Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-125

InSAR analysis of post-remedial measures on Ripley landslide, in southeastern British Columbia, Canada

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ABSTRACT: Slow-moving landslides are frequent geohazards in the Canadian landscape, threatening the integrity of infrastructures. An explicit example is a 10-km section of Thompson River Valley located in southeastern British Columbia. This corridor hosts trans-continental high-traffic tracks of two major railway companies which traverse 12 documented landslides. The objective of this study is to quantify the velocity of one specific landslide in the corridor, Ripley, before and after the remedial re-grading of the slope in the summer/fall of 2023. To achieve this, we employed space-borne interferometric synthetic-aperture radar (InSAR) to analyze ground displacements. The methodology involved processing high-resolution Radarsat Constellation Mission scenes from 2022 to 2024 using an in-house developed framework, the InSAR Facilitator of Alberta (iNFA). This allowed for a detailed comparison of the landslide's line-of-sight (LOS) velocities before and after the remedial work. The InSAR results indicate that the remediation had a varied impact on the landslide's movement. The analysis revealed an overall decrease in the average velocity of the Ripley landslide, from 44 mm/yr in 2022 to 10 mm/yr in 2024. However, this velocity change was not uniform across the landslide body. The upper portion of the landslide, close to the valley's crest, experienced an increase in velocity of at least 35%. In this specific area, the average LOS velocity accelerated from 13.7 mm/yr in 2022 to 41.6 mm/yr in 2024. These activities could be either attributed to the development of a graben or the response of upper lands to the stress relief caused by the excavations. These findings highlight InSAR's effectiveness in monitoring the complex evolution of landslide behavior post-remediation.

KEYWORDS: Slow-moving landslide, monitoring, InSAR, iNFA, Ripley, Thompson River Valley.

1 INTRODUCTION

Western Canadian Sedimentary Basin is known for hosting landslides (Biagini et al. 2022, Soltanieh & Macciotta 2022, Woods et al. 2021, Rodriguez et al. 2021). This is caused by weak geological features (e.g., pre-sheared clay seams and/or erodible materials), geometrical changes (e.g., toe erosion by rivers), shifting weather patterns, anthropogenic developments and high ground relief, especially in Canadian Cordillera (Sharifi et al. 2021). The Canadian infrastructures sustain $280-450 million annually due to landslides directly and indirectly (Porter, 2021).

Remote sensing techniques are becoming an integrated monitoring tool due to the spatial scale of landslide-prone area in Western Canada, difficulty of access to affected areas and hence the associated costs (Sharifi et al. 2023; Choe et al. 2021; Macciotta & Hendry 2021; Huntley et al. 2021; Samsonov & Blais-Stevens 2024). Most of remote sensing techniques rely on the visible light which significantly hinders the applicability of these technologies in nighttime, under poor weather conditions and also operating remotely. Another subset comprises sensors working in the microwave range of the electromagnetic spectrum such as interferometric synthetic-aperture radar (InSAR). These sensors can be used airborne, ground-based, or on a spacecraft. In this study, InSAR refers to the space-borne variant without necessarily mentioning it. The principle is however identical to all other variants. An InSAR sensor captures the line-of-sight component of the ground displacements using microwave backscatters. The sensor acquires a two-dimensional reading of the waves phase content, called a scene, which is transformed into displacement maps using Equation (1):

$$d_{LOS}=\Delta\phi\times\frac{\lambda}{4\pi}, \tag{1}$$

where d_{LOS} and $\Delta\varphi$ are shown in Figure 1 and λ is the wavelength which depends on the employed sensor (e.g., about 5.5 cm for commonly used C-band sensors like Sentinel-1).

This study features the application of an InSAR analysis framework developed at the University of Alberta, called InSAR Facilitator of Alberta (iNFA). It has been used to process high-resolution Canadian Radarsat Constellation Mission (RCM) to map the displacements of a slow-moving landslide called Ripley in southeastern British Columbia, Canada, after excavations in 2023 to re-grade the ground surface.

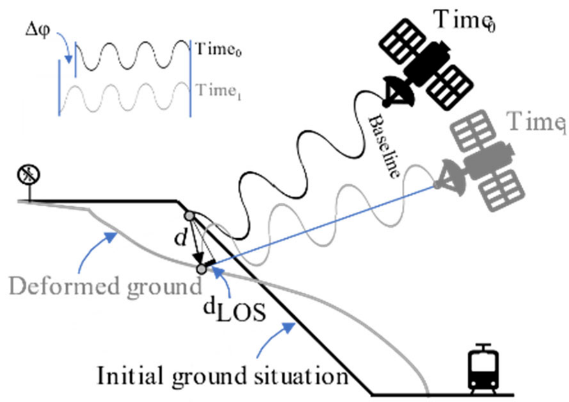

Figure 1. Displacement monitoring mechanism by InSAR ysing the microwave phase difference between acquisitions (Sharifi et al. 2024a).

2 STUDY AREA

Ripley landslide is located in the Thompson River Valley, about 10 km southwest of a town called Ashcroft in British Columbia, Canada. There is a track record of past failures and ongoing slow-moving landslides in this corridor. 12 landslides are documented in a 10-km section of the valley with some being constantly translating and others periodically active (Sharifi et al. 2024b). The two major commercial railway companies, Canadian Pacific Kansas City (CPKC) and Canadian National Railway (CN), have trackage running through this valley. These trans-continental high-traffic railways are of great financial significance in Canada considering this corridor connects economical hubs from west to east coast (Macciotta et al. 2016). Figure 2 displays the location of major landslides in the valley. The surficial geology of the region is comprised of Quaternary deposits with strata of cobble gravel, Diamicton till and Glaciolacustrine silts overlying the bedrock. Previous investigations show that these landslides are moving sub-horizontally and retrogressively on a shear surface running through a weak highly plastic clay seam with a residual friction angle less than 16° (Hendry et al. 2015). They vary in sizes and volumes from 0.4 to 15 million m^3, typically moving at rates lower than 200 mm/yr.

Ripley, recognized by the International Programme on Landslides (IPL – Project 202) by International Consortium on Landslides (ICL, Han et al. 2020; Bobrowsky et al. 2017), has been monitored consistently since 2008 by GPS units, all showing a very consistent movement geometry and a long-term velocity magnitude shown in Figure 3. However, in the short term, the velocities are dominated by river level, inducing buttressing effects and draw-down effects due to the seasonal variations. Both units are travelling at an aspect of 62-66° and a travel angle of 14-17° below the horizon with long-term magnitudes of 78 and 82 mm/yr. The measurements end prior to the construction activities began in July 2023 in which the ground was re-surfaced and surficial materials were excavated with a goal of remediation of landslides instabilities. The removed materials are also displayed in Figure 3 in the cross-sections using hatched shade.

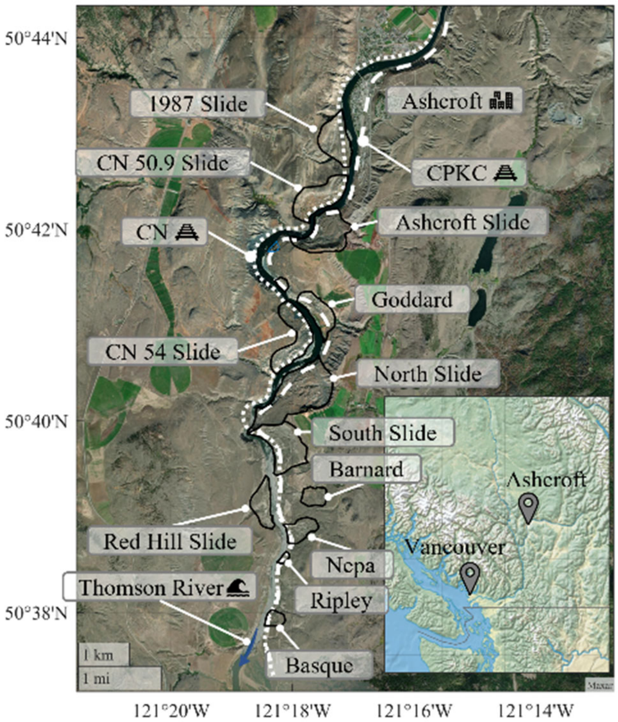

Figure 2. Daylighted boundaries of major landslides along Thompson River Valley along with CPKC and CN trackage (Sharifi et al. 2024c).

3 DATA AND PROCESSING METHODS

The data used for the InSAR analysis was 54 RCM scenes at an ultra-fine resolution of 3×3 m^2 with a nominal revisiting time of 12 days (data courtesy of Earth Observation Data Management System 2024). The satellites acquired these scenes when orbiting from the North to the South pole (descending orbit) at an azimuth of about 190° and a side-looking angle of 32°. The dataset includes scenes from July 15, 2022 to October 16, 2024, with excluded snow months from December through March. The full metadata of the used stack of SAR scenes are presented in Table 1.

Table 1. Metadata summary of SAR scenes used in this study

Parameter	Value
Sensor	Radasat Constellation Mission (RCM)
Total Number of scenes	54
Nominal revisiting time (days)	12
Spatial Resolution (m×m)	3×3 (Ultra-high)
Azimuth of satellite flight (deg)	~190
Orbital geometry	Descending (from North to South pole)
Side-looking angle (deg)	~32
Average satellite clearance (km)	700
Acquisition dates (yyyyMMdd)	20220402 20220418 20220426 20220508 20220520 20220601 20220613 20220625 20220703 20220715 20220727 20220808 20220820 20220901 20220913 20221003 20221015 20221027 20221108 20221120 20230401 20230413 20230507 20230519 20230531 20230612 20230702 20230714 20230726 20230815 20230819 20230831 20230912 20231002 20231014 20231026 20231107 20231119 20240403 20240415 20240427 20240509 20240521 20240602 20240614 20240704 20240716 20240728 20240809 20240821 20240902 20240914 20241004 20241016

iNFA starts the process by co-registration and calculating the difference between the scenes which demonstrates the variation of waves travel time to reach the objects on the ground (targets) which generate a product called an interferogram. It then proceeds to subtract the effect of topography, atmosphere, orbital variations and random noise to isolate the contribution of ground displacements. For this study, iNFA used the free digital elevation model recorded by the Shuttle Radar Topography Mission. It was used for calculation of ground terrain contribution to the radar backscatters and projecting the acquisitions in radar geometry onto orthorectified frames. To minimize the impact of errors, a highly redundant network stacks with 10 interferograms per acquisition was generated. Interested readers are encouraged to review Pappalardo et al. (2025) and Sharifi et al. (2025) for a better understanding of the applied processing methodology. The outcome of an InSAR analysis is the portion of the displacement projected on the sensor's line-of-sight (LOS). The LOS displacement/velocity is positive when the target is moving toward the satellite and negative when moving away. This makes understanding the geometry of acquisitions significant in the interpretation of kinematics. For the case of Ripley where movements are due northwest, given the acquisition azimuth of southwest in this analysis, the landslide displacements/velocities appear negative. As a baseline comparison, the average velocities reported by GPS units in Figure 3 translate into -18 and -22 mm/yr along the LOS of the satellite's viewing geometry in this analysis.

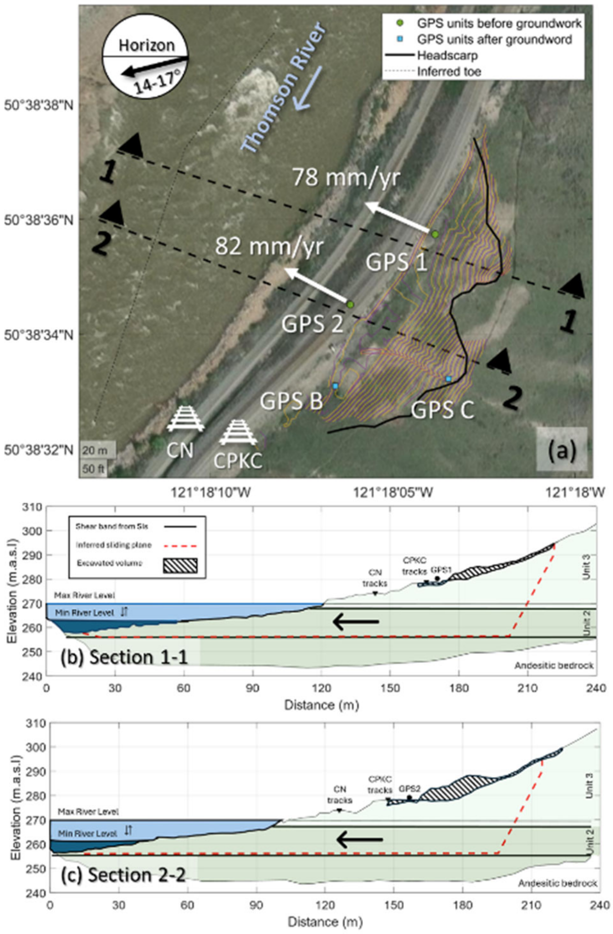

Figure 3. (a) GPS locations at Ripley, (b,c) cross sections 1-1 and 2-2 (Hendry et al. 2015; BGC Engineering Inc., 2024).

4 RESULTS

Figure 4 shows the LOS velocity over the entire dataset. The areas of most active targets sit well between the mapped boundaries of the Ripley. The average LOS velocity in 2022-2024 is found at -17.3 mm/yr with a standard dev (Std dev.) of 7.7 mm/yr.

The targets showing an average velocity of higher than 10 mm/yr in Figure 4 are considered active and their average timeseries displacements bounded by $\pm$1 Std dev. are shown in Figure 5. In 2022 and 2023, the average velocity magnitude is 41 and 37 mm/yr. Within the timeseries displacements of 2023, a sudden spike along the positive direction (marked by the red arrow) is seen. This could be attributed to the regrading work conducted about the same time since a considerable reduction in the ground elevation could result in interpreted movements toward the satellite (Figure 6). This positive LOS displacement should not be interpreted as actual landslide movements in the upslope direction. Geometrical calculations show that an average 5 m change in ground elevation can be interpreted as +15 to +20 mm LOS displacements – closely aligned with what is shown in Figure 5. While iNFA is capable of accounting for changes in the ground elevation caused by the displacements or errors in the digital elevation models, large changes caused by construction activities cannot be compensated in the analysis process.

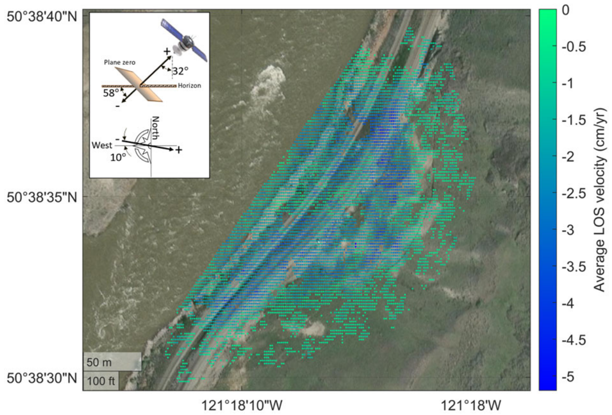

Figure 4. Spatial distribution of reliable targets in 2022-2024 RCM data and colour-coded by average LOS velocity.

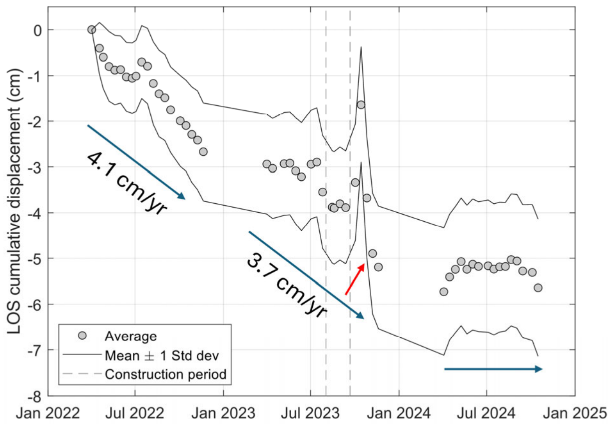

Figure 5. LOS cumulative time-series displacement of targets showing 10+ mm/yr velocity in Figure 4.

Figure 7 shows the change in average velocity from 2022 to 2024. Within Figure 7, positive values (blue) mean a reduction in the velocities while negative values indicate increased velocity (red). The majority of targets in the proximity of tracks in the northeast showed a notable decrease in velocities while targets in the upper portion of Ripley in the southeast showed increased velocity. Two potential arguments could justify the activity of this area after ground resurfacing:

- The location and shape may indicate the existence and movement of a graben, triggered and developed retrogressively by more gentle ground surface gradient of the landslide body in front of it (Glastonbury & Fell 2008).
- The upper portion of the slope is now subjected to less confining pressure, and the detected movements are attributed to the delayed response of upper land to the stress reduction caused by material removal.

The cumulative displacement of the active area is shown separately from the rest of the Ripley landslide in Figure 8 (red dataset). Figure 8 shows that the potential the active area was moving slower than the rest of the Ripley landslide in 2022 with an apparent acceleration after August 21, 2024.

The velocities of targets in this active area from 2022 are plotted versus those from 2024 in Figure 9. A 1:1 line identifies values for a consistent velocity for 2022 and 2024. Figure 9 shows all these targets show a greater than 35% increase in velocities in 2024 compared to 2022, and approximately a third of the targets showed at least a 100% increase in velocity while they were relatively stable in 2022 (< 10 mm/yr). Overall, the magnitude of average velocity for these targets increased from 13.7 mm/yr to 41.6 mm/yr from 2022 to 2024.

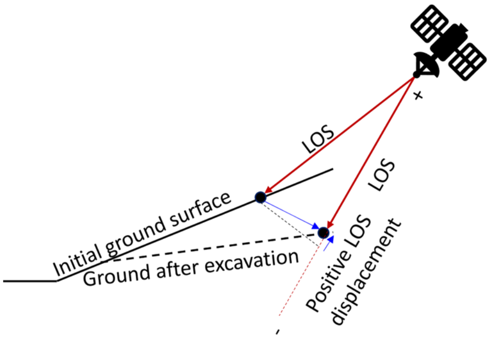

Figure 6. Positive interpretation of LOS displacement as a result of a change in ground elevation (not-to-scale).

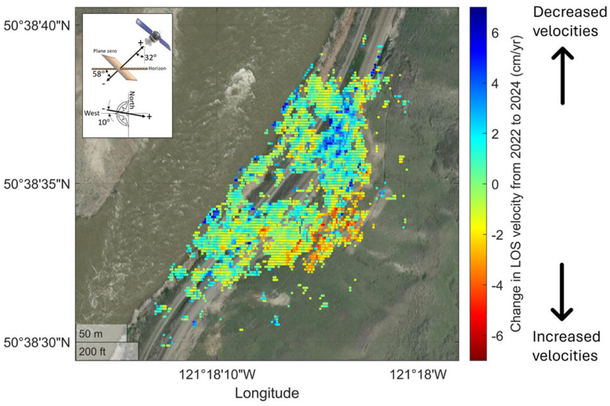

Figure 7. Change in LOS average velocity from 2022 to 2024

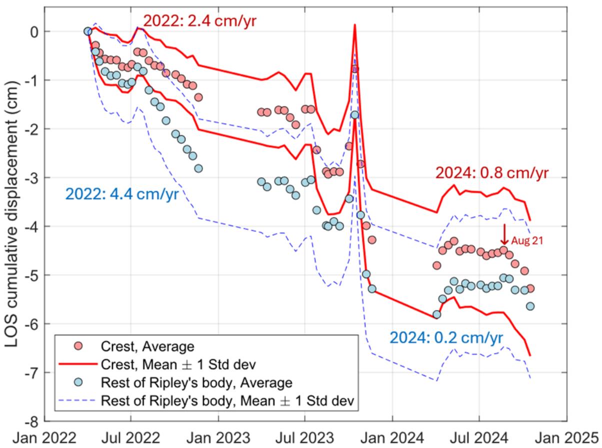

Figure 8. LOS time-series displacement of the active area (crest) separated from the remainder of Ripley

A site visit was conducted to confirm displacements and deep tension cracks were observed bordering the upper portions of the active area identified in Fig. 7. The site visit indicated that cracking was forming at the location of the observed increased slope velocities. The remediated slope was covered by coconut blanket for erosion protection which hampered the identification of cracking. Once the cracking was identified, the cracking was traced along the slope and marked with orange paint. The coconut blanket was torn in areas where the cracking was at its greatest but had to be lifted in places to trace the cracking along the slope. A tension crack measuring up to 30 cm in width and greater than 1 m in depth were measured. However, the majority of the cracking was found to only be a few 1 to 5 cm in width. The cracking was observed as high as approximately 17 m above the base of the slope and extended for tens of meters either side of the apex of cracking in an arcuate shape. An image of the typical tension crack width at the Ripley Slide is shown below in Figure 10.

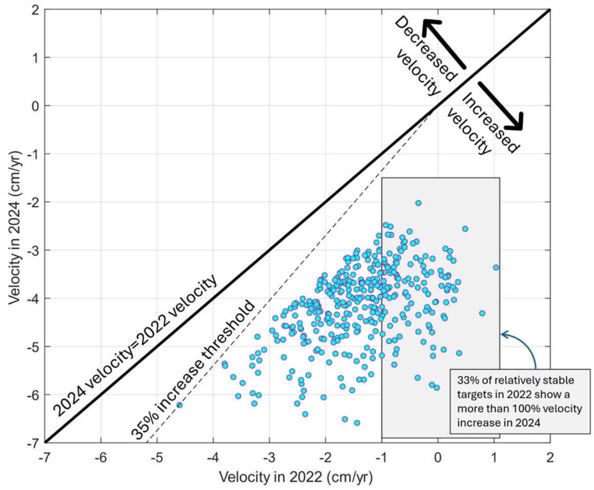

Figure 9. A comparison between velocities of targets at the location of the active area in 2022 vs 2024.

Figure 10. Tension crack at Ripley Slide (post-remediation)

Observed locations of the tension crack were recorded using a handheld GPS unit to a horizontal accuracy of approximately +/- 3 m. When the location of the tension cracking was superimposed onto the original pre-remediation tension crack, it appears that the previous maximum extent of the original slide mass comprises the currently observed, post-remediation tension crack at Ripley. The landslide has reasserted itself along its previous extents without evidence of further retrogression upslope. The pre- and post- remediation tension cracks at Ripley landslide are shown below in Figure 11. Note that the most recent GPS measurements of the current tension crack are shown as green dots, while red dots indicate pre-remediation surface fissures and cracks.

When the GPS data is superimposed on the InSAR results, the newly formed headscarp is located at the region of maximum downward velocity as shown in Figure 12. This suggests that the InSAR data accurately detects the increased velocities near the downward trending headscarp.

5 CONCLUSIONS

The results presented in this paper are part of an ongoing research program being conducted through the University of Alberta. An in-house InSAR analysis framework called InSAR Facilitator of Alberta (iNFA) was employed to study the evolution of ground kinematics of a slow-moving landslide, called Ripley, in southeaster British Columbia, Canada. The timeline of study is 2022 to 2024 which encompasses pre-, during and post-construction work in which ground geometry was modified by material excavation. The results at Ripley were discussed in this document and the concluding remarks are as follows:

- The analysis showed an overall decrease in velocity for the Ripley landslide from an average of 44 mm/yr in 2022 to 10 mm/yr in 2024.
- This change in velocity was not uniform over the slope, and the upper portion of the landslide appears to have an increase in velocity by at least 35%. The magnitude of average LOS velocity increased from 13.7 mm/yr in 2022 to 41.6 mm/yr in 2024.
- The identified active area could be an early sign of either a graben in development or the elastic response of the upper land to the stress relief caused by the excavation.
- The deep tension cracks were observed bordering the upper portions of the active area were observed during subsequent site visits. These provide confirmation of ongoing movement in this area.

Due to the known geotechnical uncertainties associated with landslide hazards, monitoring of post-remediated slopes is necessary to evaluate the effectiveness and efficiency of mitigation works to ensure the aimed levels of safety have been achieved. Remote sensing, particularly InSAR, allow a broad monitoring coverage to identify the evolution of the landslide deformation patterns in a systematic manner. Given the availability of the well-established processing algorithms and world-wide data coverage, these tools have become increasingly an integral part of risk management practices.

6 ACKNOWLEDGMENTS

This research was made possible by the Railway Ground Hazard Research Program (RGHRP), which is funded by the Natural Sciences and Engineering Research Council of Canada (NSERC), Canadian Railway Company (CN), Canadian Pacific Kansas City Railway (CPKC), and Transport Canada. RGHRP also includes partnerships with Queen's University, the University of Saskatchewan, ÉTS University and the Geological Survey of Canada.

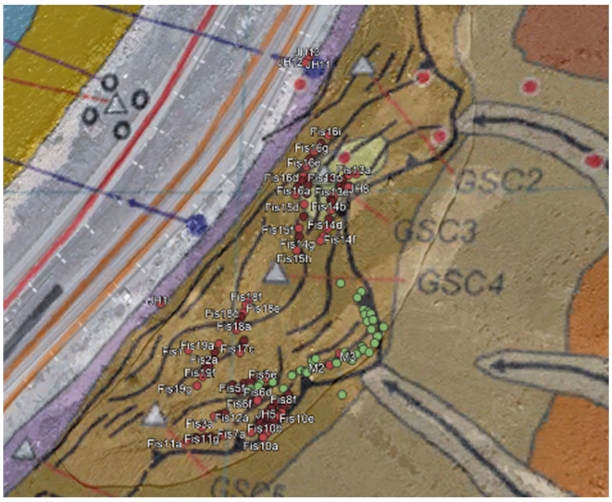

Figure 11. Pre and post-remediation headscarp locations (adapted from Huntley & Bobrowsky et al., 2014)

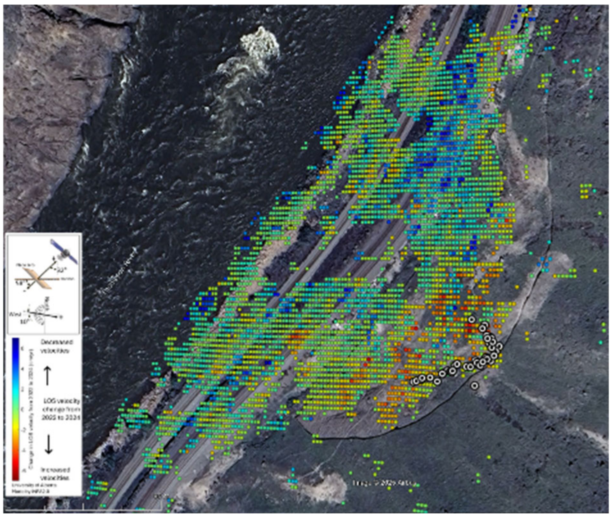

Figure 12. Observed tension crack locations relative to slide mass velocity

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