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Assessment of regional rainfall-induced landslides using 3S-based hydro-geological model

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ABSTRACT: An effective assessment of regional rainfall-induced landslides using 3S-based hydro-geological model was presented to investigate the most common shallow landslide in the Ta-Chia river watershed of central Taiwan. Several typhoon events have indicated that most shallow landslides in the study area occurred as a result of heavy rainfall. To consider the regional rainfall-induced shallow landslides, this study adopted a deterministic approach, the Transient Rainfall Infiltration and Grid-based Slope-stability (TRIGRS) model that couples an infinite-slope stability analysis with a one-dimensional analytical solution for rainfall infiltration. We examine rainfall-induced development of shallow landslides in Ta-Chia river watershed through the following steps. First, the physical, mechanical, geological and hydraulic properties were established using the GIS, GPS, and Remote Sensing framework (3S). Next, the distribution of rainfall intensity were analyzed by performing the Kriging interpolation method. Then, the response of transient pore-water pressure during a rainfall event was analyzed by TRIGRS. Finally, the applicability of model for characterizing shallow landslide susceptibility was addressed. The results demonstrated that good agreement was found between predicted shallow landslide susceptibility and the inventory.

1 INTRODUCTION

Taiwan is located in an active mountain belt created by the oblique collision between the northern Luzon arc and the Asian continental margin in which two-thirds of this island is occupied by mountainous areas. The landslides are common natural hazards in this island for a long history. The landslide hazards were insignificant until the Chi-Chi earthquake hit the central Taiwan on September 21, 1999. This earthquake triggered numerous landslides and severely disturbed montane slopes which reduced the shear strength of the slopes, thus setting the conditions for occurrence of more landslides as well as debris flows. Accordingly, frequently landslides were occurred and caused severe property damage and inflicted heavy casualties in the following years especially during several typhoon events with intense rainfall, such as Toraji in 2001, Mindulle in 2004, Airi in 2004, and Hytarng in 2005. This stimulated the interests in studying the rainfall-induced landslide at Ta-Chia river watershed in central Taiwan.

Shallow landsliding is the most common landslide type on steep natural hillslopes in the Ta-Chia river watershed. The location of the Ta-Chia river watershed is shown in Figure 1, where the landslide area indicate the landslides occurred between the 921 Chi-Chi earthquake and the Mindulle typhoon.

In this study area, it is found that shallow landslides are often triggered by rainfall as shown in Figure 2. The huge amount of debris sediment from landslides may easily mobilize into destructive debris

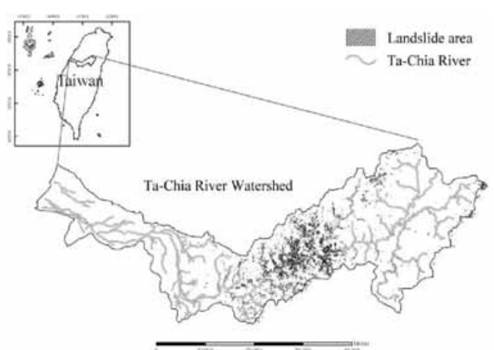

Figure 1. Location of the Ta-Chia river watershed in Taiwan.

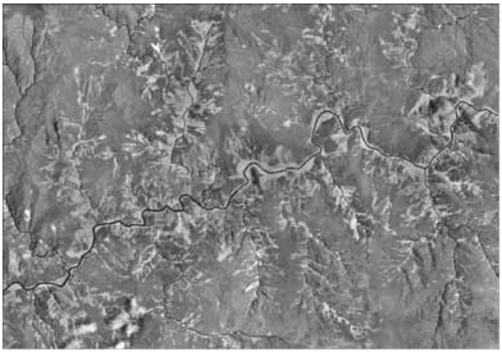

Figure 2. Numerous landslides and debris flows in the study area after the Toraji typhoon (2001).

Figure 3. (a) Destructive debris flow occurred. (b) Hydropower facilities damaged by debris flow during the Mindulle typhoon.

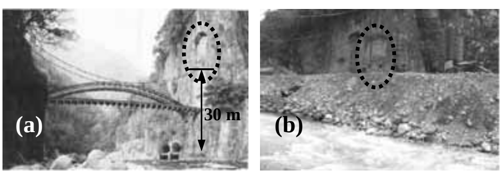

Figure 4. Dramatic alteration of Ta-Chia riverbed (a) before the Chi-Chi earthquake (b) after the Mindulle typhoon.

flows as shown in Figures 3 and 4. The rainfall-induced landslides may be caused by the infiltration of rainfall which leads to increases in pore water pressures in the near subsurface that reduces the shear strength of the colluvial mass. A variety of approaches have been used to estimate the hazard from shallow, rainfall-triggered landslides, such as empirical rainfall threshold methods or probabilistic methods based on historical records. The multivariate statistical analysis and artificial neural network analysis are also often used to evaluate the landslide susceptibility in regional scale. In most cases of studying regional landslide susceptibility, the Geographic Information Systems (GIS) is common adopted for slope stability.

TRIGRS model can be used to investigate both the timing and location of shallow landslides in response to rainfall over broad regions. In this paper, we examine rainfall-induced development of shallow landslides in Ta-Chia river watershed of central Taiwan through the following steps. First, the data of physical, mechanical, geological and hydraulic properties of the study area were established using the GIS, GPS, and Remote Sensing framework (3S). Next, the distribution of rainfall intensity were analyzed by the Kriging spatial interpolation method. Then, the response of transient pore-water pressure during a rainfall event was analyzed using TRIGRS model. Finally, the applicability of TRIGRS for characterizing shallow landslide susceptibility in the study area was addressed.

Several typhoon events have indicated that most shallow landslides in the study area occurred as a result of heavy rainfall and consequent pore pressure increases in the near subsurface. To consider the rainfall-induced initiation of shallow landslides over a broad region, this study adopted a deterministic approach, the Transient Rainfall Infiltration and Grid-based Slope-stability (TRIGRS) model that couples an infinite-slope stability analysis with a one-dimensional analytical solution for transient pore pressure response to rainfall infiltration (Iverson 2000, Baum et al. 2002, Savage et al. 2003, 2004, Godt 2004, Chen et al. 2005).

2 STUDY AREA

The Ta-Chia River watershed with a watershed area of 1,236 km^2 is located in central western Taiwan. The elevation of highest mountain in the watershed is around 3,875 m. The river stretch extends 124 km from upstream to the sea. This river valley is notable because it incorporates the Central Cross Island road that links the east and west coasts of Taiwan across the Central Mountains. This very important infrastructure was constructed in the early 1960s, and was followed by a series of significant hydroelectric schemes that extend along the length of the river, consisting of one high, concrete arch dam at Techi, and a series of dams and hydropower stations.

2.1 *Geological setting*

The study area consists of a steeply incised valley orientated approximately east-west in the eastern part of the Central Range. The geology consists of a series of interbedded Tertiary sandstones and slates, with occasional limestone bands. The geologic strata of Ta-Chia river are argillite, slate, quartzite, sandstone, siltstone and shale including Lushan Formation, Tatungshan Formation, Kankou Formation, Chiayang Formation, Szeleng Sandstone, Tachien Sandstone, Kuohsing Formation, Guandaoshan Formation, Jinshuei Formation and Jhuolan Formation. The rock mass is extensively tectonically disrupted, with a high density of fractures and joints. The slope inclination in the watershed is range from 40 to 80 degrees.

2.2 *Climatic setting*

The rainfall of Ta-Chia river watershed is abundant. There are more than 20 rainfall gauging stations installed in this area, but few of them were located at the upstream mountainous area. With the difference in location, the range of annual average rainfall is 3000–3500 mm in the upstream area, 2000–2500 mm in the midstream area, and 1500–2000 mm in the downstream, respectively. The long-term statistical data show that the main rainfall usually concentrates between May and September which was accounted for 75 percent of annual accumulated rainfall. Furthermore, the typhoons hit Taiwan frequently during summer season (June-August) when the daily accumulated rainfall could exceed more than 500 mm.

3 THEORETICAL BASIS OF TRIGRS MODEL

This paper uses the Transient Rainfall Infiltration and Grid-based Regional Slope-Stability (TRIGRS) model (Baum, 2002) to estimate the regional watershed landslide susceptibility. The TRIGRS model is based on the Iverson's research results (Iverson, 2000) to assess the time-varying slope safety of each slope unit with transient pore-water pressure during a rainfall event. First, We divide the watershed area into discrete grids. The initial water table, hydrogeological properties (e.g. infiltration rate, hydraulic conductivity and hydraulic diffusivity and mechanical parameters) and rainfall intensities for each grid were assigned by values according to its characteristics in space and time. Next, the transient pore-water pressure can be obtained by solving the unsaturated flow equation (i.e. Richards' equation). Then, the limit equilibrium method is used to estimate the safety of slope with the transient pore-water pressure and the hydro-geological properties.

In the TRIGRS model, the calculation of the transient pore-water pressure distributed with a finite depth for the case of an impermeable boundary could be described as following formula:

$$\begin{aligned}
\varphi(Z,t) &= [Z - d_z]\beta \\
&\quad + 2\sum_{n=1}^{n} \frac{I_{nZ}}{K_Z} H(t - t_n)[D_1(t - t_n)]^{\frac{1}{2}} \\
&\quad \times \sum_{m=1}^{\infty} \left\{ ierfc\left[\frac{(2m-1)d_{LZ} - (d_{LZ} - Z)}{2[D_1(t - t_n)]^{\frac{1}{2}}}\right] \right. \\
&\quad \left. + ierfc\left[\frac{(2m-1)d_{LZ} + (d_{LZ} - Z)}{2[D_1(t - t_n)]^{\frac{1}{2}}}\right] \right\} \\
&\quad - 2\sum_{n=1}^{n} \frac{I_{nZ}}{K_Z} H(t - t_{n+1})[D_1(t - t_{n+1})]^{\frac{1}{2}} \\
&\quad \times \sum_{m=1}^{\infty} \left\{ ierfc\left[\frac{(2m-1)d_{LZ} - (d_{LZ} - Z)}{2[D_1(t - t_n)]^{\frac{1}{2}}}\right] \right. \\
&\quad \left. + ierfc\left[\frac{(2m-1)d_{LZ} + (d_{LZ} - Z)}{2[D_1(t - t_n)]^{\frac{1}{2}}}\right] \right\}
\end{aligned} \tag{1}$$

where φ is the groundwater pressure head, t is the elapsed time, $Z = z/\cos\alpha$ is the vertical coordinate direction, z is the slope-normal coordinate direction, and α is the slope angle; d_Z is the steady-state depth of the water table measured in the Z direction, $\beta = \lambda\cos\alpha$, $\lambda = \cos\alpha - (I_Z/K_Z)_{LT}$, K_Z is the hydraulic conductivity in the Z direction, I_Z is the steady surface flux, and I_{nZ} is the surface flux of a given intensity for the nth time interval and d_{LZ} is the soil layer depth measured in the Z direction. $D_1 = D_0\cos^2\alpha$, where D_0 is the saturated hydraulic diffusivity, N is the total number of time intervals, and $H(t{-}t_n)$ is the Heavyside step function. The function *ierfc* (η) is the complementary error function.

The TRIGRS model imposes the physical limitation that pore-water pressure cannot exceed that which would result from having the water table at the ground surface during rainfall events, that is:

$$\varphi(Z,t) \leq Z\beta \tag{2}$$

The infinite slope analysis is based on the limit equilibrium method, in which slope angles, unit weights of soil and water, shear strength parameters, and transient pore-water pressures are combined to estimate the safety of each grid as following equation:

$$F_s = \frac{\tan\phi}{\tan\alpha} + \frac{c - \varphi(Z,t)\gamma_w\tan\phi}{\gamma_s Z\sin\alpha\cos\alpha} \tag{3}$$

where c and ϕ are cohesion and friction angle of weathered soil, γ_s and γ_w are unit weights of soil and water respectively. φ (Z, t) is the pore-water pressure calculated by equation 1 and limited by equation 2.

4 APPLICATION OF 3S TECHNIQUES

Before we apply the TRIGRS model to analyze the regional rainfall-induced landslide susceptibility for the study area, the mechanical and hydro-geological parameters and their distribution in space and time must be established in advance. In order to apply the TRIGRS model for modeling the regional scale problem, the currently wide-implemented Geographic Information System (GIS) was considered for the preparation of the data input as well as the result displaying. A GIS could combine graphical features with tabular property data and could perform extensive spatial and statistical analyses. The results of analyses could also be displayed directly and visually. So we selected the ArcGIS, which was developed by ESRI, as a work platform for digitizing, storing, interpolating, overlaying and displaying our input data for the TRIGRS model.

First, we use the Global Positioning System (GPS) to link the results of geological surveys, field tests, and topography surveys together by the three dimensional coordinates. Next, ArcGIS is used to establish specific layers involved geographical information (i.e., surface elevations, slope gradients and aspects), geological information (i.e., geological zones, formations and structures), hydrological information (i.e., spatial distribution of groundwater elevation and rainfall intensity) and geotechnical information (i.e., physical, mechanical and hydraulic properties). Then, we use the Kriging method for spatial analysis in ArcGIS to interpolate the above-mentioned information and export the results with the ASCII format to TRIGRS. Finally, the high-resolution RS imageries including the satellite images and aerial photos are adopted to verify the model results by comparing the predicted landslide locations and the inventory from RS imageries. The input-parameter layers created by ArcGIS are introduced as follows.

4.1 *Slope angle*

The terrain of Ta-Chia river watershed is very steep and its elevation drops rapidly within a short distance. According to the digital terrain model (DTM) with 40 m $\times$ 40 m scale, the range of the slope angle is from 28 to 45 degrees, and the maximum slope is over 75 degree (see Figure 5).

4.2 *Physical, mechanical and hydrologic properties*

The geological units in the Ta-Chia river watershed include Lushan Formation, Tatungshan Formation, Kankou Formation, Chiayang Formation, Szeleng Sandstone, Tachien Sandstone. Figure 6 is

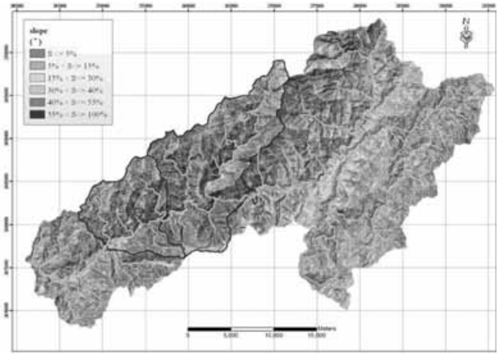

Figure 5. Slope angles in the study area.

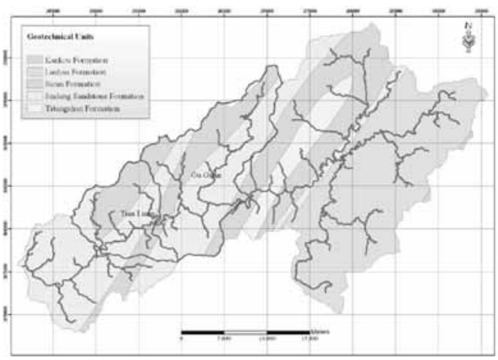

Figure 6. Spatial distribution of geological formations along the midstream of Ta-Chia river.

the 1:250,000 scale geological map of the study area that shows the plane distribution of above formations.

The adopted physical, mechanical and hydraulic properties for each zone are summed up in Table 1. We assume the physical properties of weathered layers is strongly related to properties of their fresh intact rock. Based on the assumption, the initial values of parameters are assigned to each geological zone.

4.3 *Soil depth*

Although the weathered soil thickness is related to many effect factors including the vegetation cover, the underlying lithology, the climate, the angle and curvature of slope, the land use and so on, it is more convenient to simply assume that the soil thickness decreases with the increasing slope angle for the engineering objectives. We assume that there is a function relationship between the soil thickness and the slope angle. Figure 7(a) shows the correlation between soil depth and slope angle from our field surveys and

Table 1. Physical, mechanical and hydraulic parameters of the geological units in the study area.

Formation	c (KPa)	ϕ (°)	γ_t (KN/m^3)	K_s (10^{-6} m/s)	D_0 (10^{-4} m^2/s)	I_z (10^{-8} m/s)
Kankou	16–21	26	22	5	10	1
Lushan	18–23	29	22	10	20	10
Sicun	16–22	30	21	7	14	5
Szeleng	13–19	28	21	100	200	50
Tatungshan	19–24	28	21	10	20	10

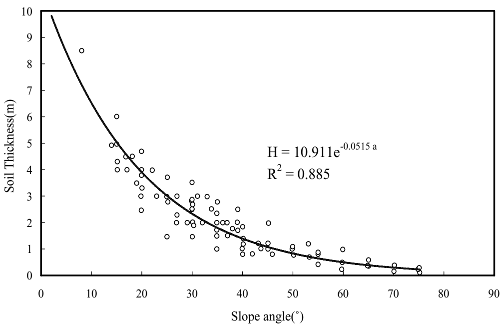

Figure 7(a). Relationship between weathered soil thickness and slope angle.

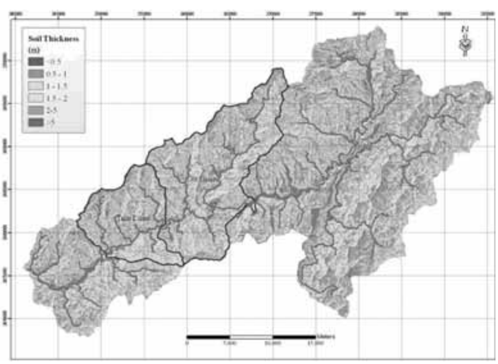

Figure 7(b). Weathered soil thickness in the study area.

the other researches related to this issue (Delmonaco et al., 2003; Salciarini et al., 2006). The correlation is used to determine the distribution of soil thickness in the study area (Figure 7(b)).

4.4 *Initial groundwater table*

There has been few exploitation and development in the mountainous areas of Taiwan. Therefore, the available data related to field surveys and tests in the mountainous areas are rare. This study collects the observed data of groundwater table from other engineering cases in the southern mountain areas of Taiwan and proposes the correlation between groundwater level (h_w) and surface elevation (h) as follows:

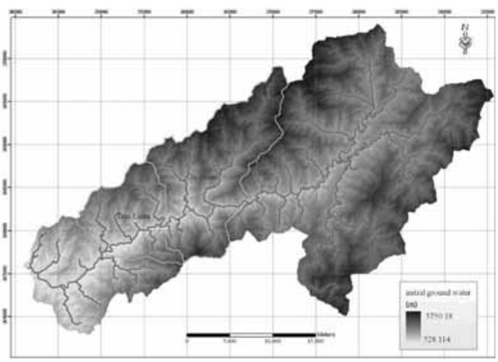

Figure 8. Spatial distribution of initial groundwater table in the midstream of Ta-Chia river.

$$h_w = 0.9672h - 4.781 \tag{4}$$

The spatial distribution of initial (steady-state) groundwater table in the study area from equation 4 is as shown in Figure 8.

4.5 *Rainfall intensity*

The rainfall intensity data during the Toraji typhoon (July 2001) are used to investigate the effects of rainfall-infiltration on the slope susceptibility in the Ta-Chia river watershed. There are more than 20 rainfall stations in the watershed. The difference of the rainfall intensity and duration recorded at above stations obviously depends on the location of typhoon center at that time. The spatial distribution of rainfall intensity in the watershed also varies with time. Figure 9 shows the distribution of rainfall intensity at the moment of the peak rainfall intensity during the Toraji typhoon. Therefore, the difference in spatial and

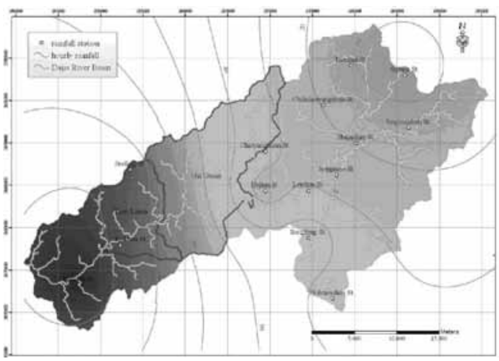

Figure 9. The spatial distribution of rainfall intensity at the moment of the peak rainfall intensity during the Toraji typhoon.

time distribution must be considered in the analysis of regional rainfall-induced landslide susceptibility.

5 ASSESSMENT OF LANDSLIDE SUSCEPTIBILITY

The results of landslide susceptibility estimated by the TRIGRS model are illustrated in Figure 10. Figure 10(a) represents the modeling results for the case of the steady-state groundwater table and shows that the safety factor of all slope units in the study area were almost greater than 1.0 before the Toraji typhoon. Figure 10(b)−(f) display the spatial distributions of landslide susceptibility at the 1st, 2nd, 3rd, 6th and 12th hour respectively. The results show that the landslide area spreads with the increase of rainfall intensity and the landslide locations develop following with the typhoon route.

Figure 11 represents the safety factor of two slope units near the Shangkukuan rainfall station varying with time during the typhoon event. One is gradually to slide (FS $<$ 1.0) and the other is safe (FS $>$ 1.0), which were analyzed by TRIGRS model based on the recorded rainfall data of Shangkukuan station. The results also show that the failure slope unit begins to slide at the 10th hour, and the safety factor of the stable one is decreasing with time and reach the minimum value at the 14th hour (i.e., still greater than 1.0). The safety factor has no variation after 14 hours because the transient groundwater table has been raised to the ground surface.

The multi-temporal RS imageries before and after the typhoon Toraji were used for landslide interpretation. The newly landslide area caused by the Toraji typhoon is 10,463,400 m^2. The predicted landslide area by the TRIGRS model is 8,789,830 m^2, which are less than the landslide area interpreted from RS imageries. The difference is mainly due to the underestimation of initial groundwater table or the overestimation of shear strength of weathered soil layer. Farther analyses may be needed to find the proper input values through the calibration process using more rainfall-triggered landslide events.

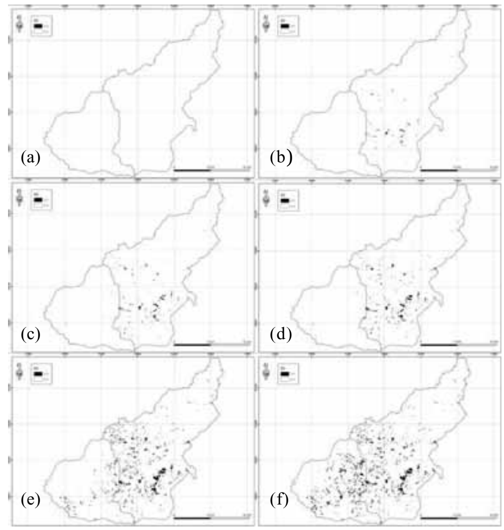

Figure 10. Spatial distribution of landslide in the study area during the Toraji typhoon. (a) before the typhoon, (b) at the 1st hour, (c) at the 2nd hour, (d) at the 3rd hour, (e) at the 6th hour and (f) at the 12th hour.

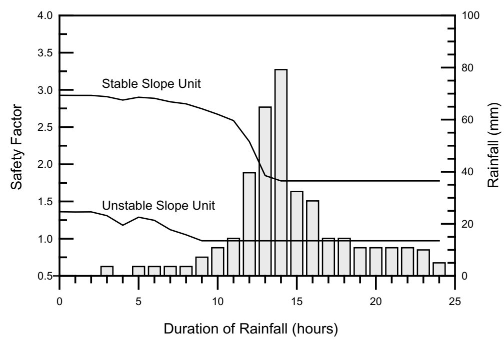

Figure 11. Respective history of safety factor for the stable unit and the unstable one with the rainfall during typhoon Toraji.

6 CONCLUSIONS

An effective assessment of regional rainfall-induced landslides using 3S-based hydro-geological model was proposed to investigate the most common shallow landslide in Ta-Chia river watershed of central Taiwan. This study depicts that the TRIGRS model is generally useful for the assessments of slope stability over regional scale. Although TRIGRS can accommodate spatially varying soil strength and hydraulic properties, it is often a paucity of the physical properties or the input data may vary significantly over a typical study area. Since detailed investigation of the physical properties for a regional scale problem is usually impractical, reasonable assumptions are necessary to made regarding input values. In our case, parameter calibration plays a crucial role for the accuracy of the predicted results. The use of remote sensing data such as multi-temporal satellite imaginary or aerial photographs can provide a useful solution for estimating the input data through the calibration process. Nevertheless, our preliminary results using estimated parameters appear to be useful for shallow landslide hazard assessments in the study area.

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