Real-Time Monitoring of Deep-Seated Gravitational Slope Deformation in the Taiwan Mountain Belt

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Abstract

The deep-seated gravitational slope deformation (DGSD) on mountain areas is widespread and overexploitation has increased the frequency of natural disasters such as landslides, rockslides, and debris flows. In Taiwan, the observation and the analysis of the deep-seated landslides suggest that these are mainly controlled by tectonic structures, which play a dominant role in the deformation of massif slopes. Considerable enhancement for morphometric interpretation can be obtained by means of the integration with Airborne Light Detection And Ranging (LiDAR) technology. On the other hand, surface displacements ranging from a few millimeters to several centimeters can be easily measured by continuous Global Positioning System (GPS). Our study analyzes the characteristics of deep-seated gravitational slope deformation using a multi-technique approach by integrating data from the photogrammetry, LiDAR, GPS, rain gauges and field observations. A continuous GPS site, TENC, located along the southern cross-island highway, Taiwan, shows a huge displacement of about 240 mm during the Morakot typhoon in 2009.

Keywords

Deep-seated gravitational slope deformation (DGSD) • Airborne lidar • GPS monitoring • Typhoon morako

234.1 Introduction

The tectonically active island of Taiwan experiences numerous earthquakes and several major typhoons each year. Several short-term surface processes are seismic and typhoon-related, for instance, the Tsaoling landslide triggered by the 1999 Chi-Chi Taiwan earthquake (Chen et al. 2005, 2006) and the Hsiaolin landslide during the 2009 Typhoon Morakot (Lin et al. 2011). After the Typhoon Morakot, some GPS sites show reactivation landslide terrains associated with the Miocene to Eocene slates, corresponding to the area of highest altitudes (Fig. 234.1c). Surface displacements ranging from a few millimeters to several centimeters during the Typhoon Morakot, are typically close to the detection limits of landslides monitoring instruments. With millimeter-accuracy GPS technique, we can easily detect sub-centimeter motions. In this study, we choose CGPS sites located along the southern cross-island

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G. Lollino et al. (eds.), *Engineering Geology for Society and Territory – Volume 2*,
DOI: 10.1007/978-3-319-09057-3_234, © Springer International Publishing Switzerland 2015

highway to study the characteristics of landslides. These sites are operated for more than 10 years and able to study the characteristics of slow- and fast-moving landslides.

234.2 Deep-Seated Gravitational Slope Deformation

A bedrock landslide is defined as a surface area larger than 0.1 km^2, incorporate predominantly parent material in the slide mass, and include channel incision, slope morphology, geologic structure, shear strength loss due to weathering, and lithologic variation in long term processes. DGSD plays an important role in slope development; it accompanies slow but continual movement of a large volume of soil and rock and sometimes transforms into catastrophic movement (Chigira and Kiho 1994; Kilburn and Petley 2003; Martinotti et al. 2011; Crosta et al. 2013). In Taiwan, the deep-seated landslides are mainly controlled by tectonic structures, which play a dominant role in the deformation of massif slopes.

After the catastrophic Hsiaolin landslides that caused 450 casualties during the Typhoon Morakot on August of 2009, how to identify potential sites of catastrophic landslides and evaluate their activity and susceptibility becomes an important issue for natural hazard mitigation. In this study, field observations and interpretation of high-resolution topographic models constructed from a light detection and ranging (LiDAR) survey indicate that failures by flexural toppling create uphill-facing scarps in the Tienchih area (Fig. 234.2). After LiDAR analysis shows typical "Sackungen", are often found along ridge crests in massive competent rocks, running parallel to slope contours and to the strike of main rock discontinuities (foliation). The toppling failure occurs by shearing and outward rotation that dips steeply into the mountainside. And the main scarps are therefore created primarily by gravitational stresses, and are not tectonic faults. The movements, although slow (long-term gravity-driven creep), can continue for long periods, producing significant cumulative displacements, these displacements are relatively small in comparison to the slope itself.

234.3 GPS Study

In recent years, Global Positioning System (GPS) has been developed to provide real-time precise locations in all weather conditions. The accuracy of continuous GPS (CGPS) data can be down to millimeters with some post-processing procedures. We present GPS data from a pre-existing GPS network in Taiwan. The Institute of Earth Sciences, Academia Sinica (IESAS) started the construction of island-wide GPS network since 1989 (Yu et al. 1997). At present, a dense continuous GPS (CGPS) array of more than 350 sites were installed by different institutions in Taiwan (Yu et al. 2003). The collected GPS data are processed with GAMIT/GLOBK software packages, version 10.3 (Herring et al. 2002) using the double-difference phase observable and the tropospheric and ionospheric modeling.

To obtain a more accurate and consistent regional deformation pattern in Taiwan, we use continuous GPS data from 362 Taiwan sites, and 17 IGS sites in the Asia–Pacific region. A least squares linear fit is used to estimate station

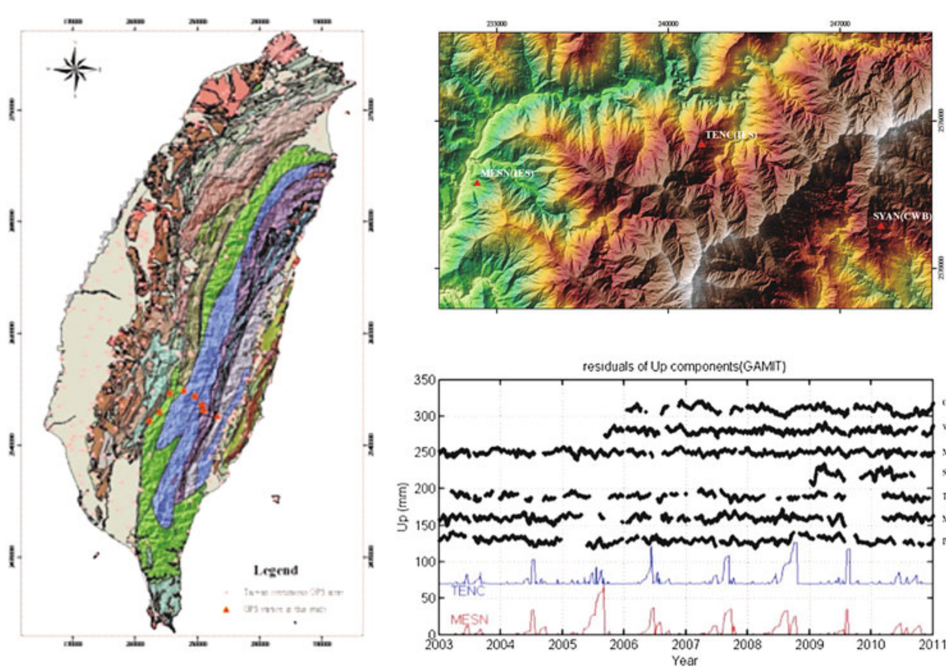

Fig. 234.1 **a** Localization of the studied area on the geological map of Taiwan, elevation in meters above sea level from a 40 m-resolution digital elevation model (Modified after 2000 CGS); **b** Inserts show the topography of the studied area with GPS locations, *MESN* Meishan, *TENC* Tienchih, and *SYAN* SiangYang; **c** Time series of continuous GPS data (*black line*) and rainfall data (*blue* and *red line*) on the southern cross-island highway

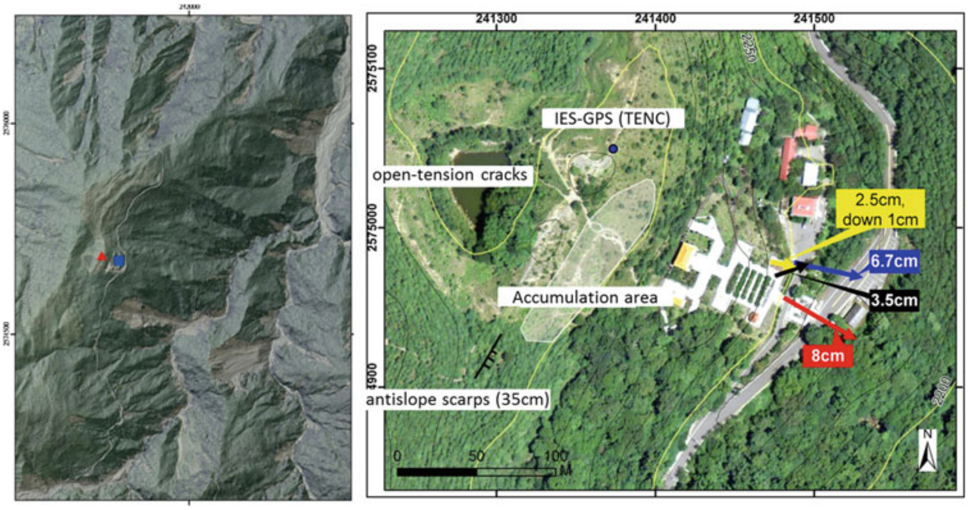

Fig. 234.2 **a** Topographic characteristics of Tienchih landslides with shaded LiDAR DEM as background; **b** Field observation of extraction crack in this study

velocity (linear rate), annual and semi-annual periodic motions, post-seismic relaxation, and offsets caused by coseismic jumps and instrument changes in station position time series (Altamimi et al. 2007). We remove outliers, liner velocities, post-seismic relaxation, as well as offsets caused by coseismic jumps and antenna changes. The residual position time series are used to compare with rainfall data.

GPS data shows movements are correlated with the direction of slope and has a high correlation with rainfall. The cumulative rainfall is up to 2,700 mm over a 5 days

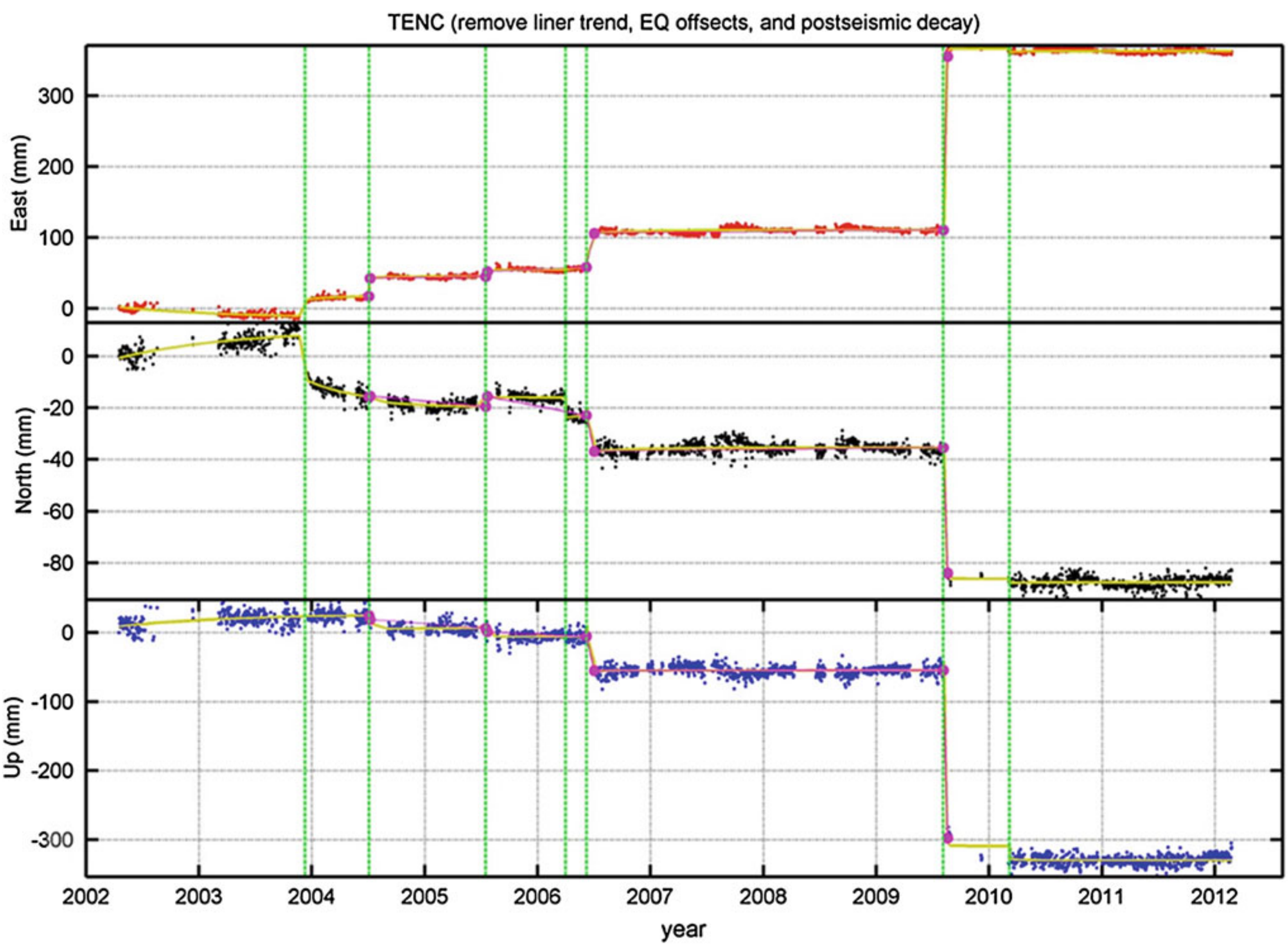

Fig. 234.3 Average displacement time series of GPS with respect to daily rainfall in the TENC site

period during the typhoon, similar to the average yearly rainfall of 2,800 mm in this area. We find a nice correlation in the temporal variation of GPS displacement time series and rainfall with little time lag, suggesting the motion is possibly related to gravitational load related to overflow of water during the typhoon (Fig. 234.3).

The TENC site moved slowly at the beginning when the rain was not strong, then the largest GPS displacements with 75, −20, −75 mm, in east, north, and vertical components occurred when the intensity of rainfall reaches ~90 mm/h. The cumulate displacements are 245, −49, −243 mm in east, north and vertical components, respectively, during the typhoon Morakot.

234.4 Result

Using High-resolution LiDAR images can identify the DGSD and their morphological features. Though simple criteria to precisely predict landslide do not exist on a regional scale. Our premier result shows the real-time GPS monitoring and rainfall intensity studies are important attempts by providing advance notice of hydrological event. Linkage between bedrock lithology, structure, and slope instability, will result in large slope failures playing an increasing role in shaping of the Taiwan mountain belt.

We find a good correlation between the GPS position time series and rainfall variations and confirm the GPS motion is related to the slow landslide in this region, but the shift in the landslide of great change in events, and the movement direction is east, and aspect. The direction of GPS motion is consistent with the slope direction, suggesting the mechanism is related to the creep of landside. The cleavage direction in the southern Central Range seems to control the deep-seated landslides. In the future, continued research on landslide processes is important because of the many factors influencing the frequency and occurrence of deep-seated gravitational slope of deformation that affect environmental policies regarding natural resource management practices, and human life.

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