THE USE OF SPACEBORNE INSAR TO CHARACTERIZE GROUND MOVEMENTS ALONG A RAIL CORRIDOR AND OPEN PIT MINE

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Abstract

Synthetic Aperture Radar Interferometry (InSAR) is a relatively new technology that provides engineers with the opportunity to measure ground movements to millimeter level accuracy using satellites orbiting hundreds of kilometers above the earth's surface. The potential use of spaceborne InSAR for commercial geotechnical applications in Canada is being investigated through a series of demonstration projects supported by the European Space Agency. This paper describes two of these projects. The first project involved examining ground movements along an 11 kilometer long river valley corridor occupied by both Canadian National Railway Company and Canadian Pacific Railway just south of Ashcroft, British Columbia. The area has experienced several large slope failures and subsequent reactivations in the past that ranged in size from several hundred meters in width and length, to over a kilometer. The second project was carried out to investigate pit slope movements at BHP-Billiton's former Island Copper Mine located on Vancouver Island, British Columbia, which was decommissioned in 1996.

Résumé

L'Interférométrie Synthétique Ouverture Radar (InSAR) est une technologie relativement récente qui fournit aux ingénieurs un outils pour mesurer les mouvements du sol avec une précision de quelques millimètres. La méthode utilise des images de satellites en orbite à plusieurs centaines de kilomètres au dessus de la terre. Le potentiel de l'utilisation d'InSAR pour des applications géotechniques commerciales au Canada est démontré grâce à certains projets pilotes développés avec l'Agence Spatiale Européenne. Cet article décrit deux de ces projets: Pour le premier projet, les mouvements du sol ont été suivis le long d'un corridor de 11 km, le long d'une vallée comprenant des voies ferrées opérées par les compagnies Canadian National Railway Company et Canadian Pacific Railway, juste au sud d' Ashcroft, Colombie Britannique. Cette région a subi de nombreux glissements de terrains. La taille des glissements, aussi bien en longueur qu'en largeur, varie d'une centaine de mètres à plus d'un kilomètre Le deuxième projet a consisté à observer les mouvements des faces d'une mine à ciel ouvert fermée en 1966 (BHP-Billiton's Island Copper Mine) située au nord de l'ile de Vancouver.

1. INTRODUCTION

Spaceborne Synthetic Aperture Radar Interferometry (InSAR) has been under development by the Canadian, European, Japanese and US Space Agencies over the last 2 decades. The technology involves transmitting microwave radiation to the earth's surface and measuring the backscattered signals from points on the ground. Using two radar acquisitions of a common area of the earth's surface, made from nearly identical orbit passes, phase differences between the corresponding reflected signals can be calculated. Because the wavelength of the radar sensor is in the order of only a few centimeters, movement in the line-of-sight of the sensor on the satellite platform can be determined to millimeter accuracy.

The European Space Agency in cooperation with the Canadian National Railway Company (CN) and BHP Billiton Base Metals (BHP) commissioned the use of spaceborne InSAR to investigate the extent and progression of ground movements over time at two sites in Western Canada. This work was carried out to better understand the mechanisms of the slope movements and to aid in the selection and development of an effective remedial methodology at each site.

This paper describes the development of InSAR deformation maps showing ground movement along an 11 kilometer long river valley railway corridor just south of Ashcroft, British Columbia. These deformation maps were completed from historical InSAR data for 3 timeframes over a 5-year period from 1997 to 2002. This paper also outlines the application of the spaceborne InSAR technology along slopes of a decommissioned open pit mine located on Vancouver Island, British Columbia. InSAR was used to examine pit slope movements over two time periods in 2002.

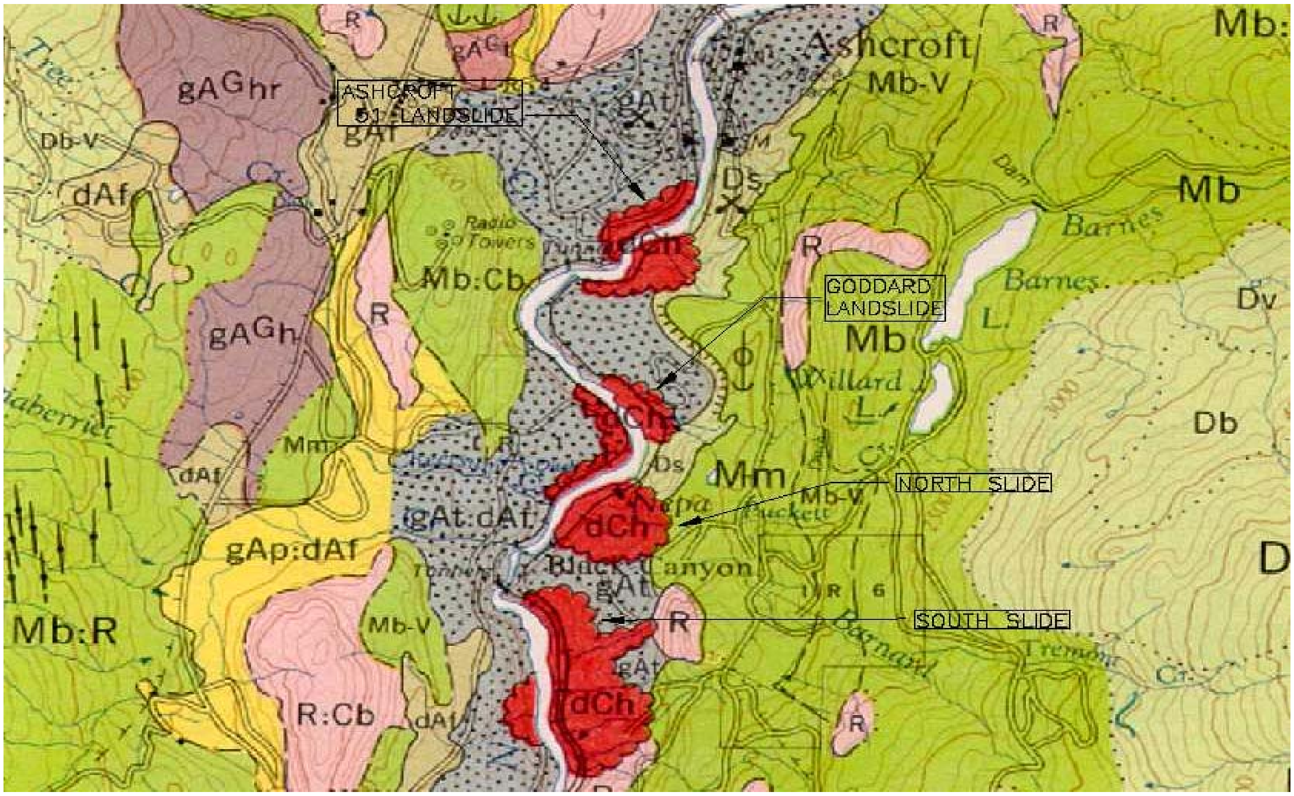

Figure 1. Regional Geology Showing Location of Past and Present Landslides.

2. ASHCROFT RAILWAY CORRIDOR

The Ashcroft railway corridor has experienced several large slope failures in the past including the Goddard Landslide, which occurred in September of 1982, the North Slide, the South Slide and the Ashcroft Mile 50.9 Landslide (Figure 1). These landslides range in size from several hundred meters in width and length, to over a kilometer.

Both CN and Canadian Pacific Railways (CP) have railway lines that travel through the Ashcroft corridor. The railway lines run parallel in a southerly direction on opposite valley slopes of the Thompson River from Ashcroft (CN on the west bank and CP on the east bank) to the location of the South Slide where the CN railway line crosses the river. From this location both railways continue to run southward on the east side of the river.

Historical records have shown that the South Slide experienced toe erosion and developed a scour hole. This occurred in the spring of 1997 after the two groynes (a breakwater made from rock erected along a river to inhibit the movement of sand to protect against longshore drift) along the Thompson River overtopped due to high river water levels. On or about February 1998 tension cracks appeared in the embankment supporting the CN Rail tracks. Geotechnical instrumentation including both inclinometers and piezometers were installed in June 1998 along the slope.

The Ashcroft 50.9 Landslide is a large ancient landslide that exhibited movement over a relatively small area (approximately 35 m x 100 m) at the toe of the slide during the winter of 2000-2001 (Figure 2). Monitoring instrumentation was installed in 2001, which included inclinometers, piezometers, and tension crack gauges. Readings taken from these instruments during the summer of 2001 indicated that this small portion of the slide was moving and the rate of movement was increasing with time. CN commissioned the construction of a berm at the toe of the slope in August 2001 to control these movements.

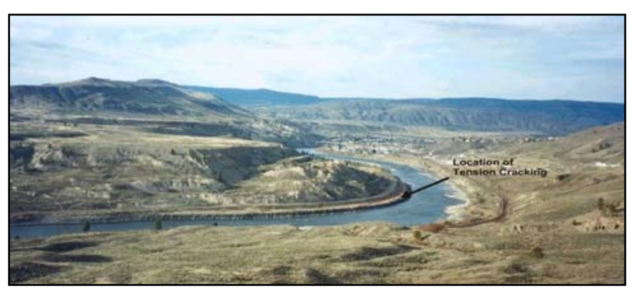

Figure 2. View Looking northwest toward Mile 50.9

3. ISLAND COPPER OPEN PIT MINE

The Island Copper Mine was discovered by the Utah Construction and Mining Company in February 1967. Production at the mine commenced in October 1971 and continued through to September 1995. BHP Minerals Canada Ltd. assumed responsibility for mine operations in 1984. During the 24 years that the mine operated, approximately 1.3 billion kilograms of copper, 31.7 million grams of gold, 336 million grams of silver, 31 million kilograms of molybdenum and 27,000 kilograms of rhenium were produced.

The mine is located at tidewater on Rupert Inlet, off Quatsino Sound, a fjord on north-western Vancouver Island, immediately adjacent to the ocean (Figure 3). The elevation of the open pit bottom was 402 m with pit slopes extending up to an elevation of 488 m. The last stages of mining required construction of a 39 m deep slurry wall approximately 1220 m long within 30 m of the base of the pit wall. The wall was designed to prevent ocean water from flowing into the pit during the mining operation.

Figure 3. Aerial View of Island Copper Mine.

After the mine was decommissioned in 1996, the open pit was flooded with seawater to form a miromictic lake. Formation of this lake has proven to be an effective long-term environmental solution. However, because the lower pit slopes were known to actively generate acid runoff, there was a concern that a future unexpected pit slope failure into the lake could displace the seawater below the fresh water cap and result in lake turnover. Therefore, BHP-Billiton has carried out extensive work to monitor pit slope movements as part of their ongoing monitoring efforts.

Slope failures in the west and north pit slopes, associated with a concentration of faults in these areas, have occurred during the operation of the mine. The north and northwest walls, extending to 76 m (250 ft) above the current lake level, have continued to exhibit instability since the mine was closed. The west portion of the pit has exhibited ongoing movements that have resulted in the mine's operator restricting access to these slopes.

The potential failure of the west pit slope was identified prior to mine closure. Remedial measures were implemented at that time which included placing volumes of material (a buttress) on the lower portion of the slope to increase the resistance to sliding. The crown of the buttress is slightly below the current lake level. The potential failure area is estimated to be 8400 m^2.

A major goal of this demonstration project was to determine whether or not InSAR products and services could be a viable alternative to geo-information obtained from conventional ground based instrumentation in evaluating the risk associated with these mine slopes and to provide adequate warning of potential failures affecting the environment.

4 SPACEBORNE InSAR

Synthetic aperture radar is an active sensor that can be used to measure the distance between the sensor and a point on the earth's surface. A SAR satellite typically orbits the earth at an altitude of approximately 800 km. The satellite constantly emits electromagnetic radiation to the earth's surface in the form of a sine wave (Figure 4). The electromagnetic wave reflects off the earth's surface and returns back to the satellite. This back-scattered microwave signal is used to create a SAR satellite image (a black and white representation of the ground reflectivity).

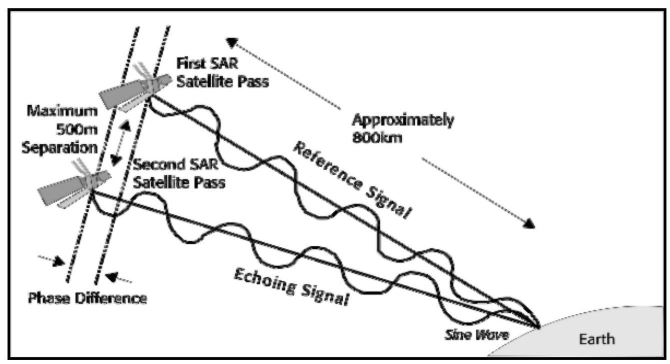

Figure 4. Basic Principle of Spaceborne SAR

SAR radar images are made up of pixels. Each pixel has a specific size determined by the SAR satellite resolution, the higher the resolution the smaller the pixel size. The ground reflection is averaged over the pixel area.

To measure differential ground movements over a specified time period, InSAR requires two SAR images of the same area taken from the same flight path, within 500 m laterally. InSAR compares the phase of the echoing signal to a reference wave for each satellite pass. The difference in phase between the two SAR images can be used to determine ground movement in the line of sight of the SAR satellite. For example, if the first pass of the SAR satellite had an echoing wavelength magnitude of ½ wavelength and the second pass was ¼ wavelength then during the time period between the two passes there has been a ¼ wavelength change in the satellite line of sight elevation.

The wavelength of the microwave signals emitted by the SAR sensor is typically in the order of a few centimeters. Because InSAR measures the phase difference resulting from the path length change between the sensor and a point on the earth's surface, the magnitude of ground movement between the two satellite passes can be measured to millimeter accuracy.

InSAR has proven highly successful in detecting ground movements in several locations and applications around the world. For example, one of the early users of the technology was the oil sector in the United States, which used spaceborne InSAR to detect very small surface movements above deeply buried reservoirs during hydrocarbon production (Van der Kooij, 1997).

Currently there are two agencies operating SAR satellites in the civilian sector, the Canadian Space Agency (CSA) and the European Space Agency (ESA). CSA has had one SAR satellite, RADARSAT-1 in orbit since 1996. ESA recently launched its third SAR satellite, Envisat, in 2002. Its predecessors, ERS-1 and ERS-2 collected SAR images from 1992 to 2000 and from 1995 to 2001, respectively.

Both CSA and ESA satellites have collected a large database of archival SAR images. In addition, the Japanese Space Agency (NASDA) operated a SAR satellite from 1993-1998. The SAR images collected by this satellite are also available.

A major advantage of InSAR is that SAR satellites do not require the sun as a light source and do not need clear weather to operate. In addition, InSAR does not require the placement of reference monuments on the ground surface. A current major disadvantage to the technology is the inability of SAR satellites to penetrate heavily vegetated areas.

Spaceborne InSAR was first used to address slope stability issues in 1991 at the La Clapiere Landslide in southern France (Benedicte et al., 1996). The landslide is located in Nice on the left bank of the Tinee River and extends a few square kilometers. InSAR derived ground measurements were found to be in good agreement with traditional ground measurements and were also able to detect small-scale spatial instability, which discrete ground measurements could not observe.

Kosar et al. (2003) describe the use of spaceborne InSAR to investigate the extent and progression of movements over time of Fountain Landslide. This landslide, which is located near the town of Lillooet in southwestern British Columbia, was reported by the provincial Department of Transportation to have experienced chronic ground movement over the last several decades. The use of historical spaceborne InSAR enabled the extent of the landslide over time to be examined. InSAR data indicated separate zones of movement within the overall landslide mass with individual blocks moving at different rates. Using InSAR, engineers were able to detect spatial ground movements that were not otherwise evident, i.e. not visually detectable.

5. INSAR GROUND DEFORMATION MAPS

5.1 Ashcroft Railway Corridor

Ground deformation maps derived using spaceborne InSAR were completed for the Ashcroft railway corridor for the following time intervals:

- August 8, 1997 through August 28, 1998;
- March 10 to October 6, 1999; and
- July 29, 2001 through April 19, 2002.

To optimize the information displayed along the corridor, each InSAR acquisition timeframe was assigned a colour. Ground movement that occurred during August 8, 1997 to August 28, 1998 was coded red, ground movement that occurred during March 10 to October 6, 1999 was coded yellow, and ground movement that occurred during July 29, 2001 through April 19, 2002 was coded blue. For any movement that occurred during any combination of timeframes, a mixture of the coded colour was displayed (1998 (red) and 1999 (yellow) - orange colour, 1998 (red) and 2002 (blue) - purple colour; and 1999 (yellow) and 2002 (blue) - green colour).

In addition, ground movement information was mapped based on ground movement greater than a base value, i.e. ground movements greater than 8 mm (Figure 5); greater than 12 mm (Figure 6); and greater than 16 mm (Figure 7).

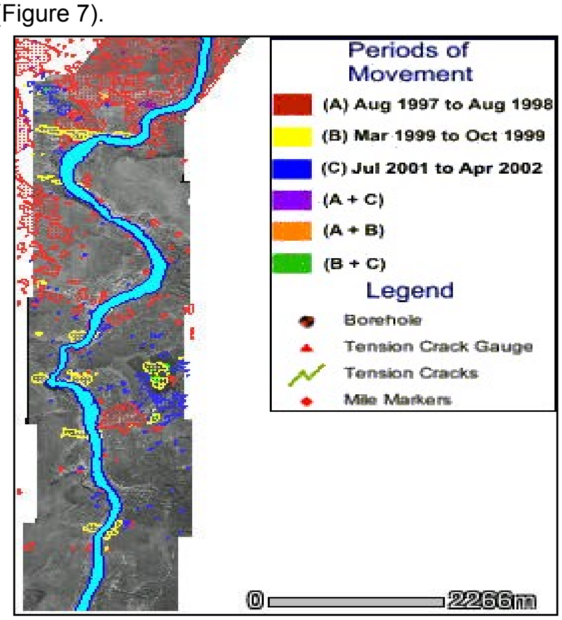

Figure 5. Ground Movement greater than 8 mm

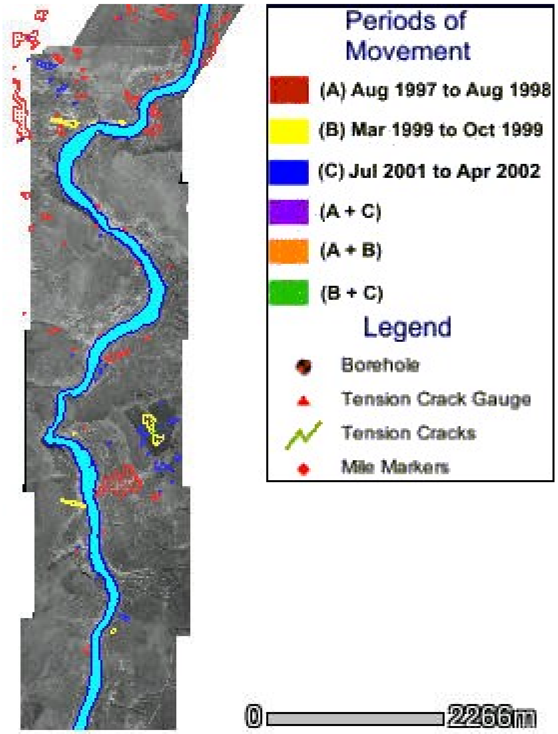

Figure 6. Ground Movement greater than 12 mm

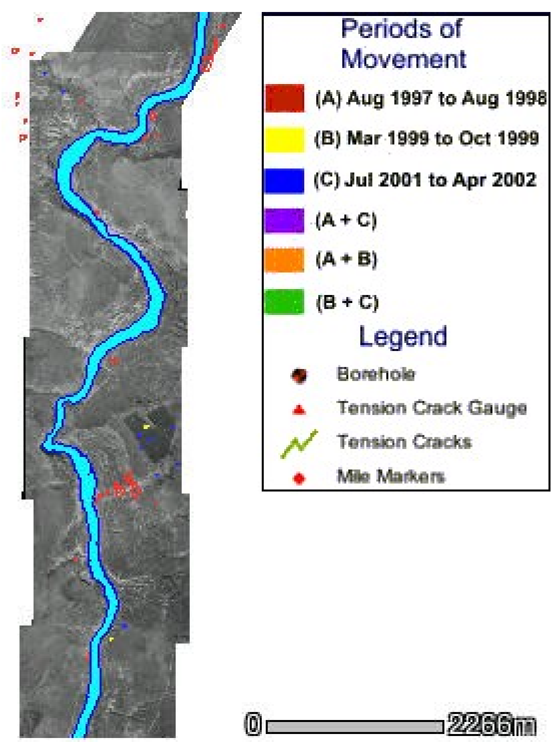

Figure 7. Ground Movement greater than 16 mm

Results obtained from the spaceborne InSAR analysis of the Ashcroft railway corridor may be summarized as follows:

1. August 8, 1997 to August 28, 1998 (1.1 years).

   This deformation map shows two areas of potential ground movement, immediately south of the South Slide, and across the river from Mile 50.9. Both areas have shown ground movements in the range of 20-24 mm. This correlates to a relatively small movement rate of about 0.06 mm/day. The area adjacent to the South Slide is approximately 575 m x 400 m, whereas the area opposite to Mile 50.9 is approximately 200 m x 200 m. There were no other significant ground movements in the corridor during this time period.

2. March 10, 1999 to October 6, 1999 (0.5 years).

   Overall, the corridor is relatively inactive during this time period and there does not appear to be any areas of significant ground movement. Some movement is evident immediately north of the South Slide. However, the magnitude of ground movement is relatively small, 8-12 mm, correlating to a movement rate of about 0.06 mm/day. The area of ground movement is about 460 m x 200 m.

3. July 29, 2001 to April 19, 2002 (0.7 years).

   Inclinometer data obtained from the toe area of the Mile 50.9 landslide by CN indicated that ground movement was intermittent (slip-stick mechanism). In addition, only portions of the 35 m x 100 m area were moving at any one time during the InSAR acquisition period. The InSAR deformation map during this time period indicates that reactivation of the Mile 50.9 very large ancient landslide had not occurred.

   The area south of the South Slide that was showing movement in the 1997-1998 deformation map also shows ground movement for this time period. The area is approximately 855 m x 800 m and extends southward from the area in the 1997-1998 deformation map. The maximum amount of movement is 20-24 mm, which equates to a movement rate of about 0.09 mm/day.

5.2 Island Copper Open Pit Mine

Two deformation maps were created for different timeframes at the Island Copper Mine pit using Canadian Space Agency's RADARSAT-1 satellite:

- January 19, 2002 to March 8, 2002 (Figure 8); and
- March 8, 2002 to May 19, 2002 (Figure 9).

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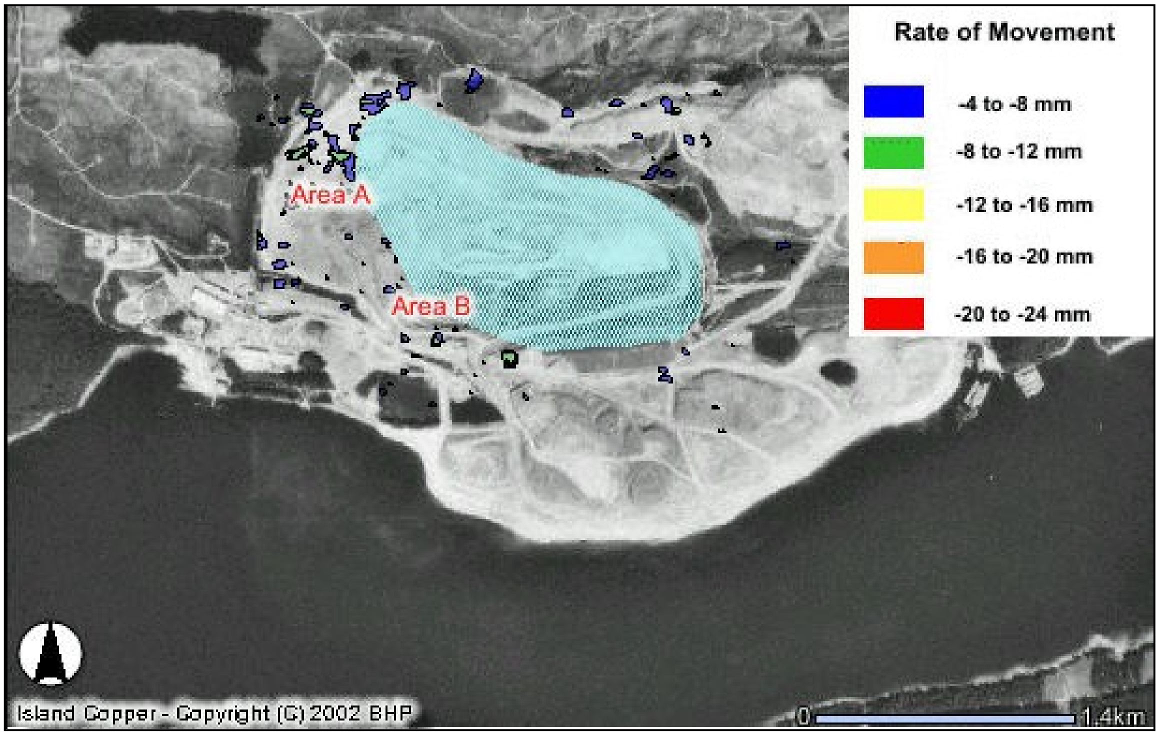

Figure 8. Ground Movements - January 19, 2002 to March 8, 2002

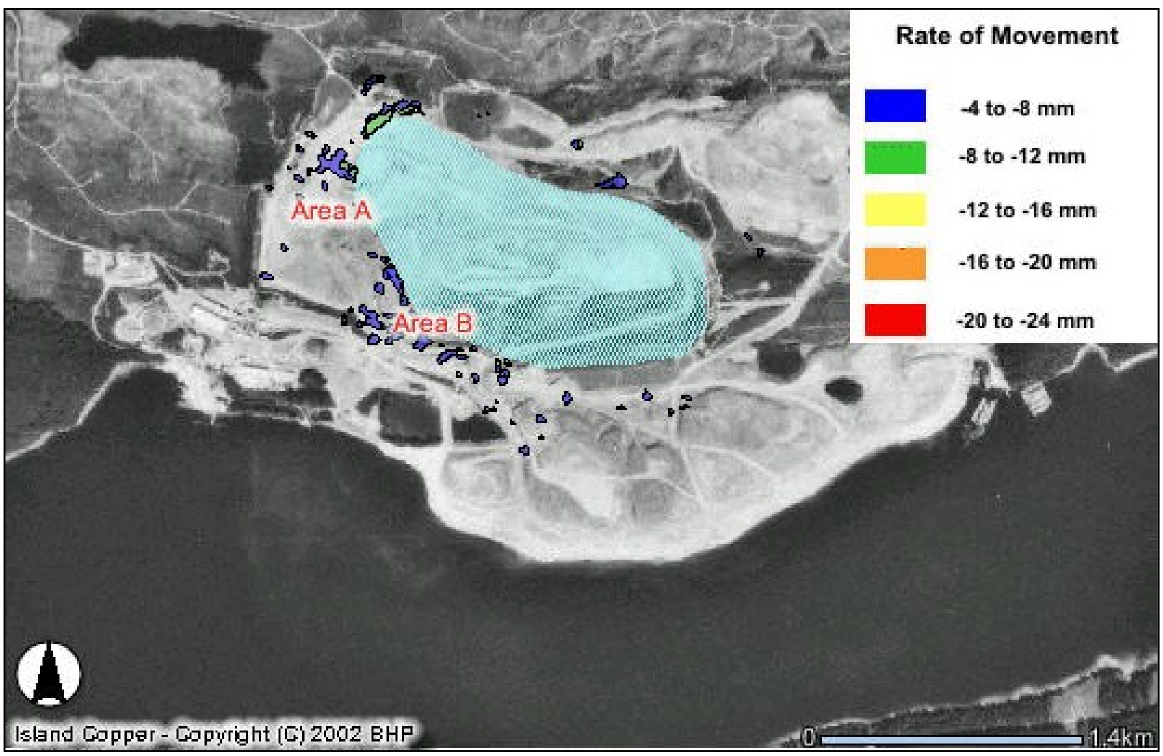

Figure 9. Ground Movements - March 8, 2002 to May 19, 2002

The key results associated with the Island Copper project can be summarized as follows:

1. <u>January 19, 2002 to March 8, 2002 *(49 days)*</u>

The deformation map derived from InSAR during this time frame shows significant ground movement (up to 185 mm/year) along the west (Area A) and south (Area B) pit slopes. Minor ground movement is also apparent in natural and man-made slopes north and northeast of the abandoned mine pit.

Area A: Ground movement extends along the entire west pit slope. The area and magnitude of ground movement increases markedly in the northern half of the slope. Ground movement ranges from 4 to 16 mm (31-123 mm/year) in the southern part of the west slope to a maximum of 24 mm (up to 185 mm/year) along the slope crest in the northern part.

Area B: Ground movement along the south pit slope was found to range between 4 and 16 mm (31-123 mm/year). The majority of movement was confined to relatively small areas in the upper portion of the pit slope.

2. <u>March 8, 2002 to May 19, 2002 *(73 days)*</u>

In general, the deformation map for this time interval correlates very well with the January to March 2002 deformation map. Again, the vast majority of ground movement was found along the west (Area A) and south (Area B) pit slopes

Area A: Significant ground movement was detected along the west slope of the pit. This ground movement, particularly in the northern portion of the slope, was in locations consistent with the January to March 2002 time period. It is noted that the maximum rate of movement was slightly lower in the March to May 2002 time period ranging from 20 to 80 mm/year.

Area B: Ground movement in this time period was found to be much more widespread compared to the January to March 2002 time interval. However, the overall rate of movement along the south pit slope decreased somewhat to 20 to 60 mm/year.

6. CONCLUSIONS

The feasibility of employing spaceborne InSAR to monitor ground movement at an open pit mine site was demonstrated in the Island Copper Mine study. The technology was successful in detecting small ground movements along relatively steep (40^{o} to horizontal) pit slopes.

An advantage of spaceborne InSAR over conventional technologies demonstrated in the Island Copper Mine project included the ability of InSAR to detect ground movement with continuous spatial coverage. To attain the equivalent information concerning ground movement at Island Copper Mine, approximately 16,500 individual GPS or survey monuments would be required. Also, the ability to use InSAR to detect ground movement remotely was a definite benefit because the mine operator has restricted physical access to pit slopes due to safety concerns.

The Ashcroft Railway Corridor project illustrated the utility of InSAR for identification and monitoring of complex, slow moving landslides. Although the technology should be used in conjunction with existing geotechnical engineering techniques, it is not redundant, but rather complementary, in that it represents a significant addition or improvement to owner's and engineer's understanding and risk management for these types of hazards. In addition, because InSAR satellites were first launched for continuous scientific and commercial use in the early 1990's, this data can be back analyzed over the last decade for a great number of sites around the world, leading in some instances to enhanced understanding of complex geotechnical behaviour.

Spaceborne InSAR may play an important role in the future management, analysis, remediation and monitoring of unstable slopes. When used in conjunction with current geotechnical techniques and practices, it has the potential to provide engineers with a reliable methodology for decision making to manage the risk and costs of existing and potential slope failures.

7. ACKNOWLEDGEMENTS

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