in soil water content that contribute to changes in landslide displacement rates. Matric suction monitoring and periodic electrical resistivity tomography (ERT) measurements are linked to soil moisture deficit (SMD) to identify impacts on landslide displacement. Stability loss during critical times of year can lead to unexpected increases in landslide displacement rates. The monitoring framework provides a means to analyse long-term local land-climate interactions in relation to pore-water pressure along the upper reaches of the slip surface. Understanding the local relationship allows for advanced warning and foresight when developing annual rail maintenance budgets.

RÉSUMÉ : Les variations de pression interstitielle négative sont mesurées à l'aide d'une combinaison d'enregistreurs de données commerciaux et fabriqués sur mesure à travers un glissement de terrain semi-aride, lent et rétrogressif près d'Ashcroft, Colombie-Britannique, Canada. Le glissement de terrain croise un corridor ferroviaire clé qui est partagé par les deux principaux exploitants ferroviaires du Canada et fournit un lien vital entre le port de Vancouver, dans l'ouest, et le reste du Canada. Cette étude examine les variations saisonnières et pluriannuelles de la teneur en eau du sol qui contribuent aux changements des taux de déplacement des glissements de terrain. La surveillance de l'aspiration matricielle et les mesures périodiques de tomographie de résistivité électrique (TRE) sont liées au déficit d'humidité du sol (DHS) pour identifier les impacts sur le déplacement des glissements de terrain. La perte de stabilité pendant les périodes critiques de l'année peut entraîner des augmentations inattendues des taux de déplacement des glissements de terrain. Le cadre de surveillance fournit un moyen d'analyser les interactions locales à long terme entre les terres et le climat en relation avec la pression interstitielle le long des tronçons supérieurs de la surface de glissement. Comprendre la relation locale permet d'avertir et de prévoir à l'avance lors de l'élaboration des budgets annuels de maintenance ferroviaire.

KEYWORDS: Retrogressive translational landslide, variable matric suction, soil moisture deficit, low-cost datalogging.

1 INTRODUCTION

The Ripley Landslide is a retrogressive translational landslide in the semi-arid Thompson River valley region near Ashcroft, British Columbia, Canada and belongs to a long list of historical landslides found throughout the valley. These landslides predominantly slip on weak glaciolacustrine sediments that have been exposed due to post-glacial river incision (Clague & Evans 2003, Eshraghian et al. 2007, 2008). A major railway corridor operated by both major railway operators in Canada, Canadian Pacific (CP) and Canadian National (CN), follows the river valley intersecting several of these landslides (Stanton 1898).

A combination of environmental factors causes variations in the stability of the Ripley Landslide, on a seasonal to multiyear scale. The base of the Ripley Landslide is exposed in the Thompson River, which reaches a seasonal maximum elevation around 270 metres above mean sea level (masl) during spring freshet and drops to a minimum of 263 masl in late winter. Previous studies have shown the importance of these seasonal river stage elevations in terms of buttressing effects, direction of hydraulic gradients, excess pore-water pressures in low permeability stratigraphy, and aggressive river scour at the landslide base (Clague & Evans 2003, Eshraghian et al. 2007, 2008, Hendry et al. 2015, Journault et al. 2017). While these studies explain a significant component of the seasonal landslide movements, the variable landslide displacement rates cannot be fully explained by these factors alone based on data accumulated over the last 20 years.

Previous geotechnical investigations have focused on the factors that influence the landslide slip plane within the glaciolacustrine deposit. The steep slope of the valley wall combined with the depth of the translational landslide base (observed around 257 masl) cause successive rows of retrogressive tension cracks to appear relatively far upslope from the river (above 280 masl). The relatively steep terrain and low water table in the upland area of the slide mass results in a large component of the landslide slip surface within unsaturated soils. Therefore, the unsaturated soil strength for the till unit overlying the glaciolacustrine sediment is an important component of the Ripley Landslide's slip surface. Any seasonal and multiyear variations in water content along the upper reaches of the slip surface would be expected to play an important role in the overall slope stability.

2 MONITORING NETWORK

Geotechnical instrumentation was installed at the Ripley Landslide as part of the 2005 construction of a CP track siding. Part of the siding construction required the construction of a retaining wall. The change in slope angle resulted in landslide movement and additional track maintenance between 2006 and 2007 (Hendry et al. 2013, 2015). Continuous and variable rate progression of the landslide led to the commission of additional instrumentation and the development of a complex network of novel instrumentation and monitoring techniques. Ongoing research at the Ripley Landslide over the past two decades produced a large database of seasonal pore-water pressure variations as well as annual displacement rates measured at the surface and on the slip surface (Macciotta et al. 2016, Hendry et al. 2018). The depth of the slip surface and rates of displacement were originally measured with slope inclinometers and differential GPS units (Macciotta et al. 2014) and later with Shape Accel Arrays (SAAs). More recently, surface movements have been measured with satellite interferometric synthetic aperture radar (InSAR), Geocube (Benoit et al. 2015), and global positioning systems (GPS) with ground-based control points. A layout of the instrumentation used in the present study is shown in Figure 1.

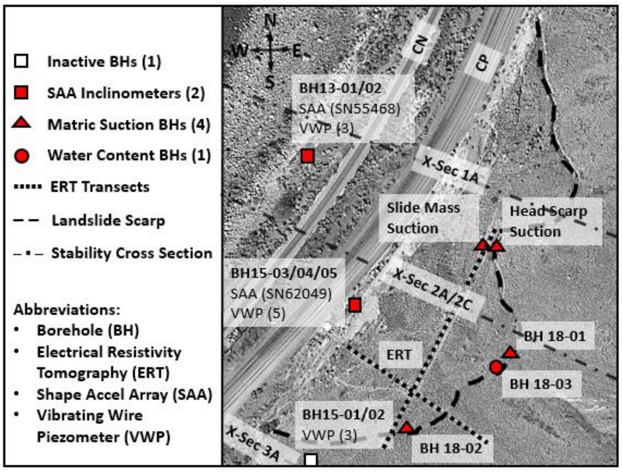

Figure 1. Geotechnical monitoring network at the Ripley Landslide.

The present study involved the installation of water content and matric suction instrumentation further upslope of the rail alignment. The additional instrumentation was designed to investigate the effect of infiltration from precipitation and snowmelt on the in-situ soil water content. The relationship between the soil water content and matric suction, known as the soil water characteristic curve (SWCC), justifies the importance of measuring a variable water content profile along the upper reaches of the slip surface. Increasing soil water content reduces the matric suction thereby, reducing the soil's shear strength (Bishop 1959, Fredlund et al. 1978).

Between 2017 and 2018, five shallow (< 3 m) boreholes were advanced by hand auger within and immediately downslope of the existing head scarp. The first set of water matric suction transducers were logged with the use of commercial dataloggers. However, the second set utilized a low-cost datalogger developed by the authors at the University of Saskatchewan (Figure 2).

Figure 2. North-facing view of low-cost datalogger located at BH18-01

3 METHODS OF ANALYSIS

While commercial dataloggers were initially installed to measure matric suction and water content, the research team decided to develop a low cost datalogger to expand the range of the monitoring network at a quarter of the cost. In addition to expanding the coverage area, testing low-cost dataloggers alongside commercial units allowed for side-by-side field comparison of the two datalogging systems. The matric suction sensors transfer data using serial digital interface at 1200 baud (SDI-12). The data transmission method is well understood and documented in detail through online support forums (SDI-12 Support Group 2019). Furthermore, open-source libraries, such as GitHub, include repositories with base code examples that have been tested in real world scenarios (Stroud Water Research Center 2020). The code used in the datalogger is available on the University of Alberta repository (Sattler et al. 2020a, 2020b).

The present study measured the long-term variations in matric suction across the head scarp region of the Ripley Landslide. The matric suction sensors used in this study were developed primarily for the agricultural irrigation industry (Campbell 1988). However, their method of measurement is well-suited to determination of a large range of matric suction in shallow boreholes or test pits. The manufacturer claims accurate soil suction measurements (± 10%) from -9 to -100 kPa that may extend down to -2000 kPa for some soils, reaching an air-dry reading at -100,000 kPa (Meter Group 2020). While errors in measurement increase with higher matric suction, the sensors have the benefit of being capable of sustaining sub-zero temperatures common to Canada throughout the winter. These sensors utilize an indirect method of relative permittivity of the porous ceramic disks to determine the water potential of the surrounding soil. The matric suction is calculated from the measured water content and the associated SWCC relationship of the ceramic disks. Provided that the soil maintains good contact with the porous ceramic stone, the soil's matric suction is equivalent to that of the ceramic stone once equilibration is reached. Tempe cell tests in the laboratory were completed to determine the SWCC relationship for the near-surface soils at the Ripley Landslide (Figure 3). The SWCC plot in Figure 3 showed that small changes in soil water content cause changes in matric suction of several orders in magnitude.

In the autumn of 2017, two perpendicular transects of electrical resistivity tomography (ERT) probes were installed to conduct regular measurements of the subsurface resistivity. The in-place ERT was installed as part of a collaborative program between the Geological Survey of Canada (GSC); the University of Saskatchewan; the University of Alberta; and the British Geological Survey (BGS). The Ripley Landslide was selected based on its arid climate as an ideal study site to install a permanent in-place ERT array to monitor seasonal and long-term variations in near-surface soil resistivity. Up until the installation at the Ripley Landslide, the BGS had deployed the in-place ERT only in wetter, more temperate climates. Variable soil electrical resistivity has been attributed to changes in the soil water content (Gunn et al. 2015). Pore spaces filled with water have low electrical resistivity, while pore spaces filled with air will demonstrate a high electrical resistivity. The BGS is currently working on calibration of soil electrical resistivity to soil water content. However, mapping subsurface changes in electrical resistivity provided valuable visual clues to infiltration across the ERT transects over large areal extents.

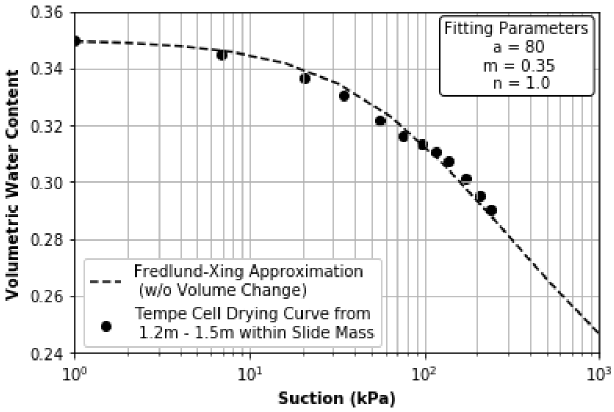

Figure 3. SWCC for near-surface soil at the Ripley Landslide.

An initial survey of electrical resistivity in late 2017 identified local stratigraphy that added to the geologic layout developed during previous geophysical surveys conducted at the Ripley Landslide (Huntley et al. 2019, Holmes et al. 2020). While water content changes also affect electrical resistivity, grain size and mineralogy have a large impact on the absolute values of resistivity. For example, well-drained coarse-grained soil have high electrical resistivity, while the opposite is true for poorly drained, fine-grained soil. Weekly measurements of the soil resistivity were collected, and the results were compared to the initial values to develop a spatial and temporal map of water content changes along the transects. The changes are attributed to changes in soil water content assuming the lithology and porosity were constant (Huntley et al. 2019). As ERT transects intersected the landslide tensions cracks, the present study was able to visualize the impact of precipitation, ground thaw, and snowmelt on temporal changes in soil electrical resistivity. Visual representation of these weekly changes was useful to determine the depth and extent of infiltration in the vadose zone.

While seasonal variations in soil water content are expected due to the arid climate, long-term variations and multiyear trends were more difficult to observe without additional data processing. Soil moisture deficit (SMD) trends over several years have been proposed as a quantitative tool for comparing climate to long-term vadose zone water content changes (Hutchinson 1995, Ridley et al. 2004, Smethurst et al. 2012, McLernon 2014). A range of meteorological variables were included in the SMD and demonstrated which years were wet or dry relative to each other when compared over several years.

The present study estimated a monthly SMD from monthly evapotranspiration (ET) and precipitation (P) (Eq. 1). Runoff was excluded from the calculation. However, runoff would be expected to further increase the SMD during mid-summer when the SMD is near the seasonal maximum. Unsaturated hydraulic conductivity is lowest when the soil is at a lower water content, leading to less infiltration and increased runoff. Infiltration is greatest in early spring when the SMD is low; the near-surface unsaturated soil approaches the saturated hydraulic conductivity; and runoff is minimal.

$$SMD = ET - P \tag{1}$$

Considering the difficulties in measuring the vegetation parameters, the water-limited evapotranspiration could not be determined with high accuracy. Instead, an estimate of evapotranspiration was based on a measured static vegetation cover. For native prairie grassland, vegetation height does not generally change throughout the year and evapotranspiration would be limited during winter. The above indicates that plant activity and water usage for native prairie grass is variable throughout the year. The evapotranspiration estimate for the Ripley Landslide was calculated from the Penman-Monteith (1965) equation (Eq. 2):

$$Q_E = \frac{\Delta(Q_{NR} - Q_G) + \rho c_p (e_{sat}(T) - e_{ref}) {r_{a-h}}^{-1}}{\Delta + \gamma(1 + r_s/r_{a-h})} \tag{2}$$

where Δ is the slope of the saturated vapour pressure curve [Pa/K], Q_{NR} and Q_G are net radiation and soil heat flux [W/m^2], ρ is the density of air [kg/m^3], c_p is the specific heat of the air [J/kg K], $e_{sat}(T)$-e_{ref} is the vapour pressure deficit [Pa], γ is the psychrometric constant [Pa/K], r_s is the surface resistance [s/m], and r_{a-h} is the aerodynamic resistance [s/m].

Estimates for solar radiation were calculated from the known slope (13°) and aspect (135°) angles based on clear sky approximations (Hargreaves & Samani 1985) using the methods presented by the American Society of Civil Engineers (ASCE-EWRI 2005) and Allen et al. (2006). Meteorological variables were collected from an on-site weather station that included hourly readings of wind speed (mechanical anemometer) and air temperature. Other variables were incorporated from Environment Canada (2020) weather stations within a 60 km radius. Provided that topographic and weather changes were not abrupt, and aridity was relatively consistent, the relative humidity and air temperature are well correlated over distances up to 100 km (Allen 1996). Based on the reliable data collection and availability, the SMD could be estimated over the past decade at the Ripley Landslide.

4 OBSERVATIONS AND DISCUSSION

Visual plots of changes in the soil's electrical resistivity (water content) have been reproduced on a weekly schedule since December 2017. Spring ground thaw and snowmelt in early 2018 led to infiltration into the head scarp tension cracks and were depicted in the ERT survey by negative changes in resistivity (increasing water content) which are shown in blue (Figure 4c and Figure 4e). Wildlife cameras show the surface conditions and accumulated snow present at the time of each ERT measurement (Figure 4b, 4d, 4f). The tension cracks act as a collection basin for blowing snow in the winter and overland runoff in the spring. When temperatures rise above melting (Figure 4g), accumulated snow releases water directly into the tension cracks. As a result, a major component of vadose zone water content is derived from tension crack infiltration.

While ERT surveys provided qualitative measurements, the matric suction and in-situ water content sensors provided quantitative measurements that verified the changes in vadose zone water content. As shown in Figure 1, two of the matric suction monitoring boreholes were installed side by side near the centre of the landslide. One set of five suction sensors were installed into the landslide head scarp, while the other set of five were installed into the main slide mass. The purpose was to

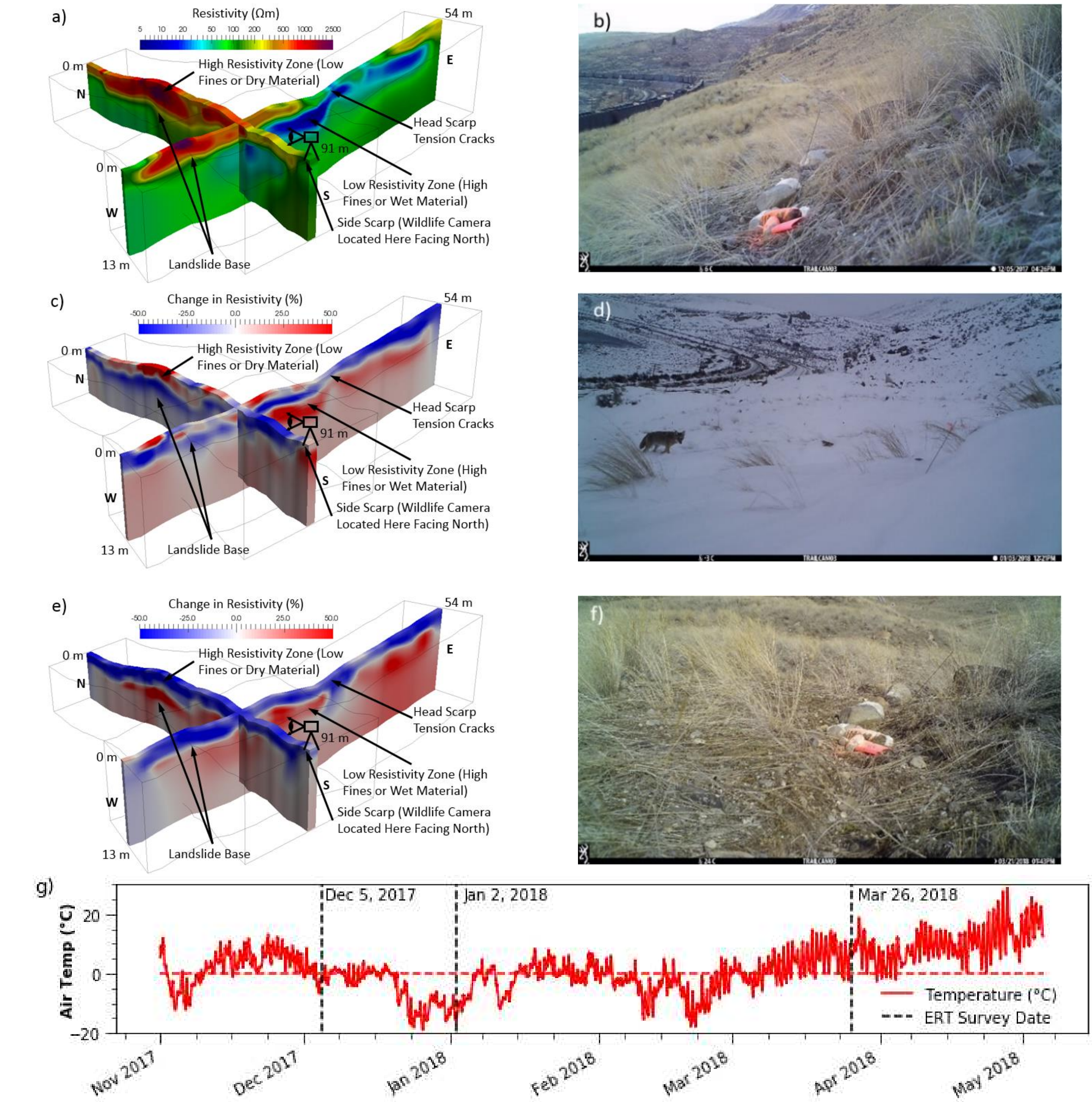

Figure 4. Changes in resistivity due to infiltration: (a) Background resistivity survey on Dec. 5,2017 (b) Field image from Dec. 5, 2017 (c) Resistivity change from Dec. 5, 2017 to Jan. 2, 2018 (d) Field image from Jan. 3, 2018 (e) Resistivity change from Dec. 5, 2017 to Mar. 26, 2018 (f) Field image from Mar. 21, 2018 (g) Temperature record between Nov. 2017 and May 2018 (after Holmes et al. 2020, Sattler et al. 2018, Huntley et al. 2019, 2020)

determine how much impact the borehole location had on the relative water content changes at various points in the year. As expected, matric suction in the slide mass changed seasonally, while water in the head scarp tension cracks demonstrated a lower and more consistent level of matric suction around 1000 kPa (Figure 5 and Figure 6). Lower matric suctions correspond to a higher hydraulic conductivity for a given soil (Fredlund, Xing & Huang 1994). As a result, there was a higher rate of infiltration within the tension cracks throughout the year.

From ERT plots and matric suction data, it was evident that seasonal variations in water content followed specific patterns. As soil suction measurements are not always available, a method was devised (using standard meteorological data) to allow for year over year comparisons of the in-situ soil water content. The present study demonstrates the use of the SMD to provide a reasonable representation of soil water content variation on a multiyear scale. In Figure 7, the SMD is compared to the slide mass matric suction over a 2-year period. This comparison demonstrates a correlation between the matric suction and the SMD. When the SMD reaches a maximum during the summer, the near-surface soil suction also peaks at a seasonal maximum. There was a slight delay between the SMD changes and the accompanying suction response. The delay between changes in matric suction and the SMD changes is due to the infiltration rate, unsaturated hydraulic conductivity, and soil depth above individual sensors.

A comparison of the SMD between 2018 and 2019 indicates that 2018 had a slightly drier summer compared to 2019 (Figure 7). The same trend is observed within the slide mass matric suction at 0.9 m below ground (BG), where the seasonal minimum suction was lower in 2019, indicating a higher soil water content. The year over year differences in matric suction correspond to antecedent precipitation, an inherent component of the SMD calculation. By estimating the SMD monthly, it was possible to conduct a side-by-side comparison of the SMD and the soil water content (correlated to suction) over several years.

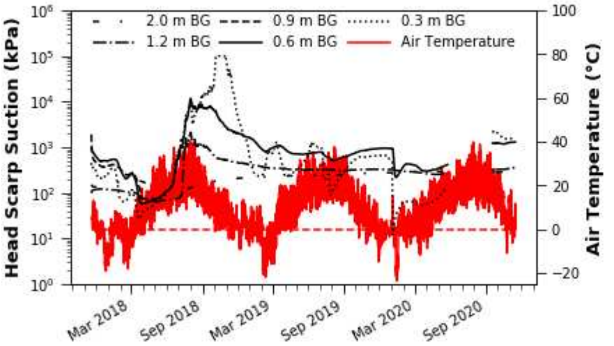

Figure 5. Seasonal variation in head scarp suction (BG – below ground)

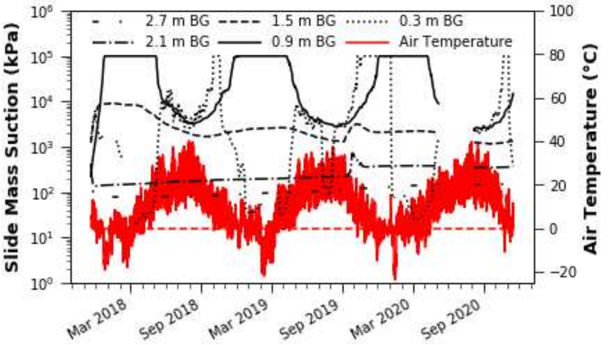

Figure 6. Seasonal variation in slide mass suction

Prior to the monitoring of the soil matric suction and water content at the Ripley Landslide, there was consistent meteorological data collection. This data was used to calculate the SMD over a 5-year period. The calculated SMD was then compared to the measured SAA displacement at 257.1 masl (Figure 8). The SMD indicates wet years (lower peaks) and dry years (higher peaks). An increased displacement rate event for the Ripley Landslide occurred in February 2017 following a particularly wet year (2016). While the seasonal maximum and seasonal minimum river levels were approximately identical between 2015/16 and 2016/17, the increased displacement was delayed until 2017 (Figure 8). Therefore, the drier year is 2015 prevented the large increase in displacement observed in 2017 which followed the wetter year with a lower peak in the SMD (2016). The buttressing effect from the relatively high seasonal minimum river elevation in winter 2017 (263.4 masl) would have benefited, not hindered, stability when compared to other years. The following year (2018) was especially dry during summer, leading to minimal displacement. The movement resumed when the SMD declined. Seasonal changes in river elevation have an important impact on seasonal changes in displacement rate, as shown by the flattening of the displacement rate during high river levels (Figure 8). However, seasonal maximum and minimum river elevation do not always provide the best early warning system to anticipate displacement. The time series in Figure 8 demonstrates that displacement is often influenced by multiyear trends in soil water content (as indicated by SMD trends), rather than solely influenced by the seasonal changes in river elevation and hydraulic gradients.

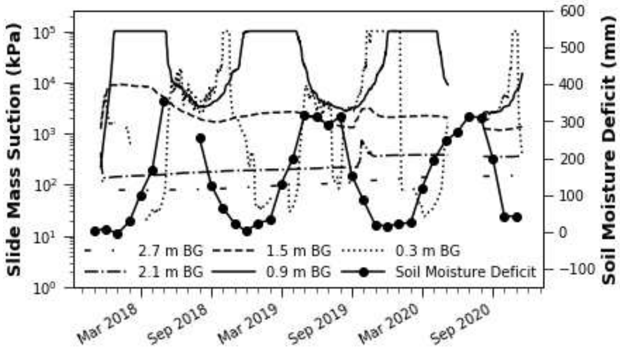

Figure 7. Slide mass suction related to soil moisture deficit

5 CONCLUSIONS

Slope stability is a primary concern when river elevation approaches its seasonal minimum. Similarly, snowmelt, precipitation, and ground thaw are also critically important if they coincide with the seasonal minimum river elevation. The soil is particularly susceptible to higher rates of infiltration in early spring as evaporation is minimal; plants are dormant; and the soil water content is relatively high due to the melting of accumulated snow at ground level and the thaw of near-surface groundwater. Increased water content along the upper reaches of the slip surface reduces the matric suction and promotes increased displacement rates.

A combination of techniques demonstrates that the upper reaches of the Ripley Landslide are susceptible to increased water content in the early spring. Visual plots from an in-place ERT monitoring network shows seasonal drops in soil electrical resistivity that correspond to increased soil water content. Placement of the ERT across tension cracks in the field illustrate the depth and extent of seasonal infiltration entering the head scarp of the Ripley Landslide. Matric suction sensors quantify the impact on stability of the ERT data which provide relative changes in water content with time. Furthermore, the suction instrumentation demonstrates that suction in the head scarp remains relatively low (< 1500 kPa) throughout the year when compared to the matric suction in the slide mass (> 1500 kPa).

A combination of standard atmospheric variables was used to calculate the SMD over several years. While meteorological data is becoming more readily available across the world, matric suction instrumentation still requires laborious field work. Therefore, the SMD was related to the matric suction using measurements from a local weather station. The results demonstrate that soil suction follows a similar pattern to the SMD, although it is somewhat delayed. When the SMD was plotted against landslide displacements over a period of several years, it was shown that increased cumulative displacement

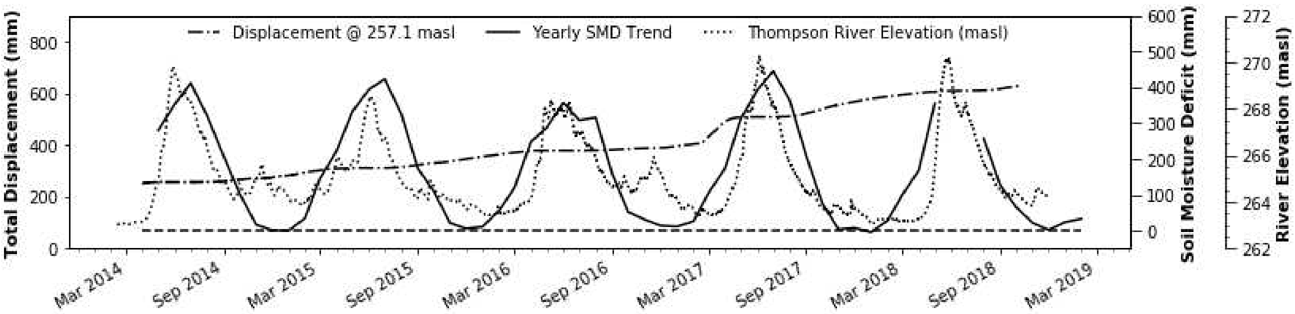

Figure 8. Lateral SAA displacement in BH13-02 at the slip surface (257.1 masl) compared to soil moisture deficit and river elevation

followed wet years, as indicated by the SMD trendline. Analysis of the SMD trends at the Ripley Landslide demonstrate that this early warning method clearly indicates conditions that resulted in the increased displacement rate of February 2017. The same displacement event would not be anticipated from studying the time series of maximum and minimum river levels from the Thompson River. Future monitoring of the SMD can be used to provide advanced warning of increasing trends in soil water content which pose a risk to landslide stability. Forewarning of increased risk is financially beneficial when planning annual rail maintenance budgets.

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