GPS instrumentation and remote sensing study of slow moving landslides in the eastern San Francisco Bay hills, California, USA

Instrumentation GPS et télédétection de glissements de terrains lents dans les collines est de la Baie de San Francisco, Californie, USA

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ABSTRACT: Active slow moving landslides in the East Bay Hills, San Francisco, California, have been the object of many investigations over recent decades, though their mechanisms are still poorly understood. Contemporary geodetic technologies, such as continuous Global Positioning Systems (GPS) and Interferometric Synthetic Aperture Radar (InSAR), allow for remote detection and characterization of ground surface displacements with sub-centimeter precision and accuracy. This project combines GPS and InSAR time series analyses for the characterization of spatial and temporal landslide deformation as a result of static and dynamic forces. Several independent InSAR time series analyses show accelerated landslide surface deformation as an effect of precipitation, though not in relation to recent seismic activity. Additionally, recent advances in InSAR analysis methods allow the observation of intra-slide deformation patterns. Since the implementation of a comprehensive continuous GPS network in January 2012, landslide related surface displacements have also been recorded in response to precipitation. Both InSAR and GPS studies not only confirm strong correlation and sensitivity to periods of precipitation but downslope sliding velocities of around 30 mm/year as well.

RÉSUMÉ : Bien que leurs mécanismes soient encore mal compris, des glissements de terrains lents dans les collines Est de la baie de San Francisco, Californie, font depuis plusieurs décennies l'objet de nombreuses recherches. Les technologies géodésiques d'aujourd'hui comme le GPS continu et l'InSAR, permettent la télédétection et la caractérisation de déplacements de la surface terrestre avec précision et exactitude millimétrique. Ce projet a donc pour but de caractériser les déformations spatio-temporelles de la surface terrestre, liés aux glissements de terrains sous effets statiques et dynamiques, par l'application de ces outils géodésiques. Plusieurs analyses indépendantes de séries chronologiques InSAR montrent une accélération superficielle de ces glissements sous l'effet de précipitation mais pas sous l'effet d'activité sismique. D'avantage, de récents progrès des méthodes analytiques d'InSAR permettent l'étude des modes de déformation intra-glissements. La mise en place d'un réseau GPS en Janvier 2012, montre aussi une accélération des glissements sous l'effet de précipitation. Ces deux méthodes confirment non seulement une sensibilité aux périodes de précipitation, mais aussi une vitesse approximative de 30 mm/an.

KEYWORDS: Landslides, creep, GPS, InSAR.

1 INTRODUCTION

Recent advances in geodetic technologies allow for remote data collection and the analysis of spatial and temporal ground surface deformation at a scale that was previously not possible. Technologies such as continuous GPS and Interferometric Synthetic Aperture Radar (InSAR) are capable of measuring active surface displacement with as much as sub-centimeter precision and accuracy. This clearly lends itself to the characterization of active slow moving landslides. Furthermore, the urgency for improved efficiency of primary geologic and geotechnical site investigations stresses that these methods be incorporated in the current state of practice.

Active landsliding across the Lawrence Berkeley National Laboratory (LBNL) site and the East Bay Hills, California, has been the object of many investigations over recent decades. Though studies suggest a trend in landslide mobility is associated with regional climate and active tectonic conditions in addition to the local geologic setting, the mechanisms of these currently slow moving slides are still poorly understood. Thus, the objective of this study is to characterize slope deformation as a result of static and dynamic forces by a careful observational program using the most current geodetic technologies. The intent is to help develop a method for the remote determination and evaluation of landslide hazards and their eventual risk assessment.

This monitoring program includes the instrumentation of individual landslides with a comprehensive network of permanent, continuously streaming GPS stations, and regional monitoring of slope surface deformation by InSAR time series analysis. To date, historical InSAR and recent GPS observations confirm similar downslope sliding velocities as an effect of precipitation, though not in relation to seismic activity. A closer review of InSAR time series also reveals a pattern of intra-slide surface deformation and important insight on internal slide mechanisms. This is a presentation of preliminary GPS findings and an observation of InSAR time series analyses.

2 GEOLOGIC SETTING

The study area for this project is located along the western flank of the Berkeley Hills, east of the San Francisco Bay, California. The local geology is the product of an approximately 360 million year old accretionary process during which the North American Plate margin transitioned from subduction of the Farallon Plate to a transform boundary against the Pacific Plate. Hence, several orogenies and accreted terranes are responsible for a wide variety of metamorphic, volcanic and sedimentary formations in this relatively small area known as the California Coast Range geomorphic province, characterized by a northwest trending and low lying mountain range.

As part of the California Coast Range geomorphic province, the Berkeley Hills are an uplifted block of Jurassic to Tertiary sedimentary, volcanic and metamorphic rocks bound by the Hayward and Calaveras faults and folded in a northwest trending synclinal form during regional transpression related to the active plate margin 1-2 million years ago. Now largely overlain by Quaternary colluvial and alluvial deposits, this highly fractured, intensely weathered, moderately soft rock is prone to landsliding.

In addition to the geologic setting, studies suggest that Berkeley Hills landslide mobility is driven by precipitation and regional active tectonic conditions (Alan Kropp and Associates 2002, Hilley et al. 2004, Quigley et al. 2010). Local orographic precipitation forms a wet microclimate and the close proximity to active fault traces within the San Andreas Fault zone brings strong seismicity. Today, several hundred landslide-related geologic and geotechnical investigation reports are available for LBNL and the Berkeley Hills alone, and form a solid background to this project.

3 METHODOLOGY

Two state of the art geodetic sensing technologies form the primary modes of data acquisition in this project: high rate, continuously streaming, GPS and InSAR. While these methods have individually been shown capable of measuring active ground surface displacement at scales that were previously not possible; the appropriate characterization of landslide related slope movement benefits from the application of both.

Where continuous GPS provides three dimensional ground surface displacement measurements with millimeter scale accuracy and precision at full temporal resolution, the spatial distribution of measurement points is sparse. On the other hand, InSAR time series analysis produces improved spatial averages at decameter resolution with sub-centimeter precision, and the inclusion of datasets spanning several decades of observations. These methods are complimentary using deformation detected across a GPS network to calibrate that measured using InSAR.

The objective is thus to accurately measure landslide slope deformation over time. Combining these methods allows for spatial and temporal analysis of ground surface displacements due to landsliding in relation to local precipitation and ground shaking events. By incorporating these surface observations with previous investigations and monitoring, the landslide mechanisms can then be modeled.

3.1 *GPS Data Acquisition*

The first phase of this project has been to establish a network of continuously streaming GPS stations to track landslide related ground surface displacement over time. This involves the instrumentation of individual landslides with autonomous, continuously streaming GPS stations, as well as several permanent reference stations. Each landslide station has been specifically designed for permanent, stand-alone installation and built to capture landslide displacement at depth. Anchored on a deep seated reinforced concrete foundation to limit the effects of surficial disturbance, the stations are solar powered and equipped with a wireless antenna for remote access. Reference station locations are chosen on the basis of proximity to the “mobile” devices and being seated on immobile ground.

Since January 2012, 5 such “mobile” stations have been successfully installed at LBNL and one at the University of California Blake Garden on the Blakemont Landslide. One reference station has been established at the Lawrence Hall of Science above LBNL. Average daily solutions are being obtained for each station based on a 1Hz data set, and a 25Hz buffer is held for displacement-time histories in the case of seismic activity. Three additional sites are in the process of being developed.

3.2 *InSAR Time Series*

InSAR time series are a record of change in radar signal return phase over time, reflecting the change in distance between the ground surface and a satellite based radar platform (or range-change). The strength of the return signal for each radar pulse is dependent of the physical properties of the target (or scatterer). Where distinct structures will return a persistent strong signal, less prominent surfaces will return lower intensity distributed signals and noise. Among others, two types of InSAR time series analyses are thus known as Permanent or Distributed Scatterer methods (respectively).

With the concurrent development of the GPS network, analysis of InSAR time series has also begun, though is not presented here in detail. Rather, a brief review of prior results is described with observations based on TerraSAR-X satellite data processed with the Tele-Rilevamento Europa (TRE) SqueeSAR^{TM} algorithm (Ferretti et al. 2011, Giannico et al. 2011).

4 PRIOR GEODETIC RESULTS

The use of InSAR time series analysis has been shown to successfully track landslide related ground surface displacement in the Berkeley Hills area using data sets from different satellites over several time periods between 1992 and 2011 (Hilley et al. 2004, Quigley et al. 2010, Giannico et al. 2011). In each case, analysis of Permanent and/or Distributed Scatterers over the period of interest clearly exhibit accelerated rates of displacement related to periods of high precipitation. Though no such relationship could be established with local seismicity, it is considered to be likely that large earthquakes can accelerate landslide motion. Furthermore, one attempt at the use of Continuous GPS to track landslide motion was also of no avail (Quigley et al. 2010).

4.1 *1992-2007 Time Series of ERS and RADARSAT*

In the InSAR time series analysis of Permanent Scatterers performed by Hilley et al. (2004), known landslides across the Berkeley Hills were successfully detected and tracked from 1992 to 2001 using ERS-1 and ERS-2 data acquisitions. Over this period, these data indicate landslide related surface displacement rates varied between 5 to 7 mm/year range-change in the radar line of sight direction. Based on local average slope inclinations, this implies equivalent downslope velocities of 27 to 38 mm/year and has been verified in the field by subsurface inclinometer displacement measurements of approximately 33 mm/year (Allan Kropp and Associates 2002). Hilley et al. (2004) also observed that periods of landslide acceleration were closely related to seasonal precipitation, though non-linear in that precipitation related displacement did not occur immediately, with lag times of up to 3 months, and did not predictably increase with larger events. Additionally, Hilley et al. (2004) suggest the potential for seismic related landslide displacement given a $M_w \approx 3.9$ Hayward fault event on December 4, 1998. Though the temporal resolution of the time series could not directly document seismically triggered deformation, unexpectedly high InSAR displacement measurements were observed relative to the amount of precipitation during the same period.

Similarly, Quigley et al. (2010) examine seasonal precipitation-related displacement, supplementing the same ERS data set with RADARSAT-1 acquisitions from 2001 to 2006. Landslide displacement was shown not only to be of same magnitude, but clearly seasonal and sensitive to variations in rainfall patterns. Detrended and stacked (by month) observations plotted against average monthly precipitation exhibited a clear 1 to 3 month displacement response lag time and a positive correlation to the intensity of precipitation.

4.2 *2007-2009 Continuous GPS Tracking.*

Quigley et al. (2010) used Continuous GPS at one known active landslide location to track surficial displacements between 2007 and 2009. Though InSAR time series (Hilley et al. 2004) and local inclinometer data (Quigley et al. 2010) clearly illustrated slide activity in the years before the station's installation, the GPS monitoring did not. This was likely due to a particularly dry period and the station was disassembled before an adequate data set could be collected to observe long term landslide behaviors.

5 RECENT INSAR TIME SERIES OBSERVATIONS

While the Permanent Scatterer InSAR method uses stable coherent targets as shown in the examples above, it is also limited by their presence. To increase the number of observed scatterers and improve time series resolution, the new proprietary algorithm (SqueeSAR™) developed by TRE (Ferreti et al. 2011), utilizes both the Permanent and Distributed Scatterer methods. Thus, a third InSAR time series analysis was performed over the Berkeley Hills by Giannico et al. (2011) applying the SqueeSAR^{TM} method to TerraSAR-X data acquisitions from 2009-2011.

As observed in the 1992-2007 InSAR time series analyses (Hilley et al. 2004, Quigley et al. 2010), landslide related displacements were clearly identifiable with velocities averaging between 6 and 8 mm/year range-change and with periods of precipitation-related acceleration. Figures 1 and 2 show the location and average displacement time histories for different areas (top, middle and bottom) within the Blakemont Landslide (respectively), plotted against cumulative precipitation over the period of observation.

Located at the northern-most end of the study area, field investigations have described the Blakemont Landslide as an approximately 915-m-long, 215-m-wide translational soil and rock landslide with nested rotational failures, and an active sliding depth of 8 to 20 m (Alan Kropp and Associates 2002). While the entire slide appears to be moving coherently downslope (increasing range-change displacement from the descending orbit acquisition), clear accelerations occur in early 2010 and early 2011, some 3 months after the onset of each wet season. Furthermore, the landslide exhibits a positive correlation between displacement and intensity of precipitation with smooth variations during a more gradual 2009-2010 wet season, in comparison to abrupt accelerations during a higher intensity 2010-2011 season.

An important advantage of the higher spatial resolution afforded by the TRE SqueeSAR^{TM} method is a better understanding of landslide mechanisms as expressed at the ground surface. A closer look at the downslope displacements of different areas within the Blakemont Landslide (Figure 2) reveals that it is in fact not moving as one coherent mass, rather with what physicists would call an "accordion effect". Differencing the average downslope displacements of each of the highlighted areas from top to bottom of the landslide, a pattern of apparent landslide shortening (positive) and extension (negative) becomes evident (Figure 3). Here the largest differential displacement variations are observed between the top and bottom areas of the landslide. During wet seasons, the difference in displacement between top and bottom of the landslide increases as the lower portions of the slide accelerate earlier than the upper portions. The same can be said for the opposite case during dry periods, when the difference in displacement between the top and bottom of the landslide decreases as the lower portions of the landslide slow and the upper portions catch up. Naturally, as this currently short dataset is augmented, it is the authors' hope to observe similar trends over longer time periods.

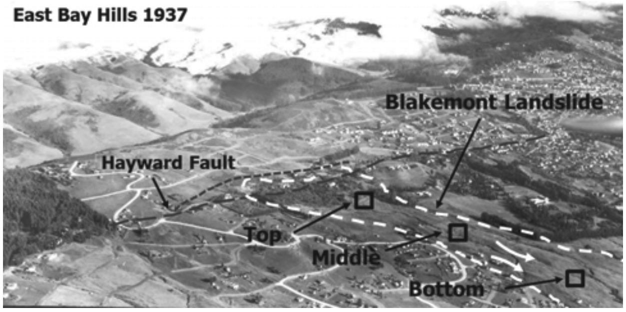

Figure 1. 1937 Oblique view of Blakemont landslide showing location of approximate highlighted areas in TerraSAR-X InSAR study.

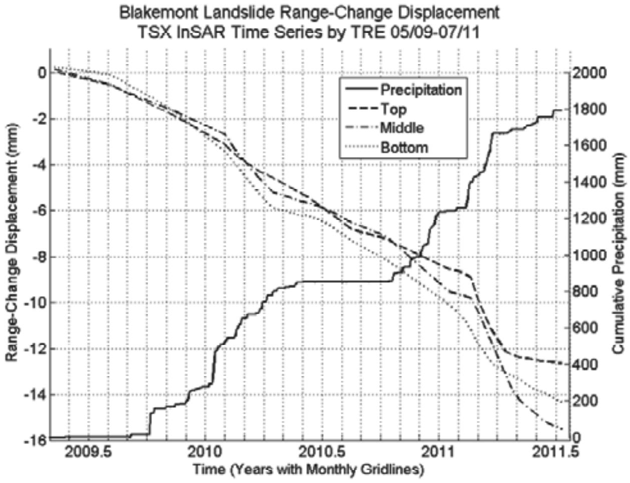

Figure 2. TRE SqueeSAR^{TM} analysis of TerraSAR-X data acquisitions (2009-2011), illustrating average downslope (negative) range-change displacement (left axis) in top, middle and bottom areas of Blakemont Landslide versus cumulative precipitation (right axis).

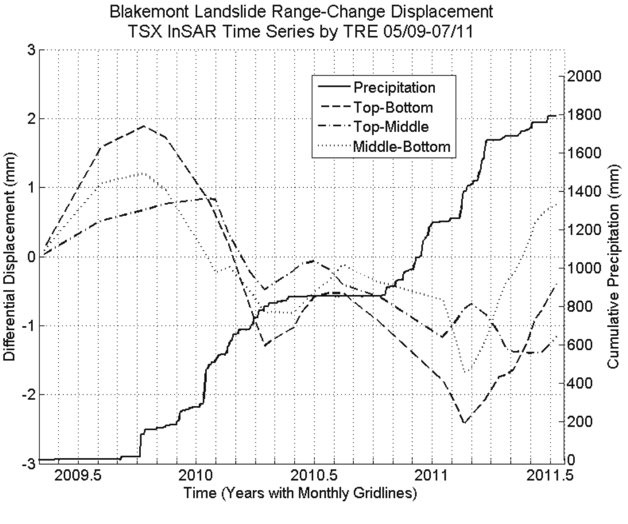

Figure 3. Differential of average downslope displacements (left axis) from TRE SqueeSAR^{TM} analysis of TerraSAR-X acquisitions (2009-2011) between highlighted areas of the Blakemont Landslide, from top to bottom, plotted against cumulative precipitation (right axis).

6 PRELIMINARY GPS RESULTS

Daily solutions from the first 6 continuously streaming GPS stations have been recorded since their installation in January 2012. Highlighted here are stations "LRA 1-3" located on the same landslide in Chicken Canyon at LBNL, as depicted in the 1935 air photo (Figure 4). While historical ground surface displacement related to this landslide has yet to be characterized and quantified, extensive field investigations have described it as an approximately 230-m-long, 75-m-wide and 24-m-deep translational soil and rock landslide with nested rotational failures (Alan Kropp and Associates 2009).

Already, a clear signal at each of these 3 stations is apparent, showing down-slope displacements of up to 3 cm which occurred directly related to local precipitation. As an example, Figure 5 illustrates the time history of daily solutions for station LRA 2 from January through October 2012, plotted against cumulative rainfall. To remove tectonic related displacements and measure actual displacement of the station, daily solutions for the station's North and East baselines are taken with respect to a fixed station (P224) several kilometers to the South. As such, LRA-2 clearly exhibits long term down-slope displacement to the southwest, accelerating during large rainfall events. Also indicated in Figure 5 is the time of the March 5, 2012 M_w = 4.0 Hayward fault earthquake with epicenter in El Cerrito, CA, approximately 10 km north of the site. While no clear seismically driven permanent slope displacements can be discerned, this may be due to the "dry" state of the landslide as well as the event's size and distance.

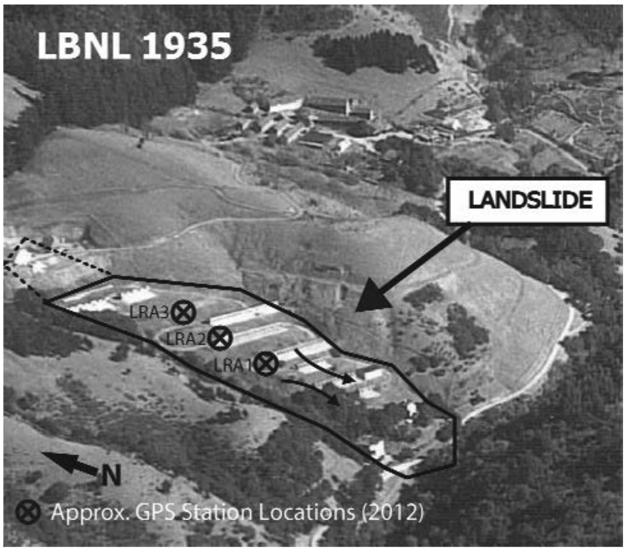

Figure 4. 1935 Oblique view of LBNL landslide with current GPS station locations.

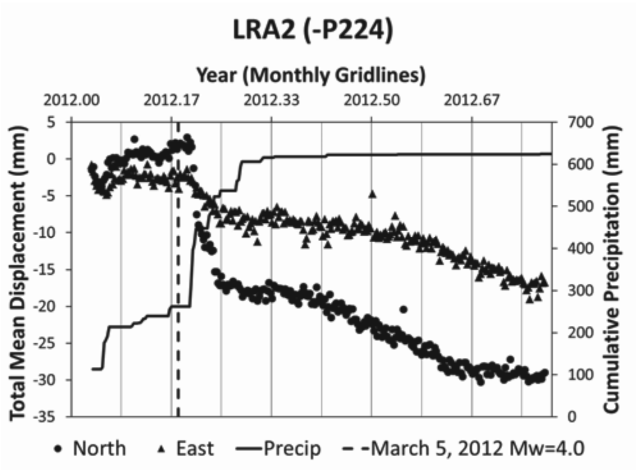

Figure 5. GPS position time series of station LRA 2 with respect to reference station P224. North (circles) and east (triangles) components of relative displacement with respect to reference site P224 are show together with cumulative precipitation (solid line) and time of M_w = 4 earthquake (dashed line).

7 CONCLUSION

A review of three independent InSAR time series analyses of the Berkeley Hills, from separate satellite acquisitions and over different time intervals from 1992-2011 shows remarkable consistency. In each case, similar mean landslide velocities were estimated, and precipitation dependent displacement behavior was observed. Though we were not able to document any motions induced by recent moderate earthquakes in the region, improved spatial resolution has allowed us to draw preliminary conclusions on the mechanics of displacement within one landslide. Further insight is expected as the quality of analysis improves and larger datasets are acquired.

After a mild wet season, the GPS instrumentation of several landslides in the Berkeley Hills, has recorded well-defined precipitation triggered slope movement. In contrast, the occurrence of a nearby M_w = 4 earthquake did not appear to have produced a measurable effect. Overall, the system has already demonstrated its capability to record landslide motions that otherwise would not have been observed with such level of detail and it continues to function and collect new data.

While both methods of observation presented here have not yet been directly compared, they do exhibit similar trends. In both cases, records of landslide related surface displacement have comparable down-slope velocities, increased with periods of precipitation and varied with its intensity. Observations over longer periods will provide important insight on the triggering mechanisms and internal landslide behavior we have described.

8 ACKNOWLEDGEMENTS

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