Landscape evolution characteristics of large-scale erosion and landslides at the Putanpunas Stream, Taiwan

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ABSTRACT
This study used multi-temporal terrain and remote sensing images to investigate the geomorphological evolution of the Putanpunas stream caused by large-scale erosion and landslides over the last decade. Discrete element method was then performed to gain the physical insight of the slope failure mechanisms and landslide movement. Our results show topographical changes in the alluvial fan downstream and the deposits in the midstream and downstream segments of the Putanpunas Stream between 2005 and 2009. In 2009, torrential rainfall induced large-scale landslides (the volume was about $8.4 \times 10^7$ m$^3$) that greatly altered the terrain of the Putanpunas Stream valley and the alluvial fan. A thick, unstable layer of colluvium (the thick of colluvium more than 150 m) was also deposited in the valley. In 2012, further large-scale landslides turned the colluvial layer into debris flows that cut across the Ryukyu Terraces downstream to the downstream segment of the Laonong Stream to the south-west. The change of debris flow direction from southeast to south-west eventually posed a considerable threat to the safety of protected targets and the access road downstream.

1. Introduction
In-depth investigations of the development of large-scale erosion development and the precise assessments of erosion, landslides, and deposits in catchments are crucial to pre-disaster preparation, stability assessment, and the planning of treatment projects. Developments associated with landslides and deposition are usually investigated using aerial photos, satellite photos, and digital elevation models (DEMs) from previous years in conjunction with onsite investigations (Cardinali et al. 2002; Leventhal and Kotze 2008). Landslides and erosion generally occur on the banks of rivers, wherein the toe of the bank is subject to downcutting, and the crowns of the sliding masses present clear tension cracks and boundary erosion (Lo and Feng 2014; Lin and Lin 2015; Weng et al. 2017). The occurrence of intense, continuous rain causes infiltration that can lead to large-scale erosion and landslides (Lo et al. 2011).

Bryan and Jones (1997) indicated that the erosion caused by surface runoff is crucial to river valley development, and it is believed that the formation of valleys in less permeable strata is associated mainly with runoff erosion (Hadley and Schumm 1961; Kirkby and Chorley 1967; Way 1978; Chorley et al. 1984; Gerrard 1988). Underground water can also lead to more pronounced erosion and
large-scale landslides (Dunne 1980; Higgins 1984; Kochel and Piper 1986; Laity 1988; Luo et al. 1997; Spence and Sauchyn 1999). Furthermore, the geostuctural characteristics of riverbanks are important factors in the progression of erosion and landslides (Fell et al. 2007; Hencher et al. 2011; Lo et al. 2011, 2014). These characteristics include the attitude of weak planes within the slope body, the geological structure, the distribution of permeable layers and water barriers, the strength of the geological material, and the permeability of the strata. However, speculation concerning large-scale erosion and landslides and the characteristics of deposits requires in-depth analysis using numerical simulations or onsite geological investigations, followed by verification of the results and on-going adjustments to ensure the reasonableness of the process.

Most previous studies on movement processes and deposition by large-scale landslides have relied on model testing and numerical simulations. The testing of physical models involves simplifying actual landslide events using indoor models with high-speed cameras to record the movements of materials during the collapse as well as the measurement of the resulting deposits (Davies and McDougall 1999; Okura et al. 2000; McDougall and Hungr 2004; Lajeunesse et al. 2005; Manzella and Labiouse 2008). Physical models can help in the characterization of movement processes and the range of deposition, they are far smaller than the actual landslides in terms of scale. For example, Iverson et al. (1997) have worked extensively on this problem using a full-scale debris flow flume and clearly articulated the specific effects of scale on landslide experiments. Moreover, actual landslides and changes in terrain are extremely complex and cannot be fully explained using small-scale models. Discrete element method can be used to elucidate movement processes and the deposition of large-scale landslides as a means of clarifying highly complex landslide phenomena (Cundall 1971; Koc 2008 Lo et al. 2011, 2016; Lin and Lin 2015). The discrete element method only simulates dry granular material of landslides, which does not consider pore-fluid effect in debris flow, but when the model set the low friction coefficient less than 0.1 in each particle which reflects the influence of pore-fluid for landslide movement (Tang et al. 2009; Lo et al. 2011). Using the discrete element method to simulate debris flows and cataclinal slope movements, Lo et al. (2014, 2016) obtained results that matched post-disaster measurements and were able to clearly explain the differences in speed, sliding mass fragmentation, and particle interactions during various stages of different types of landslide. Lin and Lin (2015) simulated the evolution of the large landslide in Putanpunas Stream caused by the Typhoon Morakot in 2009 by using discrete element method. From 2009 to 2017, several severe rainfalls triggered the landslide events that continuously happened along the Putanpunas Stream; hence, the current topography of the alluvial fan at the estuary of the Putanpunas Stream changed greatly from the simulation result by Lin and Lin (2015). As the result, the analysis on the historical evolution of the landslide events in the Putanpunas Stream is crucial for the hazard mitigation in nearby area.

This study examined the Putanpunas Stream (Figure 1) using images from Formosat-2, a satellite with flexible imaging capabilities and high spatial and temporal resolution, in conjunction with aerial photos and LiDAR data to observe topographical changes and perform landslide interpretations. We then compared the results of onsite geological investigations and numerical simulations to examine landslide and deposit characteristics in the study area and clarify the evolution process of the valley terrain along the Putanpunas Stream.

The primary focuses of this study are as follows:

1. Changes in large-scale landslides during various periods.
2. Integration of numerical simulation and interpretation results to explain the movement processes and deposition associated with large-scale landslides in the study area.

2. Study area

The Putanpunas Stream is a tributary of the Laonong Stream in Taoyuan District of Kaohsiung City, Taiwan (Figure 1). The catchment area of the Putanpunas Stream is approximately $6.85 \times 10^6 \text{ m}^2$. 
Figure 1. Geographic position, 3D topographic and geologic map of the study area (Lo 2017).
dipping gently from north-west to south-east. The upstream and downstream elevations are 2142 and 631 m, respectively. The average slope of the streambed is approximately 30°, and the slopes of the riverbank range from 30° to 50°. As a result, the undulating terrain is susceptible to large-scale erosion and landslide development. The deposition zone of the alluvial fan downstream is situated between the Ryukyu Terraces and the Shimizu Terraces, and the stream exits across from the Oupa- kaer Terraces, which means that any debris flows has a direct impact on the main access road, Provincial Highway No. 20. To this day, the highway segment located where the Putanpunas Stream flows into the Laonong Stream is still cut-off by the debris deposits delivered by Putanpunas Stream since Typhoon Morakot, thereby severely affecting local traffic and road safety.

Geologically speaking, the landslide zone at the source of the Putanpunas Stream comprises Tangenshan Sandstone (Tn, muddy sandstone) and the Changzhihkeng Formation (Cc, interbedded sandstone and shale). The left and right banks are situated on cataclinal and anaclinal slopes, respectively, and most of the alluvial fan downstream is from the Chaochow Formation (Co, hard shale or slate occasionally interbedded with sandstone) (Figure 1). Geological maps indicate that the Putanpunas Stream crosses over two faults: the Kaochung Fault upstream and the Tulungwan Fault downstream. These two faults also mark the boundaries of strata in the study area. The strata on the opposite sides of the faults differ significantly in attitude and rock mass strength. Furthermore, the faults have broad fracture zones, which facilitate the occurrence of erosion and landslides.

3. Methodology

3.1. Landforms interpretation

Thus, study performed landslide interpretation as well as analysis of geomorphological changes deposition using multi-temporal and multi-scale topographic and remote sensing images (Table 1) for the years 1904, 1985, 1992, 1999, 2006, 2010, and 2014. The scale of the topographic map of 1904 was 1/20,000, whereas the scale of the topographic maps between 1985 and 1999 was 1/25,000.

Table 1. The date, scale, and RMS error of collected data.

| Data Type               | Date    | Scale     | Total RMS error |
|-------------------------|---------|-----------|-----------------|
| Topographic maps        | 1904    | 1/20,000  | 12.85           |
|                         | 1985    | 1/20,000  | 2.71            |
|                         | 1992    | 1/25,000  | 2.42            |
|                         | 1999    | 1/25,000  | 2.07            |
|                         | 2006    | 1/25,000  | 0.47            |
|                         | 2010    | 1/10,000  | 0.22            |
|                         | 2014    | 1/10,000  | 0.13            |
|                         | 2005/07 |          | 1.01            |
|                         | 2005/10 |          | 0.87            |
|                         | 2006/02 |          | 0.84            |
|                         | 2006/07 |          | 0.92            |
|                         | 2007/10 |          | 0.77            |
|                         | 2008/07 |          | 0.81            |
| Satellite images (FORMOSAT-II) | 2008/11 | 1/10,000  | 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 |          | 0.32            |
|                         | 2009/10 | 1/10,000  | 0.35            |
|                         | 2012/11 |          | 0.27            |
|                         | 2014/10 | 1/5,000   | 0.23            |
The topographic map of 2006 was a 5 m × 5 m DEM, and the topographic maps of 2010 and 2014 were 1 m × 1 m LiDAR DEMs. The remote sensing images were taken by Formosat-2 in 2005/07, 2005/10, 2006/02, 2006/07, 2007/10, 2008/07, 2008/11, 2009/04, 2009/09, 2010/09, 2010/11, 2012/07, and 2013/07 with image resolution of 2 m, primarily showing geomorphological variations in the previous decade. The aerial images were taken in 2006/02, 2009/10, 2012/11, and 2014/10, with the resolution of the images between 2006 and 2009 being 0.25 m × 0.25 m and that of the images between 2012 and 2014 being 0.15 m × 0.15 m. The aerial images were the primary references in explaining geomorphological changes.

Variations in orthorectification methods made it necessary to conduct geometric correction of the images and reduce spatial coordinate errors in each image to within an acceptable range (1 m). This involved selecting 17 control points from the topographical maps and aerial photos where no collapses or geomorphological changes had occurred within 10 m from 1904 to 2001. Geometric correction of the various topographical maps and aerial photos was then performed before calculating RMS errors of each control point in each map or aerial photo (Table 1). The interpretation of geomorphological characteristics was based primarily on the 17 images captured by Formosat-2 between 2004 and 2014, which was aided by overlapping the DEMs from 2006, 2010, 2011, and 2014. This produced three-dimensional surface models that facilitated interpretation of the changes in the terrain and geomorphology along the Putanpunas Stream in different years. Based on the criteria established by Soeters and Van Western (1996), landslides were categorized as rockfalls, rotational slides, or translational slides, depending on geomorphology, vegetation, and drainage characteristics.

3.2. Numerical method and model setting

This study employed the program PFC3D, which is based on the discrete element method, to construct the digital models of landslides along the Putanpunas Stream. In the PFC3D program, two types of elements, particle and wall, are applied to construct a numerical model. Compared with the finite element method simulation, PFC3D allows the separation between two particles and to have a large displacement that is capable of simulating the deformation process not only before the slope failure but also the sliding and deposition of slope. The velocity and the contact force of each particle are calculated by Newton’s second law and the force-displacement law in a time-stepping algorithm (Itasca 2002). For the contact model between particles, the parallel bond model proposed by Potyondy and Cundall (2004) was adopted to simulate the bond between particles. The parallel bond considers the reactions in the normal and tangent directions, which resists not only a force but also a moment, and ruptures when the maximum tensile stress or shear stress exceeds the tensile or shear strength. However, the microscopic parameters, such as normal stiffness, shear stiffness, bonding stiffness, and bonding strength, cannot be directly determined by the macroscopic properties. Therefore, back analysis was conducted by comparing the simulation and the actual deposition of 2005 to determine the micro-parameters used in the simulations.

The numerical model of the Putanpunas Stream was divided into a loss area and a three-dimensional terrain surface. Landslide depth is difficult to predict accurately; therefore, we used terrain data from the latest map (1 m × 1 m resolution Lidar) and performed analysis of relative elevations in loss areas and at the boundaries of unaffected areas (i.e. the elevation of the boundaries of unaffected areas minus the elevation of loss areas) in order to establish the relationship between landslide area and depth (Figure 2). In this manner, we estimated the depth of loss areas for use as a reference in the construction of a numerical model. The original terrain surface was converted into 20 × 20 m wall elements using the 5 m × 5 m DEM of 2004, which resulted in 71,135 wall elements (Figure 3). The total length of the numerical model was 7182 m, and the average width was 2286 m. For sliding masses, we used 110,479 ball elements (diameter ranging from 2 to 5 m) to reconstruct 10 major landslide events that took place between 2005 and 2014, with total volume exceeding 1 × 10^8 m^3. The main size of ball element was selected as 5 m based on the resolution of DEM, and the smaller sizes of ball element were used to fit the variation of the terrain surface. For the model integrating
the ball elements and wall elements, we constructed the pre-landslide terrain before placing the ball elements into the landslide area. Once the ball elements were stable, bonding strength was applied to the contacts between balls to represent the solid rock mass that existed prior to the landslides. The simulation parameters are presented in Table 2. It was presumed that the large-scale landslides in the study area were induced by torrential rain, and the rock mass was fragmented and highly weathered. Thus, to simulate the effect of wetting deterioration of rock, we reduced the coefficient of friction on the sliding surface during the preliminary analysis of large-scale landslide movement and also set the bonding strength between rocks to diminish gradually. The numerical model also presented the attitude of the strata on both banks of the Putanpunas Stream in a simple manner: the interlayer attitude of the particle arrangements were roughly identical to those in the actual large-scale sliding area on the anaclinal slope on the right bank, whereas the ball elements were overlapped.
in a cataclinal slope manner on the left bank. In this way, the model reflected the actual landslide mechanisms and rock failure behaviour on both banks of the valley.

4. Results

4.1. Landforms interpretation

Figure 4 exhibits the interpretation results of landslides that occurred along the Putanpunas Stream between 2005 and 2013. The largest landslide took place in 2009/09 (Typhoon Morakot), covering an area of approximately $3.84 \times 10^5 \text{ m}^2$. Between 2005/07 and 2005/12, landslides occurred at the source on the left bank, and in the midstream and upstream sections of the right bank. In 2006/07, the existing landslide area continued to erode and collapse towards the source, mainly in the erosion gullies to the south of the source and gradually eroding and damaging slope toes and cliff tops. Most landslides in 2007/10 were located at the midstream and upstream sections of the right bank, with those in the midstream section being the most severe. The areas affected by the collapse reaching $1 \times 10^3 \text{ m}^2$ to $3.8 \times 10^5 \text{ m}^2$ and the depths ranging from 20 to 150 m. This greatly altered the terrain and landform of the entire valley. Between 2010/09 and 2012/07, most of the landslides occurred in the midstream and upstream sections of the right bank, with those in the midstream section being the most severe. The areas affected by the collapse were approximately $1.3 \times 10^5 \text{ m}^2$ to $1.5 \times 10^5 \text{ m}^2$, which developed from the erosion gullies at the source and to the north of the midstream section. This meant that erosion and landslides continued to develop, resulting in significant changes in the path of the streambed and the alluvial fan terrain downstream. At that time, the colluvial layer in the midstream section of the valley was also beginning to show signs of erosion and failure, which are crucial factors influencing slope stability, the alluvial fan and deposit terrain, and the path of the streambed in the midstream and downstream sections.

Table 2. Numerical parameters used in PFC modelling.

| Numerical Parameter                      | Tangenshan sandstone | Changzhikheng formation |
|------------------------------------------|----------------------|--------------------------|
|                                          | Uniaxial experiment  | Full-scale numerical     | Uniaxial experiment  | Full-scale numerical |
|                                          | model                | model                    | model                | model                |
| Unit weight of ball elements (kg/m³)     | 2500                 | 2500                     | 2580                 | 2580                 |
| Range of particle radius (m)             | 0.0025–0.003         | 2–5                      | 0.0025–0.003         | 2–5                  |
| Normal stiffness (N/m)                   | 1.2e8-1.44e8         | 4.8e10-1.9e11            | 1.0e8-1.25e8         | 4.2e9-5.7e10         |
| Shear stiffness (N/m)                    | 6.0e7-7.2e7          | 2.4e10-9.5e10            | 5.8e7-2.3e7          | 2.1e9-2.8e10         |
| Friction coefficient of ball elements in | 0.6                  | 0.6                      | 0.5                  | 0.5                  |
|   steady-state                           |                      |                          |                      |                      |
| Friction coefficient of ball elements in | 0.05-0.1             | 0.05-0.1                 | 0.05-0.1             | 0.05-0.1             |
|   debris mass sliding                    |                      |                          |                      |                      |
| Friction coefficient of wall elements    | 0.6                  | 0.6                      | 0.5                  | 0.5                  |
| Normal stiffness of parallel bond (N/m)  | 1.6e12-2.4e12        | 1.5e9-6.0e9              | 1.32e12-1.68e12      | 1.25e9-4.28e9        |
| Shear stiffness of parallel bond (N/m)   | 8.3e11-1.2e12        | 7.5e8-3.0e9              | 6.1e11-8.4e11        | 6.25e8-2.14e9        |
| Normal bond strength (MPa)               | 16                   | 16                       | 13                   | 13                   |
| Shear bond strength (MPa)                | 8                    | 8                        | 6                    | 6                    |
| Normal damping coefficient               | 0.4                  | 0.4                      | 0.36                 | 0.36                 |
| Shear damping coefficient                | 0.2                  | 0.2                      | 0.11                 | 0.11                 |

An erosion gully is a valley created by running water, eroding sharply into soil or rock. The development of erosion gullies were identified by ‘U’ or ‘V’ shaped contour lines with their closed end pointing towards higher elevation in the topographic map. The scale of the topographic map of 1904 is 1/20,000, and the scale of other topographic maps is 1/25,000. A comparison of the
distribution of erosion gullies from 1904 to 2014 (Figure 5) revealed a dendritic distribution in 1904, with the degree of erosion development on the cataclinal slopes on the left bank lower than that on the anaclinal slopes on the right bank. Most of the erosion development was on the right bank.

Figure 4. Results of landslides interpretation in the study area (Lo 2017).
Between 1985 and 1999, the erosion gullies reached the source area, with denser, more apparent development on the right bank than on the left bank, clearly showing the differences in erosion characteristics of rock in anaclinal and cataclinal slopes. Following multiple landslides brought about by torrential rain events in 2006, the erosion gullies at the source underwent vigorous development from the source upstream to the early midstream section. After extreme torrential rain events in 2009, the development of erosion gullies in the study area presented markedly different distributions. In addition to the increasing number of erosion gullies, the path of the streambed in the midstream and upstream sections had changed substantially due to large-scale colluvial deposits. Between 2009 and 2014, the height of deposits in the alluvial fan on the Laonong Stream downstream was approaching the elevation of the Ryukyu Terraces and the Shimizu Terraces. This made it possible for some of the rock materials from landslides and the colluvial layer to cut across the Ryukyu Terraces, which changed the path of the streambed downstream and expanded the area of the alluvial fan on the Laonong Stream, which severely affected the stability of the primary access road. During this period, the colluvial layer in the midstream and upstream sections and the midstream section of the left bank showed clear evidence of erosion gully development. Thus, it is highly likely that the increase in quantity of material in the alluvial fan (i.e. materials that changed the streambed downstream), originated from the severe erosion of the colluvial layer in the midstream section and the area that collapsed at the source of the midstream section of the right bank.

A comparison of the terrain in the alluvial fan downstream (Figure 6) showed little variation between 2005/07 and 2007/10. Only in 2007/10 did the alluvial fan deposits present sign of extrusion where it met the Laonong Stream. Within two years, the deposits had risen by 5 to 7 m, which
Figure 6. Results of alluvial fan interpretation in the study area.
gradually changed the elevation of the streambed of the Laonong Stream as well as its flow path. Between 2007/10 and 2009/04, the area and elevation of the alluvial fan downstream continued to increase. By 2009/04, the entire intersection was filled with rock debris, which created a small dammed lake covering an area of 17,500 m² slightly upstream from the intersection. In 2009/09, large-scale landslides and erosion expanded the alluvial fan, such that the height of the deposits gradually approached the elevation of the tops of the Ryukyu Terraces and Shimizu Terraces and reduced the area of the Ryukyu Terraces by roughly 23%. Between 2009/09 and 2010/11, several torrential rainfall events led to the accumulation of substantial quantities of surface water upstream from the intersection with the Laonong Stream, thereby creating a dammed lake 580 m long and 260 m wide. In 2011/08, the rock material at the tip of the alluvial fan downstream showed continuing signs of deposits progressing upstream, wherein the elevation of the deposits had already reached the top of the Ryukyu Terraces and Shimizu Terraces. A bend in the stream caused extreme erosion at the north end of the Ryukyu Terraces, which resulted in collapses and gradual damage to the stream banks at the upper edges of the terraces. By 2013/07, the north end of the Ryukyu Terraces had been cut through by recent debris flows to the south-western end in the downstream segment of the Laonong Stream, forming a new alluvial fan approximately 230 m long and 600 m wide, which severely threatened the safety of the village and roads in the downstream.

4.2. Landscape evolution characteristics of large-scale erosion and landslides through numerical simulation

Most of the numerical simulations were used to reproduce large-scale landslide events in 2005/07, 2005/10, 2006/07, 2007/10, 2008/07, 2008/11, 2009/09, 2010/09, 2011/08, and 2012/07 (Figures 7- and 12). To validate the numerical simulation, Figure 13 presents the comparison of simulation results and the final deposition pattern in the 2009 Morakot event. We chose 17 ground control points as the actual terrain surface for the comparison. According to Figure 13, the simulated thickness and distribution of deposition mostly agree with those of the measured DEM data, and the
prediction accuracy of the simulated distribution is approximately 0.86. The simulation results were described as follows:

(1) 2005/07-2005/10 (Figure 7): Simulations for 2005/07 revealed that the initial sliding masses on the two banks of the valley were in the form of collapses or high-speed sliding (Figure 7 –

Figure 8. Simulation results of landslide event in 2006/07 and 2007/10.

Figure 9. Simulation results of landslide event in 2008/07 and 2008/11.
32 s). By approximately 237 s, all of the sliding masses had reached the bottom of the valley, gradually decelerating into debris flows. The time herein is not actual time and it is used as a marker to describe the procedure during the modelling. At 1953 s, the front end of the debris flows reached the Laonong Stream, but ceased moving at 2058 s, with roughly 23% of the

Figure 10. Simulation results of landslide event in 2009/09.

Figure 11. Simulation results of landslide event in 2010/09 and 2011/08.
particles deposited in the streambed of the Laonong Stream and 52% of the particles deposited in the midstream and downstream segments of the Laonong Stream valley. In 2005/10, high-speed sliding ran from 0 to 27 s, and most of the sliding mass had reached the valley by 38 s. At 195 s, the front end of the avalanche reached the colluvial deposits created by the previous landslide events in the midstream and downstream sections, which caused the originally stationary materials to move further downstream. The avalanche finally halted at the streambed at 1236 s, at which point 52% of the particles were deposited between the Ryukyu Terraces and the Shimizu Terraces, thereby widening and raising the alluvial fan on the Laonong Stream. The remaining 48% of the particles were deposited near the valley downstream.

(2) 2006/07-2008/11 (Figures 8 and 9): The distributions of landslides and deposition in the four periods were very similar. The sliding masses and landslide locations that occurred in 2006/07 were closer to those in 2008/07 (all on the right bank). Between 0 and 30 s, high-speed sliding occurred, and after 40 s, the movement of the sliding mass converted to a slower avalanche pattern. After 200 s, the front end of the avalanche came into contact with deposits from previous landslide events, which pushed the stationary materials further downstream. The avalanche stopped moving after 400 and 700 s, respectively, with the newly generated deposits distributed within the valley in the midstream and downstream segments of the Putanpunas Stream. The area covered by the existing alluvial fan gradually increased. The sliding masses in 2007/10 and 2008/11 were larger than those in the other two landslide events, with movement and deposition extended to more than 850 s. The avalanche in 2007/10 was primarily distributed between the Ryukyu Terraces and the Shimizu Terraces, which accounted for approximately 70% of the overall mass. Only 30% of the materials were deposited in the valley in the downstream segment of the Putanpunas Stream. Prior the landslide event in 2008/11, the alluvial fan downstream included deposits from five major landslide events. As a result, materials from the landslide event in 2008/11 were deposited upstream of the spot between the Ryukyu Terraces and the Shimizu Terraces. The elevation of the deposits...
in the valley was close to those of the two terraces, thereby enabling later debris flows to spill over or erode the top of the terraces.

(3) 2009/09 (Figure 10): Under the extreme torrential rainfall during that period, the total volume of the sliding masses along the Putanpunas Stream reached approximately $1 \times 10^8 \text{ m}^3$. Large-scale collapses and sliding occurred between 0 and 230 s, when the average depth of the sliding mass on the cataclinal slope on the right bank at the source exceeded 80 m. In cases where both banks of the Putanpunas Stream showed signs of sliding, the sliding masses on cataclinal slopes on the left bank were shallower (between roughly 10 and 25 m) but faster (compared with the large-scale sliding masses on the right bank). This led to the rapid accumulation of substantial quantities of materials in the streambed upstream (between 40 and 60 s), which severely eroded the toes of the sliding masses on the right bank. The large-scale sliding mass on the anacclinal slope on the right bank began slumping towards the valley after 50 s. The streambed was already full of a large quantity of loose material, which greatly reduced the

Figure 13. Comparison of actual terrain surface and the simulation result. (a) Variation of the terrain surface of deposition in 2009 event (Lin and Lin 2015); (b) variation of the simulated terrain surface of deposition
moving energy of the sliding mass after reaching the valley at 86 s. This reduced the run-out distance as well as the overall fragmentation of the mass (Figure 10(b)). The duration of the event from movement to deposition took 2317 s, following which roughly 61% of the debris materials were deposited in the upstream segment and the bend in the midstream segment, which widened the streambed at the source from 45 m prior to the landslide to over 450 m. The substantial rock deposits in this section of the valley resisted being moved to the alluvial fan downstream. By the time the landslide event had taken place, the valley and alluvial fan downstream had already accumulated debris, which cluttered approximately 35% of the midstream and downstream segments of the Putanpunas Stream and greatly altered the terrain of the valley. The simulation indicates the cumulative history of landslides in the valley substantially affects the run-out of subsequent landslides. Once the front end of the avalanche moved into the downstream segment at approximately 345 s, the debris deposited downstream increased the area of the alluvial fan as well as the height of the deposits almost to the level of the two terraces.

(4) 2010/09-2011/08 (Figure 11): The sliding masses during these two periods were relatively small, and a substantial quantity of debris remained in the valley. Unstable debris fell along the banks of the valley until it hit the large quantity of loose debris in the valley, which consumed its kinetic energy and prevented the debris of recent landslides from moving to the midstream segments, downstream segment, or alluvial fan. As a result, the distribution of deposits in the alluvial fan downstream did not change significantly. Most of the landslides in the midstream and upstream segments deposited thick layers of soft, loose debris into the streambed, and there was relatively less rainfall than that in the preceding years, which prevented large-scale movements of debris with long run-out distances.

(5) 2012/07 (Figure 12): The landslides during this period were caused primarily by the extreme rainfall on 2012/06/10 and Typhoon Talim on 2012/06/19. The volume of the sliding masses was second only to that caused by Typhoon Morakot in 2009. The elevation of the landslide area was greater and the slope steeper, which led to a longer movement distance. The sliding mass scoured deeply and created a stationary colluvial layer on the streambed, which significantly changed the deposits at the edges of the alluvial fan downstream. Between 0 and 25 s, the unstable mass in the model underwent collapse and high-speed sliding. Then, it caused some debris on the surface of the deposits in the streambed to move downstream with the impact and erosion of the new sliding mass. The elevation of the alluvial fan was already close to those of the Ryukyu Terraces and Shimizu Terraces. In addition, the north end of the Ryukyu Terraces coincided with the bend in the stream (the concave bank). At 32 s, the avalanche had already begun to erode this region severely, and by 158 s, it had cut through the Ryukyu Terraces to the downstream segment of the Laonong Stream to the south-west. Consequently, later alluvial fan deposits differed greatly from those before 2012.

5. Discussion

5.1. Role of pore-fluid in discrete element modelling

Fast landslides, avalanche, and debris flow are geophysical, gravity-driven flows involving phase changes from solid to fluid in the triggering stage and from fluid to solid when the motion decelerates or stops. Accurately simulating the interaction between solid grains and pore water is of paramount importance to landslide modelling; however, it is also highly complex. This is particularly true for long run-out landslides, the fluidization of which is due to the mixing of collapsed debris and fast flowing fluid (Kent 1966). The long-standing concept of friction in landslides being reduced by interstitial water finds support in a long run-out distance associated with landslides passing over water-saturated substrates (Erismann and Abele 2001). The sliding mass converts energy accumulating on the sliding surface to produce shear effects, which has the effect of self-lubricating debris
from the ruptured rock (Campbell 1989, 1990; Cleary and Campbell 1993; Campbell et al. 1995). Wang et al. (2002) used a ring shear test to analyse the characteristics of rocks in the vicinity of Hie-gaei landslide in Japan. They posited that saturation of the slip surface led to fluidization, such that the effective stress and the shear resistance approached 0.1. They concluded that these effects were the major cause for long run-out of the landslide.

Tang et al. (2009) and Lo et al. (2011) obtained low friction coefficients (<0.1) associated with landslide movement using back-calculation based on the discrete element method. Their approach provides flexibility in handling disaggregated particles and has proven a powerful tool in characterizing the overall dynamics of high-speed landslides. The most likely explanation for the low friction along the sliding surface is a reduction in the effective friction coefficient resulted from pore-fluid. In this study, the interaction between pore-fluid and particle was not considered in the simulation, it is difficult to gain insight into flow processes during slope sliding. However, to reflect the behaviour of avalanche or debris flow, we had to adopt a very low friction coefficient of granular material. The simulation results were further calibrated by the actual terrain surfaces of deposition in the landslide events. According to these procedures, the simulation can reasonably reflect the terrain surface of deposition in the 2009 event (new Figure 13). Though the fluid effect was not considered, the simulation still provided a useful tool to predict the landslide process.

5.2 Evaluation of PFC3D model

The success of landslide modelling lies in the ability to maintain overall consistency within observed deposits, while simultaneously satisfying constraints from eyewitness and measured data. In the present case, our findings were in agreement with many of the events at the site of the actual landslide, including landslide volume, the terrain of the slip surface, and the position of the collapsed area (including the main sliding mass and cutting through the alluvial fan). We also observed a number of other consistencies that were not necessarily stipulated in the simulations. These are outlined in the following:

(1) Combining geomorphologic analysis and field observation is crucial to the reconstruction of landslides. Lin and Lin (2015) and Lo (2017) described the mechanism underlying the landslide at Putanpunas Stream as a loss of strength in the shale due to the effects of rainfall. The shale material formed a largely impermeable layer at the base of the landslide. This suggests that heavy rainfall penetrated only as far as the shale layer, at which point an increase in water pressure released the effective stress, thereby triggering the landslide. Following the initiation of movement, the shale probably played a lubricating layer at the base of the landslide material by maintaining high pore pressure (Lo 2017). In our landslide model, we adopted the low friction coefficient of particle due to the effect of pore-fluid to reconstruct the landslide event at Putanpunas Stream. Landform interpretation based on ball elements in the PFC3D model revealed that the source area, the upstream area, and the midstream area were all covered with colluvium.

(2) A comparison of deposition volume between the PFC model and terrain analysis (Lin and Lin 2015) revealed that in 2009/09, most of the debris (>60%) was deposited in the upstream segment and at the bend in the midstream segment, resulting in low fragmentation deposits. Our simulation results clearly show an increase in the amount and size of particles deposited in the upstream segment (Figure 14). Overall, the deposition thickness and area distribution closely match measurements obtained at the site.

(3) During the period of 2009/09 to 2009/09, the height of the deposition in simulations at the top of the alluvial fan of Laonong Stream approached the elevation of the two terraces. This allowed the subsequent deposition (2012/07 PFC model) to mount the Ryukyu Terraces, thereby altering the path of the streambed downstream and expanding the area and height of
Figure 14. Comparison of simulation results: (a) real landslide deposition distribution; (b) UAV aerial photo.
the alluvial fan. Our results match the substantial deposits on the right bank of the Laonong Stream. These findings largely explain the destruction of the Ryukyu Terraces (Figure 14).

(4) Our modelling of the terrace and Laonong Stream is in agreement with the events that occurred as the landslide approached the transition from the steep source area to the gentle slope and horizontal run-out surface in the midstream segment (Figure 14). The model closely reflects the characteristics of the terrain in the upstream and midstream areas, including large-scale sliding mass deposits from the landslide dam following 2009 Typhoon Morakot. These deposits gradually changed the elevation of the streambed as well as its flow path. The area of the downstream alluvial fan also increased after the landslide, and even led to the formation of a natural dam on Laonong stream. These simulation results are in good agreement with field investigations and landform interpretation.

6. Conclusions

This study integrated multi-temporal topographic and remote sensing images with discrete element method to examine the characteristics of large-scale erosion and landslides in the Putanpunas Stream area. The remote sensing images were satellite images from Formosat-2, which were merged with aerial photos and LiDAR data to assist in landslide interpretation and characterize topographical changes in the valley and alluvial fan. We then compared the results of onsite geological investigations and numerical simulations to examine landslide and deposition characteristics in the study area in order to clarify the evolution process of the valley terrain along the Putanpunas Stream. The results of landform interpretation indicate that the study area underwent few changes between 2005 and 2009. Only the alluvial fan downstream showed an increase in area and elevation. In 2009 and 2010, extreme torrential rainfall events induced landslides and changes in the valley terrain. Approximately $7.2 \times 10^7 \text{m}^3$ of colluvia was distributed in the midstream and upstream segments, and substantial debris deposits reduced the area of the Ryukyu Terraces downstream by roughly 23%, which greatly altered the path of the entire stream and the distribution of deposits. Between 2010 and 2012, further erosion and landslides in the colluvial layer deposited in the valley altered the path of the midstream and downstream segments, the terrain in the alluvial fan, and the direction in which the debris moved and created deposits downstream. A dammed lake even formed upstream of the intersection with the Laonong Stream, which affected the stability of the primary access road.

The results of numerical simulation indicate that most of the landslides in 2005 created deposits near bends in the stream constricting terrain in the midstream and upstream segments of the Putanpunas Stream (accounting for over 50% of the total deposit volume). Only 23%–40% of the deposits travelled to the alluvial fan downstream. In 2007 and 2008, materials previously deposited in the streambed downstream were pushed further downstream by newer avalanche (only 30% remaining in the streambed), which increased the depth of the deposits in the alluvial fan to levels approaching those of the Ryukyu Terraces and Shimizu Terraces. In 2009/09, large-scale landslides dramatically changed the terrain along the Putanpunas Stream. Roughly 65% of the colluvial materials were deposited in the constricting section of the valley upstream, and the remaining 35% were deposited in the midstream and downstream segments of the stream, further increasing the area and height of the alluvial fan downstream. In 2012, further large-scale landslides took place along the Putanpunas Stream, causing the Ryukyu Terraces downstream to be eroded and overflowed by debris that cut across the terraces to the downstream segment of the Laonong Stream to the south-west. The change of avalanche direction from south-east to south-west eventually posed a considerable threat to the safety of protected targets and the access road downstream.

Acknowledgments

The research was mainly supported by CECI Engineering Consultant, Inc. and the Ministry of Science and Technology of Taiwan, Grant no. MOST 104-2625-M-239-003 and 104-2625-M-390-001.
Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

CECI Engineering Consultant, Inc. and the Ministry of Science and Technology of Taiwan [grant numbers MOST 104-2625-M-239-003 and 104-2625-M-390-001].

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