

Benefits and challenges of applying GB-InSAR for use in civil projects in Canada, and ways forward

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ABSTRACT

Ground-based, interferometric, synthetic aperture radar (GB-InSAR) has been used successfully for monitoring both artificial and natural rock slopes. However, it has seen limited use within North America and Canada outside of the mining industry. GB-InSAR has many potential advantages for use on civil projects over traditional geotechnical monitoring techniques and other remote sensing technologies including satellite-based InSAR, LiDAR, and UAV photogrammetry. These advantages include very high accuracy, operation during all weather conditions, and high spatial and temporal coverage resulting in the ability for near real-time monitoring. Advantages such as these can result in a considerable increase in safety to workers, infrastructure, and equipment exposed to such risks if employed properly.

However, common Canadian conditions such as dense vegetation cover, limited communications, and long winters with periods of deep snow and short days limit solar power generation and results in challenges for the deployment of GB-InSAR. This paper presents the installation, challenges and results of the use of GB-InSAR at a research site that poses many of these challenges and significant rock landslide hazard. The site discussed is the Checkerboard Creek Rock Slope which is a 2 to 3 million m³ slow-moving bedrock landslide adjacent to the Revelstoke Dam Reservoir with a maximum rate of displacement of approximately 10 mm/year. The GB-InSAR was initially installed at site in October 2016, however, was unable to collect continuous data due to insufficient solar power generation. Therefore, improvements were made in 2018 to address this and other issues. However, preliminary results from the GB-InSAR compare favorably with conventional instrumentation already installed at site.

RÉSUMÉ

Un radar au sol, interférométrique, à ouverture synthétique (GB-InSAR) a été utilisé avec succès pour observer les pentes rocheuses artificielles et naturelles. Toutefois, en Amérique du Nord et au Canada, ce radar a été peu utilisé en dehors de l'industrie minière. Pour être utilisé dans des projets civils, le GB-InSAR a potentiellement plusieurs avantages par rapport aux méthodes d'observation géotechniques traditionnelles et d'autres technologies de télédétection incluant le InSAR par satellite, le LiDAR et la photogrammétrie par un véhicule aérien sans pilote. Ces avantages comprennent une grande précision, une possibilité d'opérer dans toutes les conditions météorologiques, ainsi qu'une large couverture spatiale et temporelle qui mène à une capacité d'observation en temps quasi-réel. Les avantages tels que ceux-ci peuvent mener à considérablement améliorer la sécurité des travailleurs, de l'infrastructure et de l'équipement qui sont exposés à des risques, si employés de façon appropriée.

Toutefois, les conditions canadiennes générales, comme le tapis végétal dense, la couverture par téléphone cellulaire limitée et de longs hivers avec des périodes de neige abondante et de courtes journées réduisent la production de l'électricité par l'énergie solaire qui alimente le radar et présentent un défi pour le déploiement du GB-InSAR. Ce mémoire présente l'installation, les défis et les résultats de l'utilisation du GB-InSAR sur un site de recherche qui pose beaucoup de ces défis et comporte des risques de glissement de terrain rocheux. Le site examiné est la pente rocheuse de la rivière Checkerboard qui s'étend sur 2 à 3 millions de m³ de masse rocheuse en glissement lent adjacente au Réservoir du Barrage de Revelstoke avec un taux de glissement d'environ 10mm par année. Le GB-InSAR a été initialement installé sur ce site en Octobre 2016, mais toutefois, le radar n'a pas été capable de recueillir des données continues car l'alimentation électrique par l'énergie solaire a été insuffisante. Par conséquent, des améliorations ont été apportées en 2018 pour résoudre ce problème et d'autres problèmes.

1 INTRODUCTION

This paper presents a brief summary of the principles of Ground-based, Interferometric, Synthetic Aperture Radar (GB-InSAR) and its typical applications, discuss its advantages and complements to other typical geotechnical instrumentation and remote-sensing, the limitations and

challenges associated with its application on civil projects, and finally applying solutions to these issues at a research site subject to typical Canadian conditions and associated results.

Generally, radar systems detect the distance and the direction of a target by transmitting and receiving electromagnetic (EM) waves. The distance to the target is

determined by evaluating the time of flight of backscattered waves from the instrument to the target and back (Atzeni et al. 2014). The direction to the target from the instrument is then obtained by using one of two radar technology types: Real Aperture Radar (RAR) or Synthetic Aperture Radar (SAR).

For the purposes of this paper, only SAR will be discussed in detail as this was the technology used in this case. However, for the purpose of discussion, the advantages of SAR over RAR will be covered.

1.1 Technology Overview

SAR is an active (meaning independent of sun illumination) microwave frequency radar system that can transmit and receive the EM signals backscattered from a target, such as the ground surface, and then arrange these signals in a 2D image map of instrument to target (Line-of-Sight, LoS) distances (Lombardi et al., 2017)

Two or more SAR images of the same area taken at different times can then be used to generate interferograms i.e. phase difference images (Wasowski and Bovegna, 2014). These interferometric SAR (InSAR) images can be presented as in 3D by projecting it on a digital elevation model (DEM), such as those obtained from terrestrial or aerial laser / LiDAR scanning (Atzeni et al. 2014). Further details about the technology and processing methodologies can be found in Atzeni et al. (2014), Wasowski and Bovegna (2014), Colesanti and Wasowski (2006), Ferretti et al. (2007)

1.2 Typical Applications

In recent years, GB-InSAR has become one of the most widely used emerging techniques for monitoring ground displacements, as such, it is of great interest as an operational tool for civil projects that deal with landslide risk (Corsini et al. 2006).

GB-InSAR has seen widespread use in the mining industry for the monitoring of open pit mine slopes both within Canada, North America, and worldwide (Dick et al. 2014, Severin et al. 2014). However, since first being applied on natural slopes in the Italian Alps (Tarchi et al. 2003), GB-InSAR has been validated and beginning to be adopted more widely as a landslide monitoring and early-warning system on civil based projects (Corsini et al. 2006, Herrera et al., 2009; Barla et al. 2010, 2007; Monserrat et al., 2013, Matteo et al. 2016), particularly within Europe.

Other less typical applications of this technology that are at varying stages of use, research and development include monitoring movements of: rockfall (Lombardi et al. 2017), sinkholes (Intrieri et al. 2015), glaciers (Noferini et al. 2009, Whitehead et al. 2010), structures (Tarchi et al., 1997), dams (Tarchi et al., 1997), and volcanoes (Spaans and Hooper, 2016).

1.3 Advantages and Complement to Other Technologies

In the past, traditional monitoring activities have such as surveying or slope inclinometers exploited point-wise, local measurement techniques usually in short-duration, low-

frequency monitoring campaigns (Crosta et al. 2013). Although very useful to understand general landslide behavior, these methodologies offered limited capabilities of: characterizing long-term landslide behavior, attaining spatially distributed data, understanding sensitivity to perturbations and related response time, and event duration; and providing suitable input to early warning (Crosta et al. 2013)

Recent advances in remote-sensing such as GB-InSAR have significant advantages over traditional means to overcome such limitations (Crosta et al. 2013). Some of these advantages as summarized by Monserrat et al. (2013) include: the ability to monitor a wide range of deformation rates from a few mm per year to meters per year, very high precision (ranging from sub-mm to a few mm depending on target characteristics and sensor to target distance). It can also cover a wide area in the scale of several square kms with a map of dense continuous data 24 hrs a day in all weather conditions (Lombardi et al. 2017). The GB-InSAR process can be highly automated and used as an operational monitoring tool, for example in emergency situations and can be installed outside the area of risk.

1.3.1 In-ground Instrumentation and Surveying

Installation of in-ground geotechnical instrumentation such as slope inclinometers and extensometers pose several challenges and associated costs. This includes gaining access for equipment such as a drill rig. As well, both down-hole instrumentation and surveying by total station (whether robotic or otherwise) only provides data for a single point on the ground surface (however, in-ground can provide several data points along its depth). These difficulties regarding access and expensive drill equipment can mean installation of a single instrument can be in the order of hundreds of thousands of dollars CAD.

However, the main benefit to this type of data when compared to GB-InSAR and other remote sensing technologies is the ability to provide subsurface data with depth which allows for the identification of distinct failure planes and increased understanding of the landslide failure mechanism. For this reason, GB-InSAR is unable to completely replace all in-ground instrumentation for many projects. However, may be able to supplement such data and reduce the number of total drillholes required.

1.3.2 GPS

GPS devices are restricted to only recording deformation data of a single data point per unit and require access to the site for installation. However, GPS monitoring does have many of the same advantages as GB-InSAR such as high frequency measurements possible during the day or night and under bad weather conditions (Pecoraro et al. 2018). Current high-accuracy GPS can detect slow landslide movements at a rate of 1–2 mm/year within a period as short as 3 years (Wang et al. 2014). Compared with conventional surveying techniques, GPS generally increases survey accuracy, productivity, monitoring capability, and reduces cost (Wang et al. 2015).

1.3.3 Satellite InSAR

Due to the “birds-eye” view and large distance from the radar to the ground surface, in the case of satellite-based InSAR, it can cover a much larger study area on the scale of tens to hundreds of kms depending on the dataset used. Although has a much lower spatial resolution, typically between 15 to 30m (Tarchi et al. 2003).

Another key limitation of satellite InSAR is that the data collected is not continuous as each satellite has an inherent revisiting time based on its orbital period. For currently and historically active SAR satellites this ranges from approximately 11 to 46 days between images. The restriction in temporal resolution prevents this technique from being used as an early warning system and limits its ability to detect very rapid ground movements such as sudden slope failures (Journault, 2017).

As with GB-InSAR, satellite-based InSAR outputs LoS displacements, however, due to the set orbit of the satellites, it is affected by the relative geometry of the aspect and inclination of the target slope (Colesanti and Wasowski 2006, Wasowski and Bovenga 2014). Ideally, ground deformations would occur in a direction sub-parallel to the LoS, thus allowing the satellite to capture real ground displacements. However, in practice the LoS is offset from the ground movement vector in both aspect and inclination, meaning InSAR will detect only a portion of real ground movements (Wasowski and Bovenga 2014).

1.3.4 Terrestrial LiDAR / Laser Scanning

Terrestrial LiDAR or laser scanning (TLS) is an emerging remote sensing method for monitoring slopes in the vicinity of infrastructure (Fey and Wichmann, 2017). TLS has many advantages including acquisition without access, no measurement point installation, and provides high-resolution spatially continuous data over a large area (Fey and Wichmann, 2017).

Unlike GB-InSAR which uses microwaves, TLS uses laser pulse returns in the infrared spectrum to create a point-cloud of distinct x,y,z coordinates. Two subsequent point-clouds can then be overlaid and compared in a methodology referred to as change detection to identify and quantify areas of deformation (Hutchinson et al. 2015).

The primary advantages of GB-InSAR in comparison to TLS is its ability to be used in all weather conditions as TLS’s wavelength is highly sensitive to atmospheric conditions. Optimal visibility such as clear skies with the absence of precipitation is therefore required for successful TLS acquisition (Luiz et al. 2009, Kromer et al. 2017). In addition, GB-InSAR typically has a finer temporal resolution with a relatively short acquisition and processing time in the order of a few minutes, where as a comparable TLS scan can take several hours. Because of this restriction, TLS is not as appropriate to be used as an early warning system and point-wise tools such as in place instrumentation or GPS, however there is some research to address these limitations (Kromer et al. 2017).

TLS however does have a higher resolution with multiple points per square meter. GB-InSAR is restricted to a minimum resolution of 0.75m due to the radar’s wavelength. In contrast, the interferometric nature of GB-

InSAR, has the ability for a much higher accuracy in ideal conditions in comparison to TLS ($\pm 0.1\text{mm}$ vs. several cms).

Table 1. Characteristics of monitoring techniques

Monitoring Technique	Accuracy	Temporal Resolution	Spatial Resolution	Range	Density
GB-InSAR ¹	$\leq \text{mm}$	$< 3 \text{ min}$	Continuous, 10,000s of pixels	$\leq 5\text{km}$	High
RAR ¹	$\leq \text{mm}$	5 – 30 min	Continuous, 100s of pixels	$\leq 2.5\text{km}$	Med. To High
Satellite InSAR ²	cm	11-46 Days	Continues, millions of pixels	Unlimited	Low
LiDAR / TLS ¹	$\leq \text{cm}$	Minutes to hours	Continuous, millions of points	$\leq 3\text{km}$	Very High
Robotic Total Station ¹	mm	Tens of minutes	Pointwise	$\leq 1\text{km}$	Point wise
UAV ³	cm	Minutes to hours	Continuous, thousands of points	$\leq 1\text{km}$	Med. To High
GPS ¹	$\leq \text{cm}$	Minutes	Pointwise	10s of kms	Point wise

¹ Atzeni et al. (2014) ² Ferretti et al. (2007)

³ Fey and Wichmann (2016)

1.3.5 UAV Photogrammetry

Unmanned aerial vehicles (UAVs) in conjunction with structure-from-motion (SfM) image processing have become common-place as a low-cost, reliable solution for geotechnical monitoring purposes (Peppas et al. 2018).

Processing of photos captured from UAV’s using SfM can be used to automatically generate dense point clouds similar to those from TLS (Snively et al., 2008; Remondino et al., 2014) and be compared using change detection techniques to determine displacement between surveys. Although GB-InSAR and TLS offers higher spatial resolution, they require much higher financial investment (Travelletti et al., 2012). Furthermore, with static TLS and GB-InSAR, occlusions can occur owing to oblique incidence angles which necessitate the establishment of numerous scanning positions (Jaboyedoff et al., 2012, Severin et al. 2014), increasing operational cost.

The accuracy of this monitoring methodology depends generally on the resolution of the photo sensor used, the nature of the ground cover (vegetation), and processing methodology used such as the use of ground control points (GCPs) or post processing kinematics (PPK) but can achieve accuracies as little as a few centimeters.

2 LIMITATIONS AND CHALLENGES OF GB-INSAR FOR CIVIL APPLICATIONS

Despite the many advantages of this technology there are certain limitations and related logistical challenges that must be considered for successful use and acquisition of reliable data of which are discussed in this section.

2.1 Line-of-Sight (LoS) Nature

One key limitation of all radar systems, whether it is SAR or RAR, is that they can only provide LoS displacement values meaning that 3D displacement information on kinematics may be missed (Severin et al. 2014). Although this may be overcome by simultaneous deployment of two GB-InSAR systems (Severin et al. 2014).

2.2 Coherence

Coherence, in general, is the interferometric phase quality of two SAR images being compared to determine displacement of an area within the target site. Essentially, it reflects the property of the target to be measurable through time (Wasowski and Bovegna, 2014). Coherence depends on the physical and geometric characteristics of the measured objects and their changes between GB-InSAR image acquisitions... the lower the noise in the images from sources such as atmospheric effects, the higher the coherence (Ferretti et al. 2007).

One of the most significant sources of noise within SAR images is the presence of vegetation. A large part of why GB-InSAR has been most widely applied in mining is because it is most effective on flat, bare-ground. This poses a significant limitation to its applicability to be used on civil projects can have dense vegetation cover.

2.3 Remoteness

Many landslide sites in Canada pose significant challenges regarding access due to their remote nature and rough mountainous terrain. These aspects therefore may influence the suitability and costs associated with different types of geotechnical monitoring equipment.

In the case of GB-InSAR, the equipment is generally quite mobile, being able to be installed in a small trailer, shelter, or left uncovered. Although, it is not as easily transported as TLS or UAVs which can be carried by a single person without considerable effort. GB-InSAR on the other hand, consists of several components that each may require several people to lift and move.

These components typically include the radar head, linear scanner rail, power supply, a weatherized laptop, connecting cables, and associated power supply and telecommunications equipment, see Figure 1.

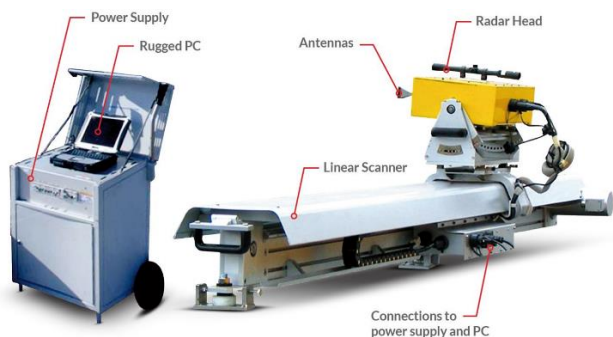


Figure 1. GB-InSAR Components (IDS Georadar, 2019)

2.4 Telecommunications

The installation of telecommunications equipment has the benefit of allowing remote connectivity to the monitoring software and data. This reduces the need for site visits and the time and costs required to collect data. Data can be transmitted via virtual private network (VPN) and processed by an offsite computer set up to allow early-warning if accelerated displacements are detected. However, remote areas such as this may have limited to no cellular data reception to allow internet access.

2.5 Power Supply

A lack of access to a reliable power source can increase costs and decrease reliability and mobility of a GB-InSAR system and is a challenge that is faced on many Canadian landslide sites. In addition, deep, steep-sided mountain valleys, short days, overcast weather, and precipitation in the form of snow can significantly decrease the opportunity for solar power generation, especially during winter.

These factors increase the cost and amount of equipment required to power the system continuously or alternative power systems to be considered. In addition, cold temperatures decrease the charge capacity of batteries used to store electrical power and run the equipment overnight when there is no power generation.

2.6 Snow Cover

Like other remote sensing techniques, snow cover on the ground surface obscures movements. Both accumulation, melt, and consolidation of the snow pack can result in apparent movements in data that are not reflective of the actual movement of the ground surface.

Snow is a complex material consisting of a mixture of air, ice crystals, and if melting, liquid water which complicates the interaction of it with the EM waves transmitted and received by the GB-InSAR. The main sources of backscattering from a snow-covered slope include surface scattering at the air-snow interface, ground-snow interface, snow layer interfaces, and volume scattering within the snow pack (Luzi et al. 2009).

The microwave frequency typically used in GB-InSAR (Ku-band: 17.05 – 17.35 GHz) is more sensitive to the presence of snow and has a lesser penetration depth (approximately 3-4m in dry snow) when compared to lower frequency radar waves in the C or S-bands (Rutt et al. 2009) used by some satellite InSARs. Despite this apparent ability to penetrate the snow surface and get backscatters from the ground surface, this has shown to lower coherence of the radar data and lead to an inability to provide useful information in winter months such as in Dehls. et al. (2010).

2.7 Available Solutions

Fortunately, there are ways to address these limitations and logistical challenges associated with the use of GB-InSAR on civil projects in Canada discussed above. Severin et al. (2014) demonstrated that 3D displacements can be determined using one or more GB-InSAR units,

however, does pose significant cost repercussions. The most cost-effective way to address this is by choosing the installation location to be directly opposite the estimated direction of movement. Otherwise, if the average displacement vector is known from other instruments, you may estimate the absolute magnitude of movement.

The most effective way of addressing a lack of coherence in areas of vegetation is to install radar corner reflectors. Same can be done in areas of snow cover by installing the reflectors above the snow pack. However, this unfortunately requires access for installation, and only provides point-wise data and adds additional costs.

There is a limited amount that can be done to address the mobility of the equipment, however installation in a trailer for sites accessible by vehicle does increase transportability and reduce set up times. In areas of reduced or no cellular data coverage, there are a few options that range in cost and installation effort including external directional antennas, cellular signal boosters, and satellite communication links.

Where connection to the electrical grid is unavailable, the most common source of electricity for GB-InSAR is either photovoltaic solar panels or small gas generators attached to a battery bank. Generators, however, require regular maintenance and fuel deliveries. Solar power systems meanwhile can operate passively with little requirement for regular site visits. In areas of little sunlight, additional solar cells and batteries can be added upon to provide adequate power. Less common remote sources of energy include wind turbines and fuel cells.

3 ADDRESSING THE CHALLENGES OF GB-INSAR AT THE CHECKERBOARD CREEK ROCK SLOPE

The research site selected to test and address these challenges with GB-InSAR on civil projects in Canadian conditions is the Checkerboard Creek Rock Slope. This landslide was selected because of the amount of precipitation (snow) and overcast days in the year, its dense vegetation cover, the exposure of a rock face at its toe, and the wide variety and spatial coverage of in-place instrumentation.

This section presents a summary of the landslide location, characteristics, geologic context and climate in the area.

3.1 Introduction

The Checkerboard Creek Rock Slope is located approximately 2km north of the Revelstoke Dam along Highway (Hwy) 23 on the east shore of the Revelstoke Reservoir, (Figure 2). It has an elevation of 260 m from Hwy 23 at its toe up to an elevation of 590 m at its crest bounded by the middle reach of the Checkerboard Creek, and an average elevation of 850 m (Figure 3). It is approximately 600 m wide and has an overall slope angle of 30°, steeper at the toe (45°) near the rock cut excavated for Hwy 23 and flatter in the upper area (25°) (Watson et al. 2004).

The area of active movement of the slide has been interpreted from the site geology, slope topography and deformation patterns (Macciotta et al. 2016). This area is

located towards the central lower portion of the rock slope and approximately 200 m wide along the direction of the highway and 150 m deep from the highway to uppermost tension cracks that define the upper boundary of the deformation area, see Figure 3. However, the lateral and toe boundaries are less clear. The active zone of deformation has an average slope angle of 45°, and deformations have been detected down to 50–60 m deep within the zone of higher weathering and lower quality rock masses. The total volume of this active zone is estimated somewhere between 2 and 3 million m³.

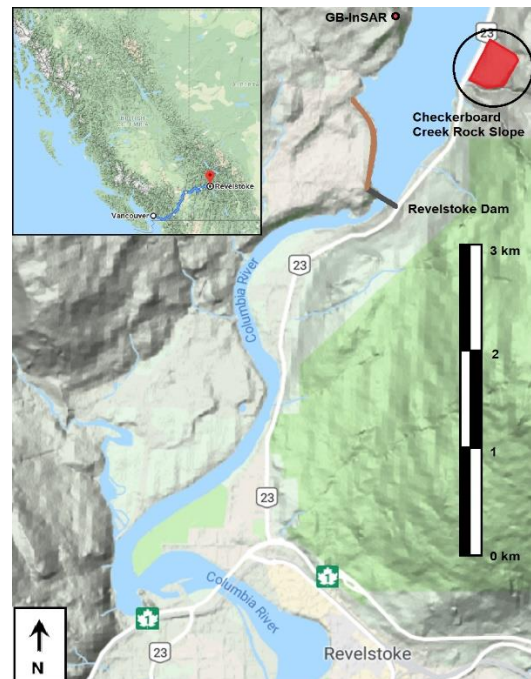


Figure 2. Location of the Checkerboard Creek Rock Slope

3.2 Geology and Other Characteristics

The slope geology consists of massive to weakly foliated granodiorite overlying the gneiss and schist of Columbia River Fault. Rock mass quality ranges from very strong, fresh, undisturbed and blocky rock to highly weathered and altered, weak and disturbed (Macciotta et al. 2018).

The groundwater levels in the slope are inferred from observations during drilling, site inspections, and monitoring of multiple piezometers. These revealed a complex groundwater system with saturated conditions at a depth of 50 to 80 m and seasonal variations in piezometric levels of up to 20 m (Stewart and Moore 2002). Instruments near the exposed rock face indicate seasonal patterns, with accelerated displacements in the fall and reduced displacement in the spring (Stewart and Moore 2002, Watson et al. 2004 and 2006). However, instrument trends further back in the landslide and at depth have a steadier displacement. Interpretation of this displacement pattern is steady with an accelerated phase during spring snow melt, when piezometric pressures are at seasonal maximums, however investigations regarding the cause(s) of the acceleration are ongoing. The displacement rate is

0.5 mm/year at the boundaries of the active area, and up to 15 mm/year within the most active area. These rates are greatest at the surface and decrease progressively with depth. Deformations have been associated with dilation of the rock mass with discrete block sliding and rotation occurring throughout the mass (Stewart and Moore 2002, Watson et al. 2004 and 2006).

3.3 Climate and Associated Challenges

Revelstoke is located in interior British Columbia, and therefore its climate has a strong coastal influence from the

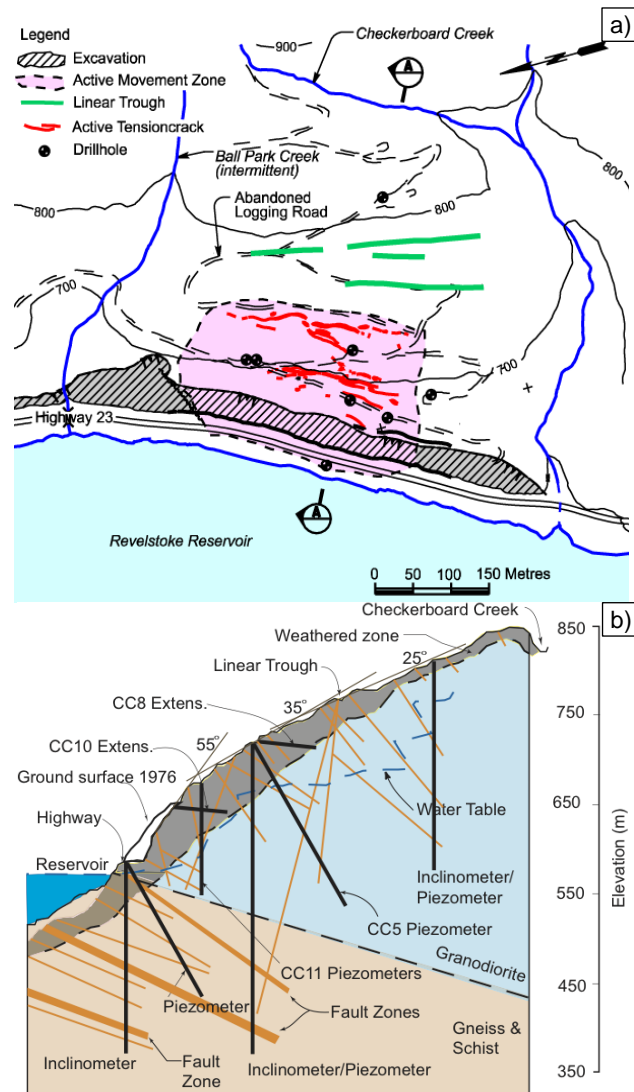


Figure 3. Plan view of Checkerboard Creek Rock Slope (a) and typical cross-section (b) after Watson et al. 2006.

from the Pacific Ocean. Annual cumulative precipitation is typically between 1500 to 2000 mm at site, approximately 40% of which occurs between October and January, usually as snow.

Air temperatures typically range between -25° and 35°C , with freezing temperatures prevailing from late November through March. Because the slope is heavily treed, snow depths are variable, however, typical snow

depths range from 1 to 2 m in mid-winter (Watson et al. 2004). Throughout the fall and winter days at the site feature short periods of direct sun light, frequent overcast weather and snow fall events between December and March.

The challenges at the site associated with this include the limited availability of sunlight for solar power generation and frequent snow falls in the winter which partially cover the rock face of the slope. These challenges are translated into limited periods of continuous monitoring and uncertainty regarding slope measurements during the winter months due to weather effects and transient snow covers. To overcome these issues and test the applicability of GB-InSAR at this location, 1 to 2-week monitoring campaigns have been conducted every 1 to 2 months and work has been completed to improve the power system.

3.4 Checkerboard Creek GB-InSAR Installation

A GB-InSAR system (IBIS-L, IDS Georadar) was installed in October 2016 on the west bank of the reservoir and directed toward the Checkerboard Creek Slope, located on the opposite side of the reservoir (Figure 2). The instrument was installed inside a shelter to protect it from weather and wildlife. Initially, the radar transmitted its signal through an opening in the side of the shelter, however a transparent protective plexiglass window was later installed in November 2016 which required the radar to be re-oriented and directed toward the north side of the slope.

The GB-InSAR was initially powered by a solar power system that consisted of a pair of 260 W panels in parallel with 3 24V, 100A, parallel battery packs, (Figure 4). This initial system allowed for 5 to 15 days of monitoring during the fall and winter months, resulting in discontinuous data acquisition from October 2016 to March 2019.

However, the short-term discontinuous nature of the acquired data over this period prevented some of the primary advantages of the GB-InSAR system to be fully utilized. Therefore, in October 2019, the solar power system was upgraded by installing an additional 4 270 W panels and replacing and upgrading the battery capacity with 4 new battery packs in insulated aluminum battery boxes. Due to the increased power generation from the additional panels, the charge controller was also upgraded from a 20 A to a 60 A unit.

In addition, to allow for remote connectivity to the GB-InSAR, telecom equipment was installed which included a cellular modem with a static IP address, and external directional antenna, and an associated power supply.

At the time of the writing of this paper, with the listed power upgrades and telecom equipment the GB-InSAR has been operating continuously for 2 months from March to May 2019 and is accessible remotely through VPN. A detailed cost breakdown of the final installation is provided in Table 2, however, the most significant cost to any GB-InSAR installation is the radar system itself and software license which can total close to CAD 400,000. Rental of GB-InSAR equipment complete with all necessary power, telecom, and shelter is available is also available at significantly lower rates (approximately CAD 10-30,000).



Figure 4: Original solar panel installation Oct 2016 – Oct 2018 (a) and battery pack and 20A charge controller (b). Upgraded solar installation Oct. 2018 – Present (c) and insulated aluminum battery boxes (d)

Table 2. GB-InSAR Approximate Installation Costs

Equipment	Unit Price (\$ CAD)	Total (\$ CAD)
270W Solar Panel	260	1560
12V DC Batteries	270	2160
60A Charger Controller	660	660
3 Panel Combiner	105	105
Cell Modem	270	270
External Outdoor Antenna	125	125
Misc. (Cables, breakers etc.)	n/a	830
TOTAL ¹	n/a	5710 ¹

¹Does not include costs for materials, construction, and installation of the shelter or battery boxes which were provided by BC Hydro.

4 DATA PROCESSING METHODOLOGY AND RESULTS

GB-InSAR data can be acquired using two different types of acquisition modes: continuous, and discontinuous (Monserrat et al. 2014). Because of the restrictions on solar

power generation during the initial installation of the GB-InSAR at this site before upgrading, the data was acquired discontinuously. This paper therefore covers the results from the analysis of the discontinuous portion of this data from Oct. 2016 to Mar. 2019.

The processing and analysis of discontinuous GB-InSAR data poses substantial technical differences when compared to continuous monitoring (Monserrat et al. 2014). One of the critical issues with discontinuous GB-InSAR data is obtaining a sufficiently high coherence, as large time gaps can lead to severe coherence loss (Monserrat et al. 2014).

Most GB-InSAR analysis software such as the IDS Guardian software that was provided with the IBIS-L are typically set to only analyze continuous data, therefore additional processing methodologies and software must be utilized for discontinuous data. In this case, IDS Georadar provided their RepeatPass software which takes the best matches from subsequent monitoring campaigns to output a 2D displacement map for locations in the monitored area within a set coherence threshold. These maps were then aggregated together in Esri ArcMap for every monitoring campaign to determine the cumulative displacement over the entire monitoring period. An assumed stable zone to the north of the slide where data coherence was higher was then selected and the data corrected to be relative to this area. The assumed stability of this area is consistent with regular historical monitoring data by BC Hydro.

Figure 5 is the GB-InSAR LoS cumulative displacement map between November 15, 2016 and March 4, 2019. The radar image does not cover the entire rock face at the toe of the slope due to the current radar orientation, protective window, and ground conditions including snow cover all contributing to a reduction in data quality and reliability. To assess the ability of the GB-InSAR to quantify movement in the upper vegetated portion of the slide, some pixels in this area were chosen, however this resulted in significant temporal decorrelation and greater than anticipated displacements (circled in red, Figure 5).

Figure 5 also shows the location of an area of interest that is in the vicinity of some in-place instrumentation with good radar returns that were used to validate the GB-InSAR results. Figure 6 is a plot of one of this area in the for comparison to the instrumentation data. The time of each data point corresponds with the best match SAR image selected for analysis. The displacements measured at CC10 correspond to the extensometer section representative of displacements at the surface despite not being the shallowest instrument (3.2m depth) its displacement rate is equivalent to a nearby survey point (M39). Figure 5 also shows the location of an inclinometer in drill hole CC3. The data plotted for this inclinometer represents the cumulative displacement at the surface for the dates measured over the monitoring period. This includes 3 measurements at Oct. 2016, May 2017, and Aug. 2018. The future projected displacement is also plotted for the average rate of previous measurements.

As demonstrated in Figure 6, GB-InSAR displacement data in the vicinity of CC10 started accelerating approximately at the same time as the measurements for CC10 (between December and January). Further, the magnitude of displacement in this

area is consistent with measured displacements at CC10 and CC3 and the average rate of the nearby survey point, see Figure 6.

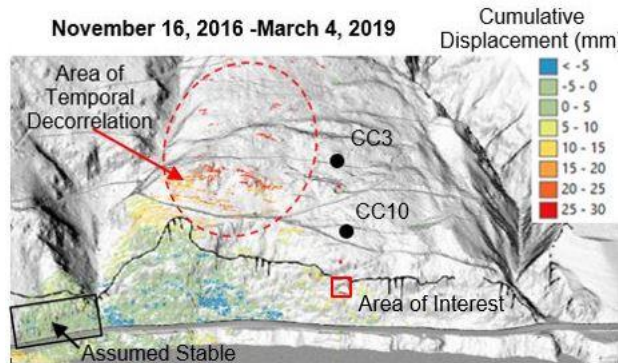


Figure 5 GB-InSAR LoS cumulative displacement map between November 15, 2016 and March 4, 2019. Locations of extensometer CC10, and in-place inclinometer CC3

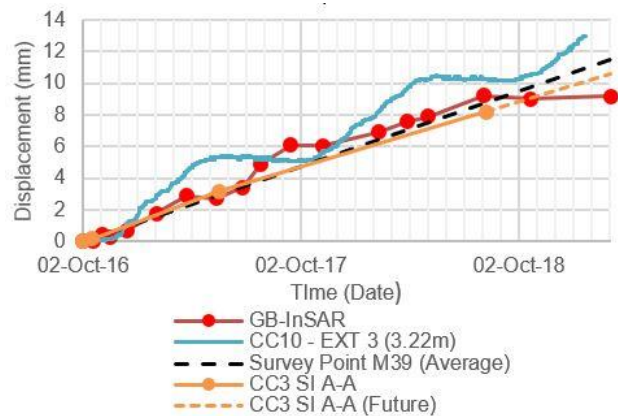


Figure 6 Cumulative displacement in the LoS direction of area in vicinity of CC10 (shown in Figure 5) and measured by extensometer CC10 and in-place inclinometer CC3

5 CONCLUSIONS

This paper provides insights into the applicability of GB-InSAR, including its advantages and complements to other typical geotechnical instrumentation and remote-sensing techniques, at locations with challenging logistics that are typical for Canadian conditions. Further, these limitations and challenges are actively being assessed at the Checkerboard Creek Rock Slope, in Revelstoke, BC; to determine its ability to monitor deformations and enhance the understanding of its deformation patterns.

Pairs of short-term (approximately 1-2 week) monitoring campaigns beginning in November 2016 were used to calculate relative slope displacements between campaigns during periods without reliable power. This does not allow for continuous monitoring but can be used to determine displacements of the rock face. Challenges associated with snow accumulation remain, however the analysis thus far appears to be consistent with numerous instruments in the vicinity of the rockface at the lower portion of the site. In addition, efforts have successfully addressed power availability and telecom issues in a cost-

effective and reliable manner and allowed the acquisition of continuous data for near real time monitoring and early warning purposes.

A primary shortcoming of the current installation is that higher quality radar images do not cover the entire rock face, however ongoing work to address these issues including the installation of corner reflectors, replacement of the window with a less reflective material, and replacing the current radar antennas with others that have a wider field of view should improve the data quality and coverage.

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