Cost-effective Landslide Monitoring GPS System: Characteristics, Implementation and Results

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ABSTRACT

Several methods are available for displacement monitoring and early warning for potential sudden movements and for improving our understanding of landslide kinematics and mechanisms. Available instruments for landslide monitoring include Inclinometers, extensometers, prism surveys, ShapeAccelArrays, RTK GPS surveys, laser scanning (TLS and ALS), and radar interferometry. All these have advantages and limitations, and the costs of installation and operation often limit these technologies to very few locations on the landslide or infrequent measurements. A recently developed GPS system technology, named Geocubes, can provide high-resolution displacement measurements at lower costs than earlier GPS technologies. This paper presents the characteristics of this system, details of their installation and operation, and the displacement measurements at the 10-mile landslide in BC.

RESUMÉ

Plusieurs méthodes sont disponibles pour la surveillance du déplacement et l'alerte précoce pour les mouvements soudains potentiels et pour améliorer notre compréhension de la cinématique et des mécanismes de glissement de terrain. Les instruments disponibles pour la surveillance des glissements de terrain comprennent les inclinomètres, les extensomètres, les levés de prisme, les ShapeAccelArrays, les levés GPS RTK, le balayage laser (TLS et ALS) et l'interférométrie radar. Tout ceci a des avantages et des limites, et les coûts d'installation et d'exploitation limitent souvent ces technologies à très peu d'endroits sur le glissement de terrain ou à des mesures peu fréquentes. Une technologie de système GPS récemment développée, nommée Geocubes, peut fournir des mesures de déplacement à haute résolution à des coûts inférieurs aux technologies GPS antérieures. Cet article présente les caractéristiques de ce système, les détails de leur installation et de leur fonctionnement, ainsi que les mesures de déplacement au glissement de terrain de 10 milles en Colombie-Britannique.

1 INTRODUCTION

Transportation corridors through the Canadian Cordillera are exposed to landslides. These pose a risk to highway users, vehicles, rail operations, equipment, and infrastructure. In this regard, landslide monitoring and early warning is vital along hazardous sections of these transportation corridors. The remoteness of some of these corridors and hazardous sections, and the requirement for real-time information; require monitoring strategies that can capture large areas, flexible and simple installation and operation, easy to maintain, and be remotely accessed, providing near real-time information. Different technologies can be used in combination to provide these requirements, including Inclinometers, extensometers, prism surveys, ShapeAccelArrays, RTK GPS surveys, laser scanning (TLS and ALS), radar interferometry and UAV photogrammetry (Smethurst, 2017).

Currently, remote sensing technologies such as Light Detection and Ranging (LiDAR) and Interferometric Synthetic Aperture Radar (InSAR) can provide high displacement accuracy over a large areal extent. However, LiDAR can have a medium to low temporal resolution not suitable for early warning, and ground-based InSAR is limited by vegetation and by logistics associated with power requirements. These limitations are matter of continuous research (Williams et al. 2017, Lato et al. 2016).

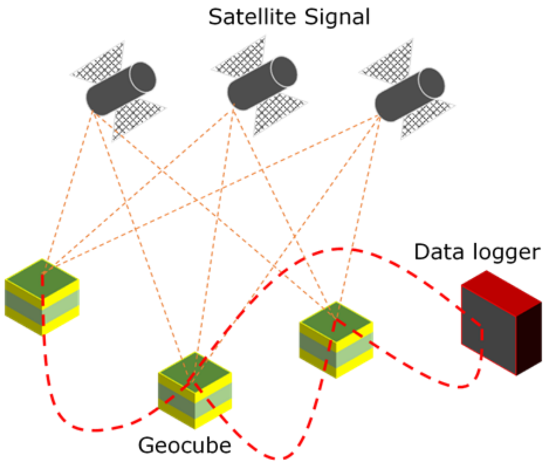


Figure 1 Principle of Geocube Network, based on Kylia (2016a, 2016c)

Monitoring systems for landslides continue to be developed and improved. The development is allowing for automated systems that collect measurements at high frequencies (several measurements per hour) allowing for near real-time monitoring of displacements and displacement rates. Moreover, unit costs of some instruments have reduced following technological advances such that extensive networks of instruments are becoming practicable. One such technology is a network of differential GPS systems, the Geocube^{TM} by Ophelia Sensors (Previously by GeoKylia^{TM}).

Recent studies highlight the influence of the frequency of monitoring in the characterization of landslide mechanisms. Williams et al. (2017) showed relationship between the frequency of scans using terrestrial LiDAR Scanning (TLS) and their resolution to detect geomorphological changes. Although laser scanning provides an increased understanding of the surface deformation patterns, complementary higher frequency monitoring systems are needed to understand short-term trends and early warning. The geocube technology can provide this complementary aspect to evaluate the evolution of landslides.

1.1 Geocube System

The geocube system is a network of monitoring GPS units (Figure 1). Each unit has a radio frequency antenna that allows communication with other units and a data logger. The system works by measuring the relative distance between one unit (reference point) and the other units in the network. Data collection corresponds to the three-directional component of movement in x, y, and z-direction. This network system allows for millimeter accuracy and high temporal resolution.

The current specification from Kylia allows up to 100 units to be monitored with one data logger with a maximum span of 15 km for the entire network. This amount of units allows monitoring large areas with one network system or monitor localized phenomena with a high density of units. Additionally, the maximum spacing between the units, under ideal weather conditions and free of obstructions, is up to 200 m with the use of an internal antenna (the default configuration), and 1000 m with an external antenna (Kylia, 2016b, Kylia, 2016c). The small dimensions of the system units and their installation requirements allow the individual units to be relocated as best suited to the landslide displacement trends.

This system has been deployed at two landslide locations in BC, the 10-mile slide and Ripley Slide. The objective of these trial sites is to evaluate the application of the system to monitor ground hazards, particularly on active landslides affecting transportation corridors in Canada. The implementation at the 10-mile slide involved 11 geocubes and one data logger (called Coordinator). The eleven geocubes are scattered on the upper and middle section of the slide as an effort to monitor the movement and retrogressive behavior of the slide (Figure 3). This paper presents the installation of the system, some of the challenges with the initial configurations and landslide displacement at the 10-mile slide.

2 THE 10 MILE SLIDE

2.1 Location and Geologic Context

The 10-mile slide is located within the Fraser River Valley, North East of the town of Lillooet, in southwestern of British Columbia (Figure 2). The slide is a smaller reactivated portion of an ancient post-glacial earthflow (Tunnel earthflow) (Bovis, 1985). The Tunnel earthflow is approximately 30 m deep at the location where a railway section crosses its deposits and reduces as the toe of the slide daylights near the Fraser river. These deposits consist primarily of layers of fine-grained sediment of clay, silt, and sand, with the presence of angular rock fragment varying from boulder to gravel size particles. The materials immediately below are glaciofluvial deposits with a thickness of approximately 10 m. These consist of gravel and sand (BGC Engineering Inc, 2016).

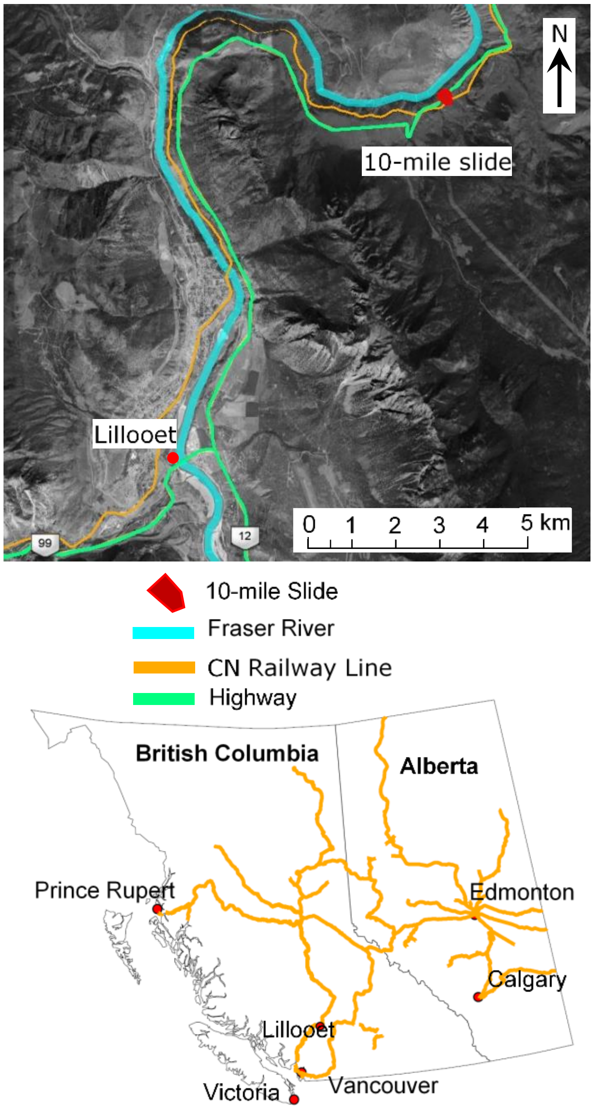


Figure 2 Location of the 10-mile slide, (Right photo, 2017 Digital Globe, Google Earth image)

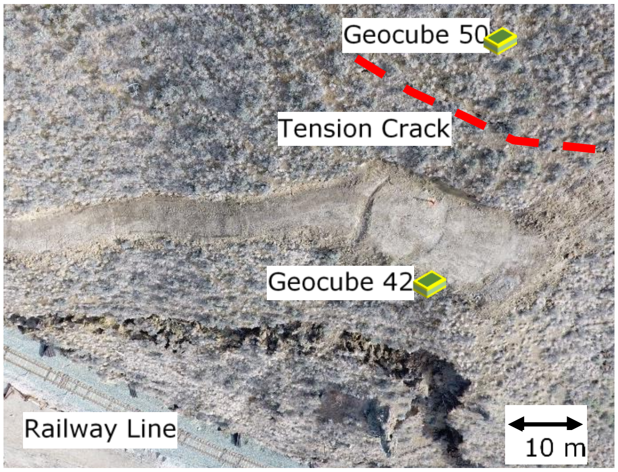


Figure 3 Location of Geocubes above the railway line and the highest tension crack

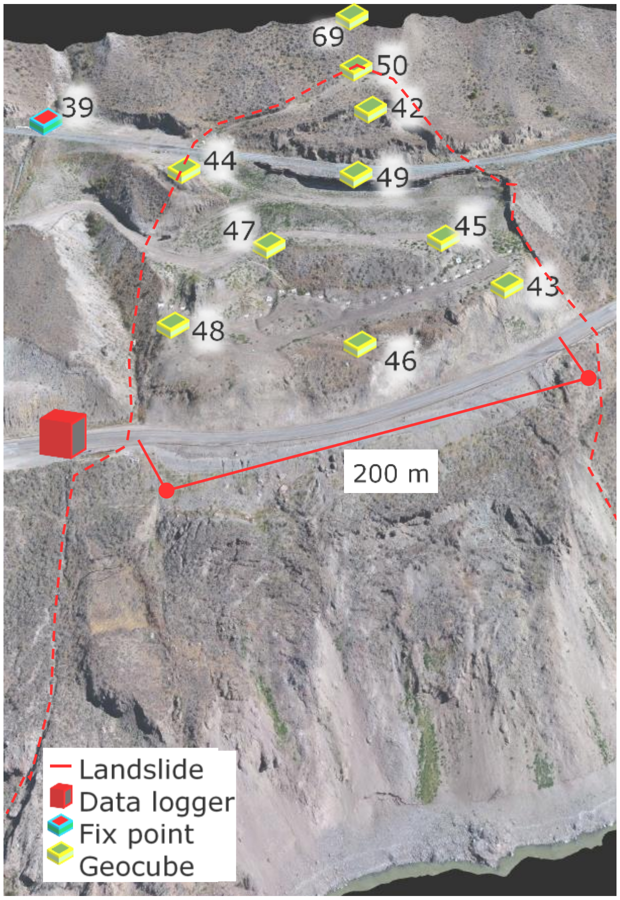


Figure 4 Front view of the 10-mile slide and distribution of Geocube network, DEM of the slide area

The slide was initially identified in the 1970's following observations of a tension crack below the highway (Gaib et al. 2012). Since the late 1980's, the landslide has been retrogressing uphill (Ministry of Transportation British Columbia, 2006). The highest identified tension crack is located 60 meters above the railway line. In the past 45 years, the slide has retrogressed approximately 200 meters upslope of the initial tension crack location. In Fall 2014, the slide movements increased in rate at the railway. Currently, the landslide is affecting Highway 99, a section of the Canadian National Railway (CN) Lillooet Subdivision, and First Nations land. Figure 4 shows a front view of the landslide generated from a digital elevation model in November 2017.

2.2 Landslide Characteristics and Displacement Patterns

The 10-mile slide is approximately 200 m wide and 140 m high, oriented to the North-West, with 750,000 m^3 of landslide deposit moving towards the Fraser River. The base shear zone is located within the deposits of the larger Tunnel earthflow. The depth of the shear zone was identified approximately at 18 meters below the surface and becoming shallower downhill, daylighting below the highway.

On the surface, the vegetation is mostly shrubs of up to 1 m height. This allows for adequate surface exposure for radar and LiDAR technologies.

Since the identification of the landslide, the surface conditions have continued to deteriorate, showing an increase in the number of tension cracks and sinkholes (Ministry of Transportation British Columbia, 2006). In the last decade, the displacement velocity has increased from 1 mm/day (Gaib et al. 2012) on 2006 to velocities of 6 mm/day in 2016 and recorded peak acceleration up to 10 mm/day (BGC Engineering Inc. 2016). Nonetheless, numerous control measures have also been implemented since the increment of movement velocity.

2.3 Applied Control Measures

Numerous efforts to maintain traffic along the highway and the railway line have followed the evolution of the landslide. These included highway and rail track realignment. Furthermore, the railway line needs to minimize track deformations to maintain safe operations. Some of the stabilization options adopted through the years include the placement of lock blocks to stabilize the ballast and railway embankment, placement of a shotcrete and soil anchor wall, and an H-pile timber lagging wall with soil anchors. Investigation has included Cone Penetration Tests, piezometer readings, and laboratory testing. Additionally, deformation monitoring included regular surveys of prisms at the H-pile wall and inclinometer readings, which have been complemented in the last ten years by aerial and terrestrial LiDAR scans (ALS and TLS).

The latest remediation work at the 10-mile slide occurred in the summer of 2016. The work completed by CN included 253 shear piles and 30 anchors installed below the railway line. Additionally, in the winter of 2017, 32 strands were installed by the BC MoTI above the highway as a temporary remediation measure to permit further realignment of the highway into the slide.

The 10-mile slide has been subject to several site investigations and instrumentation to characterize the mechanical properties and kinematics of the landslide (Ministry of Transportation and Infrastructure British Columbia, 2016). Studies are available that characterize the landslide movements, including those of Guthier et al. (2016), Carlà et al. (2017), and Lato et al. (2017).

3 GEOCUBE SYSTEM INSTALLATION AT THE 10-MILE SLIDE

3.1 Installation Details

The geocubes installed at the 10-mile Slide are shown in Figure 4. The installation consists of 11 geocube units, nine with internal antennas and two units with external antennas. Seven of the eleven geocubes are located within the slide (Nos. 42,43,45,46,47,48,49, Figure 4). Two units are located outside of the landslide near the border of the tension crack (Nos. 44, 50, Figure 4 and Figure 3). Another unit is located 30 m uphill from the uppermost tension crack (No. 69). The last unit is considered at a fixed location (No. 39 – reference point) 90 m outside of the slide (the positioning of the system over time verified the location, which has shown a variation of ±2 mm).

The distribution of the geocubes on the landslide reaches a maximum spacing between the geocube of 90 m between the Geocube 39 and Geocube 44. The maximum distance to the data logger is with Geocube 69 at 310 m.

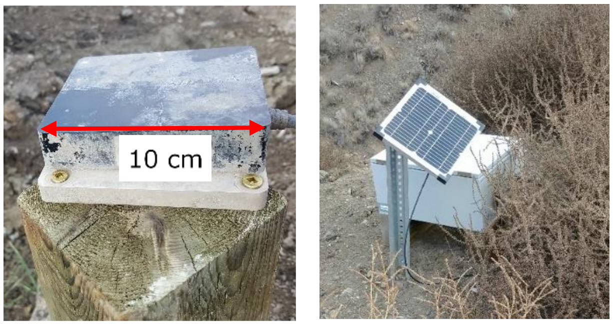
The units are installed on galvanized U-channel posts driven 1.0 m into the ground to avoid any external movement and sticking out between 30 cm and 100 cm above ground. The fixed point is bolted to concrete lock block 2.0 meters above ground. This installation is meant to be easily modified and to address signal problems within the geocube network or with the satellites. Power to each geocube unit is provided by 10 watt solar panels which charge two 100 mAh batteries. These batteries provide approximately 200 days of power without requiring recharge from the solar panel.

The data from each unit is collected every 60 seconds and stored in the data logger. Although the geocube network is designed to be accessed through an internet connection to have near real-time processing, the remote location and other future mitigation work of the site has made it challenging to provide a remote connection for the data logger. Thus, at this stage the data is being manually collected and post-processed periodically.

3.2 Considerations & Challenges

The application of the geocube monitoring system on the 10-mile slide has provided lessons on the applicability of the system to monitor landslide deformation.

Although the system has shown to be very flexible to terrain conditions as well as able to work on extreme temperature conditions, several difficulties have occurred during the implementation of the 10-mile slide. These difficulties involve weather and environmental conditions that can mask or interrupt the satellite signal and the data logger connection. At the 10-mile slide, the geocubes and solar panels had been subject to mud accumulation (Figure 5a) and snow covering the system. Also, thick vegetation has grown near the geocubes (Figure 5b). These problems required periodical cleaning the surface of the units and removal of vegetation.



a) b)

Figure 5 Field condition of Geocubes at the 10-mile slide.

Additionally, the valley landform and the orientation of the slide allows only limited sunlight to the solar panels during the winter, which is less than two hours a day in mid-winter. The sunlight conditions at the 10-mile and the requirements to have constant power supply for the data logger was resolved by accessing the power lines located on the highway. The geocube have individual powering box thus each unit had the maximum battery capacity.

4 DISPLACEMENT MEASUREMENTS AND COMPARISON WITH OTHER INSTRUMENTATION

The data from the geocube system requires signal processing which was done using MATLAB. This approach removes the initial uncertainty from the location computation of the geocubes and eliminates measurements outside of a defined threshold (identified as outliers). Details of this process are outside the scope of this paper, and the method for removing the outlier measurements should be assessed on a case by case considering landslide displacement rates and monitoring frequency.

4.1 GPS Displacements and Velocity

The data collected from the geocube showed to be scattered over time. The range between the maximum and minimum of data shows the scattering of data. The daily average range of movement in the X and Y horizontal components (local coordinate system) was +/-3 mm. The vertical component of movement had ranged +/-5 mm. The global coordinates depend on the accuracy of the coordinates of the fixed point. However relative displacements (incremental and cumulative) have a reference of zero at the time the monitoring is initiated. The high frequency of acquisition allows for improving the measurement accuracy. The accuracy of measurements was verified by calculating variability and precision of the data using the daily confidence interval and standard error of the mean. The confidence interval allowed evaluating the dispersion of the data within a 95% data sample. The standard error provided an estimate of dispersion of the sample mean by calculating the ratio between the standard deviation and the square root of the sample size The 95% confidence interval of the measurement data gives a range of about 0.025 mm and a standard error lower than 0.2 mm. Figure 6 illustrates the type of information obtained; the plot shows the average daily cumulative displacement in Geocube 46 and the standard error from all measurements between April and Nov 2017. Geocube 46 showed a maximum cumulative displacement of 400 mm by the start of November and a maximum standard error of 0.15 mm between September and October. Figure 7 shows the change in velocities of the Geocubes 46 and 43, located immediately above the highway cut.

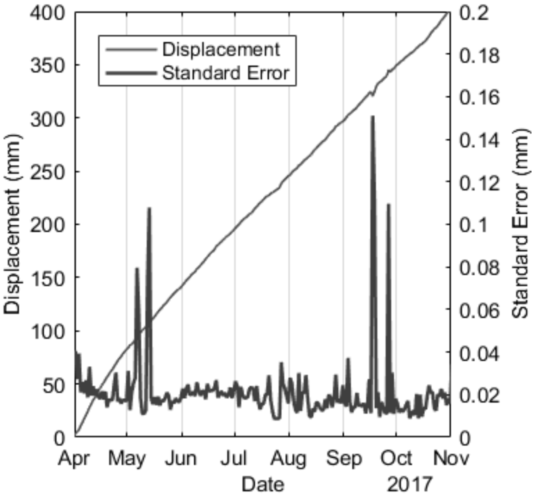


Figure 6 Cumulative displacement and standard error between April and November of 2017, for Geocube 46.

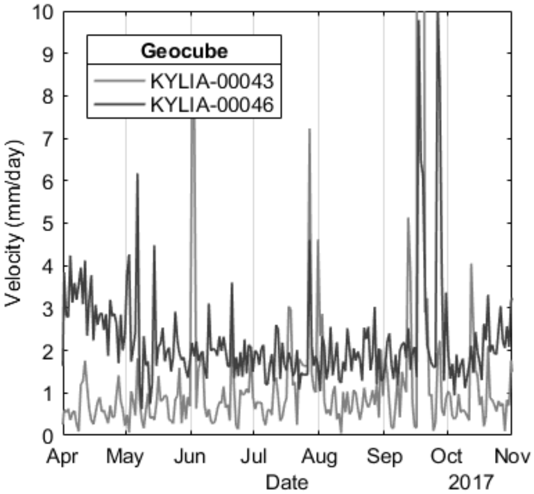


Figure 7 Daily average velocity between April and November of 2017, for Geocube 43 and 46.

4.2 Cumulative Displacements and Displacement Vectors

Monitoring between April and November of 2017 showed that left and central areas of the landslide (North West side) have the highest displacement magnitudes (Geocube 46, 47 and 48, Figure 8). At the center of the landslide and near the highway cut, Geocube 46 showed a 400mm displacement between April and November 2017. This is an order of magnitude larger than the geocubes at the south-west end of the slide. Similarly, Geocube 43 showed displacement of approximately 30 mm during the same time frame (see Geocube 43, Figure 8).

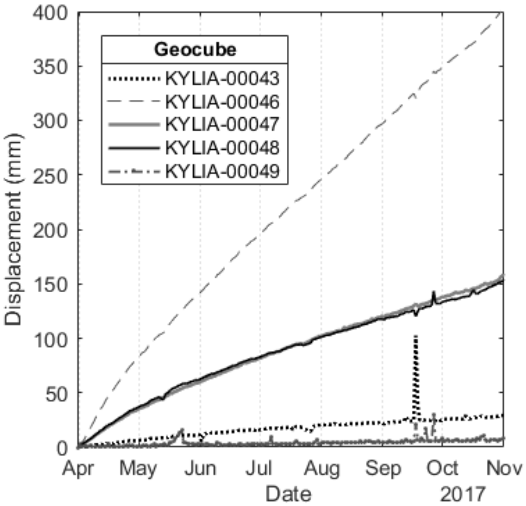


Figure 8 Cumulative displacement between April and November of 2017, for Geocube 43, 46,47,48,49

The relative cost of each geocube unit has allowed a dense array of GPS units at this site. High frequency data acquisition provides detailed quantification of the magnitude and orientation of the movement of the landslide in different areas. By combining the results obtained from the geocube network and a digital elevation model of the slide, we can visualize the different characteristics of the movement on the landslide. Figure 9 shows the scaled displacement vectors of the units in various sectors of the landslide. These results confirm previous understanding that the landslide is not moving as a continuous mass, but somewhat as independent blocks (Lato et al. 2016).

Monitoring also revealed that, although the movements of portions of the landslide are orientated towards the Fraser River and perpendicular to the strike of the slope (Geocube 46, Figure 9), the movement on the sides of the slide deviates away from the center of the slide. The displacement vectors along the entire section of landslide immediately upslope from the highway cut (Geocubes 43, 45, 46, 47, and 48) are all perpendicular to the local strike of the slope surface and slope cut.

The system has also given indications of performance of the system of shear piles installed immediately downslope the railway alignment in the summer of 2016. The measures taken in October of 2016 showed a decrease in the rate of movement upslope of the shear piles. The movement changed from 6 mm/day to 3 mm/day (measured through surveying prisms on a previously built retaining wall adjacent to the track). By April 2017, this movement decreased to an average of 1 mm/day (geocube system). Peaks in acceleration have occurred since May, which could be associated with observed surface strain below the piles (opening of tension cracks).

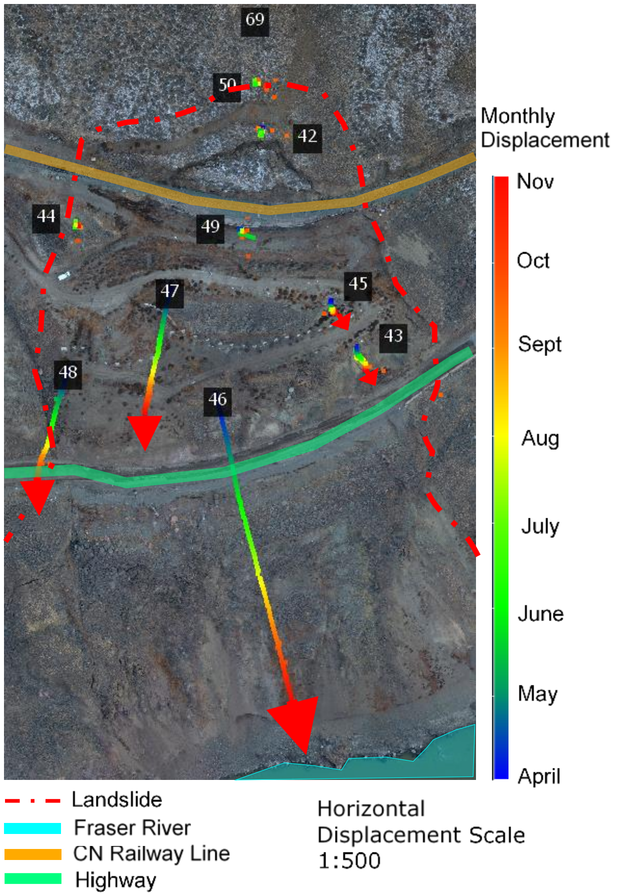


Figure 9 Movement vectors between April and November of 2017

4.3 Comparison with Manual Survey Using RTK GPS

Another survey method used to compare the geocube network measurements was the manual survey done by the BC Ministry of Transportation (MoTI) during the installation of the anchors above the highway. The MoTI installed monitoring points near Geocubes 46 and 48 above the highway and took readings twice a day during January. This information was superposed with the corresponding geocube readings (Figure 10). The comparison of both methods showed good agreement.

4.4 Comparison with Terrestrial Lidar Scanning (TLS)

The monitoring of the landslide using the geocube network has been complemented with Terrestrial LiDAR scanning (TLS). The TLS used a Long Range ILRIS scanner (Teledyne Optech Inc.) The scans have been taken across the valley from the 10-mile slide, at an average distance of 600 m and with an average spacing between measurement points of 3 to 6 cm.

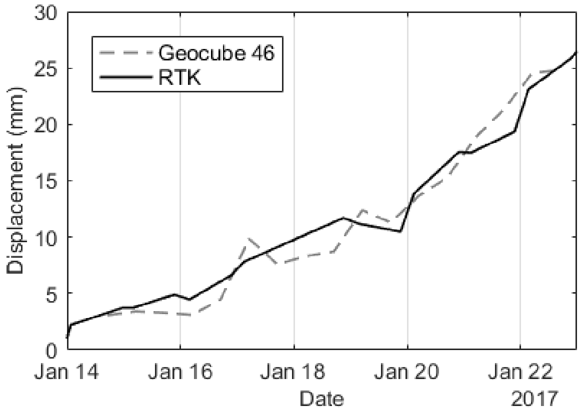


Figure 10 Displacement comparison between Geocube measures and RTK measures taken in January 2017

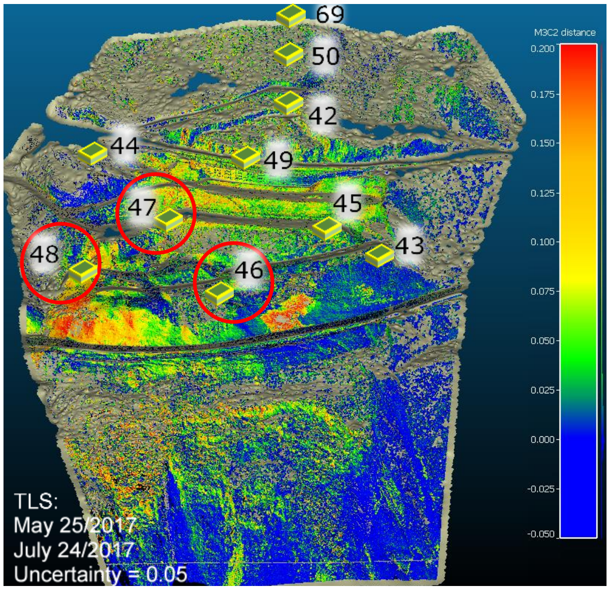


Figure 11 Comparison of cumulative displacement between the Geocubes and change detection between May and July 2017 from two TLS scans.

This information has been processed using the Cloud Compare software package (Cloud Compare V2.9 alpha, General Public License, GNU, GPL). The processing methodology has allowed generating a digital terrain model of the surface of the landslide using CANUPO Classification (Brodru et al.,2012), removing objects such as vegetation and man-made objects. After processing the scans, the M3C2 algorithm was used (Barnhart et. Al., 2013) to calculate the topographic change between scans. Figure 11 shows the distance results of the M3C2 analysis at the 10-mile slide from two TLSs made in May and July of 2017, respectively. This method of analysis allows comparing the relative topographic distance between TLSs to the geocubes on different areas of the slide.

The geocube results show high deformation on the slopes above the highway located on the left flank (Geocube 48) and center (Geocube 46) of the landslide. The results from comparing the two TLSs showed good agreement with the geocube network during the three-month period between both scans. At Geocube 48, the cumulative displacement was 75 mm, with a range of 30 to 90 mm with the TLS comparison. At Geocube 47, the displacement was 80 mm, with a range of 60 to 100 mm using change detection. At Geocube 46, the cumulative displacement was 180 mm. However, the TLS comparison results ranged between 50 to 125 mm. This difference near Geocube 46 could be associated with the lower density of TLS points on this area due to the oblique angle of the LiDAR shot. In general, a good agreement was found between the distance of the TLSs and the geocube system.

5 CONCLUSIONS

The Geocube GPS system is a near real-time and high-resolution system that allows a dense network for monitoring landslides. The geocube technology on the 10-mile slide is in agreement with traditional monitoring methods such as RTK GPS and newer remote sensing methods such as M3C2 using TLS. Although there might be challenges to the implementation and application of the system on remote areas, these were successfully overcome at the 10-mile slide.

The system showed to be very flexible; allowing relocation of units and showing its adaptability to diverse terrain conditions. Currently, the main challenge is associated with power requirements and internet connectivity. In remote locations or where sunlight can be limited during the winter period power supply can be a significant challenge.

The monitoring of the 10-mile slide using the geocube system has corroborated and enhanced our understanding of the landslide. This information will aid implementation of further controls at the landslide and will allow further research into the controlling mechanisms and triggers for its acceleration.

6 ACKNOWLEDGEMENTS

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