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Landslide hazard zoning based on numerical simulation and hazard assessment

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ABSTRACT

This study conducted terrain analysis and remote sensing image interpretation to determine the distributions of historical and potential landslides in Shang-an Village and elucidate the characteristics of landslide development within the area. Using the discrete element method, we constructed a digital model of the study area in order to explore the landslide movement processes and determine the scope of influence with regard to deposition. The scope of influence was then used to perform hazard zoning in the creation of a landslide hazard map for use as a reference in future land planning and disaster prevention. Our results revealed 13 potential landslide masses in the study area, 92% of which are on unstable slopes with limited landslide activity. These areas should be the focus of future monitoring and remediation projects. Direct impact from falling rock is the main concern in the area roughly 50 m around the sliding masses in the source areas of the study region and approximately 30 m around the creek beds upstream. In contrast, being buried by debris flow is the concern in the lowland areas roughly 30 m from creek channels in the middle and lower reaches.

1. Introduction

Numerous extreme rainfall events have caused many large-scale landslide disasters in Taiwan. Developers in the past did not pay sufficient heed in areas susceptible to large-scale landslide, and residents knew little about the topographical features and movement hazard characteristics that appear before landslides. This leads to severe losses of life and property whenever torrential rainfalls or earthquakes take place. After several painful lessons, foreign and domestic disaster prevention agencies have given priority to the identification of landslide-sensitive areas as well as identifying landslide mechanisms and zoning hazardous areas.

Lateltin et al. (2005) and Jaboyedoff et al. (2005) used hazard zoning maps from Switzerland (Figure 1 and Table 1) to classify the scope of influence of various types of landslides and create hazard maps to guide the planning of slope construction. The hazard zoning maps established by Jaboyedoff et al. (2005) comprise return periods and kinetic energy with a focus on rockfalls, dividing the level of danger into high, medium, and low. The maps are based on the notion that when the return period of a landslide disaster is shorter (such as a landslide on a smaller scale), a lower amount of kinetic energy is sufficient to constitute a high hazard level. However, the application of numerical simulation is only able to assess motion paths and the range of deposition in a small
portion of the rockfall, lacking the means to model the complex kinetics associated with large-scale landslides.

Large-scale landslides involve the movement of substantial masses within a very brief span of time, which makes sliding and stopping distances difficult to estimate. The collisions and interactions among numerous masses during motion can lead to deposition over an area extending far from the source (Okura et al. 2000). Rugged terrain has significant influence on landslide type, either accelerating the motion of sliding masses or turning them into flows when they enter river channels. Moving speed is a crucial factor in large-scale landslides, largely determining their damage potential, with the ability to cause major disasters in just seconds (Hungr 2007). Nevertheless, few studies have mentioned the transitions and scope of influence in large-scale landslides during motion, much less the separation, collisions, and movement patterns of masses. Advances in computing and numerical simulation technology are now enabling researchers to use discrete element method for the simulation of landslide movement and deposition (KOC 2008; Tang et al. 2009; Lo et al. 2011–2015). This approach enables in-depth investigation of the complex movements of separate masses as well as the deformation, disintegration, and collision of sliding masses and the transfer and consumption of energy. These methods are a key breakthrough in the simulation of landslide movements and deposition. In this study, we established a digital model based on the Shang-an Village area of the Che-nyoulan stream based on our interpretation of landslide potential (Figure 2). We also referred to the Swiss hazard zoning maps to predict landslide motion process and the range of deposits and influence.

Table 1. Criteria for designating the intensity of various landslide hazards (Lateltin et al. 2005).

| Process                  | Intensity     |
|--------------------------|---------------|
|                          | Low | Medium | High |
| Rockfalls                |     |        |      |
| Kinetic energy           | <30 kJ | 30–300 kJ | >300 kJ |
| Slides                   |     |        |      |
| Mean annual velocity     | <2 cm/year | 2–10 cm/year | >0.1 m/day |
| Displacement             | –   | –       | >1 m/event |
| Debris flow              |     |        |      |
| Debris front thickness   | –   | <1 m   | >1 m |
| Debris front velocity    | –   | <1 m/s | >1 m/s |
| Depth of soil material   | 0.5 m | 0.5–2 m | >2 m |
The primary focuses of this paper are as follows:
(a) Investigating the processes involved in landslide motion and the range of deposits and influence in the study area using the discrete element method;
(b) Assessing potential hazard levels in the study area using numerical simulations and landslide hazard classifications.

2. Terrain and geology of study area

The Chenyoulan stream is one of the main tributaries of the Jhuoshuei River, running approximately 42 km and enclosing a catchment area of 449 km². The Chenyoulan stream follows a rift valley with the Xueshan Range to the east and the Alishan Range to the west, with the terrain of the catchment dipping from the southeast to the northwest.

The study area is located at the southern end of Shuili Township in Nantou County on the right bank of the Chenyoulan stream (Figure 2). Downstream is Shang-an Village, home to nearly a thousand residents and a busy hub in Shuili Township. There are three primary tributaries upriver of Shang-an Village: No.1-Pu-Keng creek, No.2-Pu-Keng creek, and No.3-Pu-Keng creek, all of which originate from the Jiji Mountain Range. Once they pass through Shang-an Village, they cross over Provincial Highway 21 before joining the main branch of the Chenyoulan stream. The elevation runs from roughly 960 m in the upper reaches to 410 m at the bottom with an average slope of 19%. The No.3-Pu-Keng creek is designated as the Nantou 071 potential debris flow torrent.

Outcrops in the study area comprise tertiary metamorphic rock (Figures 3 and 4), consisting mainly of argillite, slate, and metasandstone. In terms of the history of the study area, Typhoon Herb caused a debris flow on the No.3-Pu-Keng creek in 1996, which damaged several public facilities upstream and caused the deaths of several residents. The 1999 Chi-chi Earthquake did not inflict heavy casualties but loosened the already weak geological structures, which increased the number of...
Figure 3. Outcrops and results of historical landslides in the study area.

Figure 4. Geologic map of the study area (scale: 1/25,000).
slope collapses greatly. In 2001, Typhoon Toraji brought torrential rains that caused major detritus slides (Figure 3(i)). Three to four stories high, the detritus rushed down along the No.3-Pu-Keng creek (Figure 3(v,vi)), rapidly widening it from less than 10 m to almost 100 m. The flow damaged roads, bridges, and houses in Shang-an Village and resulted in 17 people dead or missing, 26 houses completely collapsed, 29 houses partially collapsed, and more than 80 households suffering financial losses.

The study used multi-remote sensing images with a heavy reliance on the interpretation of stereo-aerial photography supplemented by field checking to conduct the landslide classification in the study area (Figure 5), that shows 26 landslides, including 7 rockfall (about the total number of 27%; a mass of falling or fallen rocks under gravity condition to form talus), 14 debris slide (about the total number of 54%; when comparatively dry, a mass of predominantly noncontinuously soil and rock fragments that has slid or rolled rapidly down a steep slope under gravity condition to form an irregular hummocky deposit), 2 compound slide (about the total number of 8%; compound slide are those which are composed of several simple landslides; the compound slide belong to muti-storeyed landslides in the study area), and 3 debris flow (about the total number of 11%; debris flows are those which are composed of water-laden masses of soil, fragmented rock, and debris material rush down mountainsides, funnel into stream channels, entrain objects in their paths, and form thick, fan shape deposits on downstream). These types of movement represent the vast majority of the typical landslides recognized in the study area. Although the mechanism of the typical landslides is extremely complicated in the study area, however, the primary cause was the significant quantities of cleavage and joints in the slate and argillite slopes with fragile intact rock strength (Figure 3(ii)). Moreover, the terrain was steep, which created thicker layers of regolith or colluvium that were less stable and prone to forming shallow slides and debris flows in the event of heavy rains. In general, metasandstone is brittle; it easily ruptures under stress and is highly jointed. With the downcutting of the river and decompression, the metasandstone near the ground surface is abnormally fragmented, which facilitates rock falls or slope slides. In the more gently inclined interbedded metamorphic rock, there is a thick layer of the more corrosion-resistant metasandstone, which is less susceptible to weathering. However, some roughly vertical joints (ruptures) are present within the thick layer of sandstone. Water can infiltrate these joints and create a pushing force when it freezes in colder weather, and the pushing force then causes collapses. Another possible cause is the
headward erosion of the river. The less corrosion-resistant slate surrounding the metasandstone layer is gradually eroded and cannot support the rock above it, which then causes progressive collapsing along the edges (Figure 3(ii)) and forms the material for the next debris flow. The strata downstream of the study area mainly consist of argillite, which is shale with a mineral composition of soft clay minerals that previously underwent slight metamorphism. Fresh argillite comes in the shape of blocks and is moderately hard and dense. However, weathered fragments are pencil-shaped and fragile. In steep terrain, erosion such as heavy rain can easily cause collapses (Figure 3(iv)) and result in geological disasters.

In terms of geological structure, the main branch of the Chenyoulan stream is situated on a classic fault line valley. The area presents numerous folds, which give the nearby strata well-developed joints and steep terrain. As a result, the strata in the banks of the tributaries in the study area display significant weathering and fragmentation, which facilitates slope failure. The upriver slopes of the No.3-Pu-Keng creek, in particular, comprise mostly colluvium and deformed slate, which makes them extremely unstable. This explains why disastrous slides occur so frequently when torrential rains or earthquakes occur.

3. Methodology

3.1. Terrain analysis and interpretation of potential landslide

Identifying potential landslide areas requires historical terrain data, remote sensing images, field experience, and an acute interpretation of landslide characteristics. In recent years, countries including Japan, Australia, and Italy have shifted considerable attention to the identification of potential landslide areas (Cardinali et al. 2002; Leventhal and Kotze 2008; Lee et al. 2015). Understanding the spatial distribution of terrain changes caused by landslides requires topographic contour maps from different years and tables listing changes in the distribution of the water system. The morphology of ancient landslides can be discerned according to features in topographical contours. In this study, we scanned and digitized topographic maps for the period from 1924 to 2004 to observe changes in topographical contours in the study area and identify potential landslide areas. Soeters and Van Western (1996) used remote sensing to observe the characteristics of various types of landslides and proposed a set of criteria based on morphology, vegetation, and drainage for their interpretation (Table 2). We also employed remote sensing and digital elevation models to interpret potential landslide areas based on morphology, terrain, and geological characteristics. After conducting onsite inspections, we developed a digital model of potential landslides. Stability assessment in landslide-prone areas was achieved by applying historical data to the evolution of the landscape, and performing onsite inspections. Throughout the study, we referred to the slope stability classification method proposed by Crozer in 1984 (Table 3) when assessing the stability of potential sliding masses.

3.2. Principles of discrete elements

Particle Flow Code (PFC) is a discrete element analysis program developed by Itasca in 1999 using the explicit finite difference method for the calculation of changes in a system in each time step (Itasca 2002). For each time step, the position of particles and the amount of overlap are calculated before the contact force based on the force-displacement law. The new particle speeds and positions are then derived in accordance with Newton’s second law of motion. PFC uses the contact constitutive model of each contact point to simulate the basic mechanical behaviour of the materials and provide three types of contact constitutive models: a stiffness model, a slip model, and a bonding model. The slip model is adjusted according to a set friction coefficient, wherein slippage occurs when the slipping force between the contact surfaces of elements exceeds the frictional resistance. The bonding model includes parallel bonds between particle elements, which combine elements
into other shapes. When the force applied to the elements surpasses the bonding force, the bonds break.

This study employed PFC 3D to construct the digital models for landslide movement and deposition. This software program is able to simulate the bonds and separation of objects, failures along weak planes, and large displacements following collision and interactions. The primary input parameters of PFC 3D with regard to material strength include normal and shear stiffness as well as the stiffness and strength of bonds between elements. These values reflect the strength and

### Table 2. Visual characteristics of mass movement types (Van Western 1993).

| Type of movement | Characterization based on morphological, vegetational, and drainage aspects visible in stereoimages |
|------------------|-------------------------------------------------------------------------------------------------|
| Rockfall         | Morphology: The slope is mostly steeper than 45° where the bedrock is directly exposed. Distinct rock wall or free face in association with scree slopes (20°–30°) and dejection cones<br>Vegetation: Linear scars in vegetation along frequent rock-fall paths; vegetation density low on active scree slopes<br>Drainage: No specific characteristics |
| Translational slide | Morphology: Joint-controlled crown in rock slides; smooth planar slip surface; relatively shallow surface material over bedrock; D/L ratio <0.1 and large width; hummocky runout and rather chaotic relief with block size decreasing with increasing distance<br>Vegetation: Source area and transportational path denuded, often with lineations in the transportation direction; differential vegetation on body in rock slide; no land use on body<br>Drainage: Absence of bonding below crown; disordered or absent surface drainage on body; streams deflected or blocked by frontal lobe |
| Rotational slide | Morphology: Abrupt changes in slope morphology characterized by concave and convex forms; semilunar crown and lobate frontal part; back-tilting slope facets, scarp, and hummocky morphology on depositional part; D/L ratio of 0.3–0.1; slope of 20°–40°<br>Vegetation: Clear vegetation contrast with surroundings; absence of land use indicative of activity; differential vegetation according to drainage conditions<br>Drainage: Contrast with nonfailed slopes; bad surface drainage or ponding in niches or back-tilting areas; seepage in frontal part of runout lobe |
| Compound slide | Morphology: Concave and convex slope morphology; concavity often associated with linear grabenlink depression; no clear runout but gentle or bulging frontal part; back-tilting facets associated with (small) antithetic faults; D/L ratio of 0.3–0.1, relatively broad in size<br>Vegetation: Same as rotational slides, although slide mass will be less disturbed<br>Drainage: Imperfect or disturbed surface-drainage ponding in depressions and in the rear part of slide |

### Table 3. Classification slopes of stability (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 landslide features are fresh and well defined, while others may appear older |
| Ib | Suspended landslides; slopes with evidence of landslide activity within the past year; landslide features are fresh and 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 10–50 years |
| IIc | Dormant-mature landslides; slopes with evidence of previous landslide activity that have undergone the most recent movement within the past 50–100 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; landslide potential is indicated by analysis or comparison with other slopes |
deformation characteristics of rock slopes but are micro-parameters that can rarely be obtained directly from mechanical testing. Thus, we adopted the approach proposed by Potyondy and Cundall (2004) for the establishment of material parameters and used the results of uniaxial compression tests applied to onsite drilling samples for comparison. PFC was then used to simulate mechanical experiments to enable a preliminary conversion of macro- and micro-parameters. We then compared the results of the actual and simulated experiments and revised the conversion formula to derive micro-parameters of the materials used in the simulations. In the simulation of material collisions and energy dissipation, we referred to the rebound coefficient from the onsite tests performed by Giani et al. in 2004 to obtain damping parameters (Table 4) applicable to the onsite conditions.

### 3.3. Construction of the numerical model

The proposed digital model includes sliding masses, irregular terrain, and structures. Landslide depth is difficult to estimate accurately; therefore, we used terrain data from the latest map (5 m resolution DEM) 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 6). In this manner, we estimated the depth of potential landslides in the digital model.

![Figure 6](image)

**Figure 6.** Relationship between landslide area and depth in the study area.

|                  | Normal restitution coefficient | Converted normal damping ratio | Shear restitution coefficient | Converted shear damping ratio |
|------------------|-------------------------------|-------------------------------|-----------------------------|-------------------------------|
| Bedrock slope    | 0.50                          | 0.21                          | 0.95                        | 0.02                          |
| Bedrock slope covered with broken rock | 0.35                          | 0.32                          | 0.85                        | 0.05                          |
| Slope covered with rock debris and soil | 0.30                          | 0.36                          | 0.70                        | 0.11                          |
| Soil slope covered with lush vegetation | 0.25                          | 0.40                          | 0.55                        | 0.20                          |
The irregular terrain of the digital model was made up of 228,957 wall elements converted from the 5 m DEM (Figure 7), the total length and width of which were 5215 m and 2580 m. The sliding mass comprised 11,087 ball elements, which were placed in the landslide area after the wall elements of the pre-landslide terrain were constructed. Once the ball elements were stable, bonding strength was applied to the contacts between balls to form the solid rock masses that existed before the landslide. The simulation parameters are presented in Table 5. According to the results of the deposit survey, roughly more than 70% of the rocks deposited in the valley were between 0.3 and 4.2 m in size (Figure 3(v,vi), average = 1.7 m). Thus, we adopted 0.5–1 m as the particle radius of the landslide materials in the PFC 3D model. The model contained 11,087 particles in total to simulate the deposition behaviour of rock materials between 1 and 2 m. Limited by computational resources, we could not significantly increase the number of ball elements. Although 11,087 ball elements may not be able to completely simulate complex geological conditions and the behavioural characteristics of

Table 5. Numerical parameters used in PFC modelling.

| Numerical parameters of compression test | Numerical parameters of landslide |
|----------------------------------------|----------------------------------|
| Particle density (kg/m³) | 2400 | 2400 |
| Particle radius (m) | 0.0025–0.003 | 0.5–1.0 |
| Normal stiffness (kN/m) | 4.8e7–5.8e7 | 5e8 |
| Shear stiffness (kN/m) | 2.4e7–2.9e7 | 5e8 |
| Friction coefficient of balls | 0.6 | 0.05–0.6 |
| Friction coefficient of walls | 0.6 | 0.6 |
| Normal stiffness of parallel bonds (kN/m³) | 8e11–8.5e11 | 4e8–4.3e8 |
| Shear stiffness of parallel bonds (kN/m³) | 4e11–4.2e11 | 2e8–2.1e8 |
| Normal strength of parallel bonds (MPa) | 15–17 | 15–17 |
| Shear strength of parallel bonds (MPa) | 7–8 | 7–8 |

Note: the compression test modelling means uniaxial compression test for rock/soil sample; the landslide modelling means full-scale landslide modelling of study area.
different types of landslides (such as falling rock or sliding debris impacting fragmented or irregularly shaped rock masses), they were able to recreate the debris flow, with an alluvial fan shape and midstream and downstream debris movement distances and ranges similar to those measured in situ. The rocks in the deposit zone and the ball elements in the simulation and sliding mass were also similar in size, so we could reasonably simulate the range of the landslide disaster. Compared to continuous numerical simulation programs (such as FLAC 3D, ABAQUS, and Plaxis, which cannot simulate the separation of slope elements or any landslide behaviours including rolling, skipping, colliding, deposition, and scattering), PFC3D model can more accurately simulate the falling, colliding, shattering, sliding, and piling behaviours of landslide materials. However, as landslides and geological conditions are extremely complex, numerical simulations cannot accurately represent the complex geological condition, especially for different landslides in type or combination of soil and rock fragments. The improvement of numerical simulation technology depends on the enhancement of computing speed. Although the PFC3D program cannot be used to directly simulate more elaborate landslides at present, future advances in computer CPU and memory will help more elaborate landslides simulations and make the speculation of landslides impact more reasonable. Obviously, numerical simulations at this stage cannot be completely used as reference for landslides hazard area. Therefore, the current numerical simulation is only a preliminary study; the main landslide hazard zoning is based on the field investigation with interpretation assessment. In the future, when the computational efficiency of a computer is improved, the results of coupling numerical simulation (such as PFC3D and FLAC3D coupling model) at the present stage will be greatly enhanced as a reference for the landslide hazard zoning assessment.

According to the results of the landslide classification (Figure 5), in terms of the type of the landslide, approximately 27% of the landslide on midstream and upstream slopes over 45 degrees are rockfalls, and about 54% of the landslide on slopes under 45 degrees are debris slides. Thus, we set the local damping as 0 in the PFC 3D model to cancel out the damping effects on falling or rupturing rocks during free fall or high-speed skipping. Only the collisions between materials could dissipate energy. This increased the validity of the rockfall and high-speed sliding simulations. Furthermore, approximately 19% of the landslides in the study area are debris flow and compound slide. Nevertheless, we did not include water in the PFC 3D model, so the coefficient of friction in debris materials sliding into the valley was set at 0.1 (based on comparisons of sliding distances in multiple numerical simulations and actual conditions). The low friction between particles produced a liquidizing effect and made the movement behaviour and deposition distances of the simulations closer to those measured in situ. Furthermore, the field investigation of the deposition area revealed that due to the steep terrain in the source area of the study area (80% of the slopes were between 27° and 68°), most of the different types of landslide materials on the slopes slid into the valley and became the material source of the debris flows, following which they flowed midstream and downstream to form an alluvial fan. Only a small amount of the debris remained on the valley slopes and was not part of the debris flow that flowed downstream, such as the talus deposits on the gentler slopes in the valley and the debris remaining on the slope faces. These materials were too small in size and quantity and had little influence on the assessment of landslide hazard range. For this reason, we did not consider the movement and deposit behaviours of these small landslides in the PFC 3D model and only considered those of the larger landslides.

For structures in the model, we investigated the height, primary materials, and distribution of buildings in the area. We used ArcGIS to construct structure map layers and then converted them into 28,569 ball elements using PFC3D. The resulting 3D digital model integrates sliding masses, terrain, and structures (Figure 6). To date, few researchers have sought to model landslides using 3D simulation. Digital models can increase the reasonableness of landslide movement simulations and enhance the analysis of their impact on buildings (protection targets) within the range of potential landslides, thereby providing a valuable reference for disaster prevention and pre-disaster preparedness.
4. Results and discussion

4.1. Terrain analysis and interpretation of potential landslide

(a) The results in Figure 8 reveal seven hummocky surfaces in the study area in 1924, which may have been created by gravity-induced creeping or colluvial deposits. External forces, such as torrential rains or earthquakes, may have accelerated the failure of the hummocky surfaces. Twenty years later (1944), a new hummocky surface appeared on the right bank in the middle section of the No.3-Pu-Keng creek, and the original seven hummocky surfaces all showed signs of expanding toward the upper reaches. The terrain in 1985 shows a gradual collapse of the source in the area toward the east, with nine larger hummocky surfaces still visible in the middle and upper reaches of the No.3-Pu-Keng creek. By 1992, the number had increased to 12, with most of the new ones situated at the source of the No.2-Pu-Keng creek. No significant changes were observed in the number of hummocky surfaces or the area they covered in 1999. This means that the development of deformation is more apparent in slopes in the middle and upper reaches. Future torrential rain events or earthquakes could cause failure in the hummocky surfaces, which could in turn progress into large-scale landslides, thereby increasing the risk of debris flow impact on Shang-an Village downstream.

(b) Our interpretation of the remote sensing images covering the period between 2005 and 2013 (Figure 9) indicates that most of the landslides in 2005 occurred at the source of the No.2-Pu-Keng creek (six occurred here), whereas two landslides occurred at each of the
remaining tributaries. Between 2006 and 2008, most landslide development took place at the source of No.3-Pu-Keng creek. Between 2009 and 2012, no landslides were recorded in the study area, and slight vegetation restoration can be seen. Our interpretations for 2013 revealed a number of landslides at the source of the No.3-Pu-Keng creek, which produced substantial deposits in the creek bed. Only two landslides occurred at the source of the No.2-
Pu-Keng creek, thereby indicating the greater stability of this area. A comparison of the three tributaries revealed that landslides took place most frequently around the No.3-Pu-Keng creek, displaying significantly more erosion than the areas surrounding the No.1-Pu-Keng creek and No.2-Pu-Keng creek. Comprehensive terrain analysis revealed that the source of the No.3-Pu-Keng creek displayed the most hummocky surfaces (six in total) and the most expansive hummocky surfaces in the study area, followed by No.2-Pu-Keng creek with five hummocky surfaces. Clearly, landslides occurred most frequently in areas where slope deformation took place. When weak planes in the rock slope split opened and expanded due to gravitational deformation, they promoted deeper fracture development, thereby allowing surface water and groundwater to seep into the cracks. This greatly reduced the material strength of the hummocky surfaces, which lead to bulging and/or shear damage at the slope toe, thereby increasing the possibility of large-scale failures.

(c) Our landslide interpretations and the results of stability assessment (Figure 10) show 13 potential landslide areas in the study area, ranging from $8.7 \times 10^3$ m$^2$ to $1.5 \times 10^5$ m$^2$ in area. A comparison of the three creeks revealed that the source of the No.3-Pu-Keng creek contained most of the potential landslide areas (nine in total), followed by that of the No.2-Pu-Keng creek (four in total). This highlights the differences in failure characteristics and the development of stream erosion in the study area. Based on the slope stability classification system established by Crozer (1984), 12 of the potential landslide areas are on unstable slopes with low landslide activity (two I$_a$-type areas, six I$_b$-type areas, two I$_c$-type areas, and two II$_a$-type areas). Only one area was classified as a potentially unstable slope (III-type area), which means that it shows no significant evidence of landslide activity in the past but may gradually develop landslide conditions in the future. Subsequent estimations pertaining to the influence of potential landslides were focused on the 12 I-type and II-type areas with the potentially unstable slopes being disregarded.
4.2. Numerical simulations of landslide movement

4.2.1. Results of historical landslide simulations

The diameter of the ball elements used in the numerical model of historical landslides ranged from 0.5 to 1.0 m (coloured yellow in the images), whereas the diameter of the particle elements in the buildings were approximately 1.5 m (28,569 balls, coloured red). The sequencing of the numerical simulations was based on landslide incidents in various years. We also simulated the motion processes and deposits created by all of the landslide events occurring at the same time, to provide a reference with which to determine the scope of influence. Our results are as follows:

(a) Figure 11 illustrates the simulation of landslide events in 2005, in which the potential landslide mass of the No.2-Pu-Keng creek was first stimulated for the initial stage (0 step). The red balls represent buildings. When the sliding mass attains the lower reaches, it may collide with or bury the buildings, which is more in line with reality. At 50,000 steps (50 s), the sliding mass of the No.2-Pu-Keng creek had already entered the valley and become a debris flow. The front end of the sliding mass passed the middle section of the creek but had yet to collide with or bury any nearby buildings. During the stage from 100,000 steps to 150,000
steps (100–150 s), all of the sliding mass reached the middle reaches. Some of the debris flow accelerated at creek bends, and some of the buildings on the banks were struck.

(b) During the period from 300,000 steps to 400,000 steps (300–400 s), most of the debris flow reached the lower reaches of the No.2-Pu-Keng creek, displaying signs of overflow on the higher terraces. Two or three of the buildings near the creek bed on the higher terraces were affected by debris flow, which then gradually moved towards the Chenyoulan stream along the valley. At 550,000 steps (550 s), approximately 97% of the ball elements had ceased moving. The vast majority of the debris was deposited in the lower reaches of No.2-Pu-Keng creek. Four or five of the buildings on the terraces and near the tributary channels were directly hit but not buried by debris.

(c) Figure 12 presents the simulation results when we ran all of the landslides events that occurred between 2005 and 2013 at the same time, thereby providing a situation in which the influence of landslide disasters would be at its worst. At 10,000 steps (10 s), the sliding masses had already advanced toward the valleys. During the period from 20,000 steps to 32,000 steps (20–32 s), most of the sliding masses collapsed from the steep slopes at the sources, resulting in the formation of rockfalls, which swiftly slid into the valleys. Before 60,000 steps (60 s), the sliding masses had reached in the valleys in the upper reaches and decelerated into flows. At this point, the buildings in the lower reaches had yet to be affected.
(d) During the period from 60,000 steps to 128,500 steps (60–128.5 s), some of the debris flow struck the buildings in the upper reaches of the No.3-Pu-Keng creek; three buildings on the left bank were damaged. A small portion of the debris flow in the middle reaches of the No.2-Pu-Keng creek heaped up at the creek bends and surrounded the buildings there. At 321,420 steps (321.4 s), roughly over 85% of the debris had reached the middle section of the creeks, where 17 buildings were destroyed or buried. The conditions were most severe in the middle reaches of the No.3-Pu-Keng creek.

(e) At 884,217 steps (884.2 s), approximately 32% of the debris had reached the village downstream, with the remainder halting in the middle reaches. We counted 42 buildings in this area that were struck and nine were essentially buried. Designated shelters, such as Jiyun Keng Elementary School and the local police station, were unaffected. These findings help to confirm the safety and reliability of these structures.

4.2.2. Results of potential landslide simulation:
In the potential landslide simulations, the relationship between landslide area and depth was used to construct a digital model. We observed the speed at which the ball elements moved as well as the passage of time to explain the overall landslide motion process. Our simulation results are as follows:

(a) Figure 13 shows that between 0 and 30 s (30,000 steps), unstable masses in the source area began sliding towards the creeks (average speed = 43.2 km/h, average kinetic energy = 224.6 kJ). Between 30 and 50 s (30,000–50,000 steps), colluvium with a thickness of 10–20 m formed in the valleys in the upper reaches, most of which began advancing toward the lower reaches along the two tributaries.

(b) Between 50 and 150 s (50,000–150,000 steps), all of the unstable masses had reached the valleys in the upper reaches of the study area. The significantly gentler slopes in the valley (roughly 12°–15°) caused the sliding masses to slow down, disintegrate, and pile up in the valleys (average speed = 16.2 km/h, average kinetic energy = 84.2 kJ). The reduction in speed and kinetic energy was particularly apparent between 150 and 350 s (150,000–350,000 steps) (average speed = 10.6 km/h, average kinetic energy = 55.1 kJ), inducing the movement of the sliding masses to change from a landslide to a debris flow.

(c) At 500 s (500,000 steps), the debris flow on the No.3-Pu-Keng creek had passed the undercut slope downstream of Sanan Bridge No. 1, and between 550 and 700 s (550,000–700,000 steps). After rounding the bend, it accelerated to Shang-an Village (average speed increased to 11.6 km/h, average kinetic energy approximately 60.3 kJ), striking roughly ten buildings on the right bank of the bend and further along the creek downstream. Furthermore, at 700 s (700,000 steps), the front end of the debris flow had passed Shangan Bridge and passed over the terraces, flowing directly into the lowlands and the channel of Chenyoulan stream.

(d) Between 700 and 1100 s (700,000–1,100,000 steps), the debris flow completely cut off Provincial Highway 21. The height of the moving debris flow in the simulation was approximately 19 m, and its speed was at least 10 km/h. This is sufficient to seriously damage ground surface structures (such as Jiyun Keng Bridge and Shangan Bridge) as well as the slopes bordering the terraces.

(e) Between 1100 s and 1700 s (1,100,000–1,700,000 steps), most of the sliding masses temporarily stabilized. Roughly 68% of the sliding material was deposited on the lowlands on the right bank of the Chenyoulan stream, covering an area of approximately $6.08 \times 105$ m$^2$. However, approximately 15% of the sliding material had cut off the No.2-Pu-Keng creek in the lower reaches, which increased the elevation of the creel channel by 12–15 m. This could result in the creation of a barrier lake that could greatly threaten the safety of protection targets downstream.
4.3. Scope of influence and hazard zoning

Based on previous disaster experience, we revised the hazard zoning maps of Switzerland to fit the study area (Table 6) with regard to terrain and landslide-generating conditions. We then used PFC3D simulation results and the number of landslides that had occurred in the study area as a
basis with which to create a landslide hazard map, the process and results of which are detailed in the following:

(a) **Intensity of landslide types.** The intensity of landslides was determined by the terrain and the movement characteristics of the sliding masses in the simulations. Sliding masses on slopes steeper than 55° that initially displayed free falls, up-and-down movement, or rolling were classified as rockfalls. Once these conditions were met, the intensity in the area was then determined using kinetic energy. When the sliding masses reached the valleys and formed debris flows, the intensity in the area was determined using the movement speed and thickness of deposits in the simulation.

(b) **Monitoring and analysis of movement processes during landslide simulation.** The movement speeds of each ball in the x, y, and z directions were monitored and converted into the speed and kinetic energy for the estimation of intensity. The depth of deposits in the study area was based on actual onsite circumstances (historical Lidar or high-precision DEM data analysis) as well as simulation results.

(c) **Probability analysis.** We divided the study area into a source area, a movement area, and deposition area in order to assess the number of landslides and their characteristics. In the source area, we referred to hummocky surfaces in the past as well as the distribution of actual landslide events. Slopes that presented potential landslide characteristics but were not within the drawing range and did not display signs of slope failure were designated as very low slide probability. Slopes that presented potential landslide characteristics but had not been the site of any landslides within the last 50 years or showed evidence of expanding hummocky surfaces were designated as low slide probability. Slopes that presented potential landslide characteristics and had been the site of one landslide in the past and displayed expanding hummocky surfaces were designated as medium slide probability. Slopes that presented potential landslide characteristics and had been the site of more than one landslide in the past and displayed rapidly expanding hummocky surfaces were designated as high slide probability. The movement areas and deposition areas were evaluated based on the actual number of debris flows and their distribution as well as in the simulations. Areas in which landslides occurred in the simulation but showed no actual evidence of debris flow were designated as very low probability. Areas in which one landslide had deposited debris in the last 50 years and also presented deposits consistent with those in the simulation were designated as low probability. Areas in which more than one landslide had deposited debris in the last decade and presented deposits consistent with those in the simulation were designated as medium probability. Areas in which landslides had frequently deposited debris in the last five to ten years and presented deposits consistent with those in the simulation were designated as high slide probability. In Taiwan, the probability of landslide depths exceeding 10 m is extremely low. We therefore classified cases in which the depth of the landslide

| Process          | Very low | Low       | Medium     | High     |
|------------------|----------|-----------|------------|----------|
| Rockfalls        |          |           |            |          |
| Kinetic energy   | < 3 kJ   | 3–30 kJ   | 30–300 kJ  | > 300 kJ |
| Slides           |          |           |            |          |
| Mean annual velocity | –       | <2 cm/year| 2–10 cm/year| >0.1 m/day|
| Displacement     | –        | –         | –          | >1 m/event|
| Debris flow      |          |           |            |          |
| Debris front thickness | –      | –         | <2 m       | >2 m     |
| Debris front velocity | –     | –         | <5 m/s     | >5 m/s   |
| Depth of soil material (potential debris flow) | 0.5 m | 1 m | 1–2 m | >2 m |

**Table 6. Criteria for the modification of intensity values associated with landslide hazards in the study area.**
exceeded 10 m as low probability as long as no large-scale landslide had occurred in the last 50 years. Simulation cases with landslide depths between 5 and 10 m and landslides events in the last 10 years were classified as medium probability. Simulation cases with landslide depths of less than 5 m and repeated occurrences of landslides in the last 5 years were classified as high probability. Accordingly, we drew the scope of influence of potential landslides and the hazard distributions (Figure 14).

(d) Figure 15 presents a comparison of actual and simulated debris flow distributions in the study area for the period from 2001 to 2014. This analysis revealed that the scope of influence in nearly all areas surpassed the range of the actual debris flows. The locations of buildings that had been damaged by debris flows in the actually landslide were consistent with those in the simulations, thereby demonstrating that the preliminary simulation results are conservative and reasonable. Based on the hazard map developed in this study area, we would advise prohibiting development and recreational activities in high hazard areas. Protection targets are at risk whether they are in buildings or outdoors, and buildings may be severely damaged. Evacuation routes and shelters should be moved to avoid these areas. Medium hazard areas should be considered for remediation and monitoring. Protection targets are at extreme risk, such that buildings may suffer minor or moderate damage. If evacuation routes and shelters must be established in these areas, the type of structure and upstream remediation projects should be taken into account. Disaster prevention and evacuation awareness should be concentrated in low hazard areas. Protection targets face low degrees of harm outdoors. If evacuation routes and shelters must be established in these areas, the structure type and internal shelter setup should be taken into consideration. In the event of landslide alerts, very low hazard areas should be evacuated, and protection targets should avoid these areas.
5. Conclusion

This study conducted terrain analysis, remote sensing interpretation, and numerical model construction to enable the simulation of landslide movement and deposit ranges in Shang-an Village. We revised the hazard zoning maps of Switzerland according to the particulars of the study area. Our aim was to create a landslide hazard map for use as a reference in future land planning and disaster prevention. Our results show that hummocky surfaces existed in the upper reaches of the study area as far back as 1924. The hummocky surfaces have since showed signs of advancing towards the source areas. Images from the last decade, in particular, show landslide development on the edges of the hummocky surfaces. Most of the landslides that occurred in 2005 were located near the source of the No.2-Pu-Keng creek. Between 2006 and 2008, most of the landslide development took place at the source of the No.3-Pu-Keng creek. Landslides occurred most frequently near No.3-Pu-Keng creek, which presents sign of more pronounced erosion and landslide development than do the other tributaries. The study area contains 13 potential landslide masses, ranging from $8.7 \times 10^3$ m$^2$ to $1.5 \times 10^5$ m$^2$ in area. Twelve of the potential landslide areas are on unstable slopes with low landslide activity and should therefore be the focus of future monitoring and remediation projects.

Our results pertaining to the scope and influence of the landslides (hazard zoning) indicate that areas roughly 50 m around the sliding masses in source areas and approximately 30 m around upstream creek beds are at risk of large-scale rockfalls and/or slope failure disasters. Residents should be cautious of falling rock as most of these areas pose medium to high hazards. Upon reaching creek beds in the middle and lower reaches in the study area, the sliding masses become debris flows; therefore, residents in the lowlands should be wary of the danger of being buried by debris flows, which can cover an area extending 30 m from the creek channels. Shang-an Village is situated in the debris flow deposition zone; therefore, it is very prone to being buried by slower debris flows. Buildings near the lowlands on the right bank of the Chenyoulan stream (in the medium- or high-hazard zones) are subject to the influence of debris flow deposits.
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