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Chi-Chi Earthquake Induced Landslides in Taiwan

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ABSTRACT

Liao [1] pointed out that Chi-Chi earthquake caused about ten thousand landslides to the area, each of which is larger than 625 square meters and that the total area of the landslides exceeds a hundred square kilometers. In their paper on the geotechnical hazard caused by Chi-Chi earthquake, Lin, Liao, and Ueng [2] showed that almost all of the slope failure sites are located to the right of Che-Lung-Pu fault (Fig. 1). However, for those landslides of fault scarp failures, the sliding (or falling) mass moved to the western direction of Che-Lung-Pu fault.

Among all the landslides triggered by Chi-Chi earthquake, the most catastrophic and dramatic four will be discussed in greater detail. They are: Tsao-Ling rockslides, Juo-Feng-Err-Shan dip slope failure, stripping of Juo-Juo-Fong (99 peaks), and the Ku-Kuan to Te-Chi section (mileage 34K to 62K) of the Central Cross-Island Highway.

Case studies on the Tsao-Ling rockslides and the Juo-Feng-Err-Shan dip slope failure reveal that the chance of reoccurrence is very high for those huge scale landslides.

Many highway slopes have been weakened, or even fractured, by the shaking of Chi-Chi earthquake. Rock-falls occurred during subsequent aftershocks and new earthquakes. Debris flows happened from time to times due to heavy rainfalls in February 2000 and April 2000.

INTRODUCTION

Based upon his analysis on satellite (Spot) images and aerial photo, Liao [1] pointed out that Chi-Chi earthquake caused 9,272 landslides to the area, each of which is larger than 625 square meters and that the total area of the landslides is 127.8 square kilometers. More than 21 teams, mainly professors from universities, were mobilized by the National Center for Research on Earthquake Engineering (NCREE) and the Office of the National Science and Technology Program for Hazards Mitigation (NAPHM) to carry out phase-I field investigations on the landslides. All the teams were provided with satellite (Spot) images and aerial photos of the study area. 436 landslide cases were

reported to NCREE and NAPHM. NCREE, NAPHM, and the Taiwan Geotechnical Society (TGS) published a report of the investigations jointly in February 2000. Phase-II investigations (January 2000 to June 2000) for some major landslides were sponsored by NCREE and NAPHM. The author's team was responsible for the Tsao-Ling Rockslides. In their paper on the geotechnical hazard caused by Chi-Chi earthquake, Lin, Liao, and Ueng [2] gave a very brief summary of the investigation results of slope failures. They pointed out that almost all of the slope failure sites are located to the right of Che-Lung-Pu fault (Fig. 1). However, for those landslides of fault scarp failures, the sliding (or falling) mass moved to the western direction of Che-Lung-Pu fault.

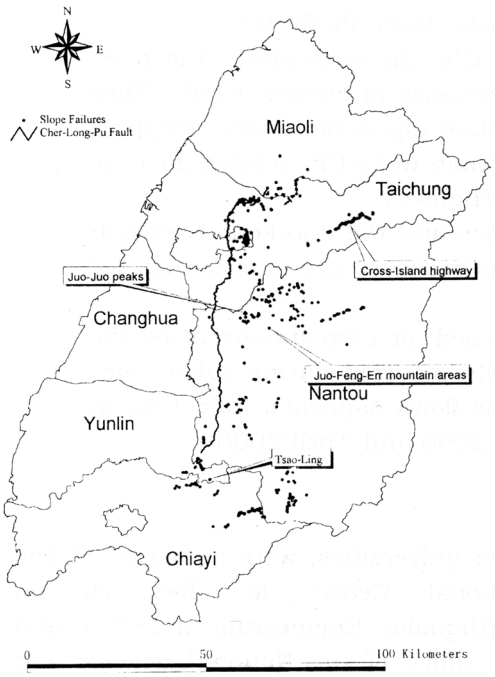

Fig. 1 The distribution of landslides induced by Chi-Chi earthquake (Courtesy of Professor Lin, Meei-Ling and Dr. Chen, Tien-Chien)

Among all the landslides investigated, four of them are really catastrophic and dramatic. They are:

* Tsao-Ling rockslides
* Juo-Feng-Err-Shan dip slope failure
* Stripping of Juo-Juo-Fong (99 peaks)
* Ku-Kuan to Te-Chi section (mileage 34K to 62K) of the Central Cross-Island Highway

In this paper, we shall highlight the four cases. Please refer to Fig. 1 for their locations.

TSAO-LING ROCKSLIDES

The Tsao-Ling area is located in the Foothill Region of central Taiwan (Fig. 1). Catastrophic dip slope failures occurred in 1862 (pre-historical, earthquake), 1941 (earthquake), 1942 (rain), 1979 (rain), and 1999 (Chi-Chi earthquake). Break of landslide dam took place in 1898 (pre-historical), 1951 (rain), and 1979 (rain). A large number of papers and reports on the case of Tsao-Ling have been published [1~16].

The pre-historical event of dip slope failure and the formation of a landslide dam on 6th June 1862 was said to have been caused by an earthquake of magnitude 6 to 7. It was also said that the landslide dam broke in 1898.

On 17th December 1941, a rockslide involving a mass movement of more than 100-million cubic meters on the dip slope forming the southwest flank of Mt. Tsao-Ling was triggered by a strong earthquake in central Taiwan. Figure 2 is a photo of Tsao-Ling rockslide area in 1941. On 10th August 1942, heavy rain caused another rockslide on the same slope. More than 150-million cubic meters of rock mass slid down the dip slope. The Ching-Shui River was

dammed with rock debris. Figure 3 is the reconstructed central profiles of 1941 and 1942 rockslide events.

Following a 5-days rainfall with cumulative precipitation of 776mm, the landslide dam (140m to 200m high, 4,800m wide at base) was overtopped on 18th May 1951 and the retained water (120-million cubic meters) was suddenly released. 137 army engineers, who were preparing the spillway on top of the landslide dam, lost their lives. 1,200 houses downstream were destroyed. The torrents of the released water flooded 3000-hectares of arable land.

In December 1976, the author visited Tsao-Ling for the first time. He also interviewed old people at the same time. They reported the 1862 event and the 1898 event told by their ancestors.

On 15th August 1979, heavy rain caused a breakaway failure (5-million cubic meters in volume) from the lower part of the remaining slope. The slide mass, of 5-million cubic meters in volume, collided with the remaining part of original landslide dam. The Ching-Shui River was once again dammed. Following 2-days rainfall with cumulative precipitation of 624mm, the landslide dam (90 meters in height) was overtopped on 24th August 1979. Two bridges downstream were destroyed. Fortunately, there were no casualties at all due to continuous monitoring and warning on radio broadcasting. The reconstructed central profile of the 1979 rockslide event is shown in Fig. 4. The sliding plane of the 1979 rockslide was in Chin-Shui shale formation.

During the 21st September 1999 Chi-Chi earthquake (M = 7.3, CWB scale) event, a rock mass of about 120-million cubic meters slid down the Tsao-Ling dip slope. A schematic central profile is shown in Fig. 5. Figure 6 shows the central profile of the dip slope after the slide. The remaining dip slope consists of 4 steps (scarps). The dip angle measured on different steps of the dip slope ranges from 12 degrees to 14 degrees. Only 20% (about 25-million cubic meters) of the sliding mass dropped into the valley of the Ching-Shui River. Most of the sliding mass (of about 100-million cubic meters), and 39 people (36 residents and 3 visitors) who lived behind the crest (called Crest Forever) of the dip slope, flew over the Ching-Shui River, and landed on top of the remaining part of the old landslide dam (called "Dao-Giao-Shan" by local people). 32 people were killed and 7 survived after the 'sliding-flying-landing'

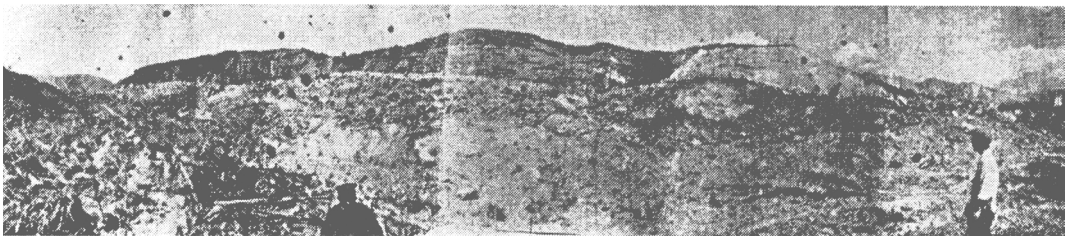

Fig. 2 Tsao-Ling rockslide area after 1941 rockslide caused by Chia-Yi earthquake on 17th December 1941, M = 7.1 [3]

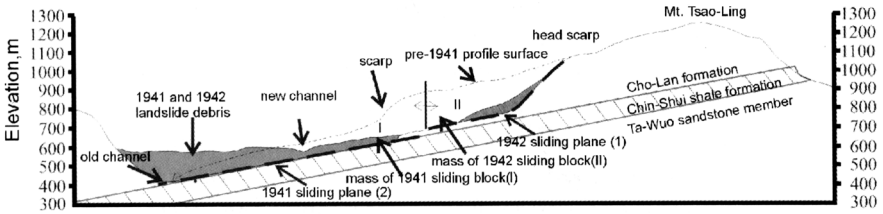

Fig. 3 Reconstructed central profile of 1941 and 1942 Tsao-Ling rockslide events

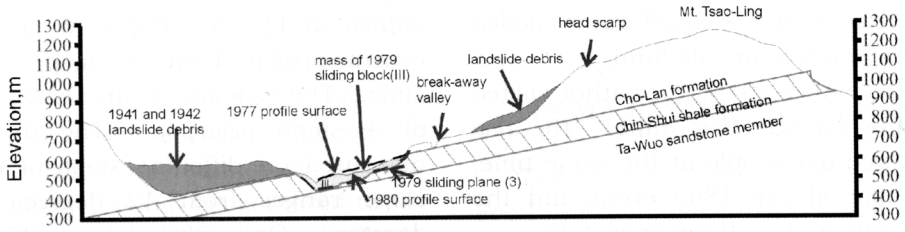

Fig. 4 Reconstructed central profile of the 1979 Tsao-Ling rockslide event

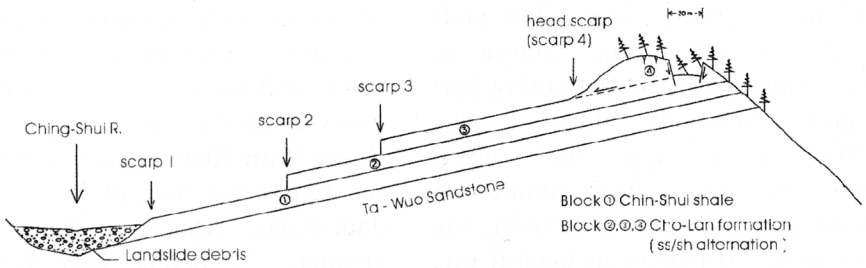

Fig. 5 A schematic central profile of the remaining Tsao-Ling dip slope after Chi-Chi earthquake (Courtesy of Sinotech Engineering Consultants, Ltd.). Not to scale

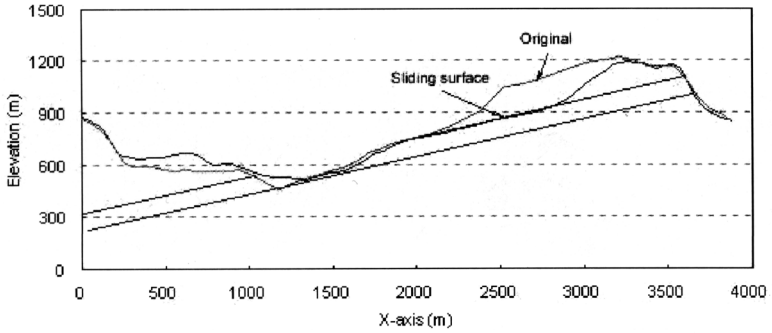

Fig. 6 The central profile of the 1999 (21st September) Tsao-Ling rockslide event (Courtesy of Professor Lin, Meei-Ling and Dr. Chen, Tien-Chien)

process. The wireless telephone in the van called Bao-Ma 747 (which traveled together with the 39 people) was used to report their situations to the office of Tsao-Ling Village. Figure 7 tells the story. Another 4 people in a lower corner of the dip slope were also killed. Stripping of a few hill-slopes downstream of the landslide dam has been observed. Air-blast or release of compressed air cushion under the sliding mass might be responsible for it. The Chin-Shui River was once again dammed after the sliding. The volume of the dam-up lake is about 45-million cubic meters. The straight-line length of the landslide dam measured 4 kilometers from upstream heel to downstream toe. The curved plug length of the Ching-Shui River channel is about 5 kilometers. The plug height of the Ching-Shui River valley is only 50 meters, which is much lower than that of the new Dao-Giao-Shan. Figure 8 is the satellite (Spot) image of Tsao-Ling area on 27th September 1999. Figure 9 is a photo showing (from left to right) a part of the Dao-Giao-Shan, the dammed valley of Ching-Shui River, and the lower section of the remaining dip slope, looking from the southeast, on 28th November 1999. The plugged section of the Ching-Shui River channel was modified (rip-rap, bulldozing, etc.) to allow for smooth and safe passage of the overflow that commenced on 22nd December 1999. Check dams are also constructed in the downstream sections of Ching-Shui River for safeguarding the people and the lands from being smashed by possible debris flow due to sudden break of the landslide dam. Figure 10 is a photo showing the bird's eye view of Tsao-Ling area on 29th June 2000. Direct field observation and photographs taken from the air (such as Fig. 10) have proved the existence of tension cracks and graben on top of the slope. Slope stability analysis reveals that sliding of the top block (i.e., block 4 shown in Fig. 5, app. 20-million cubic meters) is very likely. Dip slope failure of the rock mass above Chin-Shui shale (i.e., block 2, block 3 and block 4 together) is possible. People of Tsao-Ling village express their strong wish to keep the dam-up lake for tourism. The possibility of using the dam-up lake as a reservoir is also under discussion.

Fig. 7 A photograph which telling the story of a flying mountain, Tsao-Ling

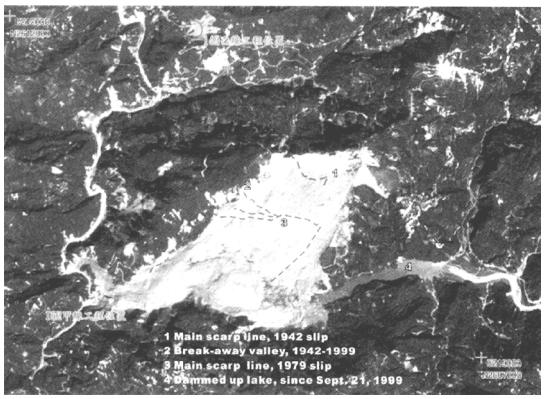

Fig. 8 Satellite (Spot) image of the Tsao-Ling area on 27th September 1999. Scarp line in red. (modified after National Central University)

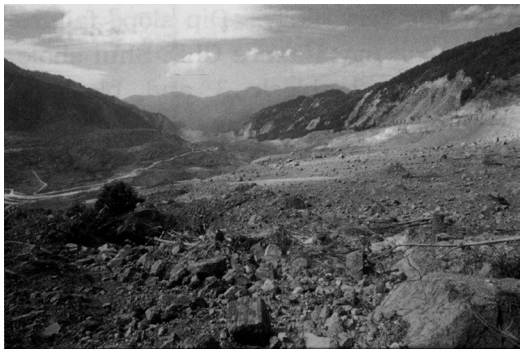

Fig. 9 A part of the Dao-Giao-Shan, the dammed channel of Ching-Shui River, and the lower section of the remaining dip slope, looking from the southeast, 28th November 1999

JUO-FENG-ERR-SHAN DIP SLOPE FAILURE

Another catastrophic landslide triggered by the Chi-Chi earthquake has been the Juo-Feng-Err-Shan dip slope (N35E/20SE) failure in Nantaou County. The size of the dip slope failure has been 200 hectares in area and 36-million cubic meters in volume. 39 people lost their lives during the sliding. The landslide debris dammed two small streams. The total volume of the two dam-up lakes is 1.9-million cubic meters. An emergency spillway has been excavated to direct the overflow water to a downstream river. Other protective structures are being constructed. Figure 11 is a photo of the site. Soon after the Chi-Chi earthquake, local people reported that landslide had occurred before at the same slope.

STRIPPING OF THE JUO-JUO-FONG (99 PEAKS)

The Chi-Chi earthquake caused severe damage of the Juo-Juo-Fong in Nantaou County. The direct translation of Juo-Juo-Fong is “99 peaks” or “99 hills”. Juo-Juo-Fong, having a total area of 950 hectares, consist groups of conglomerate (gravelly rock) hills. The 99 peaks stem out, from a common base of conglomerate formation, due to differential erosion. Before the Chi-Chi earthquake, all the surfaces of the 99 hills were covers with trees and grass. Total stripping (removal of all the tree and grass) of the 99 peaks took place during the earthquake shaking. Fragments of conglomerates came down together with the vegetation skin. Being so dramatic, the bareheaded Juo-Juo-Fong has become an attractive scenic spot (Fig. 12).

KU-KUAN TO TE-CHI SECTION (MILEAGE 34K TO 62K), CENTRAL CROSS-ISLAND HIGHWAY

The Central Cross-Island Highway (Taiwan Highway No. 8) stretches 188.4 kilometers across the foothills and the backbone-mountain belt in Taiwan. The Ku-Kuan (mileage 34K, elevation 750m) to Te-Chi (mileage 62, elevation 1,552m) section of the highway was constructed by cutting into the cliffs of a grandeur gorge. At Ku-Kuan dam site, a mountain (the Pai-Go-Ta-Shan) rises from 1,021m to 3,341m. The height of valley slope there is 2,230 meters. The gorge is composed of very strong and very hard metamorphic rocks. Yet, folding and faulting structures are

common due to mountain-building actions; pressure release joints are very well developed as a result of the valley process; fracturing of rock materials are intensive due to stress concentration.

In the aftermath of Chi-Chi earthquake, total destruction of the highway section from Ku-Kuan to Te-Chi is observed (Figs. 13 and 14). Misfortunes have not come to an end due to aftershocks of the Chi-Chi earthquake and the earthquake (M = 5.3 CWB scale) occurred on 17th May 2000. As to when will the highway be re-opened to the general public, nobody knows at the moment.

Taiwan Highway Bureau (THB) started the reconstruction operation on 23rd September 1999. The operation has been called off since the earthquake of 17th May 2000. The earthquake of May 2000 brought the highway back to what it was in September 1999. Since 21st September 1999, loss of human lives in the highway section has been 23 dead and 7 missing.

SECONDARY EFFECTS

Many highway slopes have been weakened, or even fractured, by the shaking of Chi-Chi earthquake. Rock-falls occurred during subsequent aftershocks and new earthquakes. Debris flows happened from time to times due to heavy rainfalls in February 2000 and April 2000.

The reconstruction of the Ku-Kuan to Te-Chi section (mileage 34K to 62K) of Central Cross-Island Highway has to be called off since the earthquake of 17th May 2000. There have been debates on whether the highway section should be reopened again.

CONCLUSIONS

Almost all of the slope failure sites are located to the right of Che-Lung-Pu fault. However, for those landslides of fault scarp failures, the sliding (or falling) mass moved to the western direction of Che-Lung-Pu fault.

Tsao-Ling rockslides, Juo-Feng-Err-Shan dip slope failure, stripping of Juo-Juo-Fong (99 peaks), and the Central Cross-Island Highway from mileage 34K to 62K, are really catastrophic and dramatic of the world scale. They should be further investigated, studied and monitored in the years to come.

Secondary effects of a strong earthquake, such as rock-falls and debris flows, can cause much troubles for the people living in the disaster area.

Case studies on the Tsao-Ling rockslides and the Juo-Feng-Err-Shan dip slope failure reveal that the chance of reoccurrence is very high for those huge scale landslides. This has to be taken into consideration as far as natural hazard mitigation is concerned.

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