16 Aug 2008, 8:45am - 12:30pm

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6th International Conference on
Case Histories in Geotechnical Engineering, Arlington, VA, August 11-16, 2008

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ABSTRACT

The Chi-Chi earthquake and subsequent typhoon events induced severe landslides and debris flows in the watershed of Tachia river. It inflicted severe damage to the power generation facilities and highway links. For the rehabilitation planning, quantitative assessment of landslides, debris flows and river deposits were conducted by using aerial photos and satellite images obtained at six stages of earthquake and typhoon events. The future trends of landslide and debris flow were also investigated by using empirical models. The long-term deposition or scouring was also conducted by numerical simulation. The results show that over 50,000,000 to 70,000,000m^3 of sliding volume were induced in the Chi-Chi earthquake and subsequent typhoon events during 1999 to 2005. By conservative estimation, 60% of the debris still remain in the watershed, which will cause silting of the main river channel in the future. The deposition in the main river channel will increase with decreasing rate in the future, and river channel scouring is not expected to occur in the future 20 to 30 years.

INTRODUCTION

Hydropower in Tachia river basin was most efficiently by constructing 6 reservoirs and power generation facilities. With total installation capacity of 1,100,000 KW and annual power generation of 26 Gwh, it is one of the most important peak generation stations of Taiwan Power Company’s electric power supply system.

During the catastrophic 1999 Chi-Chi earthquake in central Taiwan and subsequent typhoon events, including Toraji typhoon in 2001, Mindulle typhoon and Aere typhoon in 2004 and Haitang typhoon in 2005, widespread landslides and debris flows occurred in the watershed. Huge volume of colluvium and sediment silt up the river channel. These geohazards destroyed most of the power generation facilities in the river basin. The major power generation facilities in the basin are shown in Fig. 1.

In order to assess the impact of geohazards on the hydropower generation facilities for the rehabilitation planning, comprehensive investigations on landslides and transportation of sediment yields in the catchment area between Techi dam and Maan dam were conducted. This paper presents the results of these studies.

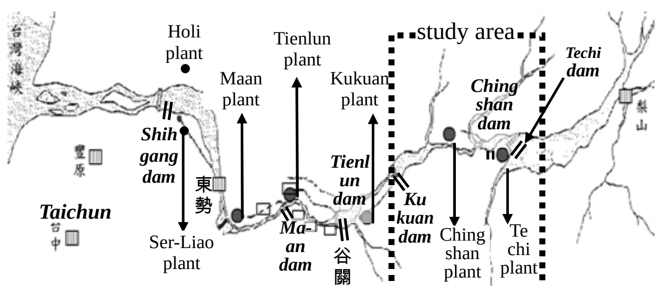


Fig. 1. six reservoirs and seven power plants along the Tachia river

ENVIRONMENT AND BACKGROUND

Topography and Geology

The study area of the Tachia river basin, starting from upstream Techi dam to the Maan dam downstream, covers a total catchment area of 181.6km^2. It is located in a mountainous region of Central Mountain Range of Taiwan with numerous peaks over 3000m high. The main river channel runs through very rough terrain with average river bank slope over 40 degrees.

The rock formation of the study area belongs to the central portion of Hsuehshan Range consisted mainly of Tachien sandstone of Eocene age and Chiayang layer of Eocene to

Oligocene age. Tachien sandstone is a very strong, thick bedded, metamorphosed rock. Chiayang layer, on the other hand, is thick layered, black or dark grey slate with well-developed cleavage.

With such geologic setting and topographic conditions, most of the landslides are associated with block sliding of heavily relieved steep slopes or surfacial sliding of weathered rocks or colluvium deposits.

Hydrology and Meteorology

The annual rainfall in the study area is about 2500 to 3000mm. The rainfall is almost concentrated in May to September, and associated with typhoon event. Daily rainfall over 500mm is quite common during a typhoon.
In this study, rainfall records at 31 meterologic stations, peak flood discharge records at 3 measurement stations and suspend load records at 2 measurement stations in the Tachia river basin were collected. The information colleted were used for establishing the rainfall pattern, peak flood discharge and suspend-load discharge for the analysis of sediment yield transportation.

GEOHAZARD INVESTIGATION

In order to evaluate the landslides and sediment yields transported in the river channel, aerial photos and SPOT2 , SPOT4 or SPOT5 satellite images at 6 stages were collected. The stages and the associated events are listed in Table 1.

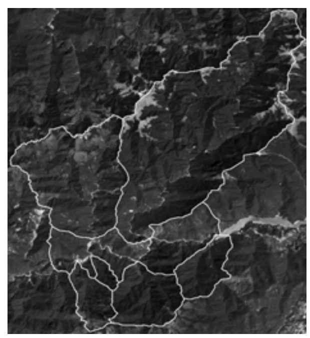
Table 1. Stages of Remote Sensing Image collected for this study

Stage	Image Date	Event	Rainfall Record
1	1999/04/01	Before Chi-Chi EQ	-
2	1999/10/31	After Chi-Chi EQ	-
3	2001/11/18	After Toraji typhoon	R_{max}=234mm R_{3day}=239mm
4	2004/07/21	After Mindulle typhoon	R_{max} =618mm R_{3day} =1000mm
5	2004/10/12	After Aere typhoon	R_{max} =314mm R_{3day} =411mm
6	2005/ -	After Haitang typhoon	R_{max} =312mm R_{3day} =335mm

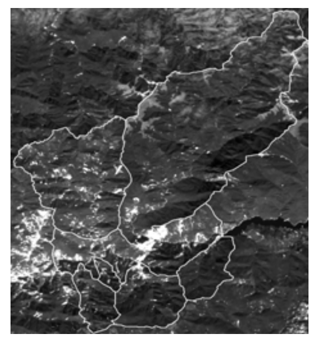
Landslides

Aerial photos were adopted to identify and quantify the landslides. The SPOT images of the study area at 4 stages are shown in Fig.2. The migrations of landslide areas at different stages are clearly shown in the images. It may be seen that most of the slides were triggered by the Chi-Chi earthquake. Mindulle typhoon, which has the heaviest rainfall in recent years, contributed significant increase in landslide area and transportation of sediments.

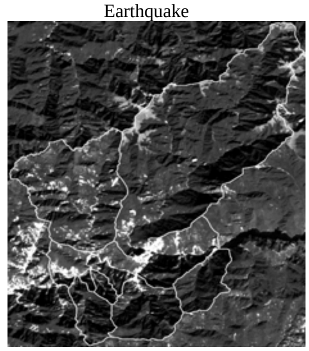
Quantitative assessments of landslides and debris flows were made by using the elevation changes in DTMs at different stages and verified by field reconnaissance. The results of landslide area at different stages for Tachia main river basin as well as several main sub-watersheds are shown in Fig. 3. This further confirms the migrations of landslide at different stages. This may also be seen from the new landslide areas at different stages as depicted in Fig. 4. The results also show a stabilizing trend as the new sliding areas decrease with subsequent events.



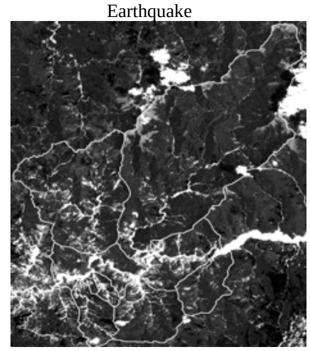
1999/04/01,Before Chi-Chi Earthquake



1999/10/31,After Chi-Chi Earthquake



2001/11/18,After Toraji Typhoon



2004/07/21,After Mindulle Typhoon

Fig. 2. SPOT images of the study area at different stages

Debris Flow and River Silting

Huge amount of sediments were produced by landslides after strong shaking of Chi-Chi earthquake and subsequently transported from the sub-watersheds to Tachia river's main channel during heavy rainfall.

Almost all of the sediment yields were transported by debris flows, and Mindulle typhoon caused most severe debris flow in the watershed.

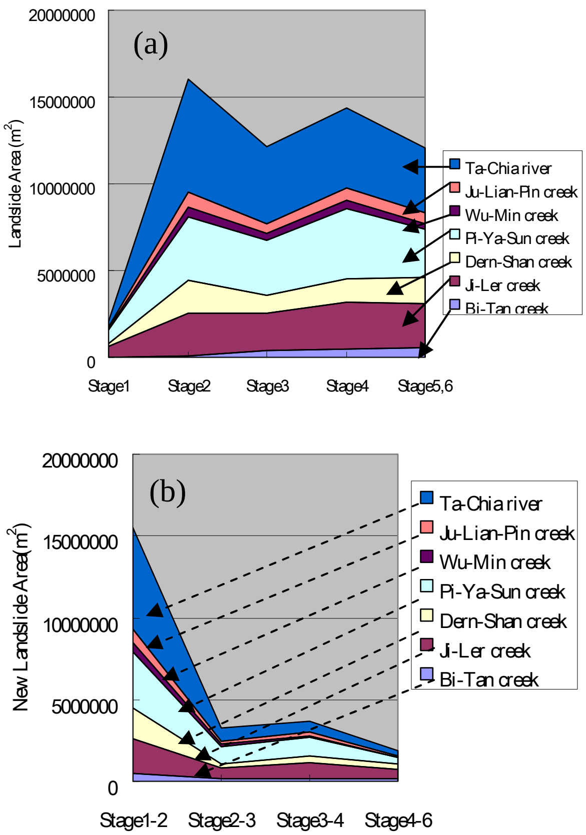


Fig. 3. (a)Total landslide areas and (b)new landslide areas after disastrous events

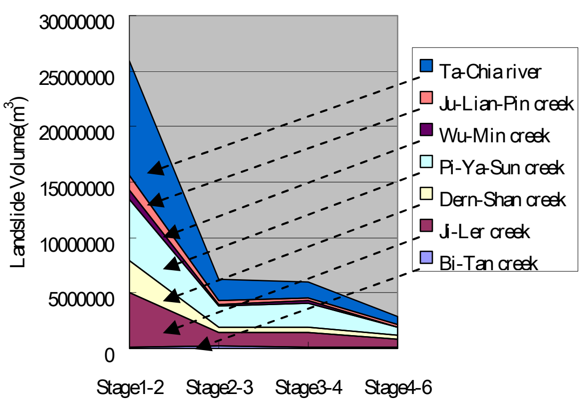


Fig. 4. Volume of landslides after disastrous events

The alluvium fans of debris flow at the tributary outlet always silted up the main river channel. Fig. 5 shows the geohazards of debris flow and silting near the Chingshan switchyard. The width of river channel increased from 50m before the Chi-Chi earthquake to 160～200m after Haitang typhoon. The total depth of deposit is over 18m.

The changes of riverbed elevation in the main channel from Techi dam to Maan dam at different stages are also shown in Fig.6. The maximum deposit occurred near the Kukuan powerhouse. Nearly 40 m of sediment accumulated over the years. This is illustrated by the changes of riverbed near the powerhouse in Fig. 7. The severe river channel silting essentially damaged nearly all of the power generation facilities in the basin.

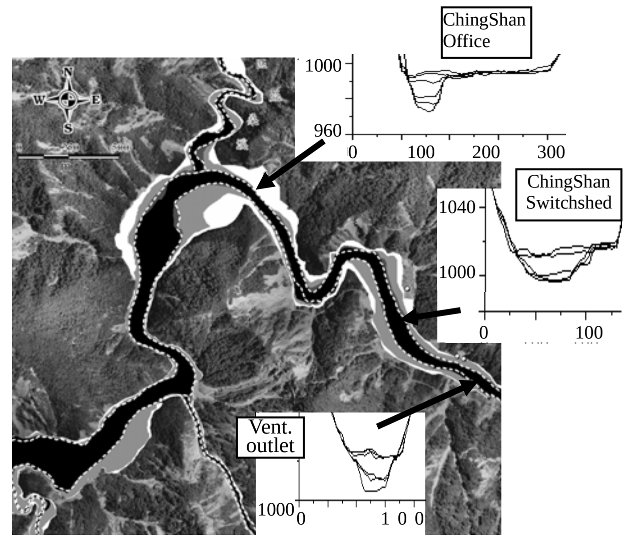


Fig. 5. River cross-sections at Chingshan switchyard, Ventilation outlet and Chingshan office.

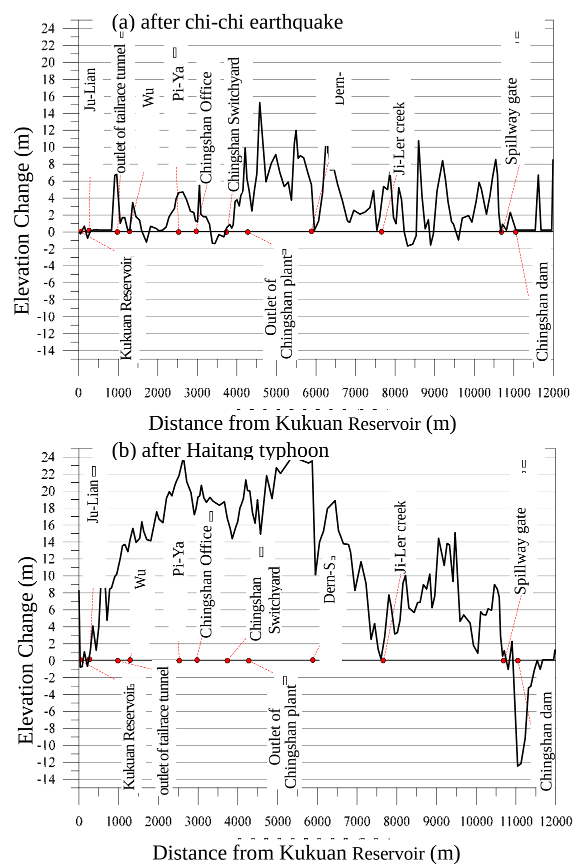


Fig. 6. Elevation of Tachia river's main channel: (a)after Chi-Chi earthquake and (b)After Haitang typhoon

(a)Before Chi-Chi Earthquake (b)After Chi-Chi Earthquake(1999)

(c)After Toraji Typhoon(2001) (d)After Mindulle Typhoon(2004)

Fig.7. Riverbed changes in front of Kukuan power house after the disastrous events

FUTURE TREND PREDICTION

Future trends of landslide and debris flow occurring and river channel deposition are important for the planning of rehabilitation of hydropower generation facilities in the river basin. Estimations of new landslide area and volume of debris flow induced by heavy rainfall in the future were made by using empirical method calibrated by the actual data collected. Also the long-term prediction of river channel deposition and scouring was conducted by using numerical simulation.

Estimation of New Landslide

In this study, the empirical method proposed by Uchihugi（1971）was adopted to predict the new landslide area of each sub-watershed. A modified model in the following form was used.

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

(1)

where Y=new landslide raito, C_a=new landslide area, a=watershed area, K and C = site specific coefficients, R=maximum daily rainfall, and r=critical rainfall for landslide to occur.

The landslide information for each sub-watershed at Toraji, Mindulle and Aere typhoon events were used to calibrate the model coefficients. The critical rainfall for landslide of 150mm per day was adopted from Cheng（1994）. The predicted average new sliding rate in the study area under the rainfall of a 200 year return period will be around 2-4 %. However, this is considered to be a conservative estimate due to the tendency of stabilization in slope observed. More recent information are needed for a better estimation.

Estimation of Debris Flow Volume

The estimation of debris flow volume adopted the modified empirical formula proposed by Hsieh（2000）, which takes the following form.

$$Vs = k\,(R-r)\,A^{0.61} \qquad (2)$$

where Vs=debris flow volume, k=site specific coefficient, R=daily rainfall, r=critical daily rainfall for the triggering of debris flow and 200mm was adopted based on the guideline proposed by Soil and Water Conservation Bureau, A=sub-watershed area. Actual measured debris flow volume for each sub-watershed was used to calibrate the site specific coefficient of the model.

The estimated volumes of debris flow in several important sub-watersheds are shown in Fig. 8. Again, due to the tendency of stabilization in slope, the source of debris should decrease with time. The estimated volume is considered to be conservative. More recent information are needed for a better estimation.

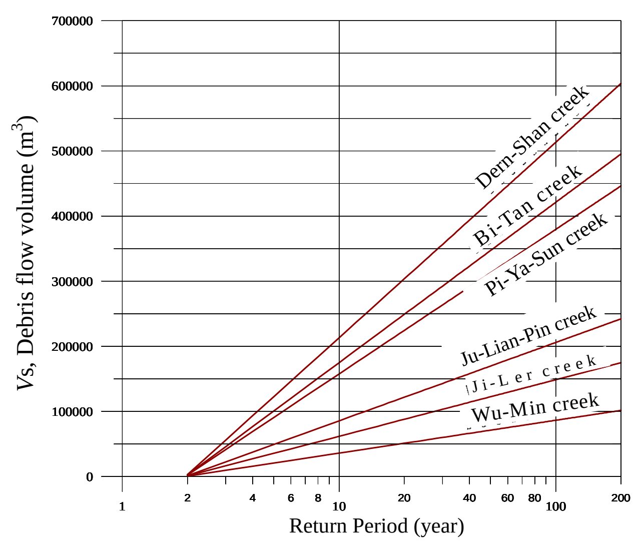


Fig. 8. Estimation of debris flow volumes

Prediction of Long Term River Channel Deposition and Scouring

The Computer program HEC-6 developed by US Army Corps of Engineers（1993）was adopted for simulating the long-term river channel deposition and scouring. In the simulation, the experience of landslide after 1923 great Kanto earthquake (M7.9) in Japan was considered. The number of landslides kept at peak value for more than 15 years after earthquake. It took more than 40 years to decrease to a stable condition. The change of landslide after Kanto earthquake is illustrated in Fig. 9. The measured riverbed elevations of main channel after Aere typhoon were used to calibrate the input parameters of the model.

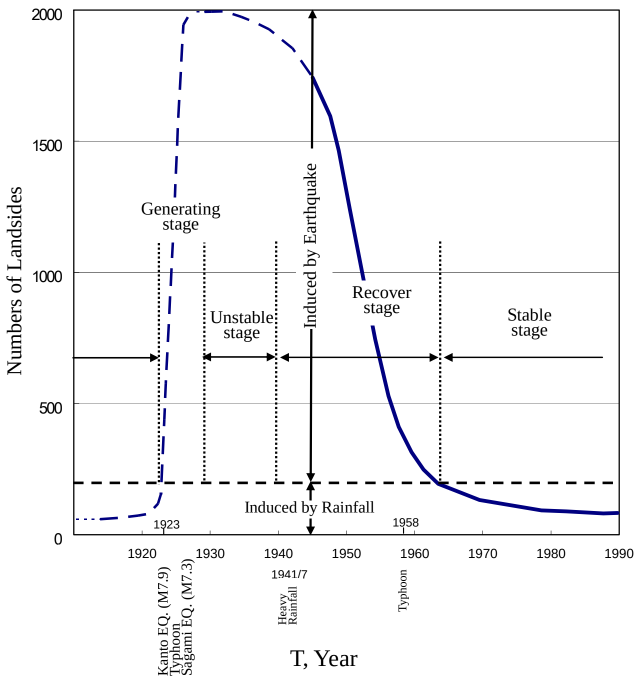


Fig. 9. Change of landslide after Kanto earthquake from 1896 t0 1980(redrawn from Nakamura et al, 2000)

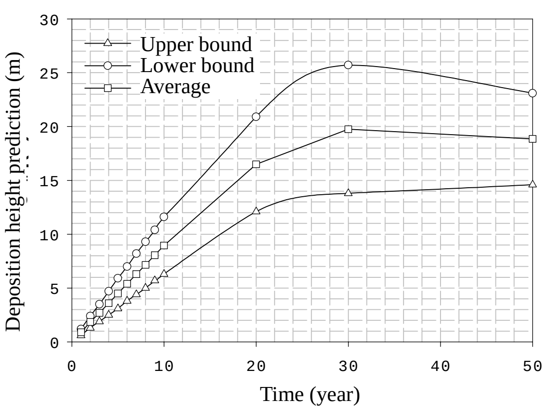


Fig. 10. Future trend of river deposition near the Chingshan power station

Fig. 10 Shows the future trend of river deposition near the Chingshan power station. The results show that with the assumption of no large earthquake will occur in the near future, the annual average height of deposition will decrease with time. Still, maximum deposition of 25.7m near Chingshan power station will be accumulated in the future 30 years. Afterwards, scouring will occur steadily with time.

CONCLUSIONS

The geohazards in Tachia river basin triggered by the Chi-Chi earthquake and subsequent typhoon events caused severe damage to the hydropower generation facilities in the basin. The magnitude and severeness are rather extraordinary. It caused tremendous difficulty in the rehabilitation of the power generation facilities. This paper presents the evaluation methods for identifying the geohazards of landslide and debris flow using multi-stage remote sensing images obtained. The methods of estimating future landslide, debris flow and river channel deposition and scouring are also presented. The conclusions drawn from this case study are as follows：

(1) The Chi-Chi earthquake caused most of the landslides in the study area than subsequent typhoon events. However, heavy rainfall induced the transportation of sediment yields which caused severe silting of river channel and damage to the hydropower facilities.

(2) Even though the subsequent typhoon events caused new landslides, the volume of slide tends to decrease with time. The trend of stabilization is important for the rehabilitation planning for the hydropower facilities.

(3) It was conservatively estimated that about 60% of the debris still remain in the watershed. Transportation of the sediment yields will cause increasing deposition in main river channel over a rather long period of time. Conservative estimate shall be facilitated in the design of hydropower facility rehabilitation.

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