Engineering Geology 166 (2013) 160–169

Contents lists available at ScienceDirect

Engineering Geology

journal homepage: www.elsevier.com/locate/enggeo

High resolution displacement monitoring of a slow velocity landslide using ground based radar interferometry

B. Lowry [a,*], F. Gomez [b], W. Zhou [a], M.A. Mooney [a], B. Held [b], J. Grasmick [a]

[a] Colorado School of Mines, Golden, CO, United States
[b] University of Missouri at Columbia, Columbia, MO, United States

ARTICLE INFO

Article history:
Received 18 October 2012
Received in revised form 8 July 2013
Accepted 14 July 2013
Available online 19 July 2013

Keywords:
Landslides
Remote Sensing
Radar
Interferometry
Monitoring
Terrestrial geodesy

ABSTRACT

Ground-based interferometric radar (GBIR) monitoring was conducted on a slow-moving, translational failure landslide in Granby, Grand County, Colorado, USA. Radar monitoring was completed over two separate surveys in 2011 using a tripod mounted real aperture sensor. The purpose of this work is to evaluate GBIR as a temporally dense monitoring technique for monitoring landslide displacement and compare the monitoring results to ongoing GPS based surveying methods to verify measured displacements. We discuss the strengths and limitations of GBIR displacement monitoring with a variety of available sensors, and place this monitoring platform, sensor, and workflow into context of previous slope stability monitoring with GBIR. For both surveys, displacement time series were created through a small temporal baseline stacking to reduce noise and maintain high temporal resolution. The results of the displacement time series were compared to average displacement rates derived from GPS based surveying. An overall verification of radar and GPS derived displacement rates was achieved, and identifies important differences relating to the precision and uncertainty of the two techniques. This work demonstrates GBIR monitoring capability of establishing high temporal resolution on tracking variable rates of landslide movements. Spatial modeling of total observed displacements was completed for both surveys verifying a conceptual model of uniform translational landslide movement, providing greater confidence for mitigation planning.

1. Introduction

The use of ground-based interferometric radar (GBIR) sensors has become increasingly valuable to the monitoring of displacements of landslides and unstable slopes. These sensors join a geodetic toolset used to monitor landslides alongside laser-based Light Detection and Ranging (LiDAR), global positioning systems (GPS), and photogrammetric imaging. GBIR monitoring enables imaging of ground surface deformation across large areas (<10 km^2) with high spatial (<1 mm) and temporal (<1 h. scan frequency) resolutions. GBIR systems have been successfully implemented for landslide monitoring with good examples presented in literature across a range of sensor types (Leva et al., 2003; Tarchi et al., 2003; Noferini et al., 2007; Barla et al., 2010; Casagli et al., 2010; Schulz et al., 2012). Table 1 summarizes these works by slope failure type, spatial and temporal resolution, sensor type, and analytical method. The use of GBIR monitoring has been accelerated by the adaptation of satellite-based interferometry software and analysis techniques. Using these advanced algorithms, and with more control over the platform scanning position, GBIR monitoring has distinct advantages for landslide monitoring applications. However, GBIR monitoring must be conducted with knowledge of limitations and integrated with traditional displacement monitoring to become a reliable and trusted landslide monitoring tool.

This paper presents a high resolution displacement monitoring application of a slow moving (according to Cruden and Varnes, 1996) landslide using GBIR verified with GPS surveying techniques. The landslide is located near Granby, Grand County, Colorado, USA (Granby landslide hereafter). Radar monitoring was conducted with a Gamma Portable Radar Interferometer (GPRI), a tripod-mounted, rotational scanning radar system with three-antenna real aperture imaging (Figure 1). This sensor uses one antenna to transmit and two receiver antennas, which can be configured for polarimetry or from multiple baselines to subtract topographic effects. The GPRI sensor is formally described in Werner et al. (2008) which addresses issues of instrument sensitivity and specific hardware configuration. This sensor differs from other platforms used to monitor landslides in its use of a real (as opposed to synthetic) aperture, a tripod mount, and rotational scanning action (as opposed to track-based), creating a platform-specific set of considerations for conducting displacement measurement monitoring.

Two sets of scans were carried out in the summer of 2011; in June for a 24-hour span and in August for a 36-hour span. Scans were carried out non-disruptively and independently from existing construction activities such as vehicle movement on the landslide, meaning that some imagery would not be useable for generating landslide displacements.

* Corresponding author. Tel.: +1 720 771 2753.
E-mail address: blowry@mines.edu (B. Lowry).

0013-7952/$ – see front matter © 2013 Published by Elsevier B.V.
http://dx.doi.org/10.1016/j.enggeo.2013.07.007

Table 1
Examples of GBIR monitoring of landslides by sensor and analysis method.

Study	Location	Failure type	Range resolution	Azimuth resolution at 1000 m	Temporal resolution (approx.)	Sensor	Analysis method
Leva et al. (2003)	Schwaz, Austria	Debris flow	2 m	4 m	30 min	Linear SAR-LISA	Interferogram stacking
Tarchi et al. (2003)	NE Italy	Tessina landslide roto-translational	2 m	4 m	50 min	Linear SAR-LISA	Interferogram stacking
Noferini et al. (2007)	NE Italy	Rotational rock block slide	5 m	15 m	30 min	GB-InSAR	Permanent scatterers
Barla et al. (2010)	NW Italy	Deep seated gravitational slope deformation (DSGD)	0.5 m	4.5 m	20 min	GB-InSAR	Permanent scatterers
Casagli et al. (2010)	Italy	Reunion landslide, Stromboli volcano	2 m	2 m	10 min	Linear SAR-LISA	Spatial averaging
Schulz et al. (2012)	Lake City, Colorado, USA	Slumgullion landslide complex	0.75 m	4.375 m	10 min	IBIS-L GB-InSAR	Permanent scatterers
This work	Granby, Colorado, USA	Translational landslide	0.75 m	7 m	7.5 min–15 min	Gamma GPRI real aperture	Interferogram stacking using temporal baseline

Radar interferometry measurement of displacement is necessarily conducted within the sensor line of sight (LOS), requiring geometric adjustment into a corrected displacement model for use in characterizing landslide kinematics, facilitated in this application by survey data. Specifically, this paper presents a case study of a particular sensor combination of GBIR and GPS monitoring on an active slow moving landslide. Generally, this work adds to the large range of application types and sensors as well as addresses how methods of analysis contribute to greater understanding of the use of GBIR in unstable slope and landslide monitoring. GBIR imaging provides a continuous field of displacement measurement serving to fill in the gaps between survey monuments, but measurements are subject to issues with image quality, line of sight correction, phase aliasing, and the specific configuration of the GBIR sensor used to acquire the imagery. This paper addresses these issues specific to a landslide monitoring context using a newly available sensor and presents a comparison with GPS surveying to verify the sensor displacement measurements and suitability of the platform for landslide monitoring. We discuss analytical approaches to optimizing the use of the imaging and processing tools to image the landslide, as well as the implications of the large increase in data collection capacity and temporal granularity provided by this remote sensing platform.

1.1. Landslide monitoring radar interferometry from terrestrial platforms

The technique of radar interferometry relies on comparison of the phase differences between the backscatter of repeated radar scans. This technique allows for measurement of millimeter scale displacement with radio wavelengths within the radar band (approx. 1 mm–30 cm), making the technique particularly suitable for tracking active landslides over a range of velocities. While success in landslide monitoring using spaceborne differential interferometric synthetic aperture radar (D-InSAR) has been demonstrated (Hilley et al., 2004; Strozzi et al., 2005), satellite-based monitoring in general suffers fundamental challenges with non-zero baselines and sensor LOS obliquity to downslope landslide movements (Cascini et al., 2010). The fixed orbital periodicities of satellite platforms range from days to weeks, preventing fine temporal scale (<1 h) monitoring of dynamically moving landslides. Other challenges in spaceborne investigations arise from variable spatial baselines between satellite positions, unresolvable phase ambiguities, and temporal decorrelation of signal in the target terrain (Colesanti and Wasowski, 2006).

In ground based platforms, the radar scanning location can be positioned to reduce effects resulting from the obliquity between the radar's LOS and landslide displacement direction. Imagery acquired from the same platform location effectively becomes a zero spatial baseline set of radar images, simplifying the workflow to monitor temporal changes from scan to scan. Small scan intervals (<1 h) and a zero spatial baseline across scans allow for significantly improved control over interferogram quality by reducing temporal decorrelation, and providing real time data acquisition.

Joint GBIR and GPS based monitoring enable the measurement of fascinating behaviors: Schulz et al. (2009) presented GPS and geotechnical monitoring data that revealed displacement rate sensitivity to atmospheric tides within the Slumgullion landslide. Follow-up monitoring with a ground based synthetic aperture radar (GB-InSAR) in Schulz et al. (2012) further verified displacement measurements by correlating kinematic elements a variety of displacement datasets collected over decades of investigation. The Slumgullion project is a good example of how high resolution techniques can be used to characterize a spatially variable landslide with many sources of corresponding displacement monitoring methods on long time scales. Further integration of GBIR imaging workflows with GPS displacement monitoring is important to more understanding of spatial and temporal landslide dynamics as well as provides models for integrating GBIR into typical geotechnical investigations.

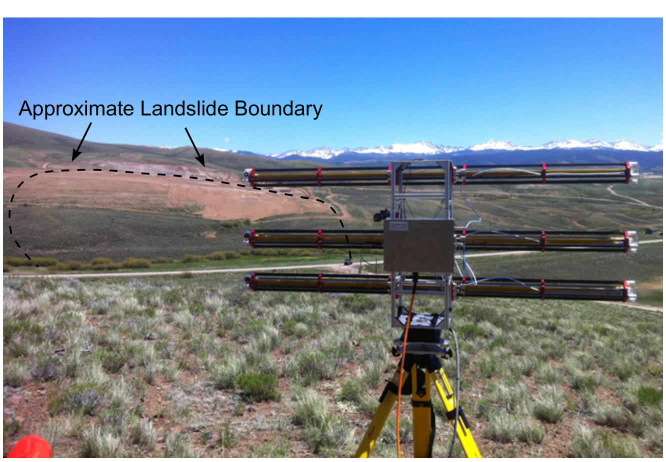

Fig. 1. Deployed GPRI system and field of view of landslide.

2. Granby landslide overview

2.1. Existing displacement monitoring challenges

Information about the Granby landslide has been gathered in an effort to assess stabilization options under a Request for Proposal document issued by Grand County in late 2011, which presents preliminary geotechnical investigation details (Grand County Government and Gagnon, 2011). The Granby landslide has a surface area of approximately 160,000 m^2 (40 acres) and is moving in a southwesterly direction. Traditional GPS based surveying performed at this landslide was collected independently by engineering consultants and is conducted on biweekly or monthly schedules, limiting the temporal resolution to the average velocity occurring between these visits. These visits require a