Instrumenting and Monitoring a Slow Moving Landslide

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Challenges from North to South
Des défis du Nord au Sud

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ABSTRACT
The performance of instrumentation in moving landslides has always been a challenge in the geotechnical industry. Movements can cause issues relating to shearing of cables or the breaking of grout used for installation. The Ripley Landslide near Ashcroft, B.C., Canada has been previously investigated using sand-pack piezometers and slope inclinometers. An investigation and monitoring program was carried out in April 2013. Grouted-in piezometers and a Shape Accel Array was installed during this investigation. The river elevations were derived from a rating curve. Pore pressures were compensated for the effect of barometric variation. The displacement and pore pressure values were validated to ensure that the values recorded could be used for further analysis.

RÉSUMÉ
Une instrumentation performante lors de glissements de terrain a toujours constitué un défi pour l'industrie géotechnique. Les mouvements peuvent causer la rupture des câbles ou du mortier utilisé pour l'installation. Précédemment, le glissement de terrain de Ripley, près d'Ashcroft, en Colombie-Britannique, a été étudié à l'aide de piézomètres à filtre en sable et d'inclinomètres. Un programme d'étude et de surveillance a été mené en avril 2013. Des piézomètres scellés et un ensemble d'accéléromètres de forme (SAA) ont été installés lors de cette étude. Les hauteurs de rivière ont été suppléées par une courbe d'étalonnage. Les pressions interstitielles ont été corrigées vis-à-vis des variations barométriques. Les valeurs de déplacement et de pression interstitielle ont été validées afin que les mesures puissent être utilisées pour une analyse ultérieure.

1 INTRODUCTION

The Thompson River Valley in southern British Columbia is a critical corridor for the rail transport of goods in Canada. There are 14 landslides located within the valley between Spences Bridge and Ashcroft. The slides range in volume from 0.6 x 10^6 m^3 to 15 x 10^6 m^3 (Hendry et al. 2014). The area has been studied in the past with the goal of better understanding the mechanisms of these landslides and manage the associated risks in a proactive manner (Macciotta et al. 2014; Clague and Evans 2003; Eshraghian et al. 2007).

In all of the Ashcroft landslides, the surface topography is dynamic and constantly changing. The loading conditions are also changing as the river rises and falls with seasonal changes in flow. The dynamic nature of these landslides result in frequent changes in pore pressures and displacement rates. Frequent, accurate, and reliable instrumentation readings are required to develop an understanding of the mechanisms driving the movement. These instruments must survive the localized shearing within the moving slide mass.

Previous monitoring of the Ripley Slide has relied on traditional slope inclinometers and sand-pack piezometers. Both of these instruments had a short-term life expectancy at Ripley. This paper presents the results from detailed monitoring of the pore pressures using grouted-in vibrating wire piezometers and shear displacements using the Measurand Shape Accel Array (SAA) technology. The pore pressures measured with the grouted-in piezometers were validated with measurements taken using sand-packed piezometers; and, the SAA measured displacements are compared to conventional SI measurements. The paper describes the methodology used to validate the pore pressures and shear displacement as the slide velocity changes.

2 THE RIPLEY LANDSLIDE

The Ripley Landslide is among the smallest identified landslides along the Thompson River Valley at 1.0 x 10^6 m^3 (Eshraghian et al 2007; Hendry et al. 2014). Figure 1 shows the location of the slide.

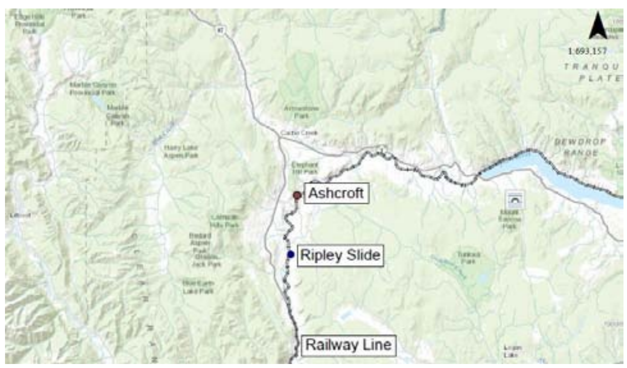

Figure 1: Location of the Ripley Slide south of Ashcroft; with major rail routes through southern BC (after Stanton 1898).

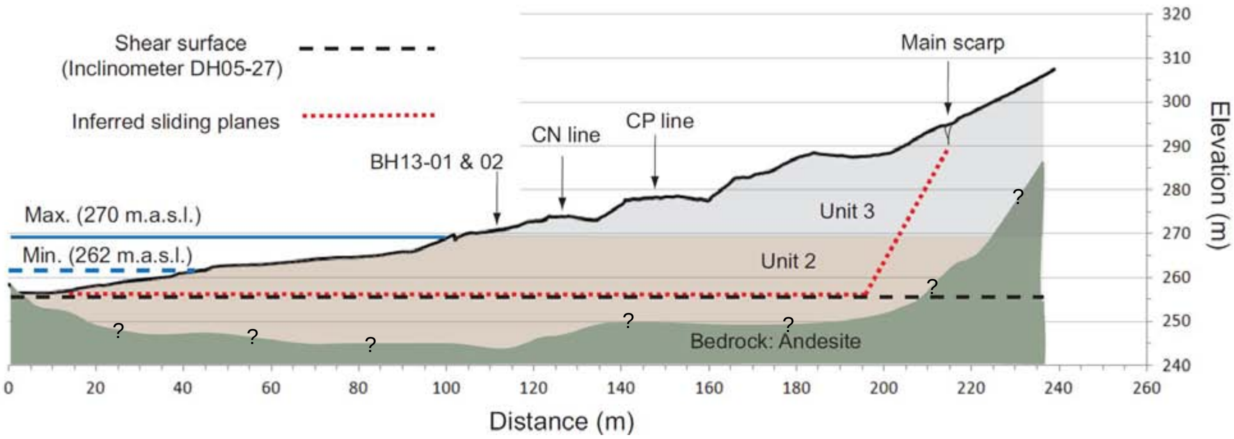

Figure 2: Section view of the Ripley Landslide showing stratigraphy of the slide and the distinct failure surface which occurs in glaciolacustrine clay deposits (after Hendry et al. 2014).

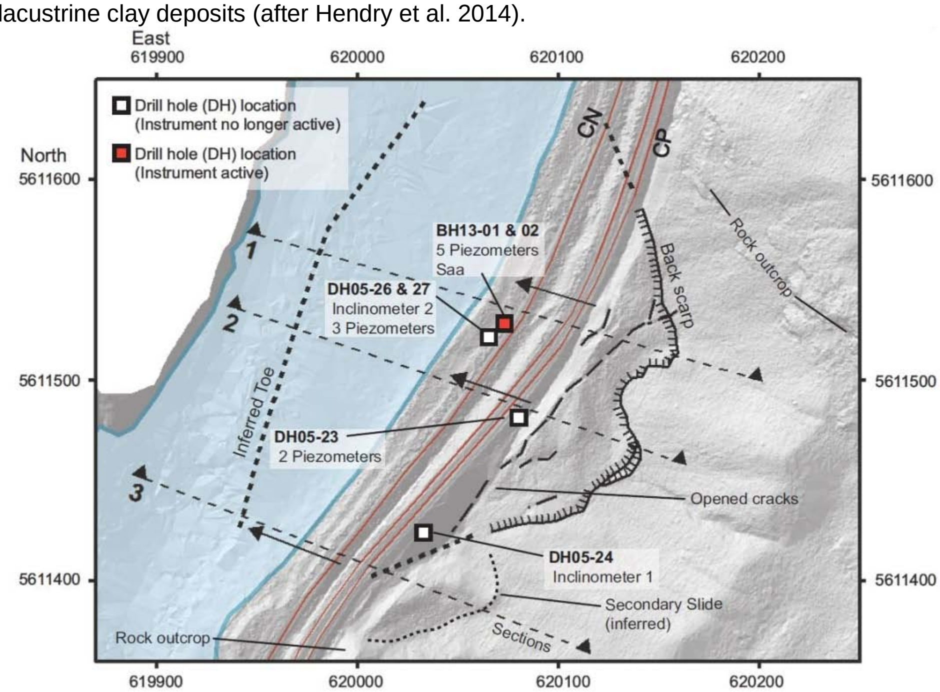

Figure 3: Plan view of the Ripley Landslide showing the location of previous monitoring equipment as well as the location of the currently active instrumentation (after Macciotta et al. 2014).

2.1 Stratigraphy

The stratigraphy of the Ripley Landslide has been established in previous investigations carried out by both Canadian Pacific Railway (CP) and Canadian National Railway (CN). The stratigraphy of the region is discussed in detail by Clague and Evans (2003).

Figure 2 shows a simplified cross section of the landslide. The instrumentation discussed in this paper is located downslope from the CN line at an approximate elevation of 272.8 m. At this elevation, there was a veneer of alluvial floodplain sediments (0 m to 2.3 m depth), underlain by a layer of glaciolacustrine sediments (2.3 m to 30.5 m depth), and an andesitic bedrock. The glaciolacustrine deposits encountered were deposited following two different periods of glaciation. The first deposit occurred in the Pleistocene and can be found below 10.5 m depth. The remaining glaciolacustrine sediments are assumed to have been deposited prior to the Pleistocene glaciation.

2.2 Previous Monitoring Programs

There have been various sampling and monitoring programs carried out at the Ripley Landslide. CP constructed a new rail siding in 2005. Inclinometers and sand-pack piezometers were installed on the site and monitored for movements of the slope. Figure 3 shows a plan view of the site with the location of the various monitoring holes that were drilled.

Based on the previous pore pressure and displacement data there were two very important conclusions that the current monitoring data will address:

a) Inclinometer readings identified the location of the distinct shear plane. The landslide appeared to be moving along a basal shear surface. The shear zone occurs at an approximate elevation of 257 m in Pleistocene glaciolacustrine clay deposits (Unit 2).
b) An upward gradient was also observed on the site. The highest piezometric elevation was recorded in the fractured bedrock beneath Unit 2.

These observations from the past investigations will be used in verifying the new instrument readings obtained using different technology.

3 CURRENT MONITORING

Two boreholes (BH13-01 and BH13-02) were drilled during the 2013 investigation near the same location as DH05-26 & 27 in Figure 3. This location was chosen to be concurrent with the inclinometer in DH05-27 as the shear zone was well defined at this location.

Data was gathered on the site using a remotely accessed data acquisition system. Hourly readings of five fully grouted vibrating wire piezometers and a SAA have been recorded continuously since May 2013.

The five vibrating wire piezometers were installed at depths of 11.3 m, 14.9 m, 15.8 m, 20.4 m, and 32.6 m below ground surface. An additional piezometer was installed in the river to record the variation of river elevation over time. Each piezometer has a rated capacity of 350 kPa and an accuracy of ± 0.35 kPa.

Figure 4 shows the finished instrument installation and data logging equipment.


Figure 4: Piezometer and Shape Accel Array installation at the Ripley Landslide in April 2013.

The SAA was used as an in-place inclinometer to allow for continuous and remote monitoring of the shear zone displacements. The SAA at Ripley was installed from an elevation of 261.2 m to 251.5 m. The location of the shear plane was identified by previous slope inclinometers (Hendry et al. 2014).

4 MONITORING RESULTS AND CALIBRATION

The pore pressure measurements from the fractured bedrock as well as the shear zone are plotted versus time in Figure 5. There are other piezometers at various depths within the glaciolacustrine clay. These additional piezometers are not essential to the analysis and were therefore omitted. The piezometer measuring the river level is also plotted. The plot does show the relationship between the measured pressures and the river level. Certain issues needed to be addressed before any further analysis could take place:

a) The incomplete river level data was the result of the river level dropping below the elevation of the piezometer for a large portion of the year and a premature failure of the piezometer in 2014.

b) The unprocessed pore pressure data had a significant amount of high frequency variation that was observed in all of the piezometers.

4.1 River Elevations at the Ripley Landslide

The Thompson River annually changes elevation at Ripley by up to 6 m in response to the spring melt in the surrounding mountains. This rise in the river level starts in late April to early May and occurs over a two month period. Consistent and strong correlations have been observed between the river elevation and the movement of the slide (Hendry et al. 2014). However, to determine if these correlations are occurring through the year, the continuous river elevation was needed throughout the year.

A well-calibrated rating curve can estimate the variation of river level throughout the year based on measured flow data. A rating curve requires river discharge volume to calculate an approximate river elevation. There is a river monitoring station installed at Spences Bridge, 30 km downstream of the Ripley landslide, which measures the river discharge volume every 20 minutes (Environment Canada 2013). It has been previously assumed that the river monitoring station at Spences Bridge could be used as a proxy for the river elevations at Ripley.

The river discharge data from Spences Bridge was previously used to develop a rating curve to estimate the river elevation at Ripley (Hendry et al. 2014). The accuracy of this curve was difficult to determine as the river level was only surveyed on three occasions during the monitoring period.

The river piezometer provided approximately 3,500 data points. The rating curve was altered based on this larger database of river elevations. The adjustment was made by computing the residual sum of squares of the power law with respect to the piezometer data. The revised rating curve is defined by Eq. 1.

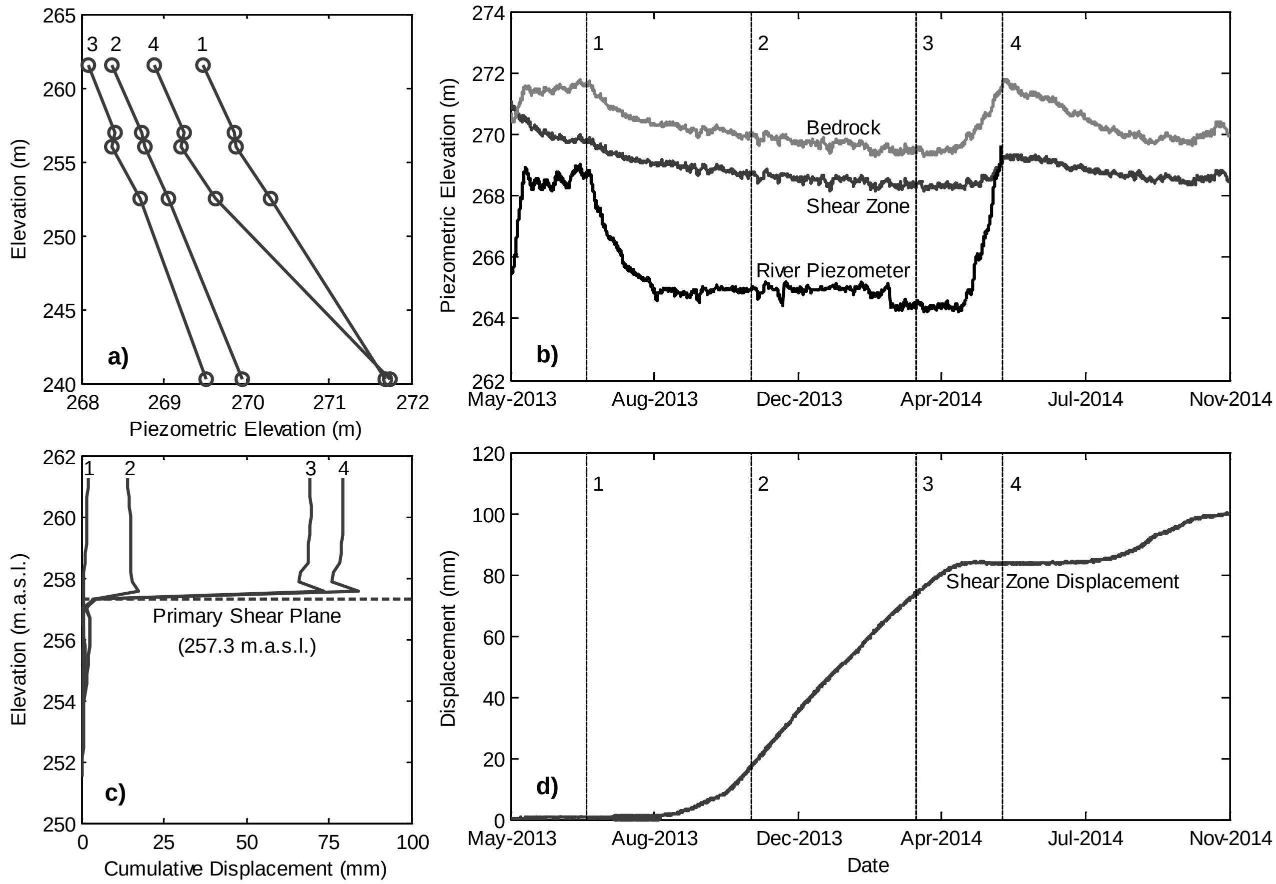

Figure 5 : Raw instrumentation data from the Ripley Landslide; (a) Variations of pore pressures with depth at various times; (b) Seasonal variation of piezometer; (c) Displacement with depth from SAA readings at various times; (d) Displacement measured across the primary shear zone at an elevation of 257.3 m over time.

$$Q = 74.110(L - 261.50)^{1.779} \quad [1]$$

The measured water levels are presented in Figure 6 with the revised rating curve. The three river elevations used to calibrate the previous rating curve are also plotted (EHD Consulting Ltd. 2008).

The revised rating curve has a higher datum by approximately 1.1 m. The previous rating curve was calibrated based on the three plotted values from EHD Consulting Ltd. (2008). Note that one of those measurements is an outlier and it is well below the curve developed from the piezometer measurements. The previous rating curve datum was skewed by this low point. The cause of the anomalous point is unknown. The data at higher flow rates also departs from this trend. This could be attributed to unsteady flow conditions at high discharge volumes (Dottori et al. 2009). A comparison of the recorded river level to the level predicted by the revised rating curve yielded a maximum difference of 0.3 m. This agreement led to the conclusion that the rating curve could be used to predict the river level throughout the year.

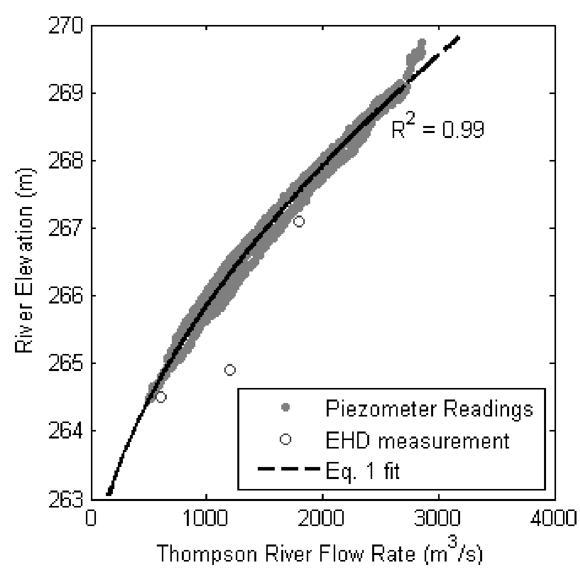

Figure 6: Correlation between river elevation measurements and flow rate of Thompson River at the Ripley Landslide.

4.2 Barometric Compensation

The unprocessed river piezometer data had a significant amount of high frequency variation when the river level was below the piezometer, i.e., the piezometer was out of the river. This variation was attributed to barometric variation as the piezometer was dry at this time. Many of these variations were also observed at the same time in the piezometers, which were grouted in the borehole. This led to the hypothesis that the apparent noise in the pore pressure data was at least partially the result of barometric pressure.

Manufacturer literature (Slope Indicator 2013) states that barometric correction is not required in a sealed borehole such as those installed in 2013. To confirm the hypothesis regarding the effects of barometric variation, a simple analysis was performed.

The raw pore pressure and barometric pressure data (Environment Canada 2013) were filtered using a 10-day moving average which removed the high frequency variation of each data set. The difference between the raw data and the filtered data was then compared to determine if the high frequency variation of pore pressure corresponded to the high frequency variation of barometric pressure. Figure 7 shows a portion of this data.

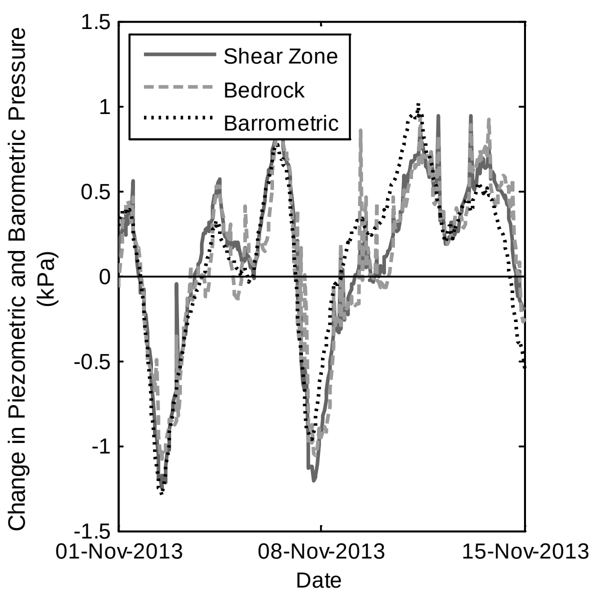

Figure 7: High Frequency Variation of Pore Pressure and Barometric Data

The value of barometric variation was multiplied by a scalar factor of 0.8 to match the amplitude of the pore pressure variation. The high frequency variation resulting from barometric pressure change can be compensated for by subtracting the barometric variation from the raw pore pressure data.

5 DATA VALIDATION

The Ripley Landslide has previously been monitored using sand-pack piezometers and inclinometers. The lifespan of these instruments was short. As newer technologies and installation methods were selected for use with the 2013 investigation, the resulting measurements needed to be validated.

5.1 SAA Displacement Data

Inclinometer casings, 70 mm in diameter, installed in the past were unusable within a year of installation. BGC Engineering made the recommendation of an alternative displacement detection system (2007).

An SAA was installed over a portion of the stratigraphy. The location was selected based on the previous investigations (Hendry et al. 2014). There was a second shallower zone of movement observed in the SI data which was potentially not captured by the SAA.

A Global Positioning System (GPS) displacement monitoring system was installed at the Landslide in 2008 to measure the surface displacement (Bunce and Chadwick 2012). Table 1 presents a simple comparison of the two displacement monitoring methods.

Table 1. Comparison of horizontal displacement monitoring methods (Macciotta 2015).

Monitoring Period	SAA (mm)	GPS (mm)
May 2013 to Oct 2013	6	15
Oct 2013 to April 2014	71	47
April 2014 to Oct 2014	17	18

The authors attribute the difference between the GPS and SAA to the different locations of the monitoring instruments. This comparison is based on horizontal displacement and does not take into account any vertical component recorded by the GPS. The movement of the shear zone in the various monitoring periods appears to be proportional to the movement of the surface. In both techniques the movements in the summer months are smaller than the winter months. The yearly movement rate appears to be within the range of rates previously determined by slope inclinometers (Macciotta et al. 2014).

Based on the comparison of these results, the SAA provides valid periods of active movement. In addition, the SAA data can also be used to verify the relative amount of movement in a given period.

5.2 Fully Grouted Piezometers

The main benefit of the use of fully grouted piezometers is the simplicity and speed of installation (McKenna 1995). Comparisons of the measurements of fully grouted piezometers to those from sand-pack piezometers have been completed (Mckenna 1995; Contrreras et al. 2008). Past studies have recommended against using fully grouted piezometers in areas where movement is expected (Mckenna 1995). The primary concern with deformation is the potential for vertical cracks forming which could cause piezometers to communicate.

There are two other concerns with the use of fully grouted piezometers. These concerns are the proper selection of the grout mix and the accuracy of the initial measurements. These concerns are addressed through examination of the current monitoring.

Grout Selection

The grout mix selected for a piezometer installation is very important. Theoretically, the grout mix should have the same permeability and stiffness as the adjacent soil (Contreras et al. 2008). The effect of the grout would be negligible if the properties matched the soil.

The grout mix used during the piezometer installation was the mix recommended for medium to hard soils (Mikkelson 2003). The stiffness and permeability of the glaciolacustrine clays have not been tested extensively. This match will need to be assessed once more testing can be performed.

Initial Equalization Time

The initial weight of the fluid grout resulted in very high initial pressure readings that diminished over time. These high pressures diminished very quickly in the bedrock and are not observed in the raw data. The piezometer installed in the clay initially showed these initial high pressures. This is demonstrated by the initial high readings of the shear zone in Figure 5b. These readings gradually dissipate and eventually follow a similar trend as the pressures in the bedrock.

The reason these initial high pressures are only observed in the clay is of interest and should be discussed. Hvorslev (1951) describes the concept of the Stress Adjustment Time Lag. The concept is that stress changes at the location of the sensor will alter the moisture content and pressure of the soil adjacent to the sensor. The stress changes can result in lower or higher pressures depending on the installation.

There is a stress change effect expected both from the advance of the borehole and the placement of grout. The net response of the soils to these stress changes will be different depending on the permeability of the soil.

The placement of the grout is potentially the reason for a higher than equilibrium pressure in the clay. The placement of fresh grout would result in a higher fluid stress than the adjacent soil initially experienced. This will result in high pressures in an area around the sensor. This assumes that the permeability of the clay leads to an undrained response to the grout placement.

Time is required for the disequilibrium pressures to dissipate. The stress adjustment time lag is a function of permeability of the soil (Hvorslev 1951). This is a logical dependence, as water needs to seep either into or out of the adjacent soil to equilibrate the pressures. This explains why the initially high pressures were not observed in the bedrock. The higher permeability of the fractured bedrock would allow any excess pressures to dissipate quickly.

The time required for this seepage also depends on if the sensor is installed within a sand-pack or is grouted-in. In the case of a sand-pack piezometer, the seepage water can drain into the sand-pack as pressures equilibrate. In the case of a grouted-in piezometer, there is no high permeability area that facilitates pressure dissipation. Excess pressures will likely dissipate much more rapidly in a sand-pack piezometer.

The time required for the disequilibrium pressure in the clay to dissipate is difficult to determine. The pore pressure readings in the clay appear to match the seasonal trends observed in the bedrock within two months of installation.

Grout cracking

Another concern for the use of grouted-in piezometers is the formation of cracks within the grout as slide movement occurs. Piezometers installed at various depths would be able to communicate if cracks were to form. The communication of piezometers would make the identification of any gradients essentially impossible and potentially skew the estimated location of the phreatic surface.

The Ripley Landslide has a significant upward gradient which has been measured in both the sand-pack and grouted-in piezometers. Analysis of these gradients with time has not identified any hydraulic connections between these piezometers. This is very evident in Figure 5a where piezometer communication would be represented by a vertical line. Hence, at present there is no evidence that grout fracturing, if it has occurred, has reduced the confidence in the data from the grouted-in piezometers.

Based on the discussion of the various potential issues associated with grouted-in piezometers, it can be concluded that the monitoring results provided by these instruments are valid. These results are representative of the pore pressures in the soil which they are monitoring.

6 CONCLUSIONS

Confidence in data from instruments that monitor localised deformation and pore pressures can be reduced when the monitoring medium is a moving landslide. This is particularly a concern when new technologies are introduced and these technologies rely on the integrity of brittle materials to house the instruments. The Measurand SAA and grouted-in piezometers were trialed at the Ripley Slide to provide continuous hourly monitoring of the slide movement and pore pressure changes.

A rating curve was developed based on a correlation of river discharge and the measured river levels. The pore pressures recorded also required barometric compensation before further analysis could be performed.

The SAA displacement monitoring technology proved to be a valid indicator of the periods of activity and provided relative amounts of movement. The SAA is providing a longer duration monitoring period compared to traditional slope inclinometers.

The grouted-in installation method of the piezometers was discussed. It was concluded that the piezometers provided valid results by addressing the various issues associated with grouted-in piezometers. The observation of an upward gradient also indicated that vertical cracks have not formed in the grout over the current monitoring period.

The validation of the displacement and pore pressure readings will allow for further analysis and interpretation.

There is enough confidence in the instrument readings to continue to analyze the Ripley Landslide based on these new results.

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