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A nationwide catastrophic landslide hazard assessment in Taiwan

Évaluation des risques de glissements de terrain à l'échelle nationale à Taiwan

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ABSTRACT: After Hsiaolin Landslide that caused over 450 casualties during 2009 Typhoon Morakot, the government of Taiwan has constructed a nationwide 1 m resolution LiDAR derived DEM, which has been proven to be an effective tool for identifying deep-seated landslides. Since 2010, more than 9,000 deep-seated landslides that are over 10 ha respectively were identified in the DEM according to their morpho-tectonic features like the main escarpment, trench, double ridge and counterscarp. Additionally, a nationwide catastrophic landslide hazard assessment program was initiated in 2017. In the program, the activity of identified sites is evaluated based on InSAR analysis. The landslide susceptibility of these sites is also evaluated using a model constructed from the landslide inventory of Typhoon Morakot. According to the evaluation results of landslide activity, susceptibility and estimated vulnerability, 182 sites were further selected to carry out detailed investigations. Among them, 23 sites were installed with continuous GPS as the early warning system; some structural countermeasures have been made to 50 sites to reduce their level of risks; and a great effort has been put into the program to determine the rainfall triggering threshold and critical displacement rate for monitoring sites.

RÉSUMÉ: Après le glissement de terrain de Hsiaolin, responsable de la mort de plus de 450 personnes, lors du typhon Morakot en 2009, le gouvernement de Taiwan a construit un LiDAR MNT (Modèle Numérique de Terrain) sur tout l'ile. Cet outil s'est révélé efficace pour l'identification des glissements de terrain profonds. Depuis 2010, plus de 9,000 glissements de terrain profonds de plus de 10 ha ont été identifiés sur le DEM, en fonction de leurs caractéristiques morpho-tectoniques telles que : escarpement principal, tranchée, double crête et contre-pente. En outre, un programme national d'évaluation des risques de glissements de terrain catastrophique a été lancé en 2017. Dans le programme, l'activité récente des sites identifiés est évaluée sur la base d'une analyse InSAR. La susceptibilité de ces sites en terme de glissements de terrain est également estimée à l'aide d'un modèle construit à partir de l'inventaire des glissements de terrain liés au typhon Morakot. D'après les résultats visant à évaluer l'activité, la susceptibilité et la vulnérabilité aux glissements de terrain, 182 sites ont été sélectionnés dans le but de mener des études détaillées. Parmi eux, 23 sites ont été instrumentés avec des GPS continus fonctionnant comme système d'alerte précoce; des mesures structurelles ont été prises sur 50 de ces sites pour réduire leur niveau de risque; et une part importante du programme a été consacrée à la détermination du seuil de déclenchement des précipitations et du taux de déplacement critique pour les sites de surveillance.

Keywords: Deep-seated landslides; LiDAR derived DEM; TCPInSAR; Singal GPS monitoring

1 INTRODUCTION

Taiwan is located on the convergent boundary between the Eurasian plate and the Philippine Sea plate. This has resulted in the island's broken geological structure and high frequency of earthquakes. Due to the geodynamical context characterized by mountain building that creates great topographic relief, deep-seated landslides are commonly observed in mountainous region of Taiwan (Lin et al., 2013, Tsou et al., 2015).

Deep-seated landslides, also known as deep-seated gravitational slope deformation (DSGSD), usually carry an enormous volume of soil and are hardly to be noticed. Taiwan's subtropical climate characteristics and the influence of extreme climate not only make the Taiwan main island even more geologically fragile under the impacts of frequent typhoons and heavy rainfall, but also potentially trigger the transformation of slow-moving deep-seated landslide into a fast-moving catastrophic failure and induce severe hazards.

The catastrophic Hsiaolin landslide occurred in 2009 and caused over 450 casualties is one of the most famous and recent example in Taiwan (Tsou et al., 2011, Kuo et al., 2013). How to find deep-seated landslides on the main island of Taiwan and assess their activity has since then become a significant task for the government in disaster prevention and mitigation. This is the reason that, after Typhoon Morakot, the Taiwanese government has adopted many new technologies in disaster prevention and mitigation tasks, and promoted large-scale landslide prevention plans.

As a government agency, Soil and Water Conservation Bureau (SWCB) of Council of Agriculture (COA), Executive Yuan has long has been co-working with industrial and academic circles to study and monitor deep-seated landslides. In 2017, SWCB invested over US$140 millions in nationwide catastrophic landslide hazard assessment programs to prevent and mitigate possible damages caused by deep-seated landslides.

2 IDENTIFY POTENTIAL SITES OF CATASTROPHIC FAILURE USING LIDAR DERIVED DEM

After Typhoon Morakot, a national mapping program spanning from 2010 to 2015 was launched to simultaneously capture the LiDAR and photogrammetric data of entire conuntry. The project was conducted by Central Geological Survey (CGS) of Ministry of Economic Affairs (MOEA), which has spent six years and NT$1.5 billion on establishing the country's LiDAR database. The datasets that we used to interpret geomorphic features of deep-seated landslides include 1 m airborne LiDAR derived DEM, high-resolution aerial imagery, geographical data and field surveys.

The LiDAR data was acquired from Leica ALS60/DMC equipped on an airplane flying around 4,000 m with a pulse rate of 44.3 kHz. The digital aerial photographs have elementary position information derived from the on board IMU, and have been orthorectified with the LiDAR derived DEM data on the same flight. The average survey point density for LiDAR was specified to be greater than 2 points/m^2 to generate 1 m resolution DEM.

We manually analyzed landslide signatures using the LiDAR derived DEM and aerial photographs, which are proven to be effective in identifying geomorphic features of deep-seated landslides, and 3D viewed images by Arc sense of Arc GIS were employed to identify deep-seated landslide morphologic features such as main escarpment, double ridge, trench, reverse slope, crown scarp, extension fracture, transverse ridge and crack, and deformed slope toe (Agliardi et al., 2001; Chigira, et al., 2014; Chen et al., 2015). In recent years, we succeeded in firstly locating deep-seated landslides by identifying their topographic features from LiDAR derived DEM in the country and eventually succeeded in identifying over 9,000 of deep-seated landslides throughout the island. that were sized over 10 ha respectively (Figure 1).

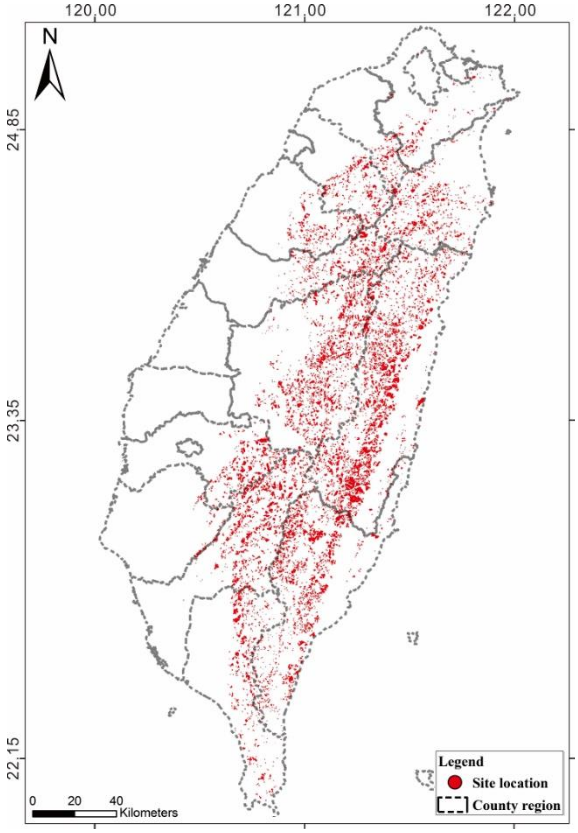


Figure 1. Map of deep-seated landslides that are sized over 10 ha respectively by 1 m LiDAR derived DEM.

Within these deep-seated landslides, 182 significant deep-seated landslides with secured objects were selected based on the population and major infrastructure (such as villages, reservoirs, roads and bridges). In the past, a number of monitoring and borehole survey instruments had been used to precisely assess the vulnerability of catastrophic failure. However, not only are geological drill equipment and survey instruments rather expensive, but also the data are limited to single points, showing difficulties in locating the sliding surface and discussing the sliding mechanism. Therefore, SWCB has newly adopted Temporarily Coherent Point SAR Interferometry (TCPInSAR), a technique that provides the possibility to quickly and effectively monitoring deep-seated landslide activity over extensive areas.

3 EVALUAT LANDSLIDE ACTIVITY USING INSAR TECTONIQUE

Despite the rapid development of Interferometric Synthetic Aperture Radar (InSAR) over the decades, it still is a challenge to map and monitor landslides in forest regions with conventional InSAR technique due to volume and temporal decorrelation, atmospheric delay anomaly, topographic error, and decorrelation raised large deformation gradients (Hanssen, 2001; Ferretti et al., 2007; Samsonov et al., 2011).

To overcome these limitations, we employed here a modified small-baseline InSAR technique termed TCPInSAR proposed by Zhang et al. (2011) for SAR data processing. In contrast to conventional small-baseline InSAR techniques that select interferograms simply according to the thresholds of spatial, temporal and doppler baselines, TCPInSAR selects interferograms fully based on the coherence that serves as an indicator of interferometric quality. TCPs are points that remain coherent in one or several interferograms of SAR acquisitions (Zhang et al., 2012). The coherence of interferograms is a useful normalized index of the local signal-to-noise ratio of interferometric phase (Colesanti and Wasowski, 2006) and shows the temporal invariant of surface to SAR.

Therefore, to overcome the highly vegetated and mountainous environment of Taiwan, TCPInSAR analysis is based on ALOS/PALSAR (L-band radar) images acquired from December of 2006 to March of 2011 with a satellite recurrence cycle of 46 days that can penetrate through the dense vegetation (Sandwell et al. 2008; Meng and Sandwell, 2010; Champenois et al. 2012) . The annual deformation rates are derived from images taken in three periods from 2006 to 2009, 2009 to 2011, and 2006 to 2011 separately. In this study, we applied the technique to construct the annual deformation in 182 deep-seated landslides, the annual deformation rate calculated from more than 20 satellite images. In Figure 2, sites marked in red refer to deep-seated landslide areas.

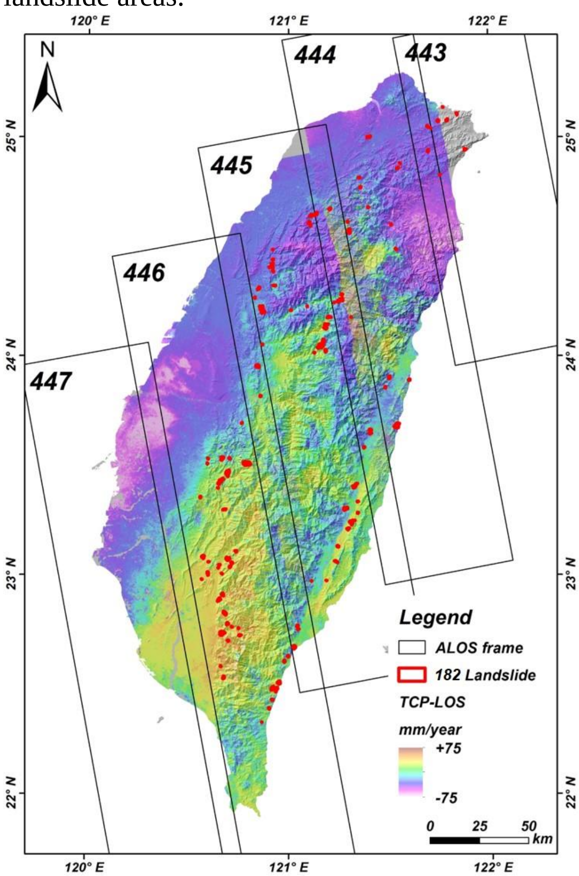


Figure 2 The results of nationwide deep-seated landslide monitoring using the multi-temporal InSAR (MTInSAR) technique.

InSAR technique has been proven as an effective and economical method for monitoring and inventorying landslide movements over large areas, and the monitoring results can also facilitate the development of early warning systems for catastrophic landslides. Furthermore, such monitoring can lead to the classification of deep-seated landslides and determine hazard zonation based on different deformation rates, which are considered as the key index of deep-seated landslides corresponding to precursor of catastrophic landslides. This helps us not only to select the locations for installing the GPS monitoring system in the future, but also to establish relevant disaster prevention and mitigation standards.

4 SURFACE DISPLACEMENT MONITORING SYSTEM

For the purpose of the near real-time landslide monitoring, single-frequency L1 GPS receivers provides high precision positioning that is comparable with dual-frequency receivers, if their relative distance is only a few kilometres (Chen et al., 2015). In this project, in order to better understand kinematic behaviour of landslide and to validate the TCPInSAR analysis results, 23 sites were selected to install near real-time surface monitoring system, which is a relatively economical and valid approach for providing early warning and evacuation required information (Figure 3).

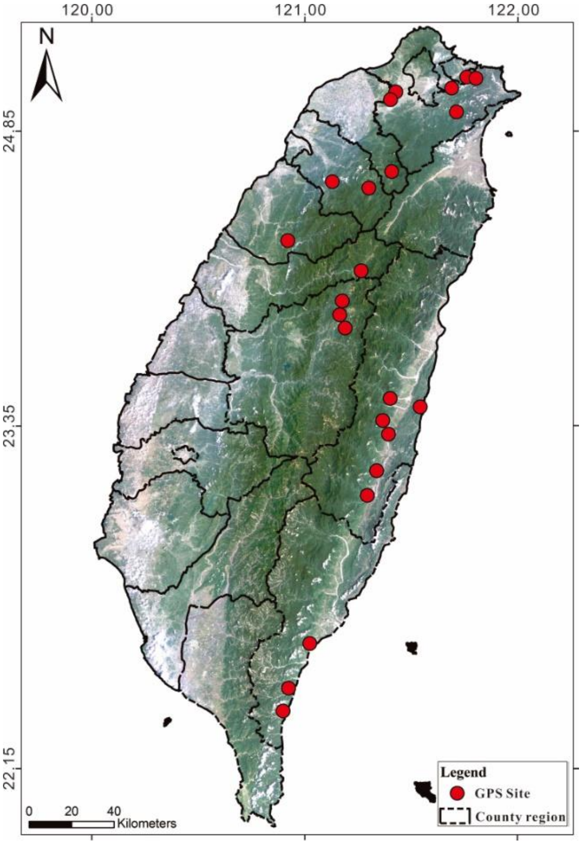


Figure 3 Surface displacement monitoring system and analysis of the recorded data of potential large-scale landslides in Taiwan.

Besides, we also replaced the traditional dual-frequency GPS with single-frequency GPS to reduce the installation cost. The system consists of 6 to 8 single-frequency GPS receivers and a rainfall gauge (Figure 4). In the system, all of the received data was transferred to a data processing server via the 4G wireless network. The data were processed into the standard receiver independent exchange format (RINEX) with defined epoch length for the following post-positioning processes. Broadcast or precise ephemerides were retrieved from the International GNSS Service (IGS) web site. The Bernese GNSS Software developed by the Astronomical Institute of the University of Bern (AIUB) was utilized for the high-precision multi-GNSS data processing.

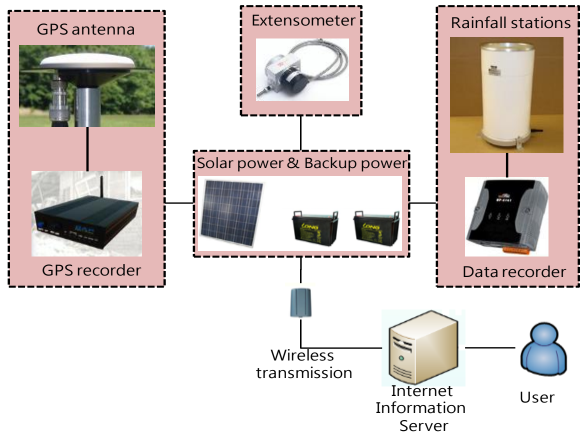
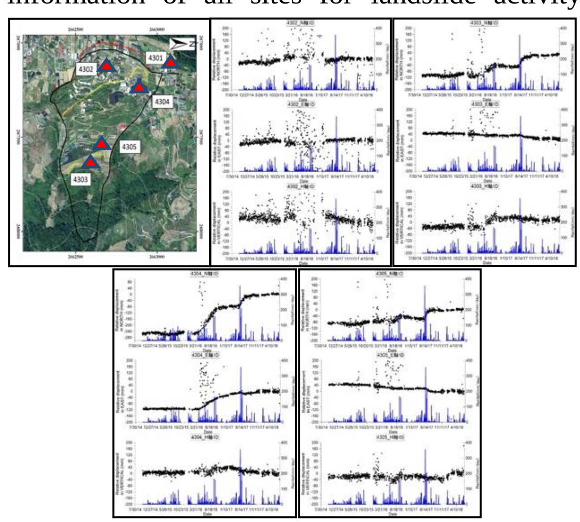


Figure 4. Equipment and framework of GPS surface monitoring system.

The single-frequency continuous GPSs were installed in different blocks in order to acquire activity related information of these blocks. After that, the positioning results were stored in an on-line database and displayed via a webpage. Figure 5, shows that stick-slip movements associated with heavy rainfall have been successfully recorded, although no catastrophic event has been recorded. The positioning results via internet provide real-time displacement information of all sites for landslide activity



monitoring and early warning assessment.

Figure 5. An example of GPS data acquired from a monitoring site in Cingjing area in central Taiwan, where significant movemtns were recorded by GPS during some heavy rainfall events.

5 CONCLUSIONS

After the 2009 Typhoon Morakot event, the Taiwanese government launched a series of deep-seated landslide monitoring plans and succeeded in identifying over 9,000 deep-seated landslides in LiDAR erived DEM according to their morpho-tectonic features. Within these deep-seated landslides, 182 significant deep-seated landslides with secured objects were selected based on the population and major infrastructure (such as villages, reservoirs, roads and bridges).

Based on the InSAR analysis results, 23 sites were further selected to install the single-frequency continuous GPSs as the early warning system; some structural countermeasures were made to 50 sites to reduce their level of risks; and a great effort has also been put into the program to determine the rainfall triggering threshold and critical displacement rate for monitoring sites.

Within these deep-seated landslides, only 182 sites were selected as the monitoring targets according to their vulnerability of catastrophic failure. This study shows the great potential of LiDAR and TCPInSAR technique for determining slope stability and locating potential hazards in highly vegetated mountain areas; TCPInSAR technique can provide large-scale surface deformation data, identify more active block and facilitate the following installations of single-frequency GPS monitoring system.

In the meantime, SWCB has launched a project to establish the deep-seated landslide monitoring database and integration platform. All deep-seated landslide investigation and monitoring data, such as GIS, satellite imagery, InSAR analysis results, aerial photos, and UAV imagery, are integrated in the database in specific data format. On the other hand, the platform, which provides an access to check GIS information, investigation methods, investigation results, monitoring results, 3D demonstration and other information of deep-seated landslide, is open to parties who are related to the field of disaster prevention and mitigation to facilitate their works. In other words, our objectives are not only to develop deep-seated landslide monitoring techniques, but also to transform our study results into practical and usefaul information in order to achieve our goal of early warning.

Finally, 2019 is the 10th commemoration of Typhoon Morakot. Because of this catastrophic event, the Taiwanese government understands the destructive damages of and importance of studying deep-seated landslides. However, this is not the end. Despite the importance of this indicative study, the results that we have in hands are not perfect and this requires the efforts from all of us.

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7 REFERENCES

Agliardi, F., Crosta, G. and Zanchi, A. 2001. Structural constraints on deep-seated slope deformation kinematics. *Engineering Geology*, **59**, 83-102.

Champenois, J., Fruneau, B., Pathier, E., Deffontaines, B., Lin, K.-C. and Hu, J.-C. 2012. Monitoring of active tectonic deformations in the Longitudinal Valley (Eastern Taiwan) using Persistent Scatterer InSAR method with ALOS PALSAR data.

Earth and Planetary Science Letters, **337-338**, 144-155.

Chen, H. Y., Kuo, L. C., Lee, J. C., Tung, H., Su, S. H., Yao, S. S. and Lee, H. 2015. Reducing distance dependent bias in low-cost single frequency GPS network to complement dual frequency GPS stations in order to derive detailed surface deformation field. *Survey Review*, **47**, 7-17.

Chigira, M., Tsou, C.Y., Matsushi, Y., Hiraishi, N. and Matsuzawa, M. 2013. Topographic precursors and geological structures of deep-seated catastrophic landslides caused by Typhoon Talas. *Geomorphology*, **201**, 479-493.

Chigira, M. 2014. Geological and geomorphological features of deep-seated catastrophic landslides in tectonically active regions of Asia and implications for hazard mapping. *Episodes*, **37**, 284-294.

Ferretti, A., Savio, G., Barzaghi, R., Borghi, A., Musazzi, S., Novali, F.,and Rocca, F. 2007. Submillimeter accuracy of InSAR time series: Experimental validation. *IEEE Transactions on Geoscience and Remote Sensing*, **45**, 1142-1153.

Hanssen, R. F. 2001. Radar interferometry: data interpretation and error analysis (Vol. 2). *Springer Science & Business Media.*

Kuo, Y.S., Tsai, Y.J., Chen, Y.S., Shieh, C.L., Miyamoto, K. and Itoh, T. 2013. Movement of deep-seated rainfall-induced landslide at Hsiaolin Village during Typhoon Morakot. Landslides, **10**,.191-202.

Lin, C.W., Chang, W.S., Liu, S.H., Tsai, T.T., Lee, S.P., Tsang, Y.C., Shieh, C.L. and Tseng, C.M. 2011. Landslides triggered by the 7 August 2009 Typhoon Morakot in southern Taiwan. Engineering Geology, **123**, 3-12.

Lin, C.W., Tseng, C.M., Tseng, Y.H., Fei, L.Y., Hsieh, Y.C., Tarolli, P. 2013. Recognition of large scale deep-seated landslides in forest areas of Taiwan using high resolution topography, *Journal of Asian Earth Sciences*, **62**, 389-400.

Meng, W., Sandwell, D.T., 2010. Decorrelation of L-band and C-band interferometry over vegetated areas in California. *IEEE Trans. Geosci. Remote Sensing*, **48**, 2942–2952.

Samsonov, S., van der Kooij, M., and Tiampo, K. 2011. A simultaneous inversion for deformation rates and topographic errors of DInSAR data utilizing linear least square inversion technique. *Computers & geosciences*, **37**, 1083-1091.

Tsou, C.Y., Chigira, M., Matsushi, Y. and Chen, S.C. 2015. Deep-seated gravitational deformation of mountain slopes caused by river incision in the Central Range, Taiwan: Spatial distribution and geological characteristics. Engineering Geology, **196**, 126-138.

Zhang, L., Ding, X., and Lu, Z. 2011. Ground settlement monitoring based on temporarily coherent points between two SAR acquisitions. *ISPRS Journal of Photogrammetry and Remote Sensing*, **66**, 146-152.

Zhang, L., Ding, X., Lu, Z., Jung, H. S., Hu, J.,and Feng, G. 2014. A novel multitem-poral InSAR model for joint estimation of deformation rates and orbital errors. *IEEE Transactions on Geoscience and Remote Sensing*, **52**, 3529-3540.

Tsou, C.Y., Feng, Z.Y. and Chigira, M. 2011. Catastrophic landslide induced by typhoon Morakot, Shiaolin, Taiwan. *Geomorphology*, **127**, 166-178.