# EVALUATING LANDSLIDES AND SEDIMENT YIELDS INDUCED BY THE CHI-CHI EARTHQUAKE AND FOLLOWED HEAVY RAINFALLS ALONG THE TA-CHIA RIVER

Shian-Jin Chiou[1], Chin-Tung Cheng[2], Shih-Meng Hsu[1], Yan-Hsiang Lin[1], and Shu-Yeong Chi[3]

## ABSTRACT

Chi-Chi (Taiwan) earthquake and the followed typhoons induced heavy landslides and debris flows in the watershed of Ta-Chia river, the sediment yields from landslides caused lots of damages on the infrastructures including dams, power plants, bridges, villages and recreative parks. In order to evaluate the geohazards due to landslides and sediment yields along Ta-Chia river, the quantitative evaluation was conducted by using remote sensing images obtained at 6 stages of major disastrous events. Furthermore, the HEC-6 program was adopted to simulate the condition of deposit of Ta-Chia river in the near future according to the case history in Japan. The results show the highest level of riverbed deposited around the Chingshan office would raise more than 20 m in addition. Among the branch creeks of Ta-Chia river, Pi-Ya-Sun creek and Ji-Ler creek brought the larger sediment yields from landslides in the sub-watershed than other creeks. The area and volume of new landslides induced by disastrous events from 1999-2005 were over 24 million $m^2$ and 50-70 millions $m^3$, respectively. The new landslide area induced by the rainfall with 200-year return period will be approximately 4 million $m^2$ in the future. If the great earthquakes no longer occur, the sediment yields in the Ta-Chia main river will reduce with time and the riverbed will be scoured after 30 years. Therefore, it seems that the geological condition will be gradually stable in the future.

*Key words:* Chi-Chi earthquake, typhoon, landslide, sediment yields.

## 1. INTRODUCTION

Ta-Chia river is one of the abundant water resources in central Taiwan. Along the main river, there are seven hydro power plants of Taipower Company (TPC), which are Techi, Chingshan, Kukuan, Tienlun (including New Tienlun), Maan, Houli and Sheliao (as shown in Fig. 1). After the catastrophic Chi-Chi earthquake and the followed typhoons, including Toraji typhoon in 2001, Mindulle typhoon in 2004, Aere typhoon in 2004, and Haitang typhoon in 2005, caused wide spread landslides. The huge volumes of colluviums were flushed into riverbed. Debris flows were also occurred in the tributaries of Ta-Chia river and deposited as fan shapes in the river junction, which silted up the river channel and raised the flood level (Lin *et al*., 2004). These geohazards destroyed most of the infrastructures and villages nearby the river, especially the hydropower generation facilities. In order to assess the impact of the huge amounts of landslides and sediment yields along Ta-Chia river to propose the strategy of mitigation, the remote sensing technology and the comprehensive survey on landslides and sediment yields was conducted. This paper presents the result of these works.

Note: The dots are branch power plants; the stars are stations.

**Fig. 1 The six reservoirs and seven branch power plant along Ta-Chia river**

## 2. BACKGROUND

### 2.1 Topography and Geology

Topography

The study region is located at the Her-pin village of Taichung County, the watershed is between Techi dam and Kukuan dam (shown as Fig. 2). The length of main river in the study region is 13.87 km and the watershed area is 181.6 $km^2$. The inclinations of steep slopes of the Ta-Chia river bank are always more than 40 degrees. The riverbed elevations range from 950 to 1,500 m. The higher mountains in the study region are Dasyue Mountain (3,530 m) in the northern, the Tachien Mountain (3,594 m) in the eastern, and Bikuda

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[1] Researcher, Sinotech Engineering Consultants, Inc., Taipei 110, Taiwan, R.O.C. (e-mail: chiu@sinotech.org.tw)
[2] Researcher (corresponding author), Sinotech Engineering Consultants, Inc., Taipei 110, Taiwan, R.O.C. (e-mail: chiu@sinotech.org.tw)
[3] Manager, Sinotech Engineering Consultants, Inc., Taipei 110, Taiwan, R.O.C.

**Fig. 2 The study region and 6 branch creeks**

Mountain (3,341 m). There are 6 branch creeks in the study region, which are Ju-Lian-Pin creek, Wu-Min creek, Pi-Ya-Sun creek, Dern-Shan creek, Ji-Ler creek, and Bi-Tan creek.

Geology

The rock formation of the study region belonges to the central portion of Syue Mountains. The strata of the study region are Tachien sandstone layer in Eocene epoch age and Chiayang layer from Eocene epoch to Oligocene epoch age. The Tachien sandstone strikes in northeastern to southwestern direction, and the lithologic character of them is almost metamorphic sandstone with thick layer, granular texture, and blocky failure type. But some portions are shown with slate and metamorphic shale alternately. Chiayang layer and Tachien sandstone layer always reveal alternately in the Eocene epoch age. The lithologic character of Chiayang layers is thick layered, black or dark gray slate. There are sometimes fine sandstone revealed within the layers, and the cleavage also well developed in Chiayang layers.

### 2.2 Hydrology and Meteorology

Rainfall

The rainfalls and water resources are abundant in the study region. The annual rainfall is about 2,500 to 3,000 mm in average. However, more than 75% of annual rainfall is allocated from May to September. The rainy seasons begin in April and the most of rainfall increased in June to August. Moreover, the heavy rainfall with more than 500 mm per day is usually occurred in the typhoon season. The dry seasons begin in October till the next April, and just hold 25% annual rainfall totally.

Discharge and Suspended Load

The discharge is 3,752 cms in 200-year return period of time in Kukuan at the end of the study region (TPC, 2006). The suspended-load discharge on the upstream of Ta-Chia river (Sungmao station during 1986-2004) remains the same tendency after Chi-Chi earthquake, but that on the downstream (Pailu Bridge station during 1978-2003) presents obviously increasing tendency. The regression of suspended-load discharge as a function of water discharge is shown in Fig. 3.

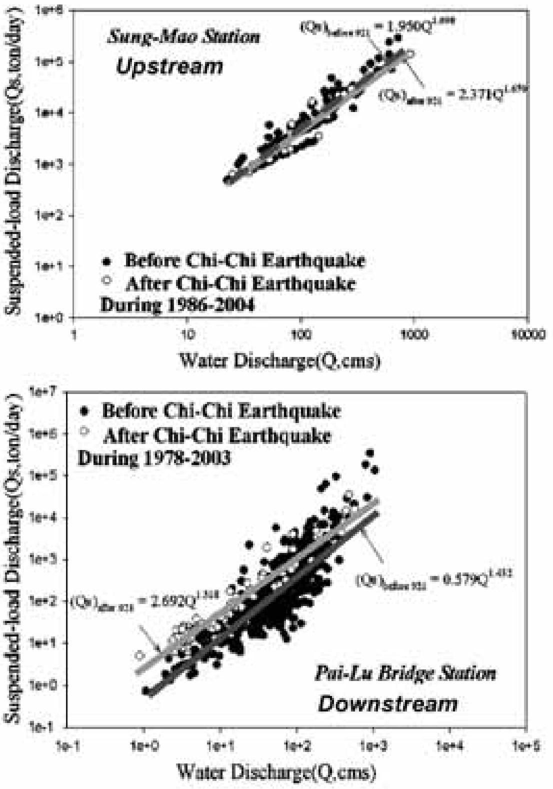


**Fig. 3 Regression of suspended-load discharge**

## 3. RECOGNITION OF GEOHAZARDS USING REMOTE SENSING IMAGES

### 3.1 Selection of Remote Sensing Images

In order to evaluate the landslides and the sediment yields transported in the riverbed, aerial photos and satellite images of 6 stages were used. They were stage 1 before Chi-Chi earthquake, stage 2 after Chi-Chi earthquake, stage 3 after Toraji typhoon, stage 4 after Mindulle typhoon, stage 5 after Aere typhoon and stage 6 after Haitang typhoon, and the individual dates of the remote sensing images of the stages are listed in Table 1.

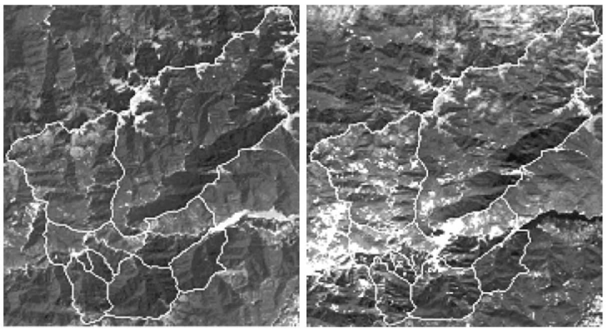
### 3.2 Natural Disastrous Events

Earthquake

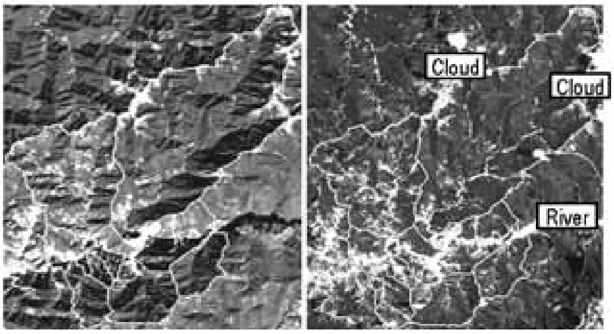
The largest earthquake within 50 km of the study region from 1900 to 2005 is Chi-Chi earthquake, magnitude $M_W$ 7.6, and focal depth 8 km. Some magnitudes of aftershock were also greater than $M_W$ 6. The study region is located on the hanging wall of Chelungpu fault rupture area. Therefore, the intensity of ground motion was almost higher than 250 gal

**Table 1 The dates of the remote sensing images**

| | Stage | Aerial Photos | SPOT Image |
|---|---|---|---|
| 1 | Before Chi-Chi earthquake | 1997.12.21 ~ 1999.09.10 | 1999.04.01 |
| 2 | After Chi-Chi earthquake | 1999.10.31 ~ 2000.12.09 | 1999.10.31 |
| 3 | After Toraji typhoon | 2001.08.14 ~ 2003.02.21 | 2001.11.18 |
| 4 | After Mindulle typhoon | 2004.07.07 ~ 2004.07.30 | 2004.07.21 |
| 5 | After Aere typhoon | 2005.01.21 | 2004.10.12 |
| 6 | After Haitang typhoon | 2005.08.01 ~ 2006.01.21 | |



Before Chi-Chi earthquake After Chi-Chi earthquake



After Toraji typhoon After Mindulle typhoon

**Fig. 4 The SPOT images of the study region**

during Chi-Chi earthquake and triggered a lot of landslides. Figure 4 are the SPOT images of the study region, which show the huge amount of landslides induced by Chi-Chi earthquake, and most of the landslides occurred on the both sides of Ta-Chia riverbank. Some loose rocks did not slide immediately after Chi-Chi earthquake, but slid in the followed heavy rainfalls.

#### Heavy Rainfalls

After Chi-Chi earthquake, there were heavy rainfalls during Toraji typhoon in 2001, Mindulle typhoon in 2004, Aere typhoon in 2004 and Haitang typhoon in 2005. The Sinpokon rainfall monitoring station is at the downstream of the study region and the monitored rainfalls of those typhoon evens are described as following:

(1) Toraji typhoon occurred on 7/28/2001-07/31/2001, the maximum daily rainfall was 234 mm; the sustained rainfall was accumulated to 239 mm in three days.

(2) Mindulle typhoon occurred on 06/28/2004-07/03/2004, the maximum daily rainfall is 617.5 mm; the sustained rainfall was accumulated to 1,000 mm in three days.

(3) Aere typhoon occurred on 08/23/2004-08/26/2004, the maximum daily rainfall is 314 mm; the sustained rainfall was accumulated to 411 mm in three days.

(4) Haitang typhoon was occurred at 07/16/2005-07/20/2005, the maximum daily rainfall was 312 mm; the sustained rainfall was accumulated to 335 mm in three days.

The aerial photos were used to identify the landslides of different stages. The left side of Fig. 5 shows the new landslides induced by Chi-Chi earthquake with color of black, the right side of Fig. 5 shows the increased landslides induced by a series of heavy rainfalls with black color. However, it reveals that Chi-Chi earthquake triggered the great majority of landslides.

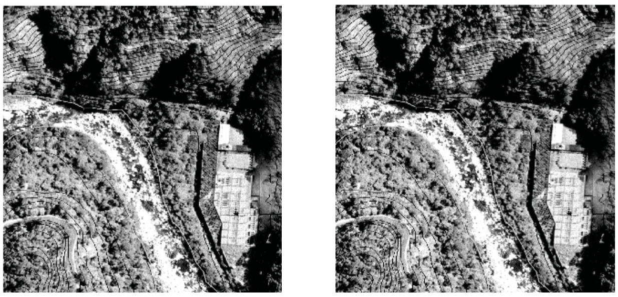
Induced by Chi-Chi earthquake Induced by those heavy rainfalls

**Fig. 5 The new landslides with black color induced by Chi-Chi earthquake and heavy rainfalls (the color of old landslides is gray)**

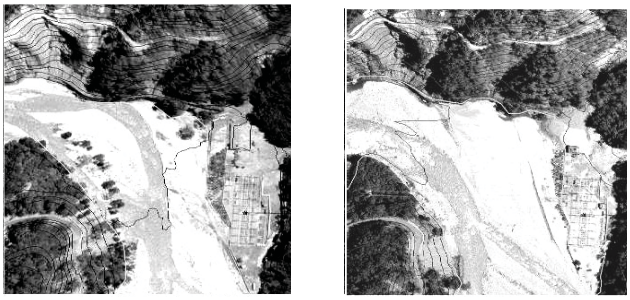
### 3.3 Identification of Geohazards Distribution in Aerial Photos

The aerial photos were adopted to identify the geohazards at different stages. It was very useful to identify the large-scale topographic migration. Chingshan office and Chingshan switchyard were chosen to demonstrate the geohazards from the aerial photos shown as Figs. 6 and 7. Figure 6 indicates the hazards of landslides and river channel silting up near the Chingshan switchyard. Before Chi-Chi earthquake, the width of channel was 50 m and the height from riverbed to the terrace of Chingshan switchyard was more than 15 m. After Haitang typhoon, the width of river channel became 160 m to 200 m and the level of riverbed was raised over the terrace of Chingshan switchyard.

Figure 7 reveals that the debris flows of Pi-Ya-Sun creek struck the Chingshan office. The sediment yields from Pi-Ya-Sun creek made an alluvium fan, which almost silted up the river channel. The width of the channel of Pi-Ya-Sun creek was pretty small before Chi-Chi earthquake. However, after Chi-Chi earthquake and a series of heavy rainfalls, the riverbed in front of the office was raised more than 20 m and the width of the channel increased from 40 m to 150 m.



Before Chi-Chi earthquake (1998) After Chi-Chi earthquake (2000)



After Mindulle typhoon (2004) After Haitang typhoon (2005)

**Fig. 6 The hazards of landslides and river channel silted nearby Chingshan switchyard**

**Fig. 7 The debris flows from Pi-Ya-Sun creek struck the Chingshan office**

## 4. EVALUATION OF LANDSLIDES AND DEM CHANGES

### 4.1 Landslide Area

(1) Total landslide area

The whole area and volume of landslides within the study region are shown in Table 2. Figure 8 reveals that the both sides of Ta-Chia river and the Pi-Ya-Sun creek generated the great amount of landslides. The landslide area of stage before and after Chi-Chi earthquake shows the maximum difference, the total landslide area of stage 2 was about 8 times larger than stage 1. After Mindulle typhoon, the landslide area of watershed increased again, but the landslide area was still smaller than that after Chi-Chi earthquake. The total landslide area decreased after the last disastrous event, it seems to be stable in this situation.

**Table 2 The summation of the whole landslide area and volume in each stage**

(a) Landslide area ($m^2$)

| Watershed | Stage 1 | Stage 2 | Stage 3 | Stage 4 | Stage 5, 6 |
|---|---|---|---|---|---|
| Bi-Tan creek | 14,020 | 452,192 | 436,507 | 445,071 | 559,628 |
| Ji-Ler creek | 646,626 | 2,477,200 | 2,064,360 | 2,695,888 | 2,570,745 |
| Dern-Shan creek | 102,612 | 1,957,157 | 1,098,415 | 1,347,719 | 1,439,581 |
| Pi-Ya-Sun creek | 815,150 | 3,613,469 | 3,111,384 | 4,090,058 | 2,804,295 |
| Wu-Min creek | 57,674 | 579,695 | 429,774 | 507,427 | 354,678 |
| Ju-Lian-Pin creek | 80,301 | 848,581 | 575,170 | 688,152 | 582,272 |
| Ta-Chia river | 332,819 | 6,474,731 | 4,437,545 | 4,573,417 | 3,732,404 |
| Study region | 2,049,202 | 16,403,025 | 12,153,155 | 14,347,732 | 12,043,603 |

(b) The new generated landslide area ($m^2$)

| Watershed | Stage 1-2 | Stage 2-3 | Stage 3-4 | Stage 4-5, 6 | Total |
|---|---|---|---|---|---|
| Bi-Tan creek | 449,575 | 143,697 | 174,321 | 197,325 | 964,918 |
| Ji-Ler creek | 2,163,050 | 674,858 | 999,897 | 574,149 | 4,411,954 |
| Dern-Shan creek | 1,917,581 | 230,338 | 336,822 | 276,232 | 2,760,973 |
| Pi-Ya-Sun creek | 3,366,913 | 1,035,876 | 1,204,772 | 388,682 | 5,996,243 |
| Wu-Min creek | 569,931 | 103,591 | 100,003 | 28,786 | 802,311 |
| Ju-Lian-Pin creek | 847,793 | 190,074 | 206,852 | 87,976 | 1,332,695 |
| Ta-Chia river | 6,223,983 | 760,666 | 647,838 | 328,305 | 7,960,792 |
| Study region | 15,538,826 | 3,139,100 | 3,670,505 | 1,881,455 | 24,229,886 |

(c) Landslide volume (not include the volume of rock mass increased after collapsed) ($m^3$)

| Watershed | Stage1-2 | Stage 2-3 | Stage3-4 | Stage4-5, 6 | Total |
|---|---|---|---|---|---|
| Bi-Tan creek | 150,556 | 237,357 | 144,819 | 143,769 | 676,501 |
| Ji-Ler creek | 4,903,111 | 1,182,740 | 1,293,251 | 705,496 | 8,084,598 |
| Dern-Shan creek | 2,807,337 | 502,134 | 432,960 | 327,138 | 4,069,569 |
| Pi-Ya-Sun creek | 5,561,772 | 1,867,943 | 2,251,942 | 702,724 | 10,384,381 |
| Wu-Min creek | 805,995 | 180,194 | 146,173 | 58,489 | 1,190,851 |
| Ju-Lian-Pin creek | 1,415,744 | 344,620 | 344,839 | 178,782 | 2,283,985 |
| Ta-Chia river | 10,270,154 | 1,931,678 | 1,347,207 | 715,567 | 14,264,606 |
| Study region | 25,914,669 | 6,246,666 | 5,961,191 | 2,831,965 | 40,954,491 |

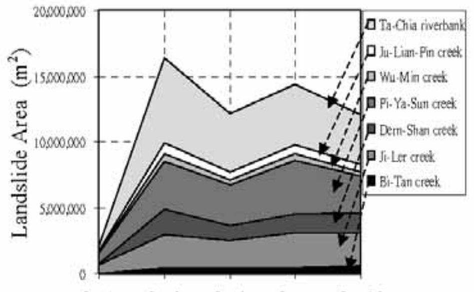


**Fig. 8 The landslide areas in each stage**

(2) New generated landslide area

Figure 9 shows the increased landslide area between two adjacent events, and the summation of the new generated landslide areas induced by different disastrous events was accumulated to 24 million $m^2$ (Table 2(b)). Most landslide in

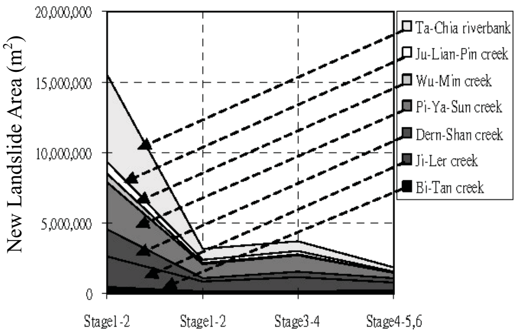


**Fig. 9 The new generated landslide areas in each stage**

the study region was induced by Chi-Chi earthquake, the new generated landslide area induced by Chi-Chi earthquake was about 5 times comparing with the other disastrous events. Even though the typhoon caused some new landslides, the new generated landslide area became smaller and smaller. It seems that the geological condition would be gradually stable in the future.

(3) The volume of landslides

In order to quantify the volume of landslides, the multi-temporal DEMs (digital elevation models) were used for analysis. From the differences between multi-temporal DEMs, the evolution of the terrain change in the study region could be found. Table 2(c) and Fig. 10 show the volume of landslides in each watershed, which were obtained by the calculation of differences of DEMs between two adjacent disastrous events. The landslide volume of each event also became smaller and smaller. It reveals that the landslide volume induced by Chi-Chi earthquake is at least 2 times the landslide volume induced by entire typhoon events. The total volume of landslides was at least 41 million $m^3$ before collapsed.

However, when the rocks fell down and deposited as taluses, the volume of rock mass would be increased after collapsed (Turner and Schuster, 1996). If the rate of increasing in volume assumed to be 20%, Ta-Chia main river and its branch creeks had generated the volumes of colluviums from landslides at 17 million $m^3$ and 32 million $m^3$, respectively. Furthermore, if the increasing rate assumed to be 33% and consider the error of DEM, Ta-Chia main river and its branch creeks had generated the volumes of colluviums from landslides at 24.3 million $m^3$ and 46.7 million $m^3$, respectively.

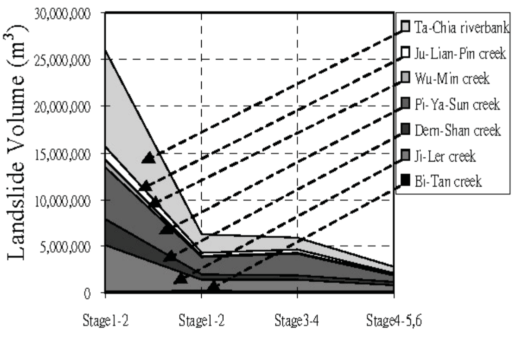


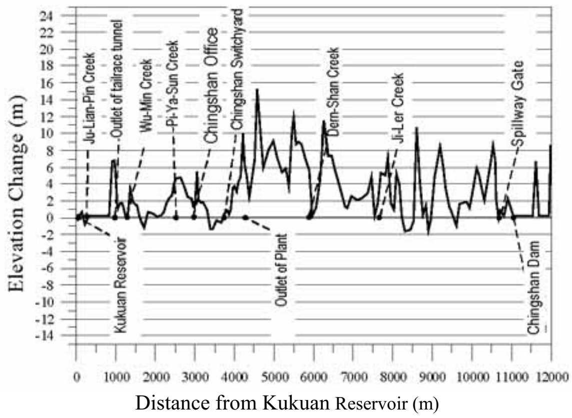
**Fig. 10 The volume of landslides in each stage (not include the volume of rock mass increased after collapsed)**

In summary, the total volume of colluviums from landslides within the watershed between Techi dam and Kukuan dam would be approximated from 50 million $m^3$ to 70 million $m^3$.

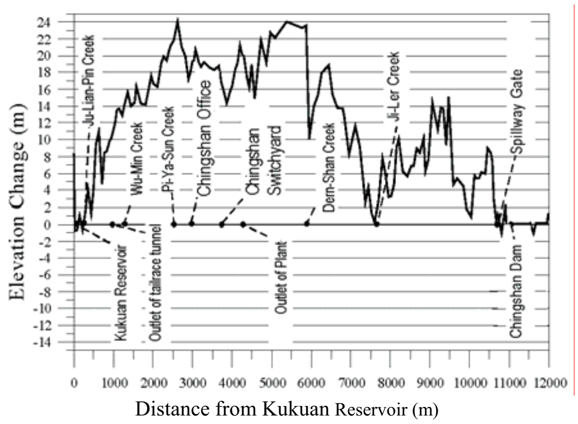
### 4.2 Riverbed Changes

Figure 11 shows the total elevation changes in the Ta-Chia main river from Chi-Chi earthquake to Haitang typhoon (1999-2005). After Chi-Chi earthquake, the elevation at the front of Chingshan office changed slightly, but the upstream of the switchyard deposit more than 5-m height. After followed typhoon events, maximum elevation change of the riverbed was situated between Chingshan office and switchyard, the change of elevation was more than 20-m height. It seems that the huge sediment yields came from the debris flow of Dern-Shian creek and the talus on the riverbank of Ta-Chia river.

Chingshan office and switchyard were taken as examples again. Figure 12 reveals that the width of the entire riverbed became wider and wider passed through those heavy rainfalls, and the widths of the shrunk sections were changed slightly. Figure 12 also shows the elevation changes of riverbed from multi-temporal DEMs, the deposit of river cross-section at the front of Chingshan office was about 20-m height as well as Chingshan switchyard and the outlet ventilation of tunnel. Mindulle typhoon was the most serious event, which transported the huge amount of sediment into Ta-Chia river.

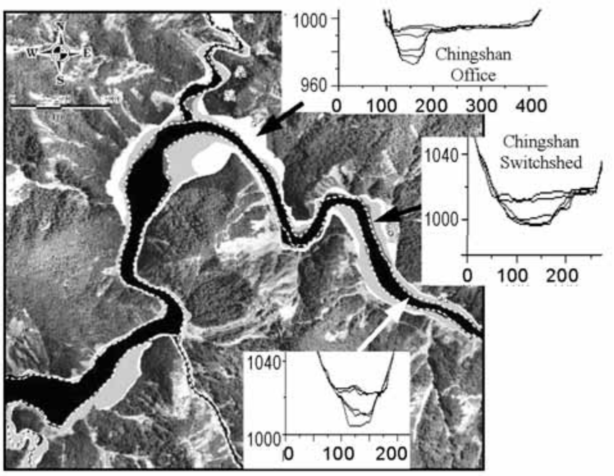


(a) From stage 1 to stage 2



(b) From stage 1 to stage 6

**Fig. 11 The elevation change of riverbed from Chi-Chi earthquake to Hi-Tang typhoon**



Note: The dash line is the original width of river. The colour of river becomes more and more white represents that river was more and more wide from stage 1 to 6.

**Fig. 12 The width and elevation of river cross-sections**

## 5. DISCUSSIONS

### 5.1 Characteristics of Geohazards

After Chi-Chi earthquake, the geologic condition has become more vulnerable. Due to the steep slopes and the well-developed joints of rocks, debris flows and rock falls were the typical cases of mass movement in the study region. The huge sediment yields would be transported to downstream after each heavy rainfall, and landslides will be occurred in the next heavy rainfall again. The characteristics of landslides and sediment yields are described as follows.

(1) Landslides

The slope angle of riverbank in this study region is very steep, and the inclinations of most slopes are over 45 degrees. It is a typical V-shape river valley. According to the pictures from site investigation, there were some typical conditions of geohazard shown as Fig. 13. Joints and cleavages of rock slopes are well developed along the Ta-Chia river. Therefore, the landslide types of the study region were rock-falls, debris avalanches and wedge slides. According to the comparison of Tables 2(a) and 2(c), the average thickness of landslides was about 1.5 to 3 m, however, the thickness of landslides in some region is over 10 m. In addition, the waste materials of road construction also contributed large amount of slide volume. There was also some gravel layers on the higher terrace along Ta-Chia and its tributaries. The toes of the slopes always became unstable when the toes were eroded by high flood level. Because of the topography of the gravel layers were very steep and cemented poorly; therefore, it resulted in serious landslides after Chi-Chi earthquake.

(2) Sediment yields

During the followed heavy rainfalls, the huge amounts of sediments produced by landslides were subsequently transported from tributaries to the main river, and Mindulle typhoon caused the most of sediment yields transported by debris flows. The riverbed of Ta-Chia river became more and more silted up; it was obvious at the alluvial fans of tributaries. The width of the main river channel and its tributaries became wider than that before Chi-Chi earthquake. The height of alluvial fan at the mouth of Dern-Shan creek was more than 25 m, and the riverbed at the front of Chingshan switchyard was raised at least 22 m. The riverbed of Ta-Chia river was raised more than 10 m in average between Techi dam and Kukuan dam. Furthermore, the mouths of Pi-Ya-Sun creek and Dern-Shan creek are very close to Chingshan office and switchyard, which will be at the highly disastrous region of debris flows in the near future.


The rock-falls The debris avalanches
The waste materials The gravel layer
Joints and cleavages The wedge slide

**Fig. 13 The landslide types of this study region**

### 5.2 Estimate New Landslide Area in the Future

In order to estimate new landslide area induced by heavy rainfall in the future, Uchihugi's empirical model (1971) was adopted to predict the new landslide rate of each sub-watershed of Ta-Chia river. Figure 14 illustrates the meaning of Uchiogi's empirical model, and the equation of the model was shown as below.

$$Y = \frac{C_a}{a} = K \times 10^{-6}(R-r)^2 \tag{1}$$

where $Y$ = new landslide rate, $C_a$ = new landslide area, $a$ = watershed area, $K$ = site specific coefficient, $R$ = maximum one day rainfall, and $r$ = critical rainfall for landslide.

The new landslide rate ($Y$) listed in Table 3 could be calculated by new landslide area ($C_a$) and watershed area ($a$) listed in Tables 2 and 3, respectively. The new landslide

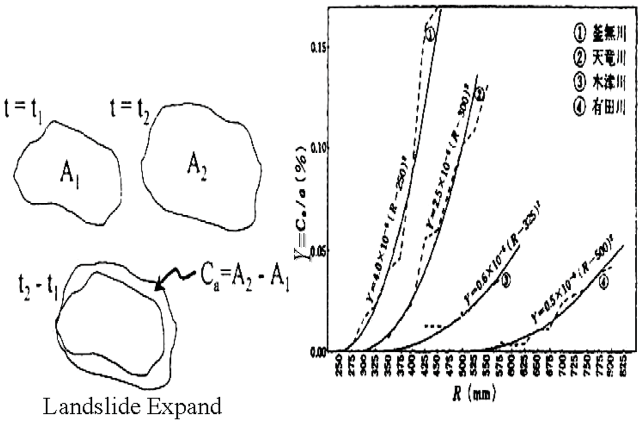


**Fig. 14 Uchiogi's empirical model (Uchihugi, 1971)**

**Table 3 New landslide rate for various return period rainfalls**

| Watershed | *R* | 345 mm | 603 mm | 504 mm |
|---|---|---|---|---|
| | Watershed area (m$^2$) | Toraji typhoon | Mindulle typhoon | Aere typhoon |
| Bi-Tan creek | 8,694,095 | 5.17% | 1.65% | 2.01% |
| Ji-Ler creek | 87,846,882 | 2.46% | 0.77% | 1.14% |
| Dern-Shan creek | 14,048,381 | 13.65% | 1.64% | 2.40% |
| Pi-Ya-Sun creek | 37,154,904 | 9.06% | 2.79% | 3.24% |
| Wu-Min creek | 2,106,447 | 27.06% | 4.92% | 4.75% |
| Ju-Lian-Pin creek | 7,594,847 | 11.16% | 2.50% | 2.72% |

induced by Chi-Chi earthquake was not considered in Table 3, because Uchiogi's empirical model was only suitable for rainfall events. Table 3 also shows maximum one day rainfall (*R*) from typhoon Toraji, Mindulle and Aere at Shangkukuan station (1990-2004) nearby the study region (Ku *et al.*, 2006; NCDR, 2004; WRAP, 2005). Due to lack of actual critical rainfall (*r*) for landslide in the region, the critical rainfall (*r*) was assumed as 150 mm according to the work of Chen (1994) at A-Li-Shan Mountain of Taiwan and JSECE (1993) in Japan. Furthermore, the rainfall frequency in different return period of this study area is shown in Table 4 (Ku *et al.*, 2006). Therefore, the regression Eq. (1) could be obtained and the results of parameter *K* were listed in Table 5.

Based on Eq. (1), the total area of new landslide induced by next heavy rainfall (200-year return period rainfall) will be approximately 4 million m$^2$ in the study region (see Table 5). The results show that new landslide area of Pi-Ya-Sun creek nearby Chingshan office is the largest quantity. Due to the limited data, although Uchiogi's model has been adopted to estimate new landslide area in the future, it is still difficult to calibrate the model's parameters (critical rainfall for landslide *r* and site specific coefficient *K*). Therefore, it is necessary to monitor the long-term changes for landslides induced by heavy rainfalls.

**Table 4 The return periods for rainfall (mm) (Ku *et. al*, 2006)**

| Return period | 5 year | 10 year | 20 year | 25 year | 50 year | 100 year | 200 year |
|---|---|---|---|---|---|---|---|
| Average | 291 | 355 | 420 | 441 | 507 | 575 | 646 |

Note: Considering Chingshan (1940-1945,1949-1999) and Chiayang mountain (1967-2002) rainfall monitoring stations.

**Table 5 New landslide area in various return period rainfall (10$^3$ m$^2$)**

| Return period / Watershed | *K* | 5 year | 10 year | 25 year | 50 year | 100 year | 200 year |
|---|---|---|---|---|---|---|---|
| Bi-Tan creek | 0.128 | 22 | 47 | 94 | 142 | 201 | 274 |
| Ji-Ler creek | 0.058 | 101 | 214 | 431 | 649 | 920 | 1,253 |
| Dern-Shan creek | 0.135 | 38 | 80 | 161 | 242 | 343 | 467 |
| Pi-Ya-Sun creek | 0.152 | 112 | 237 | 478 | 720 | 1,020 | 1,389 |
| Wu-Min creek | 0.225 | 9 | 20 | 40 | 60 | 86 | 117 |
| Ju-Lian-Pin creek | 0.135 | 20 | 43 | 87 | 131 | 185 | 252 |
| Total | | 303 | 641 | 1,291 | 1,944 | 2,755 | 3,752 |

### 5.3 Long-Term Prediction of Riverbed Scour and Deposition

How long will it take for the slopes to be stable after Chi-Chi earthquake took place? There are no actual and better answers for the prediction up to now. Actually, it is a lack of long-term data to establish the relationship between the discharge and the total sediment load and to simulate the future tendency of riverbed scour and deposition. Therefore, the case history of the change of landslides after 1923 great Kanto earthquake (M 7.9) from 1896 to 1980 in Japan was referred in this study. The numbers of landslides kept on the high peak more than 15 years after Kanto earthquake (Nakamura *et al.*, 2000); it took more than 40 years to reduce the numbers of landslides to the stable condition (shown as Fig. 15). The relationship between the rate of landslide reduction and time was established as shown in Fig. 16 and the regression equation as follows.

$$R_1(T) = \frac{0.9405}{1 + \exp\left[-\frac{(T - 21.2082)}{3.5204}\right]} \tag{2}$$

where $R_1$ is the rate of landslide reduction based on maximum numbers of landslides shown in Fig. 15 (1 = 100%), *T* is the time (year).

Furthermore, in order to predict the future tendency of sediment yields transported in Ta-Chia river, the computer program HEC-6 developed by the US Army Corps of Engineers' Hydrologic Engineering Center (HEC) was adopted to simulate the situation of the riverbed. HEC-6 is a one-

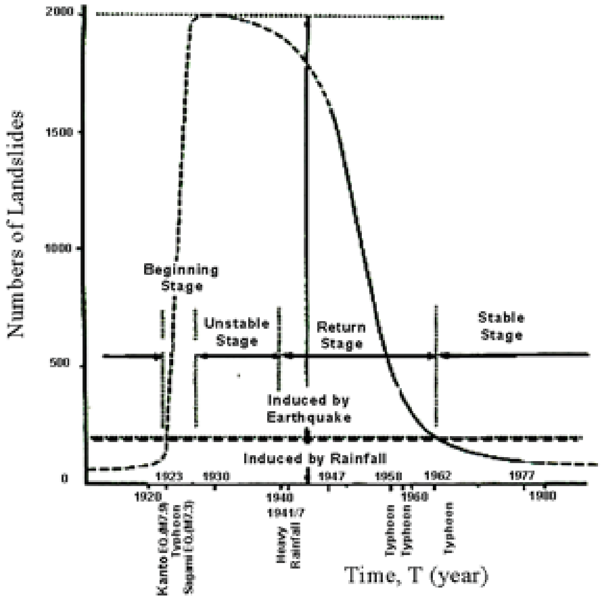


**Fig. 15 The change of landslides after Kanto earthquake from 1896 to 1980 (redrawn from Nakamura *et al.*, 2000)**

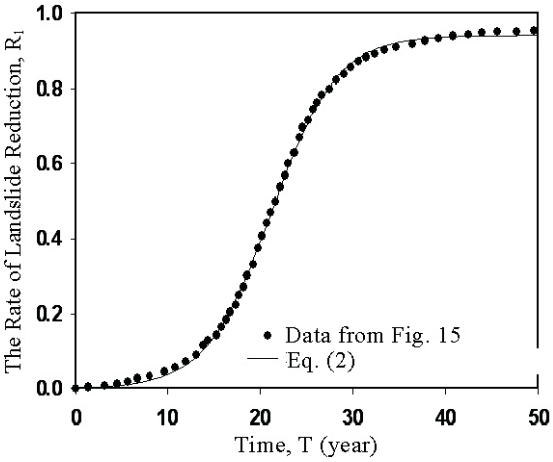


**Fig. 16 The relationship between the decreasing rate of landslides and time**

dimensional moving boundary computer code designed for open channel flow to simulate the changes in river profiles resulting from scour and/or deposition in rivers (USACE, 1993). Three main input data groups for HEC-6 model are geometry data, sediment data and discharge hydrograph. The elevation mass points, cross section, bed forms, and other physical characteristics of the river were obtained from remote sensing images, DEMs and site survey, *etc*. The river was divided into sections with approximate 100 meters per section and the geometries of 150 cross sections were input in HEC-6 model for analyses. The input data of stage 4 after Mindulle typhoon (initial condition) and stage 5 after Aere typhoon (calibration target) were adopted in the analyses, and the sediment transportation processes were simulated using Yang equation (1973). Figure 17 shows the results of numerical simulation and field survey at stage 5, the mean error of riverbed elevation was about 22 cm for 150 cross sections.

The cross section between Chingshan switchyard and Chingshan office was chosen for demonstration. It is important to assume the relationship between the future discharge and the total load after Chi-Chi earthquake. The rate of sediment discharge reduction ($R_2$) based on the condition of stage 5 after Aere typhoon was chosen to be 0%, 20%, 40%, 60%, 80%, and 90%, respectively. Hence, a polynomial to predict the annual average height of sediment, $H(R_2)$, could be developed by the different conditions of sediment discharge. The $H(R_2)$ is a regression equation of rate of sediment discharge reduction (illustrated as Fig. 18), and the polynomial shown as follows:

$$H(R_2) = 1.185 - 2.410\,R_2 + 5.217\,R_2^2 - 4.476\,R_2^3 \qquad (3)$$

where $H$ is annual average height of sediment (m), $R_2$ is the rate of sediment discharge reduction (1 = 100%).

Furthermore, if the reduction tendency of sediment discharge was assumed to be similar with landslides after large earthquake, then $R_2$ in Eq. (2) would be replaced by $R_1$ in Eq. (3). Therefore, the height of sediment ($H$) would be a function of time ($T$). The regression of the height of sediment show good agreement with HEC-6 simulation.

The detailed hydraulic modelling procedures are not shown here due to page limitation. In the condition that large earthquake will not take place in the future, the annual average height of sediment will reduce with time increasing as shown in Fig. 19 and the sediment after 30 years will be flushing in the Ta-Chia main river. Therefore, future condition of the Ta-Chia main riverbed could be predicted and simulated by Eq. (3). Table 6 lists the scour and deposition of riverbed between Chingshan switchyard and Chingshan office. Ta-Chia main river between Chingshan switchyard and Chingshan office could still deposit in the next 50 years, if the assumption is reasonable and the site will never be dredged in the future.

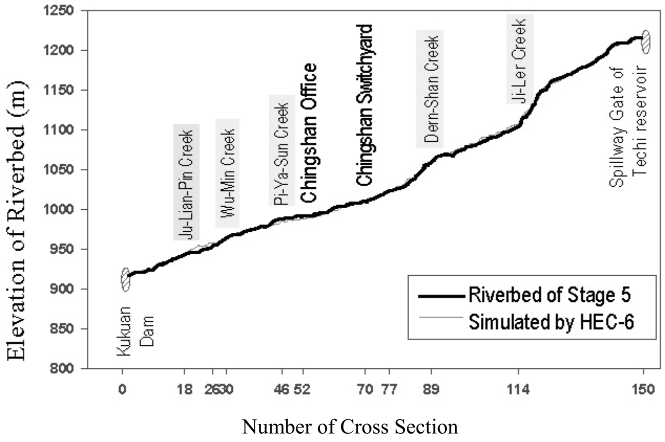


**Fig. 17 Comparison with the riverbed of stage 5 and the result simulated by HEC-6**

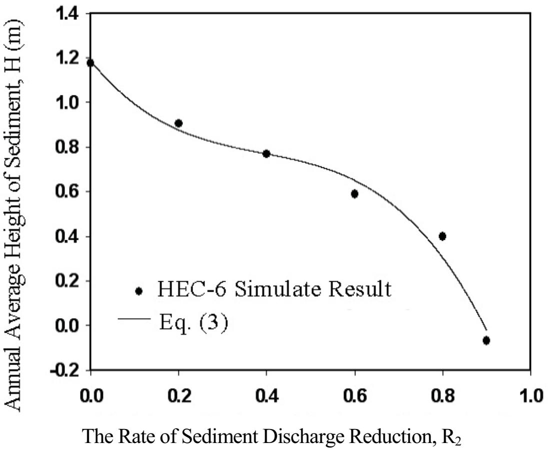


**Fig. 18 The relationship between annual average height of sediment and the rate of sediment discharge reduction**

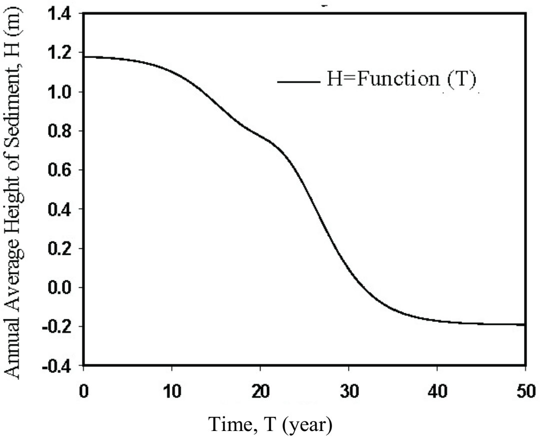


**Fig. 19 The assumed height of sediment against time**

**Table 6 The height of sediment of riverbed nearby Chingshan plant (m)**

| *T* (year) | 10 | 20 | 30 | 50 |
|---|---|---|---|---|
| The height of sediment deposit (m) | 11.6 | 20.9 | 25.7 | 23.1 |

## 6. CONCLUSIONS AND SUGGESTIONS

This paper presents an evaluation technique that can identify grohazards of landslides and sediment yield from remote sensing images, and can estimate the area and the volume of landslides based on the elevation changes of multi-temporal DEMs. The methods to predict new landslide area generated and long-term riverbed scour and deposition in the future were also described and discussed. The conclusions and suggestions were obtained from the case study of the landslides and sediment yields induced by Chi-Chi earthquake and followed typhoons.

(1) It is obvious that Chi-Chi earthquake induced the greatest majority of landslides than the heavy rainfalls. However, the heavy rainfalls induced the hung amounts of sediment yields in riverbed. After followed typhoon events, maximum elevation change of the riverbed was situated between Chingshan office and Chingshan switchyard; the change of elevation was more than 20-m height and the width of the river increased from 40 m to 150 m.

(2) The summation of the new landslide areas induced by different disastrous events was about 24 million m$^2$, and Chi-Chi earthquake generated the new landslide at least 5 times than the other disastrous events. The total volume of landslides induced by Chi-Chi earthquake and the followed heavy rainfalls were estimated about 50-70 millions m$^3$. There is 60% of the total volume induced by Chi-Chi earthquake and the rest by the followed typhoons events.

(3) Even though the typhoon caused some new landslides, the area and volume of new landslides became smaller and smaller in the study region. It seems that the geological condition will be gradually stable in the future.

(4) The total area of new landslide induced by 200-year return period rainfall is approximately 4 million m$^2$ in the study region.

(5) It is difficult to handle the huge amount of sediment yields remained in the main river. It is impractical to remove the total sediment yields considering large quantities of colluviums will remain in the tributary watersheds, which would be transported to the main river channel in the next heavy rainfall events.

(6) The sediment yields will still be generated and transported by the next heavy rainfalls. Therefore, it is more important to conduct a long-term monitoring plan on the situation of the landform and the river as well as to rebuild the stations for collecting the information of the rainfalls, discharges, and suspended loads.

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