Evolution of deep-seated landslide at Putanpunas stream, Taiwan

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ABSTRACT
This study used multi-stage remote sensing data in the analysis of the evolution of deep-seated landslides at Putanpunas stream, Taiwan. Terrain analysis, landslide interpretation, and the assessment of underlying mechanisms were included. Our results show that the evolution of deep-seated landslides can be divided into four stages: (1) erosion and decompression of the gully, (2) deformation of the rock slope, (3) the development of sliding surfaces, and (4) movement of the sliding mass. A large quantity of colluvium has accumulated on the slopes and in upstream and midstream gullies. In the future, we predict that the erosion of this colluvium will greatly influence the direction of flow and terrain in the alluvial fan. This activity is also expected to threaten the safety of inhabitants and property in the area intersecting Laonong stream.

KEYWORDS
Multi-stage remote sensing data; deep-seated landslide; terrain analysis; landslides interpretation; mechanism assessment

1. Introduction
Deep-seated gravitational slope deformation (DSGSD) refers to slow-moving large-scale landslides that occur within a rock mass (Agliardi et al. 2001). This type of rock mass deformation can lead to deep-seated catastrophic landslides (Broili 1967). In this study, deep-seated landslides are defined as follows: a bedrock landslide composed primarily of parent material with limited run-out distance, surface area > 10 ha, and sliding depth > 5 m. Most previous field investigations tasked with deciphering the spatial and temporal patterns associated with bedrock landslides have been limited in scope, due to the expense and difficulties involved in measuring slope stability (such as drilling and monitoring). These investigations have also been hampered by the need to take into account long-term factors that condition slopes for failure, such as channel incision, slope morphology, geologic structure, shear strength loss due to weathering, and lithologic variations. These difficulties are further complicated by the fact that slope stability depends so heavily on seismic events and short-term hydrologic processes. Recent developments in remote sensing technology have revealed that many unstable slopes present characteristic topographic features, such as crown, scarps, trenches, and bulging areas, prior to the occurrence of deep-seated landslides (Varieses 1978; Chigira & Kiho 1994; Agliardi et al. 2001; Ventura et al. 2001; Chigira et al. 2003; Glenn et al. 2006; Dewitte et al. 2008; Crosta et al. 2013). In the past, these features could be interpreted only through the study of aerial stereo photographs obtained before and after a landslide (Chigira & Kiho 1994). Today, the same thing can be achieved by combining satellite images, aerial photos, and digital elevation models (DEM); however, direct observation of the subtle features of deep-seated landslides remains a serious challenge.

High-resolution (1 m) LiDAR (light detection and ranging) technology has greatly reduced the negative influence of vegetation in the interpretation of landslide sites (Glenn et al. 2006; Tarolli...
et al. 2012). This in turn has greatly facilitated the identification of topographic features associated with deep-seated landslides. High-precision DEM has been widely used to determine the location of landslides. Singhroy and Molch (2004) used RADAR images to monitor the distribution and movement patterns of landslides in the formulation of guidelines for mapping large-scale deep-seated landslides in forested areas. LiDAR data has also been used in the development of detailed landslide inventory maps (Lin et al. 2013; Tseng et al. 2015; Chen et al. 2015). Moreover, DEM data has been used in combination with spectral information to identify the geomorphologic features of landslides (McKean & Roering 2004; Metternicht et al. 2005; Agliardi et al. 2013; Crosta et al. 2013; Lin et al. 2014). Both of these methods are able to represent subtle topographic features through improved resolution and reduced interference from vegetation, thereby improving accuracy in the interpretation of deep-seated landslides. In fact, a number of LiDAR-specific applications have been developed for the mapping of landslide features and the evaluation of landslide activity in areas partially or completely covered by dense vegetation (Sekiguchi & Sato 2004; Van Den Eeckhaut et al. 2007; Kasai et al. 2009; Razak et al. 2011; Lin et al. 2013). Nevertheless, the cost of high-precision DEM measurement and the difficulty in obtaining topographic information in real time preclude their use in most applications. In contrast, satellite images enable long-term monitoring in near real time over large areas at high resolution and relatively low cost.

In this study, we focused on Putanpunas stream, Kaohsiung, Taiwan, where deep-seated landslides occurred after typhoon Morakot in 2009. Geomorphologic observation and interpretation were conducted using images from Formosat-II in combination with LiDAR data as well as topographic maps and aerial photos obtained over the last one hundred years. We investigated the characteristic developments in hummocky terrain in the surrounding watershed during various periods as well as the historical boundaries of sliding masses and historical deep-seated landslides, using ground control points (GCPs) for geometric correction. Our interpretation results were compared with those obtained in field investigations to elucidate the characteristics of landslides and deposition, as well as to clarify the process by which deep-seated landslides evolve. This paper discusses the following points:

a. Changes in landscape associated with deep-seated landslides during various periods;

b. Evolution of deep-seated landslides and their sliding characteristics.

2. Terrain and geology in study area

Putanpunas stream is a tributary of Laonong stream located in Taoyuan District, Kaohsiung (Figure 1). Putanpunas stream has a catchment area of approximately 6,850,000 m², the terrain of which slopes gently from the northwest to the southeast. The upstream and downstream elevations are a.s.l. 2142 m and a.s.l. 613 m, respectively. The average slope angle of Putanpunas stream is approximately 30°, and the slope angle of the streambed in the source area exceeds 50° on both sides, resulting in dramatic changes in terrain. Variations in geological formations along the stream result in various types of landslide (Lin & Lin 2015). Putanpunas stream is situated between Fuhising Township and Qinghe Township of Kaohsiung County, and the downstream alluvial fan is between two river terraces: Ryukyu terrace and Shimizu terrace. The stream’s outlet faces Oupakaer terrace directly. A large road that passes along the edge of Oupakaer terrace sustained damage after typhoon Morakot. Currently, at the confluence of Putanpunas stream and Laonong stream, the road remains choked with the accumulation of soil and sand brought by Putanpunas stream.

From the upstream to downstream (northwest to southeast), the geological strata along Putanpunas stream changes from Tangenshan sandstone (Tn) to the Changzhihkeng formation (Cc), which is mainly interbedded sandstone and shale layers, to the Chaochow formation (Co), which consists mainly of argillite or slate (Figure 2). The study area is dominated by Tangenshan sandstones and the Changzhihkeng Formation. The left bank of the study area is a cataclinal slope, and the right
bank is anacinal. Geological maps reveal two faults crossing Putanpunas stream: Kaochung fault located upstream and Tulungwan fault located downstream.

3. Methodology

3.1. Data

Multi-stage remote sensing data (Table 1) were used for landslide interpretation. The primary source of topographic information was seven-stage topographic maps (1/25,000). The topographic map produced in 2006 is based on 5 m × 5 m DEM, whereas those produced in 2010–2014 are based on 1 m × 1 m LiDAR. Topographic maps produced between 1904 and 1999 were used primarily to account for historical changes in terrain and in the primary identification of hummocky terrain. The topographic maps produced between 2004 and 2014 were used mainly as a reference in explaining recent changes in hummocky terrain.

The remote sensing images used in this study included 13-stage satellite images (resolution of 2–8 m) from Formosat-II (launched in 2004). The satellite images were used mainly as a reference for the investigation of geomorphologic changes over the last ten years as well as in the analysis of surface displacement. The aerial photos include four stages.

3.2. Terrain analysis

Contour line interpretation is a key method in the analysis of terrain, particularly in areas with deep-seated landslides or reactivated landslides. Figure 3 shows the terrain influenced by ancient slides.
Table 1. Multi-stage remote sensing data in this study.

| Data type               | Date    | Scale/resolution | Total RMS error (m) |
|-------------------------|---------|------------------|--------------------|
| Topographic maps        | 1904    | 1/20,000         | 12.85              |
|                         | 1985    | 1/25,000         | 2.71               |
|                         | 1992    | 1/25,000         | 2.42               |
|                         | 1999    | 1/25,000         | 2.07               |
|                         | 2006    | 1/10,000         | 0.47               |
|                         | 2010    | 1/10,000         | 0.22               |
|                         | 2014    | 1/10,000         | 0.13               |
| Formosat-II satellite images | 2005/07 | 2 m × 2 m     | 1.01               |
|                         | 2005/10 |                  | 0.87               |
|                         | 2006/02 |                  | 0.84               |
|                         | 2006/07 |                  | 0.92               |
|                         | 2007/10 |                  | 0.77               |
|                         | 2008/07 |                  | 0.81               |
|                         | 2008/11 |                  | 0.75               |
|                         | 2009/04 |                  | 0.72               |
|                         | 2009/09 |                  | 0.59               |
|                         | 2010/09 |                  | 0.66               |
|                         | 2010/11 |                  | 0.69               |
|                         | 2012/07 |                  | 0.75               |
|                         | 2014/02 |                  | 0.68               |
| Aerial photographs      | 2006/02 | 0.25 m × 0.25 m  | 0.32               |
|                         | 2009/10 | 0.25 m × 0.25 m  | 0.35               |
|                         | 2012/11 | 0.15 m × 0.15 m  | 0.27               |
|                         | 2014/10 | 0.15 m × 0.15 m  | 0.23               |

Figure 2. Geologic map of the study area.
The contour lines of the crown protrude upstream (V- or U-type tip pointing upstream), and the high density contour lines indicate slump scarps or cliff features. The contour lines at the toe of the landslide protrude (V- or U-type tip) downstream. Typically, contour lines in the upper areas tend to be relatively sparse, whereas those in lower areas are relatively dense, indicating that this portion of the mass compresses toward the slope toe to form a bulge (hummocky terrain). From the perspective of mechanics, Kvapil and Clews (1979) was able to identify an active zone, a transition zone, and a passive zone in a model of slope sliding. The active zone presents limited fragmentation; however, an escarpment and/or tension cracks can form at the top of the slope. The central portion of the

Figure 3. (a) Contour map of hummocky terrain; (b) diagram of slope slide and degree of brittle fracture (modified from Kvapil and Clews 1979).
slope is a transition zone between active pressure and passive pressure, where crushing and deformation are the most severe but the terrain slope is relatively gentle. Due to the effects of compression, crushing and deformation are more severe in the passive zone (slope toe) than in the active zone, resulting in surface bulges (Figure 3). The observation of gully erosion is crucial to the identification of potential landslides, because this commonly occurs at the boundary of historical landslides. As a result, potential landslides can be identified via a comparison of topographic maps produced in different years.

The topographic maps in this study were produced between 1904 and 2014. Unfortunately, variations in surveying techniques, scales, and error margins mean these maps are not necessarily suitable for research purposes (Shen & Chang, 2003). We used 1:10,000 scale topographic maps (2014), as well as 1:20,000 scale topographic maps (1904). The 2014 maps provide considerable detail; however, they do not cover as large an area. The 1904 maps are suitable only for large hummocky surface features (i.e. greater than 10000 m²), and all results obtained from this source must be interpreted with care.

### 3.3. Interpretation

Large sliding masses commonly break into several small, cracked masses after sliding only a short distance; however, this is not always the case. The ability of a sliding mass to maintain its original shape is a primary indicator of a deep-seated landslide. The second indicator is a deepening of the slope into the rock stratum. Both of these indicators are easily observed during field investigation or in remote sensing images. Soeters and Van Western (1996) proposed standards for the classification of landslide type according to characteristics observed in remote sensing images. They used the morphology, vegetation, and drainage characteristics of the slide area as standards by which to distinguish landslide types (Table 2). The terrain in Putanpunas stream area presents a gentle slope covered with low plants. Furthermore, we were able to obtain a great deal of remote sensing data obtained during various periods.
To compensate for variations in the orthographic processing of remote sensing images, we conducted geometric corrections to ensure that any errors with regard to spatial coordinates were within a tolerance of 1 m. Seventeen GCPs (Figure 2) were selected from topographic maps and aerial photos for use in the geometric correction of topographic maps and aerial photos obtained at different times. Table 1 lists the total RMS error of the GCPs in the images or topographic maps, as calculated using GIS. Based on the work of Crozier (1984) on classifying the stability of slopes (Table 3), we sought to characterize the degree of activity of every sliding mass along Putanpunas stream. This data were then used as a basis for the comparative analysis of changes in deep-seated landslides.

### Table 3. Classification of slope stability (modified from Crozier 1984).

| Class | Description |
|-------|-------------|
| I Unstable slopes |
| Ia | Active landslides; material is currently moving; landslide features are fresh and well defined |
| Ib | Reactivated landslide; material is currently moving and represents renewed landslide activity; some features are well defined, while others may appear older |
| Ic | Suspended landslides; slopes with evidence of landslide activity within the past year; landslide features are well defined |
| II Slopes with inactive landslides |
| IIa | Dormant-historic landslides; slopes with evidence of previous landslide activity that have undergone the most recent movement within the past 10 years |
| IIb | Dormant-young landslides; slopes with evidence of previous landslide activity that have undergone the most recent movement within the past 10 to 50 years |
| IIc | Dormant-mature landslides; slopes with evidence of previous landslide activity that have undergone the most recent movement within the past 50 to 100 years |
| IId | Dormant-old landslides; slopes with evidence of previous landslide activity that have undergone the most recent movement more than 100 years ago |
| III Potentially unstable slopes |
| Slopes with no evidence of previous landslide activity but are considered likely to develop landslides in the future |

4. Results

4.1. Terrain analysis

a. The topographic map from 1904 (Figure 4) shows four suspect hummocky areas \((8.5 \times 10^3 \text{ m}^2 - 2.2 \times 10^5 \text{ m}^2\) in area) on the right side of the cliff, whereas only one area on the left side appears hummocky. The terrain on both sides of the stream underwent considerable change between 1904 and 1985. The number of hummocky areas on the right bank increased by five (to a total of nine) (average area: \(5.1 \times 10^3 \text{ m}^2\)), whereas the number on the left side increased by six (to a total of seven) (average area: \(2.6 \times 10^5 \text{ m}^2\)). Between 1985 and 2006, the terrain underwent only minor changes: only two new hummocky areas formed. Furthermore, during this period, only a portion of the hummocky areas on the left upstream bank and right midstream bank showed signs of expanding toward the slope top. The prolonged torrential rainfall of typhoon Morakot at 2009 greatly increased the number of landslides in Putanpunas stream. As a result, the hummocky terrain underwent considerable change between 2006 and 2010, resulting in the formation of 11 new hummocky areas on the right bank and 10 new hummocky areas on the left bank. During this period, most of the colluvium accumulated in upstream and midstream areas. The area affected by this accumulation is approximately \(6.8 \times 10^5 \text{ m}^2\), and the total volume reached \(7.2 \times 10^7 \text{ m}^3\). Between 2010 and 2014, obvious landslides occurred on the left midstream bank (near the crown). A portion of the collapsed mass accumulated around the cliff to form hummocky terrain. Most of the collapsed material moved downstream rapidly, which resulted in the widening of the riverbed and changed the direction of stream flow. It also caused dramatic changes in the terrain of the alluvial fan.
b. We conducted analysis on the distribution of erosion gullies between 1904 and 2014 (Figure 5). In 1904, the erosion gullies presented a rough dendritic distribution. Between 1985 and 1999, gully erosion extended into the source area. Most of the erosion gullies developed on the right bank of the stream. We also observed a remarkable difference between the cataclinal slope and anacinal slope with regard to the state of erosion. Following the occurrence of landslides (under the effects of torrential rain prior to 2006), the development of new erosion gullies in the source area accelerated, expanding from the midstream area to the upstream source area. The torrential rain brought by typhoon Morakot in 2009 had a profound effect on the development of the erosion gullies throughout the entire study area. This manifest as an increase in the number of erosion gullies as well as notable changes in the direction of flow in midstream and upstream areas due to the massive accumulation of colluvium. During this period, the riverbed in downstream areas changed only slightly. Between 2009 and 2014, the height of the alluvial fan in the downstream portion of Putanpunas stream approached the height of the terraces distributed along the banks of Laonong stream (Figure 1). Consequently, landslides after 2009 caused a portion of the colluvium to break away, whereupon the resulting debris flow cut through Ryukyu terrace and changed the direction of flow in downstream areas. This expanded the area of the alluvial fan affected by the accumulation of material, greatly undermining the stability of the principal road along Laonong stream.

Figure 4. Hummocky terrain in the study area over the years.
4.2. Interpretation

a. Among the 12 periods of frequent landslide activity, 2009/09 was the most active, covering an area of approximately $1.58 \times 10^3$–$3.84 \times 10^5$ m$^2$ (Table 4 and Figure 6). During 2005/07–2005/12, most of the landslides occurred in midstream and upstream areas. Translational slides occurred at 22 sites along the left bank, compound slides occurred at 15 places along the left bank, and rational slides occurred at 9 places along the right bank. Most of the landslides in the 2006/07 period occurred along the right bank (midstream and upstream), and most of these were small-scale rotational slides. Most of the landslides in the 2007/10 period occurred along the left bank (midstream and upstream), and most of these were large-scale translational slides, presenting a collapse area of $1.95 \times 10^3$–$1.38 \times 10^5$ m$^2$. Most of the landslides between 2008/07 and 2009/04 occurred in the source area and along the right bank (midstream and upstream), most of which affected areas of $2 \times 10^3$–$8 \times 10^3$ m$^2$. The prolonged torrential rainfall in 2009 led to massive landslides along the midstream and upstream areas of the left bank and along the entire right bank. The area affected by these landslides was approximately $1 \times 10^5$–$3.8 \times 10^5$ m$^2$, and the depth of sliding has been estimated at 20–150 m. These landslides greatly altered the terrain and landforms in the study area. Most of the severe landslides that occurred between 2010/09 and 2012/07 were along the right bank (midstream and upstream), affecting an area of approximately $1.3 \times 10^5$–$1.5 \times 10^5$ m$^2$. Most of these (at 29 locations) were compound slides. During this period, colluvium within the stream (in the midstream area) underwent severe erosion and the banks collapsed in many places. It is likely that this will eventually influence the direction of flow and even the course.
of the river in the future. This will probably also be a key factor influencing the stability of slopes and terrain in the alluvial fan.

b. Figure 7 illustrates the distribution of slides and cracking between 2005 and 2014. The study area was divided into zones A, B, C, D, and E in accordance with observed geomorphologic changes. Zone A is primarily in the source area. During 2005 and 2006, most of the landslides occurred in erosion gullies in the southern part of the source area, and a few small landslides occurred in erosion gullies in the northern part. The number of cracks on the cliff increased significantly, particularly in areas of erosion in the slope toe, thereby paving the way for the next stage of landslides. In 2007 and 2008, the erosion gullies presented obvious signs of landslide development. Cracking increased significantly after 2009/04, and landslides have occurred in the vicinity of nearly all of the cracking activity, with signs of collapse toward the source area. Since 2010, most of the landslides in this area occurred in conjunction with a growing number of cracks and cliff retreat in the northern erosion gully.

c. Zones B, C, and D are located along the left bank in the study area. Most of the landslides in these zones are translational and compound slides. Between 2005 and 2008, most of the landslides and erosion occurred at the slope toe. Cracking and landslide distribution gradually move up from the slope toe to the crown year by year. As shown in image obtained in 2009/04, the distribution of newly developed cracks coincided with the distribution of massive landslides in 2009/09. This reveals a strong correlation between cracking and landslide development. After 2009/09, cracking in the source area of zone C increased yearly, and a large-scale

| Recording time | Landslide type     | Landslide number | Landslide area (m²) |
|----------------|--------------------|-------------------|---------------------|
| 2005/07        | Translational slide| 5                 | 3.54 × 10⁴–4.81 × 10⁵ |
|                | Rotational slide   | 6                 | 3.33 × 10⁴–4.33 × 10⁵ |
|                | Compound slide     | 8                 | 3.13 × 10⁴–1.03 × 10⁵ |
| 2005/10        | Translational slide| 11                | 3.50 × 10⁴–2.18 × 10⁵ |
|                | Rotational slide   | 1                 | 1.44 × 10⁵          |
|                | Compound slide     | 6                 | 3.50 × 10⁴–2.18 × 10⁵ |
| 2005/12        | Translational slide| 6                 | 2.69 × 10⁵–1.32 × 10⁵ |
|                | Rotational slide   | 2                 | 9.81 × 10⁴–1.27 × 10⁵ |
|                | Compound slide     | 1                 | 6.93 × 10⁴          |
| 2006/07        | Translational slide| 9                 | 8.22 × 10⁴–2.08 × 10⁶ |
|                | Rotational slide   | 15                | 2.06 × 10⁵–2.54 × 10⁶ |
|                | Compound slide     | 7                 | 1.22 × 10⁵–8.57 × 10⁵ |
| 2007/10        | Translational slide| 12                | 1.95 × 10⁵–1.38 × 10⁵ |
|                | Rotational slide   | 4                 | 1.19 × 10⁵–3.20 × 10⁵ |
|                | Compound slide     | 10                | 3.74 × 10⁵–2.16 × 10⁶ |
| 2008/07        | Translational slide| 4                 | 5.32 × 10⁵–1.88 × 10⁶ |
|                | Rotational slide   | 9                 | 2.83 × 10⁵–1.42 × 10⁶ |
|                | Compound slide     | 3                 | 2.84 × 10⁵–3.99 × 10⁶ |
| 2008/11        | Translational slide| 10                | 1.50 × 10⁵–4.16 × 10⁶ |
|                | Rotational slide   | 2                 | 2.91 × 10⁵–9.89 × 10⁵ |
|                | Compound slide     | 3                 | 5.71 × 10⁵–1.27 × 10⁶ |
| 2009/04        | Translational slide| 2                 | 2.96 × 10⁵–5.54 × 10⁵ |
|                | Rotational slide   | 5                 | 4.03 × 10⁵–7.56 × 10⁵ |
|                | Compound slide     | 10                | 6.75 × 10⁵–6.44 × 10⁵ |
| 2009/09        | Translational slide| 8                 | 9.10 × 10⁵–3.84 × 10⁵ |
|                | Rotational slide   | 4                 | 1.14 × 10⁵–3.45 × 10⁵ |
|                | Compound slide     | 14                | 1.58 × 10⁵–2.98 × 10⁵ |
| 2010/09        | Translational slide| 2                 | 1.27 × 10⁵–1.37 × 10⁵ |
|                | Rotational slide   | 0                 | 0                   |
|                | Compound slide     | 5                 | 3.33 × 10⁵–1.49 × 10⁶ |
| 2011/08        | Translational slide| 0                 | 0                   |
|                | Rotational slide   | 0                 | 0                   |
|                | Compound slide     | 15                | 1.35 × 10⁵–1.76 × 10⁵ |
| 2012/07        | Translational slide| 1                 | 1.14 × 10⁵          |
|                | Rotational slide   | 1                 | 2.59 × 10⁴          |
|                | Compound slide     | 9                 | 2.58 × 10⁵–2.39 × 10⁵ |
landslide occurred in 2012/07 in one area significantly affected by cracking. This landslide altered the direction of flow of the entire riverway and greatly affected the terrain in the downstream alluvial fan. Zone E is located on an anaclinal slope in the midstream and upstream areas. Most of the landslides were rotational slides and compound slides, wherein the terrain and landforms in this area presented evidence of primary and secondary slump scarps. Between 2005 and 2009, most of the landslides in zone E developed along the riverway and extended upward year by year. Cracking also progressed with the development of landslides. Cracking on primary and secondary slump scarps increased noticeably. It appears that the rock slope in this area underwent considerable deformation, which led to extensive cracking and sliding on slopes, far exceeding that observed in other areas. Since the massive landslide in 2009/09, scarps in the source area have undergone considerable changes due to downthrow. This area still shows signs of multi-stage scraps, which indicates that if this deformation of the rock mass continues, then this area faces a serious threat of deep-seated landslides.

d. As shown in Figure 8, the landslide development can be divided into two stages. We adopted the method proposed by Crozier (1984) for the classification of slope stability as a reference for the evaluation of landslides in the study area. Our results show that prior to 2009, landslides occurred in 27 locations. Among them, three belong to Ia, two are located in the southern erosion gully of the source area, and one is located on the attacking slope on the left bank midstream. Three locations belong to Ib, with two located at the attacking slope on the left bank midstream and downstream and one located on an anaclinal slope on the right bank, midstream and upstream. These landslides were clearly rotational slides (Figure 9(a,b)) and present clear evidence of local landslides in recent years (Figure 9(b,c)). Three of these locations also belong to IIa or IIb with low landslide activity. These are situated mainly around the
Figure 7. Landslides and cracks distribution from 2005 to 2014.
northern erosion gully on the left bank of the source area and on the attacking slope on the left bank downstream. Eight locations in this area belong to IIc, and six of these are located on a cataclinal slope on the left bank midstream, whereas the other two are located on an anlcalinal slope on the right bank midstream and downstream. Ten locations belong to III on slopes with no evidence of previous landslide activity; however, they are considered likely to produce landslides in the future. Only a few places (most of which are located downstream) provide no evidence of landslides. Typhoon Morakot produced significant changes throughout the entire study area. Thus, we used remote sensing images obtained from 2009 to 2014 to reinterpret 31 deep-seated landslides, among which 22 locations (71% of the total) belong to Ia–Ic on unsteady slopes. Only four of these belong to II with low landslide activity, and the remaining five locations belong to III on potentially unstable slopes. Since the occurrence of these massive landslides, the entire area has been in a highly unstable state. The remaining colluvium and unstable rock masses are expected to deform over time and/or collapse under the effects of rainfall, thereby threatening the safety of residents and property downstream.

5. Discussion

5.1. Comparison of methodologies

Methods based on the interpretation of photographic images can be implemented manually, automatically, or semi-automatically. In this study, we opted for manual interpretation of multi-stage remote sensing images and LiDAR data. The rough topography and ground cover in landslide prone areas impose considerable difficulties in interpretation and field survey work. High-resolution LiDAR DSM is well suited to the identification of geomorphologic and geologic features, except in areas with an extremely abrupt topography and excessive ground cover. Lo et al. (2010) compared the spatial resolution of DEM (40 m) with that of LiDAR-derived DSM (1 m) within an area of rock fall covering 0.2 km². This area included cliffs, talus deposits, joints, and erosion gullies. The 12 × 12 grid produced by DEM proved unable to illustrate the features of the terrain, whereas LiDAR

![Figure 8. Classification results of the slope stability from 2005 to 2014.](image-url)
DSM proved highly effective in capturing ground variability. LiDAR-derived high-resolution DEMs reveal the topography of the bare earth, including subtle features that cannot be distinguished in aerial photographs or satellite images (Chen et al. 2015). LiDAR DEM has also been applied in the detection and characterization of deep-seated landslides (Chigira & Kiho 1994).

Figure 9. Type I failure mechanism in the right bank of the study area.
The manual interpretation of images by well-trained geologists using stereoscopes is a highly effective approach to differentiating individual landslides. Photo-interpretation techniques are commonly used in conjunction with ground surveys to locate and characterize landslides (Mantovani et al. 1996). When applied at a scale of 1:10,000, this approach enables the identification of landslide precursors, characteristic features, and factors that predispose an area to landslides. These methods have also been used to locate and map previous events, known movements, and zones of instability. Unfortunately, the complexity of this approach means that it is time-consuming and difficult to apply to large areas. It is also highly subjective and requires expert knowledge pertaining to landslide hazards (Mc Kean & Roering 2004). Lin et al. (2013) evaluated an objective approach to the identification of topographic signatures related to large-scale deep-seated landslides in areas covered by vegetation. The visual interpretation of morphological features is greatly hampered in areas of dense vegetation. Furthermore, it is not always possible to conduct field surveys in remote areas, which means that the interpretation of aerial photographs or satellite images cannot always be verified. In this study, we adopted the method proposed by Tarolli et al. (2012), which involves the statistical analysis of variability of landform maximum curvature derived from high-resolution LiDAR DTM. This approach makes it possible to define a threshold by which to facilitate the extraction of landslide features. This approach also enables the rapid preliminary interpretation of phenomena, which can be of considerable assistance during field surveys when seeking to create an accurate inventory of deep-seated landslides in forested areas.

This integrated approach adopted in this study combines a variety of methodologies (manual, automatic and statistical/analytical interpretation) to overcome many of the weaknesses related to the use of manual interpretation, and the limits imposed by a complex morphology.
5.2. Potential failure mechanism

Potential failure mechanisms can be classified into three types (Figures 9–11):

a. Type I mechanism: This failure mechanism was observed in many locations on anclinal slopes along the right bank in the study area (Figure 9). This mechanism involves progressive failure under the long-term effects of gravity. This failure mode is similar to the flexural toppling type (Goodman & Bray 1976). Flexural toppling often occurs on laminar rock strata due to an unstable slope toe, which causes the upper rock mass to bend forward and induces slipage in rock strata. When active pressure from a rockslide moves from the upper rock mass to the slope toe, the rock mass is subject to increased bending deformation, leading to failure at the surface. The sliding surface gradually cuts through the rock strata in areas subject to bending deformation. Tension cracks in the rock slope then expand from the destroyed slope toe to the crown, due to the lack of a passive zone. They may even develop towards the top of the slope to form tension cracks and sliding surfaces. This can lead to massive landslides under the long-term effects of gravity or external forces, such as rainfall or earthquakes (Goodman & Bray 1976). Figure 9(a) shows the most massive landslide caused by the Type I mechanism in study area. According to previous interpretation results (Zone E in Figure 7), most of the landslides in this area developed from the slope toe to the top of the slope.
Tension cracks developed toward the source area along the slope toe and expanded over time. Most deep-seated landslides are triggered by extreme rainfall. In this study, many instances of flexural toppling were discovered on the right bank, and potential sliding surfaces caused by toppling deformation were identified in midstream and downstream areas (Figure 9(b,c)).

b. Type II mechanism: This mechanism commonly occurs on cataclinal slopes along the left bank in the study area (Figure 10). We found that the gully erodes the toe of cataclinal slopes through rapid downcut (Figure 10(i)), thereby daylighting the entire slope toe. The establishment of free surfaces and the release of tectonic stress on the two sides of the gully led to extension/decompression-induced exfoliation nearly parallel to the slope (Figure 10(ii)). This allowed the penetration of surface water into the slope along the weak plane, which gradually made the entire slope unstable. The disappearance of passive resistance in the cataclinal slope and the penetration of surface water gradually reduced the shear strength, thereby accelerating slope deformation and the development of sliding surfaces (Figure 10(iii)). Collapse of the slope top resulted in the formation of tension zones and tension cracks (Figure 10(iv)), which aggravated instabilities in the slope. Our interpretation results reveal that the damage began with the erosion and disintegration of the slope toe, which subsequently moved toward the source area producing cracks along the slope. Following the disintegration of the slope toe, cracks near the top of the slope expanded, subsequently leading to deep-seated landslides.

c. Type III mechanism: This mechanism was seen to occur on both banks of the gully in the study area (Figure 11). The extreme rainfall event in 2009 gave rise to deep-seated landslides and the subsequent accumulation of large volumes of colluvium on the slope along the streambed in midstream and downstream areas. Under the combination of gravity, erosion, and rainfall, the colluvium gradually slid downstream resulting in the appearance of multiple sliding surfaces (Figure 11(e)). Even today, a great deal of colluvium continues accumulating along both banks of the Putanpunas stream (Figure 11(f)). Extensive erosion since 2010 has aggravated topographic changes in the alluvial fan located downstream.

5.3. Evolution of deep-seated landslides

In this paper, the results of topographic analysis, image interpretation, and field investigation were integrated in a profile (A-A’) diagram of the evolution process of deep-seated landslides. The A-A’ profile refers to the midstream area of Putanpunas stream. According to the DTM analysis by Lin and Lin (2015), the capacity of the landslide mass reached a value of 8.4e7 m$^3$ during typhoon Morakot at 2009, causing major depositions and landslide dams in the midstream area of Putanpunas stream. It is surprising to note that the depth of the landslide reached 180 m along the right bank midstream (the left bank was slip about 80m depth), whereas the deposition at the midstream also had a dramatic height of 160 m. The magnitude of this landslide far exceeded that of previous disasters, such as the Hsiaolin landslide (2009). Thus, we selected the A-A’ profile that is representative of the evolution of deep-seated landslides, which can be divided into four main stages (Figure 12). Stage 1 involves erosion of the gully. The release of tectonic stress on the two banks of the gully led to extension/decompression-induced exfoliation parallel to the slope, which is conducive to retrogressive erosion. Moreover, surface water infiltrated into the slope along this area of exfoliation and leaked into the more fragmented areas. Stage 2 involved deformation of the rock slope. The rock mass above the slope toe gradually lost its support following exposure due to severe downcut erosion. This deformation led to interlayer sliding within the strata of the rock mass. It also aggravated the deformation and fragmentation of the slope and promoted the development of tension cracks at the top of the slope. Stage 3 involved the development of sliding surfaces in the rock slope. When the deformation of rock strata on anacinal slopes exceeded a particular threshold, surface ruptures appearing near the largest deformation band developed into a sliding surface once they connected together. This sliding surface passed through the entire rock stratum, thereby creating conditions favourable to the occurrence of landslides. On cataclinal slopes, a deformation band
Figure 12. (a) Profile map of the deep-seated landslide evolution development; (b) 3D satellite image at upstream from 2005.
developed from the weak plane (shale stratum) caused the cataclinal slope to lose stability, leading to slow sliding along the weakest plane in the rock stratum. This led to shearing deformation along the weak plane of the sliding surface during temporary stagnation of the sliding mass. Consequently, the intensity of the shear forces decreased sharply, thereby causing the entire mass to slide, deform, and become increasingly broken. Step 4 involved movement of the sliding mass. The penetration of a large quantity of surface water eroded the slope toe, which rapidly decreased shear strength along the sliding surface, thereby allowing the mass to slide once again. At this point, the entire sliding surface began moving as a deep-seated landslide.

After integrating the results of topographic analysis, manual interpretation, and field investigations with the classification results of slope stability from 2005 to 2014 (Figure 8), we drew up classification diagrams indicating the potential failure mechanisms associated with deep-seated landslides in the study area (Figure 13). These results have been confirmed by the results of five field surveys. Figure 13 shows our analysis of the failure mechanisms associated with deep-seated landslides before and after 2009. Along the right bank of Putanpunas stream, 9 deep-seated landslides prior to 2009 and 11 events since 2009 could be categorized as Type I. Along the left bank of Putanpunas stream, 13 deep-seated landslides before 2009 and 7 events since 2009 could be categorized as Type II. In the headwater area of Putanpunas stream, only 4 deep-seated landslides before 2009 could be categorized as type III, however, 13 of the deep-seated landslides that occurred since the extreme rainfall in 2009 could be categorized as type III. This can be attributed to the large accumulation of earth and debris flows that produced considerable changes in topography. Between 2009 and 2014, increased erosion and the development of massive quantities of colluvium in the upper and middle parts of the gully altered the direction of flow, the downcutting rate, and the terrain in the downstream alluvial fan. Thus, the type III mechanism is dominant in Putanpunas stream at present.

6. Conclusions

In this study, we investigated the evolution of deep-seated landslides, using Putanpunas stream in Taiwan as a case study. Topographic analysis revealed significant cliff retreat on anclinal slopes on
the right bank in the midstream and upstream areas between 1985 and 1904. Extreme rainfall events during 2009 and 2010 caused deep-seated landslides and topographic changes, resulting in the accumulation of $7.2 \times 10^7$ m$^3$ of colluvium in the mid- and up-stream streambed. Since 2010, severe erosion and sliding of the colluvium has dramatically altered the direction of stream flow in midstream and downstream areas as well as in the alluvial fan downstream.

Our interpretation results indicate that most of the landslides on cataclinal slopes on the left bank in midstream and upstream areas can be categorized as translational slides. In contrast, most of those that occurred on anacinal slopes on the right bank are rotational slides. Images obtained in 2009/04 indicate a sharp increase in the formation of cracks along the slope, which has seriously affected slope stability. These images also revealed that since the occurrence of these deep-seated landslides, more of the landslides have been compound slides. Furthermore, the colluvium has been undergoing serious erosion. This is expected to contribute to changes in the flow direction in downstream areas, undermine the stability of slopes, and alter the terrain of the alluvial fan in the future. Among the 31 deep-seated landslides in the study area, 71% are on unstable slopes and 13% are largely inactive. The remaining 16% of landslide activity is on potentially unstable slopes, which should be the focus of on-going observation in the future.

Our results also indicate that the evolution of deep-seated landslide in the area around Putanpunas stream can be divided into four stages: (1) gully erosion and stress release, (2) rock slope deformation, (3) development of sliding surfaces in the rock strata, and (4) slope sliding. The large quantity of colluvium that remains on the slopes and in the gullies is liable to be a key factor in deep-seated landslides and topographic changes in the future. Owing to the large colluvium accumulated in the upstream and began moved from 2009, parts of the colluvium from sliding transform to flow, these slope toes on both sides of the upstream were daylight and slope failure because of severe erosion by the earth or debris flows. The infiltration of substantial quantities of rainfall and increased gully erosion caused the slope toe to collapse first. This destabilized the nearly saturated rock mass in upstream areas, thereby allowing it to slide downstream. In 2012, large-scale landslides that took place along Putanpunas Stream led to the erosion of the Ryukyu Terraces downstream as well as the overflow of debris, which eventually cut across the terraces to the downstream segment of the Laonong Stream. This greatly altered the terrain of the alluvial fan. These observations lend credence to concerns about the accumulation of large quantities of colluvium upstream, which poses a considerable threat to the safety of inhabitants and property downstream.

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