Monitoring of the Ripley Landslide in the Thompson River Valley, B.C.

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ABSTRACT
The Ripley Landslide is located along a strategic railway transportation corridor in British Columbia. It moves along a discrete shear surface at a rate between 25 and 180 mm/year, making it a very slow landslide. The importance of a proactive risk mitigation strategy for the landslide lies in the potential consequences to the railway transportation network if a sudden downslope movement occurs. A downhole ShapeAccelArray (SAA) has been installed to enhance the real time monitoring capabilities of a previously deployed Global Positioning System (GPS) monitoring system. Also, ground-based LiDAR and Satellite InSAR are being used to monitor changes in the slope's surface shape and displacement patterns. A preliminary assessment of the compatibility between the displacements measured with all of these technologies at the Ripley Landslide suggests that a reliable and comprehensive hazard management approach can be achieved through a monitoring and early warning system that combines different technologies.

RÉSUMÉ
Le Ripley Landslide est situé le long d'un corridor de transport stratégique en Colombie-Britannique. Elle glisse le long d'une surface de cisaillement discrète à un taux compris entre 25 et 180 mm/an, ce qui en fait un glissement de terrain très lent. L'importance d'une stratégie d'atténuation des risques proactive pour la lame se trouve sur les conséquences potentielles pour le réseau de transport ferroviaire si un mouvement brusque vers l'aval se produit. A cet effet, un ShapeAccelArray fond (SAA) a été mis en œuvre pour améliorer les capacités réelles de contrôle du temps d'un système de suivi GPS précédemment déployé. Aussi, LiDAR terrestre et satellite InSAR sont utilisés pour surveiller les changements dans la forme de la surface et de déplacement des modèles de la pente. Une évaluation préliminaire de la compatibilité entre les déplacements mesurés avec toutes ces technologies à la diapositive Ripley suggère qu'une approche de réduction des risques fiable et complète peut être obtenue par un système de surveillance et d'alerte précoce qui combine différentes technologies.

1 INTRODUCTION

The Ripley Landslide (Figure 1a) is a soil slide located in the Thompson River Valley in the Province of British Columbia. This Valley hosts an important railway corridor that connects the city of Vancouver and its port with interior of British Columbia and the other provinces of Canada to the east. Both Canadian Pacific (CP) railway and Canadian National Railway (CN) use this corridor, as such it is vital for the economic health of the region.

As shown in Figure 1a, the Thompson River Valley south of Ashcroft hosts several landslides that have been examined by Stanton, 1898; Clague and Evans, 2003; Eshraghian et al., 2007; Eshraghian et al., 2008; Bishop et al., 2008 and others. Some of these soil slides have volumes of up to 15,000,000 m^3; in comparison the Ripley Landslide's estimated volume of 750,000 m^3 is relatively small. However, because CN's and CP's track traverse this landslide, it requires a proactive hazard management approach.

The Ripley Landslide moves at a rate between 25 and 180 mm/year, thus defined as a very slow landslide according to Cruden and Varnes' (1996) classification system. The deforming mass is approximately 200 m long and 40 m from the highest detected open crack to its toe, the width is approximately 300 m (Figure 1b).

The Landslide was first identified in 1951 by Charles Ripley (Leonoff and Klohn Leonoff Ltd., 1994). Since then, the landslide has either been inactive or moving so slowly that regular maintenance of the track has kept up to the deformations (Bunce and Chadwick, 2012). CN and CP have both recognized the need to increase our understanding of the mechanisms of and triggers for the slope movement, as well as to implement a monitoring system for hazard control. See also Bobrowsky et al. (in press) and Huntley et al. (in press) for additional details regarding monitoring at this site.

1.1 Previous Studies and Slope Behaviour

In 2005, CP constructed a new rail siding that required slope cuts and the construction of a lock-block retaining wall. As part of the geotechnical investigation and monitoring for the construction, four boreholes were cored and two inclinometer casings and five vibrating wire piezometers were installed. Shortly after, deformations

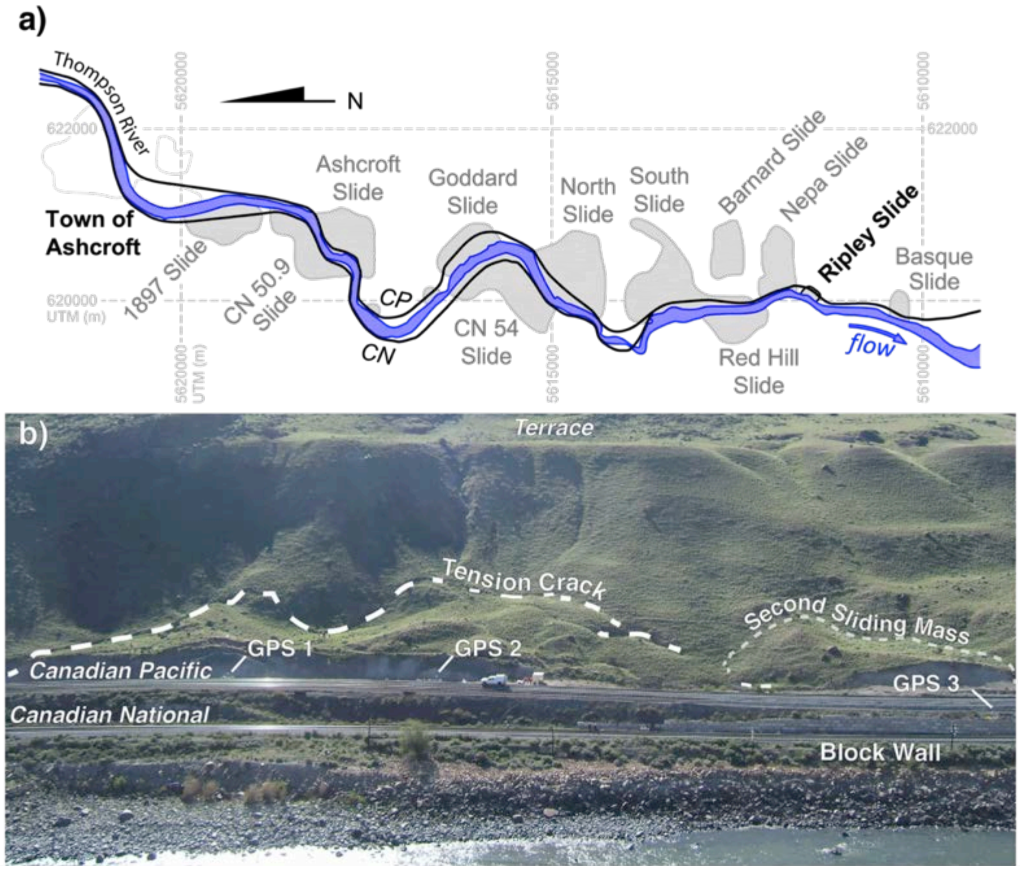

Figure 1. (a) Location of the Ripley Landslide and (b) extent of the landslide after Hendry et al. (in press)

were noticed at the newly constructed lock-block wall, and the inclinometer casings sheared within 17 months (Hendry et al., in press).

In 2007, survey pins were installed on the slope to monitor the landslide surface displacement. In 2008, a Global Positioning System (GPS) was installed to provide continuous measurements of the landslide displacement and to develop an early warning system (Bunce and Chadwick, 2012).

Figure 2 shows a plan view of the Ripley Landslide and interpreted features from some of the available monitoring data and site investigations. The locations of both active and inactive instruments are also shown in Figure 2. An analysis of the displacement monitoring data and piezometric elevations within the slope leads to the following conclusions:

a) The Ripley Landslide is sliding along a weak, basal shear surface within a high plastic clay layer. The materials within the moving soil mass are developing secondary steep shear surfaces.

b) The elevation of the horizontal sliding surface is coincident with the bottom of the riverbed or slightly below. Thus, the continued down cutting of the river may result in further instability.

c) There is an upward hydraulic gradient at the base of the sediment layer containing the slide base.

d) The pore pressures within the landslide are defined by both the regional hydrogeological regime and the elevation of the Thompson River (Bishop et al. 2008). When the river is at its highest level, the slope displacement rate is at its lowest. This would correspond to an increased stability of the landslide most likely due to a combination of a buttressing effect of the river and the increase in mobilized shear strength with increasing effective stress along the sliding surface.

CP completed a risk assessment of the Ripley Landslide which compared the risk to life and the environment with the cost of stabilizing the slope. It was decided that the risk to life and the environment was extremely low and that stabilizing the slope was costly, may not be effective, and could have a substantial negative impact on the Thompson River (Bunce and Chadwick, 2012). A Global Positioning System (GPS) based monitoring and early warning system was adopted to manage the risks associated to the operations and to increase the understanding of the deformation mechanisms and potential triggers for sudden movement.

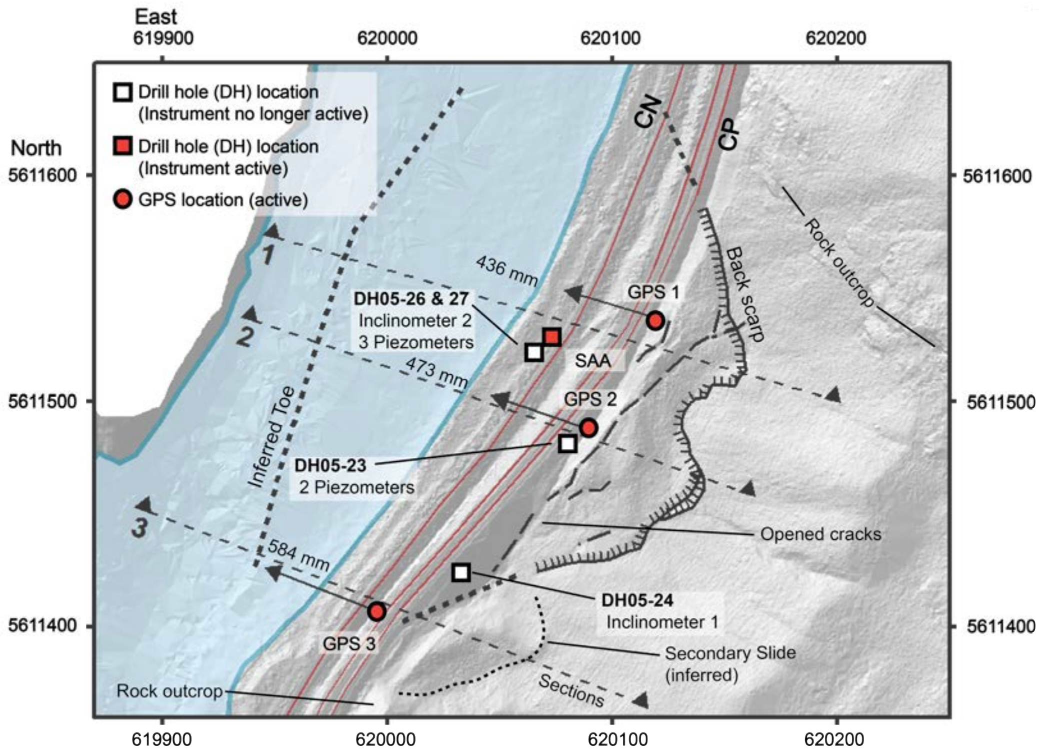

Figure 2. Plan view of the Ripley Landslide. The features of the landslide are interpreted from the available monitoring data and site investigations. The locations of the instrumentation for the active and inactive instruments are also shown (modified from Hendry et al., in press)

2 ONGOING MONITORING

The monitoring instrumentation at the Ripley Landslide was enhanced in May 2013. A Measurand Inc. ShapeAccelArray (SAA) was installed within a borehole cored in the vicinity of a previous inclinometer (Inclinometer 2 in Figure 2). Six vibrating wire piezometers were also installed to replace those that had been damaged and to provide continuous monitoring of pore pressures within the slope. During the installation of this instrumentation, a continuous core sample of the soil was taken down to the bedrock. Laser scans of the slope were also taken from across the Thompson River. The scans had an average 10 cm resolution. These scans were combined with the existing bathymetry of the Thompson River beds and used to generate a digital elevation model. The plan view in Figure 2 was generated from this model. The following section presents some of the instrumentation installed for the monitoring of slope displacement patterns and preliminary results.

2.1 GPS Monitoring System

An array of GPS antennas was installed in 2008 to provide continuous measurements of the movement of the slide. The system consisted of three GPS monitoring stations (Figure 2) and one reference station located on stable bedrock outside the landslide area (Bunce and Chadwick, 2012). The Leica GPS stations installed use single-phase receivers in a differential GPS mode. The system was designed to detect 12.5 mm of cumulative ground movement with a variability of ± 1 mm.

Leica GeoMOS software was used to retrieve the GPS data. The data can be manipulated to produce vector diagrams of displacement, velocities, accelerations, and longitudinal and vertical displacements. Figure 3 shows the cumulative displacement measured by the three GPS stations between October 2010 and January 2014. The horizontal displacement in the direction of slope movement increases towards the positive values, and the vertical settlement increases towards the negative values. The GPS data in Figure 3 are the result of a 24-hour running average of hourly location measurements.

These measurements suggest that the landslide is moving towards the Thompson River at an average velocity of 70 to 100 mm/year over the monitoring period. The displacement rate appears to be increasing from the northern portion of the landslide (70 mm/year in GPS 1) towards the south (100 mm/year in GPS 3). The rate of vertical settlement also seems to be increasing towards the south portion of the landslide. GPS 1 and 2 show about 25 mm/year of vertical settlement whereas GPS 3 is settling at about 80 mm/year. Both the horizontal displacements and the vertical settlements show a seasonal deformation trend that accelerates in the cold months and is near zero in the warm months. During the active period of the landslide, the average horizontal displacement rate is between 0.2 and 0.35 mm/day.

2.2 ShapeAccelArray (SAA)

An SAA was installed in May 2013, within a borehole located in the toe of the slope (Figure 2). It consists of an array of rigid segments separated by flexible joints. Gravity sensors in the rigid segments measure the tilt of the segment. Cumulative displacements relative to the SAA tip can be calculated knowing the tilt and length of each segment.

Figure 4 shows the cumulative horizontal displacement with depth measured by the SAA. The shear surface identified by the SAA is at an elevation between 256 and 257 m. Both the magnitude of displacements and the elevation of the shear plane in Figure 4 are consistent with the GPS measured displacements and inclinometers. The vertical displacement profiles are sequenced in (approximately) one-month intervals.

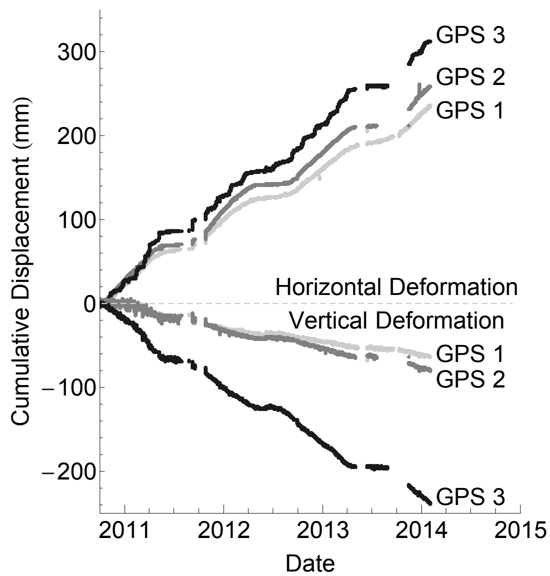

Figure 3. Cumulative displacements measured by the three GPS stations in the horizontal plane in the direction of slope movement (positive) and vertical settlement (negative). The data correspond to the period between October 2010 and January 2014

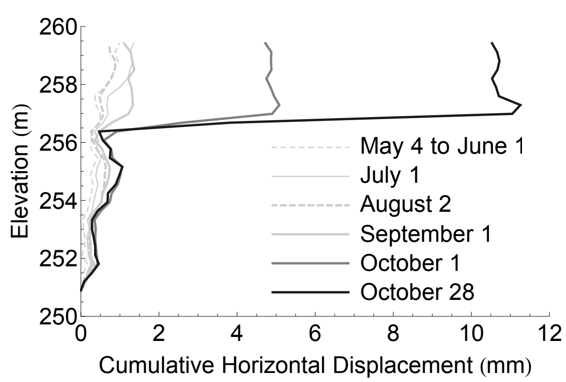

Figure 4. Cumulative horizontal displacement with depth measured by the SAA between May 4 and October 28, 2013

The horizontal displacement in Figure 4 suggests that the velocity of the slope increased in August to September of 2013. This would correspond to a velocity approaching 0.2 mm/d by October 2013.

2.3 Satellite InSAR

A three-year (2013-2016) project for monitoring the surface displacements at the Ripley Landslide using satellite imagery was initiated in September 2013 by the Geological Survey of Canada. For this project, ultra-fine beam mode RADARSAT-2 imagery is being acquired and Interferometric Synthetic Aperture Radar (InSAR) technology is being used to estimate the ground displacements. The imagery has a 3 m spatial resolution (size of one pixel as detected by the radar) that is accurate enough to detect ground objects and features. The system allows for displacements to be measured along the line of sight between the terrain and the satellite which is primarily vertical. Such measurements can then be presented as the vertical component for interpretation. The time between measurements depends on the satellite's orbit.

Nine corner reflectors were installed to facilitate radiometric and geometric calibrations of the satellite-based SAR data (Figure 5).

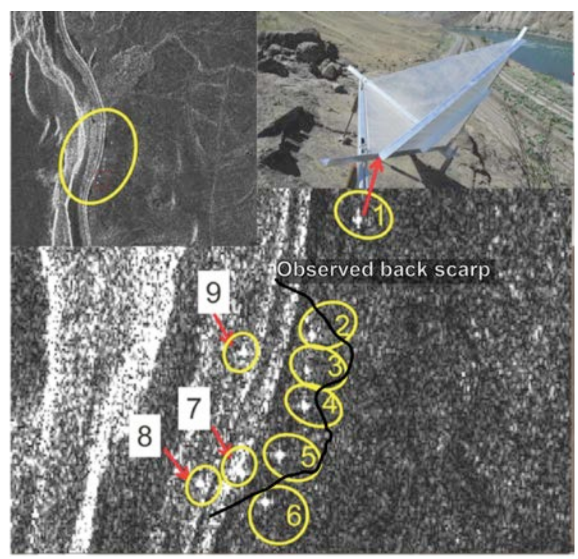

Figure 5. The nine corner reflectors are clearly visible in the RADARSAT-2 images.

Six RADARSAT-2 images were acquired between September and November 16, 2013. Preliminary InSAR processing was performed for a 48-day period (September 8 to October 26, 2013).

The preliminary results of this project have identified the active area of the Ripley Landslide. Corner reflectors 1 and 6, and the areas where they are located (Figure 5) did not show signs of deformation during this period. These reflectors were located beyond the observed tension cracks, and these results are consistent with the previous interpretation of the landslide extents. According to these preliminary results, the greatest measured displacement occurred at the toe area with 9.0 mm of vertical displacement. This would correspond to 68.5 mm per year. Less displacement was measured at the region near the back scarp.

2.4 Ground-Based Laser Scanning

The Ripley Landslide was scanned with an Optech ILRIS 3D laser scanner from the west side of the Thompson River in July 2013. The average resolution of the scan was 10 cm (1 laser point every 10 cm). The accuracy of the system is sub-millimetric under ideal conditions. However, weather effects (incremented by the presence of the Thompson River at the toe of the slope) and the grass on the slope decreases this accuracy and the approach can not be used to track slope displacements for warning purposes. The objective was to obtain a detailed digital elevation model (DEM) of the slope that would be the basis for further interpretation of the kinematics of deformation and stability analyses. This initial DEM can also be used as a datum against which future scans can be compared and general slope changes in the surface be detected (changes in roughness and differential movements).

2.5 Comparison of the Displacement Measurements

A comparison of the landslide displacements measured by the GPS system, the SAA and the Satellite Interferometry was performed. Figure 6 shows the Ripley Landslide displacement between October 2012 and January 2014. The displacements measured by the GPS system were plotted relative to October 2010. The SAA is located in the proximity of GPS 1 and 2 (Figure 2). The initial reading of the SAA was set as that of GPS 2 on the same date (212 mm on May 4, 2013). Figure 6 shows that the total displacement measured by the SAA is consistent with the horizontal displacement measured by GPS 2 and has the same trends as those measured by all three of the GPS units.

The preliminary results from the InSAR show a maximum vertical displacement near the toe of the slide of about 9 mm between September 8 and October 26, 2013. The maximum settlement recorded by the GPS system was at GPS 3. As such, the initial vertical displacement for the InSAR should be comparable with GPS 3. Figure 7 shows the vertical displacements recorded by the three GPS stations between October 2012 and January 2014, as well as the maximum vertical displacement measured by the InSAR and as expected the InSAR displacements appears to be consistent with the vertical displacement recorded by GPS 3.

3 MONITORING AND VELOCITY BASED EARLY WARNING SYSTEM

The slope failure scenario being considered is an increase in velocity over a period of days or weeks, leading to excessive deformations and potential collapse of the slope. The ideal monitoring system would provide notice of an increase in slope velocity before collapse.

The seasonal displacements measured by the GPS system in Figure 3 appear to have consistent trends from year to year. From the displacements measured to date the maximum velocities of up to 0.5 mm/day and 0.8 mm/day are manageable with current rail maintenance programs. This suggests that changes in the landslide behaviour could be noticed with an early warning system based on an unseasonably high slope velocity.

Both the GPS system and the SAA have the capability to provide measurements with the temporal resolution for this application. However, the accuracy and variability of the measurements constrains the confidence in the measured velocities. The following analysis of the GPS and SAA data quantifies the variation of the measurements and the time intervals required for the identification of a change in velocity.

3.1 Variability of GPS Measured Velocity

The 24-hour running average of hourly velocity measurements from GPS 1 is shown in Figure 8. The variability in these data is in the order of ± 5 mm/day. The variability in the GPS measurements is attributed to the constantly changing availability of satellites for measurement, their line of sight with the GPS system, and weather conditions. This is excessive for an early warning system for a slide showing a displacement rate of less than 1 mm/day. The high variability in the measured GPS displacements makes it difficult to monitor any trend change within a 24-hour period.

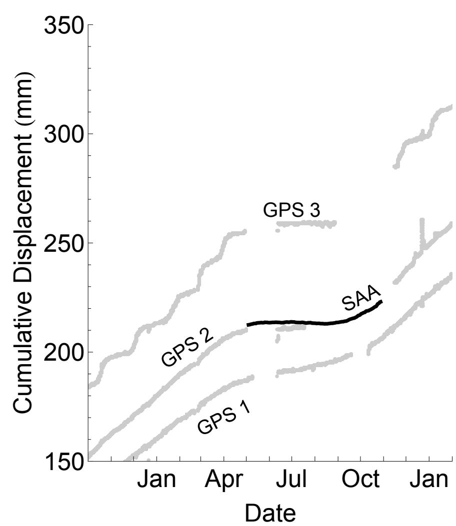

Figure 6. Cumulative horizontal displacement measured by the GPS and the SAA between October 2012 and January 2014. GPS displacements are cumulative starting October 2010

The hourly GPS positioning data can be processed and filtered to reduce this variability. This processing consists of the removal of outliers (> 20 mm of displacement between measurements) and a filtering of the velocities with a running average. A running average over different lengths of time was applied to the measured GPS displacements. The time windows considered were 1 day, 3, 7, 15 and 30 days. The variations of the running averages were estimated by assuming the 60-day running average of the GPS positions is a good indicator of the true displacement trends. The seasonal variation of the landslide velocity was visible in the 15-day averaging but obscured in the 1-day averaging. The 1-day averaging showed that the variation of the velocities is between -0.3 and 0.8 mm/day for GPS 2 and 3, and between -0.3 and 0.6 mm/day for GPS 1. The 15-day averaging showed less than ± 0.1 mm/day of variability. The variation of the measured velocity versus the duration of the sampling window is plotted in Figure 9.

To have confidence in the measured change in the slopes velocity, the movement must be well in excess of the variability of the measured values. For the purpose of this analysis it was assumed that a change in velocity twice that of the variation is reasonable to detect.

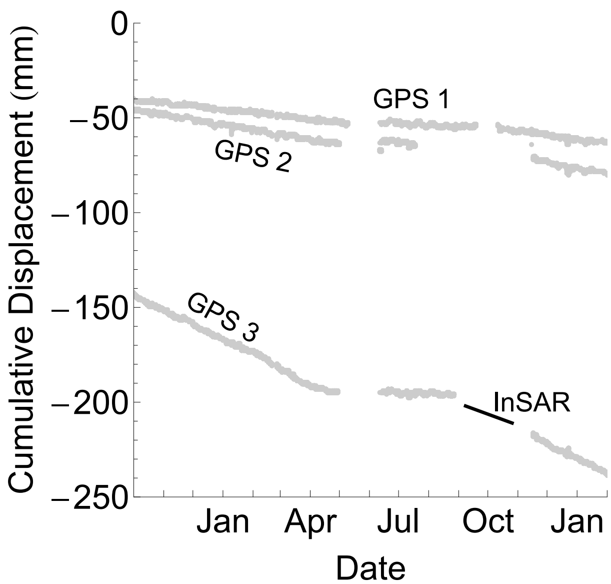

Figure 7. Cumulative vertical displacement measured by the GPS and the InSAR between October 2012 and January 2014. GPS displacements are cumulative starting October 2010

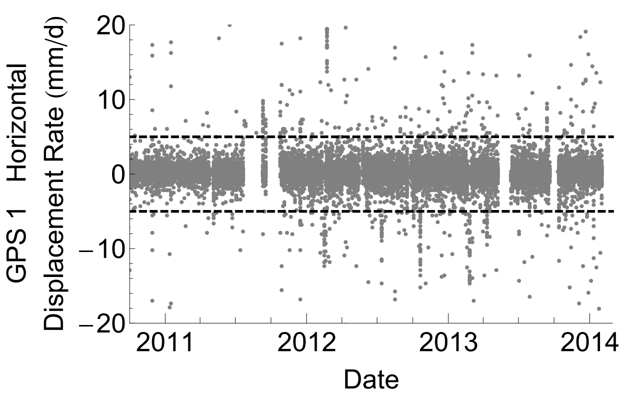

Figure 8. 24-hour running average of GPS 1's displacement rate. Data corresponds to hourly GPS positioning measurements

From Figure 9: a 1-day running average has a variability of ± 1.15 mm/day, therefore the increase in velocity that can reasonably be measured is 2.30 mm/day, or 290% to 460% more than the current peak velocities; a 7-day running average has a variability of ± 0.25 mm/day, therefore the increase in velocity that can reasonably be measured is 0.5 mm/day, or 63% to 100% more then the peak velocities; and a 15-day running average has a variability of less than ± 0.1 mm/day, therefore the increase in velocity that can reasonably be measured is 0.2 mm/day, or a 25 % to 40 % increase over the peak velocities.

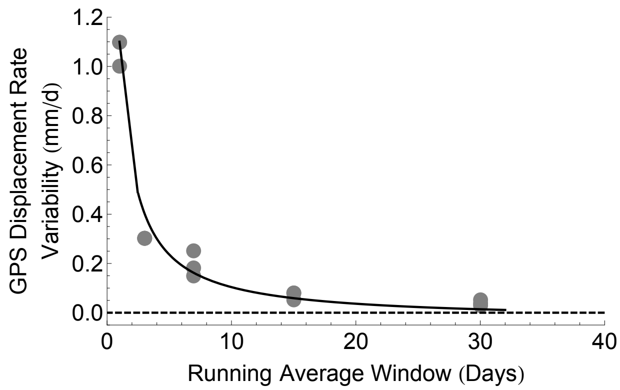

Figure 9. Displacement rate variability for running averages of different time windows. The variability was measured as the dispersion of values around the trend for the 3 GPS units

3.2 SAA Velocity Monitoring

The SAA displacements were measured every hour, but have been averaged for a 24-hour period. Figure 10 shows the average velocity determined between pairs of filtered measurements (24-hour interval). Comparing Figure 10 to Figure 8 confirms that velocities determined from the SAA are far less variable than those determined from the GPS. Figure 10 clearly shows a trend of slow horizontal displacement followed by acceleration between mid August and the end of October 2013.

From Figure 10, the velocities determined from a 24-hour interval have a variability of approximately ± 0.1 mm/day, the increased in velocity that can reasonably be measured is 0.2 mm/day, or a 25 % to 40 % increase over the peak velocities. This increase in velocity is approximately the same as that shown in Figure 10 between the start of August 2013 and the start of October 2013.

These preliminary results suggest that the GPS system would require significantly more time to confidently identify an increase in velocity than the SAA system. A small increase in slope velocity that the SAA can measure in one day would require almost two weeks for the GPS system to identify.

However, from the variation of the GPS measurements, the GPS system should be reliably able to measure a change in the slope velocity of 0.6 mm/day, during which time only 1.8 mm of displacement will occur.

Dangerous rates of movement are in the 15 mm/day range or an order of magnitude higher.

There are also limitations with the SAA system. The deformations on the shear plane are being measured over one SAA segment of 0.305 m in length. When an SAA segments rotates to more than 45° from the horizontal the accuracy declines. This requires that the SAA to be replaced every ~200 mm of movement, which at the current rate of movement would be every 2 to 2.5 years.

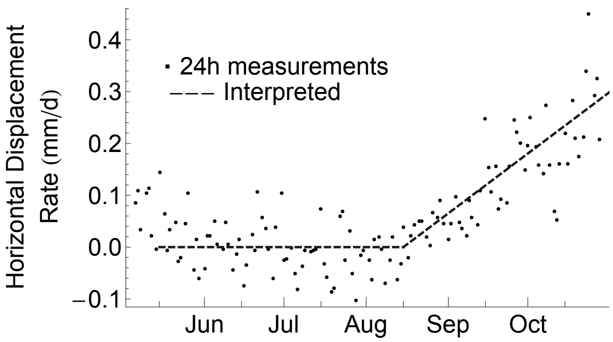

Figure 10 Horizontal displacement rate (mm/day) averaged over a 24-hour period and its interpreted trend between May and October 2013

4 CONCLUSIONS

The Ripley Landslide displacement is being monitored through several approaches, four of which are presented here. The GPS monitoring system provides real time measurements of the position of three locations on the surface of the landslide. The SAA provides real time slope displacement with depth at one location. The Satellite InSAR provides the relative displacement map over the landslide surface. The ground-based LiDAR allows for changes in the slope shape to be monitored in detail. Results of the GPS system and preliminary results of the SAA and the InSAR are presented in this paper. The outcome of the first LiDAR scan is also presented; however, tracking slope changes requires multiple future scans.

The assessment of the monitoring compatibility of these systems at the Ripley Landslide is based on a short period of time and should only be considered as preliminary. However, these initial results are encouraging. The current monitoring and early warning capabilities provided by the GPS system at the Ripley Landslide is adequate for a scenario where the slide shows an increased velocity over weeks before a sudden downslope movement. Variations over shorter periods of time (within a week) are masked by the variability of the data. The use of SAAs appears to be an appropriate enhancement of the system that allows for monitoring slope displacements with depth and monitoring changes in the displacement rates in short periods of time. Enhancing the early warning system with data provided by the SAA can increase the reliability of the system by making it more robust and will increase the ability to identify a scenario where a sudden downslope movement is preceded by a relatively short period of acceleration.

The addition of Satellite InSAR and ground-based LiDAR images provides a means of monitoring slope displacement trends and geometric changes on the entire surface of the slope. These will increase our understanding of the mechanisms and kinematics of the Ripley Landslide. The displacement measured by the InSAR as well as the features highlighted by the ground-based LiDAR confirm the extent of the Ripley Landslide as inferred from previous investigations.

Further analyses of the Ripley Landslide behaviour are being undertaken and will continue in light of newly acquired data. The ultimate objective is to achieve a reliable and comprehensive risk control strategy for the railway operations in the corridor. The occurrence of a sudden displacement of the Ripley Landslide could lead to excessive deformations of the railway track or collapse of the slope. These can compromise the safety of operations and are considered the main scenarios for hazard and risk control. As such, enhancement of the monitoring and early warning system will focus on the detection of sudden slope movements that could potentially compromise the safe operation of railway traffic.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the contribution of Canadian Pacific and Canadian National Railway for providing both the project and funding. This research was made possible through the (Canadian) Railway Ground Hazard Research Program and the Canadian Rail Research Laboratory (www.carrl.ca), both of which are funded by the Natural Sciences and Engineering Research Council of Canada (NSERC), CPR, CN, and Transport Canada. Both BGC Engineering and Ian Chadwick from EDH Consulting contributed greatly to this analysis through the results of their investigations and monitoring. The authors would like to thank the Cooks Ferry Indian Band for allowing access to Basque Ranch during this study. The corner reflectors were acquired and installed with funding from the Geological Survey of Canada, and Transport Canada.

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