3rd Taiwan-Japan Joint Workshop on Geotechnical Natural Hazards
2008, Keelung, Taiwan

A Study on Earthquake and Typhoon Induced Geohazards in Da-Chia River Watershed

Cheng-Yu Ku [a], Chih-Hao Tan [b], Shih-Meng Hsu [b], Shu-Yeong Chi [b], Li-Yuan Fei [c], Jiin-Fa Lee [c], Tai-Wei Su [c]
[a] Department of Harbor and River Engineering, National Taiwan Ocean University
[b] Geotechnical Engineering Research Center, Sinotech Engineering Consultants, Inc.
[c] Central Geological Survey, MOEA, Taipei, Taiwan

Abstract. In this paper, we present a detailed study on the earthquake and typhoon induced geohazards in Da-Chia river watershed. To explore the coupling between the Chi-Chi earthquake and sequential regional debris flow hazards in the Da-Chia river watershed, analyses of rainfall characteristics, rainfall-induced landslides, and debris flow formation from rainfall-induced landslides were conducted. Our findings indicate that the regional geohazards in the Da-Chia river watershed were mainly caused by the huge amount of sparsely deposited materials from landslides triggered by the Chi-Chi earthquake. Rapidly increasing water pressure caused by typhoon events with specific rainfall intensity provided a powerful force that moved the sparsely deposited materials into gullies and then triggered the debris flow movement.

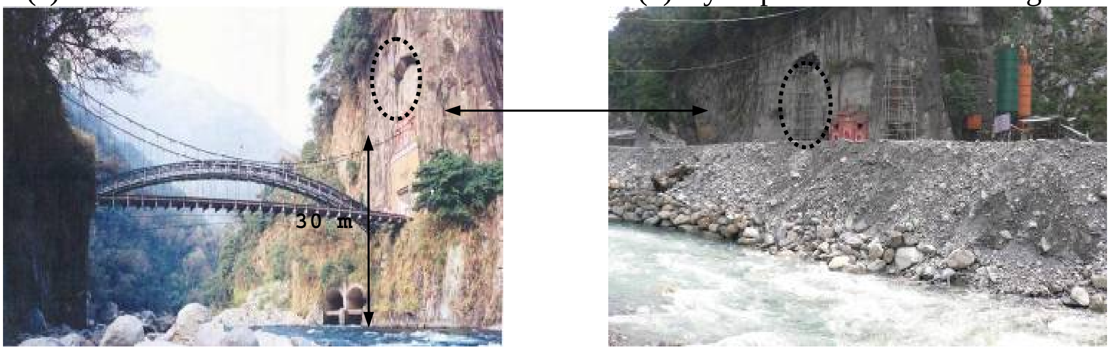
Introduction

It is widely recognized that most shallow landslides in Taiwan occurred as a result of heavy rainfall and consequent pore pressure increases in the near subsurface. Historically typhoon events with high-intensity, long-duration rainfall often triggered shallow, rapidly moving landslides, i.e. debris flows, resulting in casualties and property damage in the Da-Chia river watershed along the past decades. A number of studies have demonstrated that rainfall-induced landslides can be transformed into debris flows as they move downslope. Large-scale geohazards occurred in the Da-Chia river watershed during typhoons that passed through Taiwan from 2001 to 2008 without forewarning. Especially, the Minduli typhoon event in 2004 hit Taiwan which caused severe property damage and inflicted heavy casualties, as shown in Figure 1. Though landslide-induced debris flows present a hazard that is being increasingly recognized, such a large-scale debris flow hazard in the Da-Chia river watershed still appears to be particular. Until now, few detailed case studies of regional debris flow hazards in the Da-Chia river watershed have been presented in the literature.

In this paper, we present a detailed study on the earthquake and typhoon induced geohazards in the Da-Chia river watershed and reveal the trigger mechanism of the landslides and debris flows. To explore the coupling between the Chi-Chi earthquake and sequential regional debris flow hazards in the Da-Chia river watershed, the remote sensing data, Digital Elevation Model (DEM), historical landslides, and rainfall data were adopted in this study. For characterizing temporal aspects of the hazard, aerial photographs and satellite images of multi-temporal stages were used. Analyses of rainfall characteristics, rainfall-induced landslides, and debris flow formation from rainfall-induced landslides were conducted. In addition, the study of spatial distribution of landslides and rainfall characteristics were also discussed.

(a) Destructive debris flow occurred.

(b) Hydropower facilities damaged.



(c) Dramatic alteration of Da-Chia riverbed before the Chi-Chi earthquake (left) after the Mindulle typhoon. (right)

Fig1. Geohazards in the study area

1. Study Region

The study region includes a major river, named the Da-Chia river, one of the abundant water resources in central Taiwan as shown in Figure 2. The Da-Chia river watershed area is about 1,236 km^2. The elevation of the 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. A series of significant hydroelectric schemes that extend along the length of the river, consisting of one high, concrete arch dam at Te-Chi, and a series of dams and hydropower stations were built in 1960s. There are also many tributaries along the Da-Chia river. In our study region, about 20 tributaries were found between Te-Chi dam and Ma-An dam. The area of our study region is 396.5 km^2. The geohazards were insignificant until the Chi-Chi earthquake hit the central Taiwan in 1999. Accordingly, the following discussion is focused on the events after 1999 in the study region.

1.1 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 the Da-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 as shown in Figure 3. The rock mass is extensively tectonically disrupted, with a high density of fractures and joints. The slope inclination in the watershed is ranging from 40 to 80 degrees.

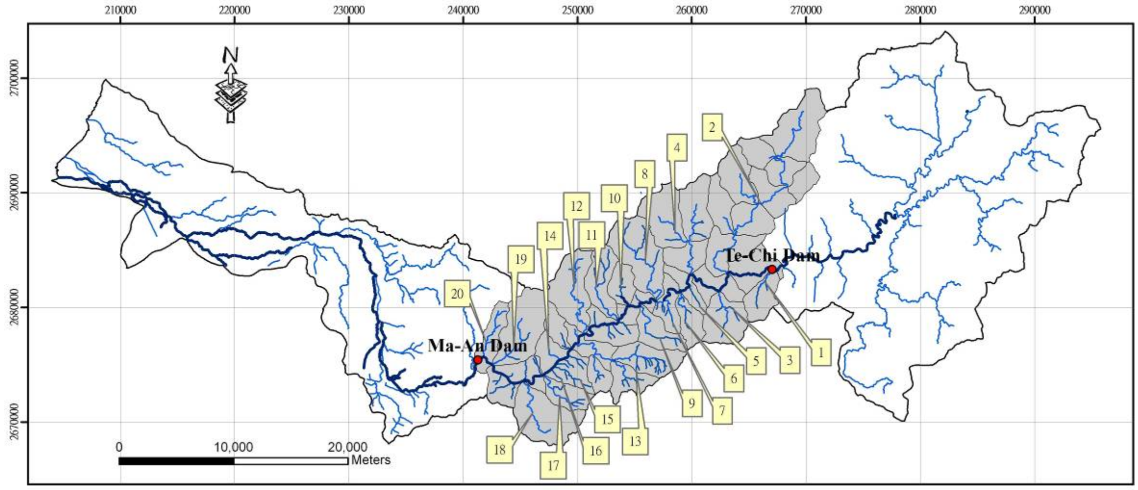


Fig2. Study region and tributaries.

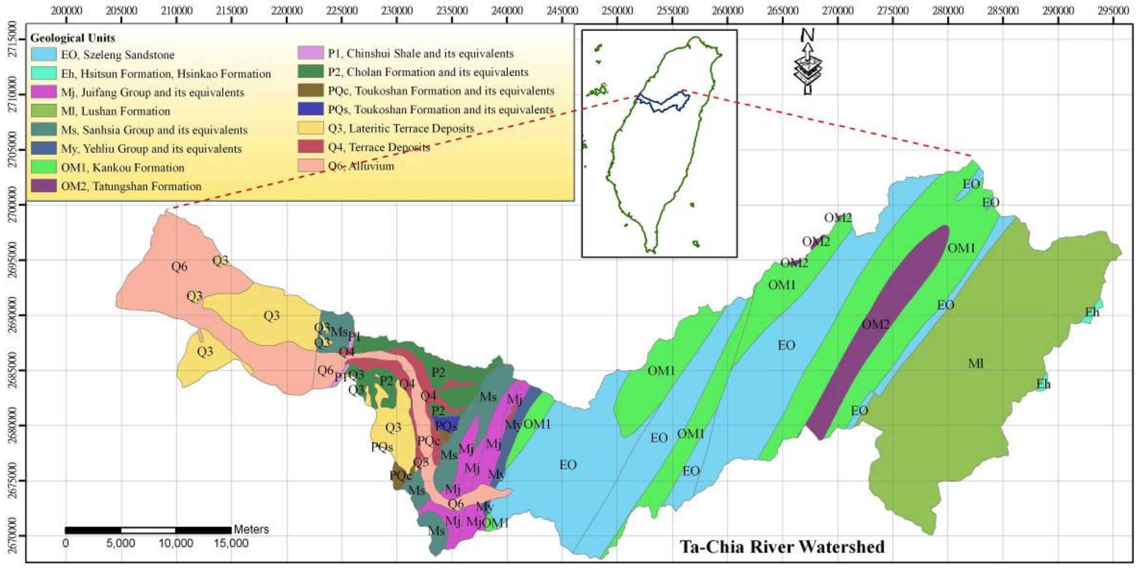


Fig3. Location of the Da-Chia river watershed in Taiwan and its geological map.

1.2 Major Heavy rainfall Storm Events in the Study Area

During 1996 to 2005, according to the Central Weather Bureau of Taiwan, the following storm events including typhoon Herb in 1996, typhoon Toraji in 2001, typhoon Minduli in 2004, typhoon Airi in 2004, Hytarng in 2005, Sinlaku and Angmi in 2008 have hit the study area. Within this period, the Chi-Chi earthquake on 21 September 1999 which is the largest in Taiwan for 50 years, was also occurred. This typhoon-earthquake-typhoon sequence represents a natural experiment that provides quantitative information about the impact of a large earthquake on landslides and transfer of sediment to debris flows.

2. Characteristics of Geohazards in the Da-Chia River Watershed

2.1 Characteristics of Landslide Region

Shallow landsliding is the most common landslide type on steep natural hillslopes in the Da-Chia river watershed. Multi-temporal remote sensing data including aerial-photograph and SPOT satellite imaginary were used for landslide mapping. For characterizing temporal aspects of the debris flows, remote sensing data include aerial photographs and satellite images of five temporal stages which are the stage before and after Chi-Chi earthquake, the stage after typhoon Toraji, the stage after typhoon Minduli, the stage after typhoon Airi and Hytarng. Table 1 shows before and after the Chi-Chi earthquake (1989) the landslide rates are 0.68% and 7.54% respectively. After typhoon Toraji in 2001, typhoon Minduli in 2004, and typhoon Airi in 2004, the landslide rates are 6.05%, 7.80%, and, 6.92% respectively. Comparing the landslide rate from these events, it is found that the Chi-Chi earthquake has caused significant landslides in the study region.

Table 1: Landslide area mapping from multi-temporal remote sensing data.

	Landslide area (km^2)	Landslide rate	Increase area (km^2)	Increase rate
Before Chi-Chi earthquake	2.69	0.68%	~	~
After Chi-Chi earthquake	29.91	7.54%	28.34	7.15%
After typhoon Toraji	23.99	6.05%	6.68	1.68%
After typhoon Minduli	30.94	7.80%	14.04	3.54%
After typhoon Airi	27.43	6.92%	6.68	1.69%

Note: The landslide rate is the landslide area divided by watershed area (396.5 km^2).

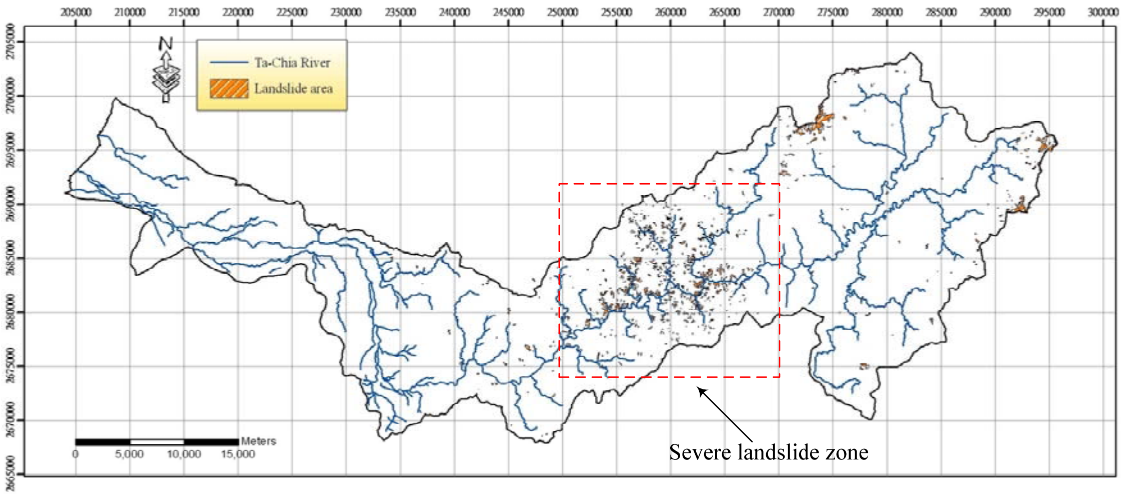


Fig4. Spatial distribution of landslide areas.

Furthermore, we computed the new landslides triggered by each event and found that the increase rates of slope failures occurred by these events are 7.15%, 1.68%, 3.54%, and, 1.69%% for four events including the Chi-Chi earthquake, typhoon Toraji, typhoon Minduli, and typhoon Airi, respectively. Accordingly, we have revealed that the Chi-Chi earthquake with the landslide increase rate of 7.15% is the major event for inducing the landslides and typhoon Minduli with the landslide increase rate of 3.54% is the second. From the results of landslide mapping as shown in Figure 4, we found that the landslides were most located in the areas between Te-Chi dam and Ma-An dam.

2.2 Characteristics of Major Debris Flows

Table 2 shows the occurrence record of the debris flows in the study region. Before the Chi-Chi earthquake, no observations of debris flows have been reported for decades. After the Chi-Chi earthquake and the first typhoon Toraji hit the region in 2001, three branch rivers (# 13, #14, and #17) with the occurrence of debris flow have been reported. Severe debris flow hazards have been reported during the typhoon Minduli in 2004. The occurrence of debris flow was found in almost all of the branches, except one in the downstream. The following two typhoon events such as Airi in 2004 and Hytarng in 2005 also moved huge amount of debris sediment from these branch rivers into the main the Da-Chia river.

Table 2: Occurrence record of the debris flows

Branch river #[1]	Watershed area	Watershed slope	Branch river slope	Landslide rate (%)	Occurrence of debris flow[2]	Occurrence of debris flow[3]	Occurrence of debris flow[4]	Occurrence of debris flow[5]
1	8.86	33.8	11.5	10.26	No	Yes	Yes	Yes
2	88.24	33.5	3.2	4.87	No	Yes	Yes	Yes
3	13.74	37.0	20.2	17.83	No	Yes	Yes	Yes
4	36.30	35.5	6.6	16.82	No	Yes	Yes	Yes
5	1.98	40.0	24.6	40.73	No	Yes	Yes	Yes
6	7.35	36.1	13.9	17.57	No	Yes	Yes	Yes
7	3.49	40.4	21.0	32.50	No	Yes	Yes	Yes
8	22.12	33.2	7.1	18.68	No	Yes	Yes	Yes
9	9.70	35.9	13.1	24.21	No	Yes	Yes	Yes
10	6.76	37.2	15.2	29.73	No	Yes	Yes	Yes
11	12.12	32.7	6.8	9.56	No	Yes	Yes	Yes
12	18.57	31.1	5.6	10.65	No	Yes	Yes	Yes
13	31.09	34.4	7.6	12.34	Yes	Yes	Yes	Yes
14	3.66	32.1	9.2	21.27	Yes	Yes	Yes	Yes
15	3.75	32.5	14.3	15.44	No	Yes	Yes	Yes
16	0.57	32.6	21.7	11.10	No	Yes	Yes	Yes
17	7.76	30.8	10.0	7.88	Yes	Yes	Yes	Yes
18	20.50	28.9	4.4	11.64	No	Yes	Yes	Yes
19	20.89	30.4	6.2	11.34	No	Yes	Yes	Yes
20	5.98	28.2	9.5	4.23	No	No	No	No

[1] The branch river # is shown in Figure 2. [2] After typhoon Toraji in 2001. [3] After typhoon Minduli in 2004. [4] After typhoon Airi in 2004. [5] After typhoon Hytarng in 2005.

A debris flow is usually triggered by heavy rainfall over mountainous areas. It is made up of mud, soils, gravels, rocks, and water. Solids or soils on steep slopes slide downward due to weathering processes and mechanical influence such as gravity. From the occurrence of the debris flow hazard in the study area, it is obvious that the weathering process is not the major cause for creating such a large scale of the debris flow hazard. The mechanical influence from the Chi-Chi earthquake disturbed montane slopes, thus setting the conditions for the occurrence of the regional debris flows.

3. Analysis of rainfall-induced Geohazards in the Da-Chia River Watershed

3.1 Analysis of Rainfall Characteristics

Precipitation exerts two controls on the Da-Chia river watershed. One is as a trigger of landslide and therefore as materials on the occurrence of debris flows. The other is by providing water, therefore enhancing the mobility of debris flows. To explore the trigger mechanisms of the typhoon-earthquake-typhoon sequence, analysis of rainfall characteristics was conducted in this study. Precipitation data from more than 20 rainfall stations operated by Water Resources Agency of the Taiwan Ministry of Economic Affairs and other government agencies in the watershed were adopted for conducting the rainfall frequency analysis. The results of the frequency analysis were represented as the return period of rainfall. The return period of a storm event is the expected value of its average value measured over a very large number of occurrences. Table 3 is the comparison of accumulated rainfall of 1, 3, 6, 12, and 24 hours for Toraji, Minduli, Airi, and Hytarng typhoon events and the computed return period of rainfall for 2, 10, 25, 50, and 100 years on the upper Gu-Gang rainfall station. From the frequency analysis, we have found that the 1 and 3 hours accumulated rainfall of typhoon Minduli are over the 50-year return period of rainfall. Typhoon Minduli with heavy rainfalls brought sufficient water transporting significant amounts of sparsely deposited debris from landslides in upland into gullies and then induced the regional debris flow hazards.

Table 3: Comparison of accumulated rainfall for major typhoon events and the return period of rainfall on the upper Gu-Gang rainfall station

Accumulated rainfall	Toraji	Return period	Minduli	Return period	Airi	Return period	Hytarng	Return period
1 hour (mm)	77.5	75 (10 yrs)	94.5	92 (50 yrs)	56.5	50 (2 yrs)	28.5	50 (2 yrs)

		85 (25yrs)		99 (100 yrs)		66 (5 yrs)		
3 hours (mm)	173.5	174 (25yrs)	199	191 (50 yrs) 208 (100 yrs)	158	149 (10 yrs) 174 (25 yrs)	63	92 (2 yrs)
6 hours (mm)	259.5	226 (10 yrs) 268 (25 yrs)	271	268 (25 yrs) 298 (50 yrs)	297.5	298 (50 yrs)	117.5	133 (2 yrs)
12 hours (mm)	317	283 (5 yrs) 341 (10 yrs)	394.5	341 (10 yrs) 411 (25 yrs)	426	411 (25 yrs) 461 (50 yrs)	196	193 (2 yrs)
1 day (mm)	344.5	295 (2 yrs) 447 (5 yrs)	603	545(10 yrs) 636 (20 yrs)	504	420 (5 yrs) 513 (10 yrs)	452.5	420 (5 yrs) 513 (10 yrs)

Further analysis also conducted to reveal the spatial distribution of rainfall in the study region. We plotted contours of the 200-year return period of rainfall for each gauging station in the Da-Chia river watershed as shown in Figure 5. Results demonstrated that the spatial distribution of the precipitation in the study region mainly concentrated around the upper Gu-Gang rainfall station.

From the results of landslide mapping as shown in Figure 4, we found that the landslides were most located in the areas between Te-Chi dam and Ma-An dam. Comparing Figures 4 and 5, it is found that the regional debris flow hazards in the Da-Chia river watershed are strong related to the spatial distribution of rainfalls.

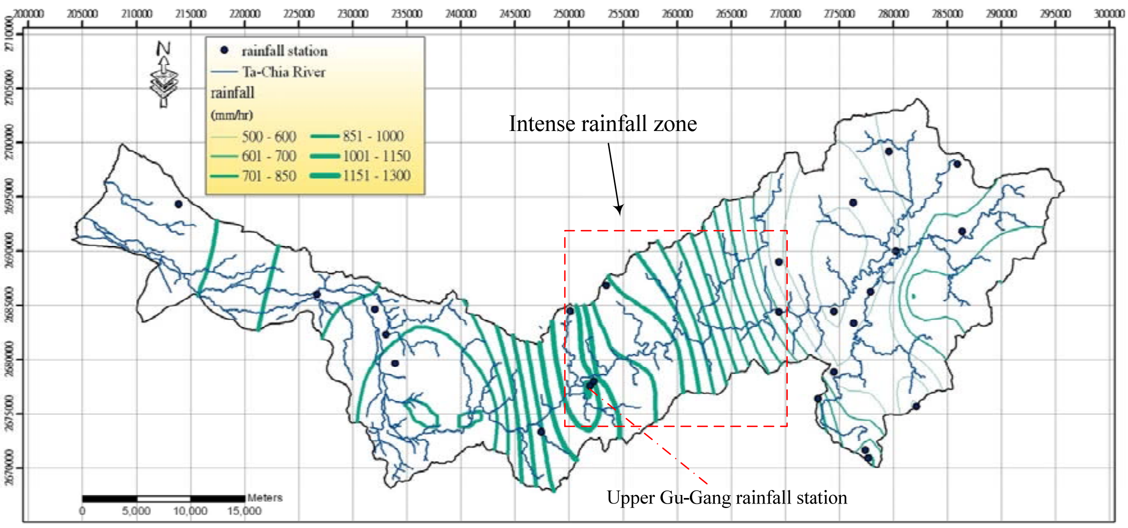


Fig5. Spatial distribution of rainfall characteristics.

3.2 Analysis of Rainfall-induced Landslides

Further analysis was conducted to study the rainfall-induced landslide susceptibility using the Transient Rainfall Infiltration and Grid-based Regional Slope-Stability (TRIGRS) model (Baum, 2002). The TRIGRS model is based on the Iverson's research results to assess the time-varying slope safety of each slope unit with transient pore-water pressure during a rainfall event. 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. 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:

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

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 n^{th} 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 $ierfc(\eta)$ 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:

$$\varphi(Z,t) \le Z\beta \qquad (2)$$

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:

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

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. $\varphi(Z, t)$ is the pore-water pressure calculated by equation (1) and limited by equation (2).

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.

After the verification and calibration of the TRIGRS model, the response of the Da-Chia river watershed from heavy rainfall with 200-year return period was predicted. The results of landslide susceptibility estimated by the TRIGRS model are illustrated in Figure 6. The predicted landslides were most located in the areas between Te-Chi dam and Ma-An dam.

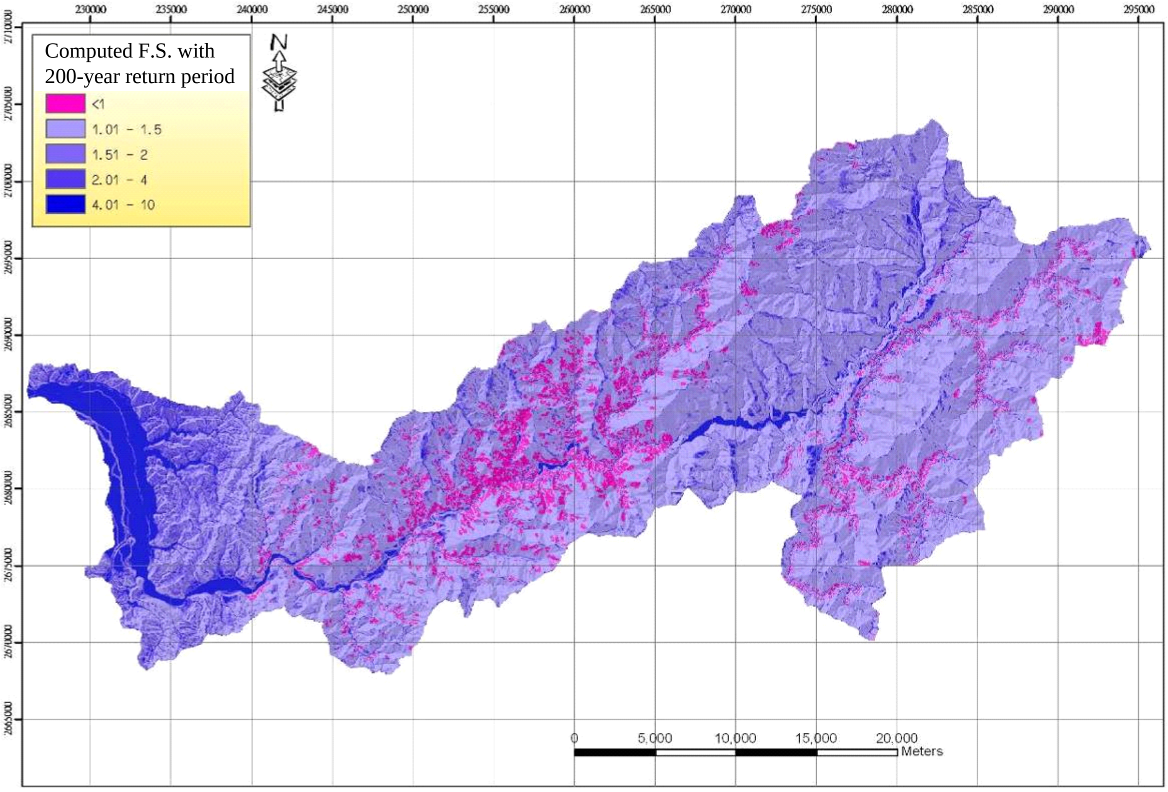
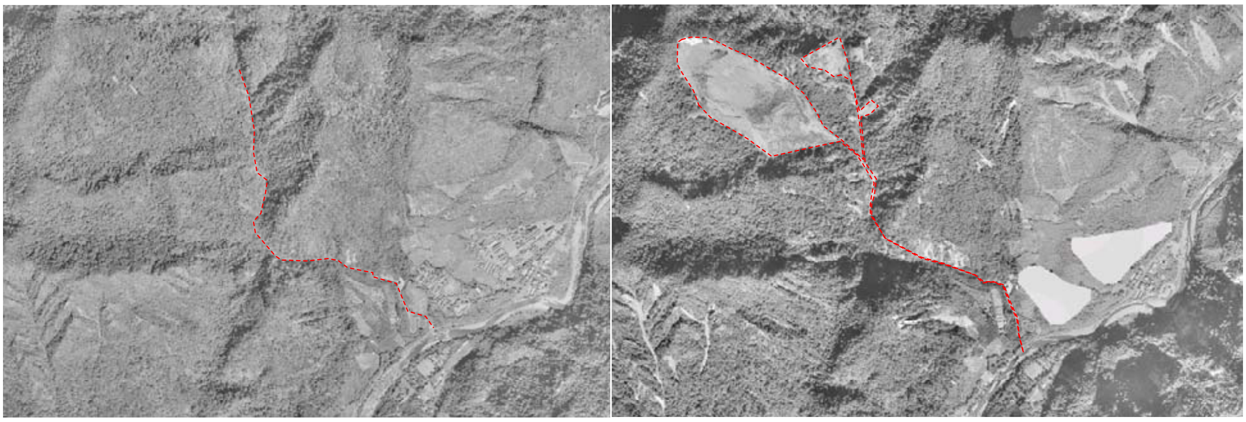


Fig6. Prediction of landslide susceptibility map with 200-year return period rainfall.

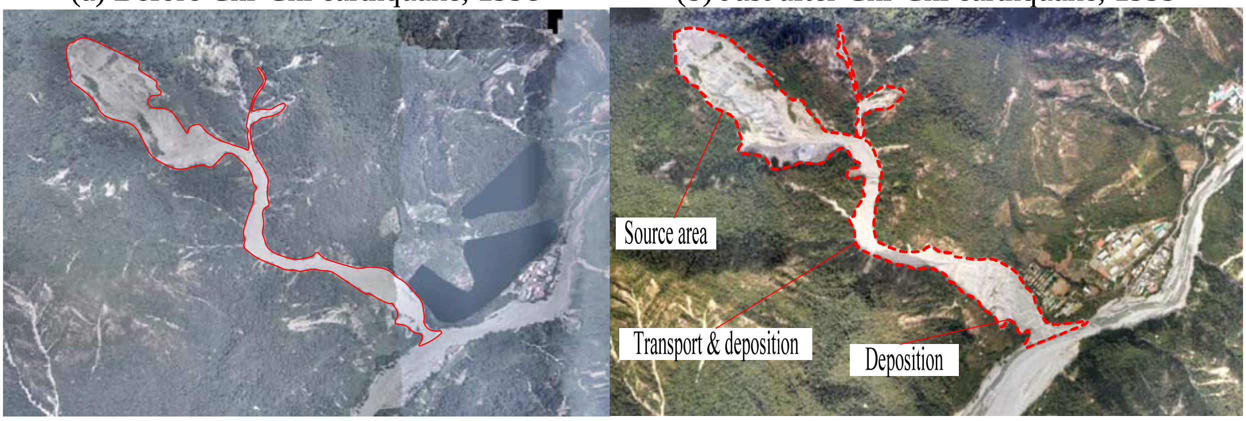
3.3 Analysis of Debris Flow Formation from rainfall-induced landslides

It is widely recognized that slope instability can be caused by increased subsurface pore pressures during periods of intense rainfall, which reduce the shear strength of slope materials. A number of recent studies have demonstrated that rainfall-induced landslides can be transformed into debris flows as they move downslope. Figure 7 shows multi-temporal aerial-photographs of the formation of a debris flow. In this figure, the four stages including before and after Chi-Chi earthquake, after typhoon Toraji, and after typhoon Minduli of aerial-photographs were presented. Before the Chi-Chi earthquake (1998), it was clear that the branch # 14 was just a regular gully that the water flow only presents in precipitation. In 1999 (after the Chi-Chi earthquake), landslides initiated from the source areas but no debris flow occurred. In 2001, typhoon Toraji hit this region. The appearance of water flow during storm precipitation is advantageous for mixing with accumulated material from source areas to stir the progression of a beginning landslide into a debris flow. Field reconnaissance of this study area revealed that the trigger mechanism of this debris flow took place in two stages: the primary slope failure was due to the Chi-Chi earthquake from the source area. The hydraulic movement was transferred to the landslide mass of the source area flowing into brook track, following slope surface exposure to the action of running water.

Debris flows are commonly triggered by the sudden increase in pore water pressure on the material. However, in the Da-Chia river watershed, the geohazards of landslides and sequential debris flows were caused by the earthquake-induced landslide materials. Rapidly increasing water pressure from typhoon-induced heavy rainfall provided a powerful force that moved the sparsely deposited materials into gullies and then triggered the debris flow hazards.



(a) Before Chi-Chi earthquake, 1998 (b) Just after Chi-Chi earthquake, 1999



(c) After typhoon Toraji, 2001 (d) After typhoon Minduli, 2004

Fig7. Debris Flow Formation(branch # 14) from earthquake and rainfall-induced landslide

Conclusions

Large-scale geohazards occurred in the Da-Chia River watershed during typhoons that passed through Taiwan from 2001 to 2008 which caused severe property damage and inflicted heavy casualties. In this paper, we present a detailed study on the earthquake and typhoon induced geohazards in the Da-Chia river watershed. Findings from this study are described as following.

1. Shallow landsliding is the most common landslide type on steep natural hillslopes in the Da-Chia river watershed. In this study, we have revealed that the Chi-Chi earthquake with the landslide increase rate of 7.15% is the major event for inducing the landslides and the Minduli typhoon with the landslide increase rate of 3.54% is the second in the study area. From the landslides and sequential debris flows in the study area after Chi-Chi earthquake in 1998, it is obvious that the weathering process is not the major cause for creating such a large scale of the debris flow hazard. The mechanical influence from the Chi-Chi earthquake disturbed montane slopes, thus setting the conditions for the occurrence of the regional debris flows.

2. Analysis of rainfall characteristics demonstrated that the spatial distribution of the precipitation in the study region mainly concentrated around the upper Gu-Gang rainfall station. Results of landslide mapping and the analysis of rainfall-induced landslide susceptibility map also demonstrated that the landslides were most located in the areas between Te-Chi dam and Ma-An dam. With sufficient deposited materials and rainfall, it is found that the regional debris flow hazards in the Da-Chia river watershed were also occurred in the areas between Te-Chi dam and Ma-An dam.
3. Our findings indicate that the regional geohazards in the Da-Chia river watershed were mainly caused by the huge amount of sparsely deposited materials from landslides triggered by the Chi-Chi earthquake. Rapidly increasing water pressure caused by typhoon events with specific rainfall intensity provided a powerful force that moved the sparsely deposited materials into gullies and then triggered the debris flow movement. Furthermore, analysis results from the spatial distribution of rainfall in the study region demonstrated that the regional debris flow hazards in the Da-Chia river watershed are strong related to the spatial distribution of rainfalls.

References

Baum, R.L., Savage, W.Z. & Godt J.W. 2002. TRIGRS—A fortran program for transient rainfall infiltration and grid-based regional slope-stability analysis. U.S. Geological Survey Open-File Report 02-0424.

Chen, C.Y., Chen, T.C., Yu, F.C. & Lin, S.C. 2005. Analysis of time-varying rainfall infiltration induced landslide, Environmental Geology. 48: 466-479.

Chen, Hongey, Dadson, Simon, Chi, Yi-Guan, Recent rainfall-induced landslides and debris flow in northern Taiwan, 77, 112 – 125, Geomorphology, 2006.

Central Geological Survey, Geological Investigation Of Upstream Watershed For Flood-Prone Areas And Database Establishment (First Execution Phase) - Investigation Of Hydrogeology on Slope Stability, 2008.

Delmonaco, G., Leoni, G., Margottini, C., Puglisi, C. & Spizzichino, D. 2003. Large scale debris-flow hazard assessment: a geotechnical approach and GIS modeling. Natural Hazards and Earth System Sciences. 3: 443-455.

Iverson, R.M., Landslide trigger by rain infiltration. Water Resour Res. 36(7): 1897-1910, 2000.

Keefer, D. K., Wilson, R. C.,Mark, R. K., Brab, E. E., Brown, W. M., Ellen, S. D., Harp, E. L., Wieczorek, G. F., Alger, C. S., and Zatkin, R. S., Real-time landslide warning during heavy rainfall,, Science 238, 921 – 925, 1987.

Keefer, D.K. (1994) The importance of earthquake-induced landslides to long-term slope erosion and slope failure hazards in seismically active regions. Geomorphology, v. 10, 265-284.

Maleta J.-P., D. Laigleb, A. Remaıˆtrea, O. Maquaire, Triggering conditions and mobility of debris flows associated to complex earthflows, Geomorphology 66 215–235, 2005.

Tan, C.H., Ku, C.Y., Chi, S.Y., Chen, Y.H., Fei, L.Y., Lee, C.F. and Su, T.W. (2008) “Assessment of Regional Rainfall-induced Landslides Using 3S-based Hydro-geological Model”, 10th International Symposium on Landslides and Engineered Slopes, June 30-July 4, 2008, Xi'an, China.

Taiwan Power Company, Investigation and Strategy Study of Landslide and Debris flows in Da-Chia river Basin Between Te-Chi and Ma-An, 2006.