Application of global satellite navigation system and telemetry image analysis technology to assess activity of potential large-scale landslide in forest land area – a case study on Taoyuan district no. D346, Kaohsiung city

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Abstract. The investigation, monitoring, and prevention of large-scale landslides, also known as deep seated landslides, are important research topics for slope disaster prevention. Some national forest land managed by the Forestry Bureau is located at the upstream watershed area, which has relatively unstable geological and topographical factors, and there are major large-scale landslides. However, those areas with protected objects are still the priority for investigation, governance, and management. There are 14 large-scale landslides with high and moderate risk located in the region of the Pingtung Forest District Management Office. For the implementation of future disaster prevention practices, the most important thing is to evaluate the activities of the large-scale landslides. This study takes Kaohsiung City-Taoyuan District-D346 as an example. The scars/linear structures in the potential area of a large-scale landslide are identified using high resolution LiDAR DEM. On-site global satellite navigation system monitoring and multi-sequence telemetry images are conducted to understand the activity and sliding direction of the block, meaning that the surface activity of the potential large-scale landslide area can be monitored. There are number of mature technological developments recently. Compared with the funding for underground geological exploration and subsequent project management, the funding for surface activity assessments with multiple telemetry images and monitoring equipment is relatively simple, after checking the activity of the large-scale landslide, the high resolution of LiDAR DEM, aerial photography and satellite images are the perfect tools to be applied before the follow-up key treatment and management funds are invested.

1. Introduction

In 2009, Typhoon Morakot brought prolonged, heavy, and extensive rainfall to central and southern
Taiwan, resulting in many large-scale landslides in the mountains. The landslides caused a large number of compound sediment disasters, and part of the sediments were even piled in the rivers, which created landslide dams, and 10 years later, the slide sediments are still not fully removed, as most sediments that moved downriver are still piled in the rivers, causing dramatic changes to the riverbeds. Due to the significant effects and harms caused by the initial disasters and the secondary sediment disasters of large-scale landslides, it is necessary to carry out potential disaster investigation and disaster prevention monitoring, which are the basis to assess the disaster scale and prepare management strategies[1-7].

After the disaster caused by Typhoon Morakot, an investigation of the potential areas for large-scale landslides was conducted throughout the country. The National Science & Technology Center for Disaster Reduction (NCDR) defines a large-scale landslide as one with the area of 10 ha, estimated landslide (sliding) earth quantity of 100,000 m3 or the landslide (sliding) depth of 10m, which is also known as a deep landslide, as adopted in Japan, due to its landslide (sliding) depth[8-13]. Upon preliminary planning of these areas, there are 14 places at the medium and high levels of risk under the jurisdiction of the Pingtung Forest District Management Office, Forestry Bureau. After that, on-site investigation, surface displacement monitoring, and wide-area monitoring were adopted to study the degree of damage and possible influencing scope, while GPS surface displacement monitoring stations were employed to monitor parts of the high risk areas in advance, and the accumulated long-term basic monitoring data of the slopes in the potential areas were used to identify their mobility and activity, or to identify the moving precursors of the potential areas of large-scale landslides[14-20].

Upon the successive investigations of the potential areas for large-scale landslides, the Pingtung Forest District Management Office incorporated highly protected areas under its jurisdiction into the observation objects, and expected to investigate the activities of these high risk areas through wide-area monitoring for subsequent planning, monitoring, and rectification. At present, the potential area of a large-scale landslide, numbered as Kaohsiung City-Taoyuan District-D346, is equipped with a single-frequency GPS surface displacement monitoring system, and after the rainfalls, the slope displacement records showed a westward trend and a downward movement trend of elevation. The single-frequency GPS surface displacement monitoring system does not draw a conclusion by comparing the situations before and after an event, but makes judgments based on the overall trend through long-term monitoring. The slope changes are understood based on the long-term continuous observation data, and various basic studies and monitoring data are accumulated, which are expected to understand the mechanisms of large-scale landslides.

2. Materials and Method

2.1. Location of research area

Taking Kaohsiung City-Taoyuan District-D346 as an example, this paper is mainly to explore the potential areas of large-scale landslides, as investigated by the Forestry Bureau. Kaohsiung City-Taoyuan District-D346 has a medium high level of risk, and is under the jurisdiction of the Pingtung Forest District Management Office. On-site investigation, surface displacement, and wide-area monitoring are adopted to assess the damage degree and possible influencing scope, GPS surface displacement monitoring stations are employed to monitor parts of the high risk areas in advance, and the accumulated long-term basic monitoring data of the slopes in the potential areas are used to identify their mobility and activity, or to identify the moving precursors of the potential areas of large-scale landslides.

A potential area for a large-scale landslide of Kaohsiung City-Taoyuan District-D346 is located in Baoshan Village of Kaohsiung City, Taoyuan District (Figure 1), which has the potential landslide area of 96.58 ha, and is affiliated with national forest land, meaning No. 104 forest land in the business area of the Laonong River. Xiaoguanshan forest road is located on a slope, which is on the right bank of the Baolai River and about 2.7 km from the confluence of the Laonong River.
The high resolution LiDAR DEM and satellite image results showed that there were multi-level collapses on the northeast side of the potential area. Besides, the slope was located in an often attacked area of the river, and the toe was exposed, where the edge of the main collapsed cliff at the upper rim of the slope in the potential area is still visible and the toe of the potential area is at risk of river erosion (Figure 2).

According to the Operation Book for Hazardous Area of Large-Scale Landslide (2016) of the Soil and Water Conservation Bureau was used to obtain hazard zone of large-scale. Upon on-site investigations, the protected residents adjacent to the bank in the Baolai settlement in the downstream area were classified as influence objects, (Figure 2).

Figure 1. Geographic location for potential large-scale landslide.
2.2. Research materials

The common methods to monitor slope changes are mainly divided into 3 types according to the settings, including air, surface, and underground. The underground monitoring instruments are usually applied with drills, which is an expensive method, and may not be necessary in the preliminary
investigation of potential large-scale landslides. The common monitoring methods are described, as follows:

- **Global Navigation Satellite Systems (GNSS)**

  GNSS is a continuous (several hours to 24 hours) positioning system with high temporal (all-weather) and spatial (large-scale) resolution and high precision (up to millimeter grade).

  The precise times and locations calculated by GNSS satellite receivers can be used as reference for all kinds of civil navigation, geodetic surveying, and scientific experiments. GNSS receiving stations use satellite positioning to obtain the absolute coordinates, and then, calculate the relative displacements with the remote fixed points. The surface displacement deformation trend can be obtained by long-term observations. In the satellite receiving equipment, dual-frequency receiving stations have high unit prices, but can eliminate ionospheric errors, while single-frequency receiving stations have low prices and low precision. In recent years, single-frequency receiving stations used with dual-frequency receiving stations for correction can achieve precision results close to that of dual-frequency receiving stations.

- **LiDAR Terrain**

  Light Detection and Ranging (LiDAR) terrain monitoring refers to the numerical terrain imaging produced by optical remote sensing technology, which uses pulsed lasers emitted by laser transmitters. The lasers that are emitted from the carriers hit plants or buildings, thus cause scattering and reflection. Some light waves will return to the receivers on the carriers by backscattering, which converts the optical signals into electrical signals for recording. Meanwhile, the matching timers record the time of the same pulsed optical signals from emission to being received, in order to obtain the distances from the carriers to the targets, and both the measurement precision and unit price for shooting are high.

  Due to the measuring characteristics of high precision and high density, combined with the multiple reflection signals of laser pulses and the characteristics of vegetation filtering, different surface features can be provided. The results of surface deformation can be obtained through comparison of the LiDAR terrains produced in different periods.

- **Synthetic Aperture Radar**

  Synthetic Aperture Radar (SAR) is a microwave observation technology. Its basic principle uses the fact that satellites continuously emit radar waves while in operation, and receive the radar returns for calculation to obtain the imaging results. Being excellent in penetration, radar waves can penetrate clouds and dust to the surface more easily than visible lights, and can be received by satellites after reflection. In addition, they can be used for measurements at nights.

  By using differential interferometric technology, the surface signals obtained from synthetic aperture radar images are used to determine satellite-to-surface deformations, which can also be used to monitor surface or natural disasters. The continuous differential interferometric synthetic aperture radar (DInSAR) is used for elevation change analysis, and due to the continuous calculation of multiple images, it can reduce analysis errors by comparing 2 images. In addition, most continuous analysis methods use continuous surface observation points, which is beneficial for the continuous observation of single points.

  When time-sequence synthetic aperture radar images are used for interferometric analysis, the main interferometric phase information produced includes terrain, surface feature changes, surface movement, and atmospheric effect. Among them, the errors in the phase change information of terrain can be eliminated by high-precision numerical terrain and the length of the short baseline, the coherence value threshold adjustment can remove the influence of low coherent areas, the precision of by-product numerical terrain can be improved, and the errors in atmospheric effect can be reduced by long-term multiple image observation. After the possible sources of errors are eliminated, only the surface movement and phase difference of noise are left, which can be used to obtain reliable surface deformations with high precision. In theory, this technology can be used to measure the centimeter-level surface deformations over days or years, to monitor natural disasters, such as earthquakes, volcanic eruptions, and landslips, and for structural engineering, particularly settlement monitoring and structure stability.
Images by Unmanned Aerial Vehicles

Unmanned Aerial Vehicles (UAVs) have the features of speediness, maneuverability, and operating under low altitude clouds, as well as the advantage of immediacy in image data acquisition when applied to on-site investigation, and they create high-resolution images. The images with geodetic coordinates can be obtained upon geometric correction, which can be combined with existing topographic maps, aerial photographs, and satellite images, be used for nesting, and can detect surface deformations by comparison.

Aerial Photograph (AP)

AP is an aerial photograph taken by placing a camera in the belly of an aircraft and pointing the camera’s optical axis perpendicular to the ground. Due to less displacement, vertical images are suitable for mapping and resource investigations. Aerial photographs have the advantages of large coverage, stereo viewing, permanent recording, and fast access to information. Aerial photographs recorded during different periods can be compared to obtain the results of relative surface deformations.

On-site Investigation

Investigators conduct reconnaissance in a target area to identify artificial structures, surface evidence, terrain changes, and vegetation conditions, as well as further detailed information by means of ground object exploration (seismic investigation, ground resistance investigation) and geological drilling, in order to determine signs of surface deformation.

3. Results and Discussion

On-site investigation results of Kaohsiung City-Taoyuan District-D346 can be roughly divided into 2 zones, which run through the whole slope from the center and are bounded by erosion gullies, with the main event block in the north and a collapsed slope due to lateral erosion of the bank of the Baolai River in the south. The slope in the south zone is exposed due to the hard laccolith, the only remaining colluvial soil is on the abdomen of the slope, and the lower slope has severe lateral erosion of the bank of Baolai River. Due to continuous development and collapse of lateral erosion, the upper slope tends to be stable, while the lower slope continues to collapse and go upstream. The northern border of the sliding block is the northern erosion gully, which is the lateral collapse of the sliding block travelling slightly parallel with the sliding direction. Moreover, due to the tension and fracture development of the slide (Figure 3), this point location is the area with the most significant surface activities. In a sliding block, rock cracks and strain breaks on the upper half of the slope are often under tension due to collapse (Figure 4), and such pushing and fracturing on the lower half of the slope are often caused by collapse and slides.

Analysis of GNSS surface displacement monitoring system

The GNSS data solution interval is from December 2018 to October 2019 (Figure 5), and the major rainfall events of this year were 0611 plum rain front and 0815 southwest airflow heavy rain. All the sites in this area are obviously displaced toward northeast and slightly skew to the main slope direction. Moreover, the difference of the displacement during flood and non-flood seasons is quite obvious; in 2019, the displacement was about 20mm/month during the flood season and about 10 mm/month during the non-flood season. The calculation results of all sites obviously show that the changes are low from January to June 2019; however, after the heavy rain in mid-June, the three axes of the sites began to change significantly; in particular, the changes were more significant due to the heavy rain in August.

Analysis of the high accuracy digital terrain data with LiDAR and multi-sequence telemetry images (InSAR)

According to the LiDAR shadow map (Figure 6), the collapses in this area are concentrated in the northern sliding block, which shall become continuously developing and movable large-scale landslides under gravity traction and subsequent gully erosion, and cross after the toe is eroded. The development scope of erosion gullies are shown on the CS map (Figure 7). The erosion gullies in this area concentrate in the northern sliding block with continuous upstream signs. The figure clearly
shows that the erosion gully at the northern boundary of the sliding block is well developed. By combining the LiDAR terrain changes in 2000 and 2017 (Figure 8), it can be clearly observed that, in addition to the landslide on the slope of the right bank of Baolai River, as caused by lateral erosion, other areas with large terrain changes concentrate in the northern sliding block, and the upper half of the block is mostly descending (light blue to purple), while the lower half of the block is mostly uplifted (light green to orange). According to the calculation results of InSAR during December 2016 to August 2019 (Figure 9), although the northern sliding block is uplifted in the central erosion gully, the detailed terrain difference is caused by the sliding of the block.

The topographic profile is made based on the LiDAR numerical terrain of 2000 and 2017, in order to further explore the terrain changes and collapses of the terrain features. The profile locations are shown in Figure 10, and the results are shown in Figure 11 to 17. The A-A' and B-B' profiles obviously show the terrain changes after the sliding block collapsed downward. As the block moved down completely, it was easy for the gentle upper slope to show descending or initial backward inclination, while the lower steep slope was uplifted (Figure 11 and 12). By estimation, the longitudinal profile of C-C' (Figure 13) is the possible depth and sliding boundary of the sliding block.
Figure 6. 2017 LiDAR hill shade image for potential large-scale landslide. (Azimuth 045°)

Figure 7. 2017 LiDAR CS map for potential large-scale landslide.

Figure 8. 2010-2017 LiDAR DEM geomorphic change for potential large-scale landslide.

Figure 9. Analysis results of InSAR for potential large-scale landslide. (2016/12-2018/08)
Figure 10. The sites of cross-section for potential large-scale landslide.

Legend:
- Overturned Bedding
- Profiles
- Main Sliding Mass
- Foliation
- Main Scarps
- Minor Scarps
- GNSS Positions
Figure 11. Cross-section A-A’ of 2010 and 2017 LiDAR DEM.

Figure 12. Cross-section B-B’ of 2010 and 2017 LiDAR DEM.
4. Conclusion
Landslides in forest land areas are generally large-scale, and thus, must be assessed and monitored by the global satellite navigation system and telemetry image analysis technology. Moreover, the main event block in the potential area of large-scale landslides can be further drawn by using multi-sequence telemetry images, and the activity and sliding direction of the block can be understood according to the on-site global satellite navigation system monitoring.

This paper takes Kaohsiung City-Taoyuan District-D346 as an example for monitoring. The results show that the local changes in this area are significant with the monthly movement up to the centimeter level, and ground subsidence and deformation are also continuing. There is a consistent trend of movement assessment by using the high accuracy digital terrain data with LiDAR and InSAR images. Perhaps this provides the opportunity to enter the site to begin a more complete investigation and exploration, so as to provide references for subsequent governance planning and construction.

As a large number of landslides occur in forest areas, the government is unable to respond to the budget and human needs of governance projects or landmine detection. In recent years, a number of technologies have been developed and become mature for monitoring surface activity in areas with the potential for large-scale landslides. In the assessment of the advantages and disadvantages of various technologies, if rapid and accurate preliminary exploration conclusions can be reached before in-depth investigation and further governance are conducted, it will be an important issue to effectively allocate limited resources under the existing background of extreme climate changes, in order to hit the mark more accurately.

The assessment of surface activity through multiphase telemetry images and monitoring equipment costs less than underground geophysical exploration, and the subsequent engineering management requirements, in the potential areas of large-scale landslides. Many aerial and telemetry technologies have been developed, and numerous studies have been conducted, such as high-precision LiDAR numerical terrain and various aerial or satellite images, all of which are weapons for investigation before major funds are invested.

In addition to the continuous accumulation of data and verification of previous study results, surface monitoring after the selection of high potential areas can also be used for on-site alterations or
disaster warnings released for current events. There is little information regarding the warning values in this paper, which is still an issue for further studies.

Acknowledgments
This study is particularly grateful for the financial support of Forestry Administration Pingtung Forest District Management Office, and also to thank the analysis assistance from the Disaster Prevention Center of NCKU.

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