Long term effects of landslides induced by catastrophic events

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ABSTRACT

Taiwan is located in the junction of tectonic plates, which causes complex and fragile geological conditions. The hazardous landslides induced by heavy rainfalls and severe earthquakes often occurred. The Chi-Chi earthquake occurred in 1999 caused severe landslide hazard in Taiwan. Years after Chi-Chi earthquake, landslides have repeatedly reactivated due to the effect of earthquake. In 2009, typhoon Morakot carrying heavy rainfall also induced severe landslide hazard. It was found that the landslide hazard remained at a severe condition for years after typhoon Morakot. It suggested a prolonged effect of catastrophic events such as Chi-Chi earthquake and typhoon Morakot, and study of the time series evolution of landslides and debris transportation would be essential for evaluation of the influences of such events on landslide disasters.

Keywords: long term effects; landslides; catastrophic event; landslide ratio; debris transportation

1 INTRODUCTION

Situating at the juncture of the Euro-Asian continental plate and Philippine Sea plate, the geological condition in Taiwan was fragile with more than 70% area as the mountain area. The frequent earthquakes and severe rainfalls by torrential rain and typhoons often cause landslides and debris flows. The Chi-Chi earthquake struck central Taiwan on September 21, 1999, with a local magnitude of 7.3. Strong seismic motions were observed, which induced severe landslide hazard. For years after the earthquake, continuous landslide hazard recurred and were related to the landslides caused by the earthquake. In 2009, typhoon Morakot carried heavy rainfall of as high as 3000 mm, which induced severe landslide hazard in southern Taiwan. Severe landslides and debris flow hazard continue to recur in the areas significantly affected by typhoon Morakot.

In both cases, the induced landslides recurred years following the catastrophic events, and they appeared to have a prolonged effect on sediment transportation and hazard mitigation. In order to understand the long term effects caused by such catastrophic events, the time series landslide information were collected and extracted using remote sensing images, and analysis was conducted. The extend and trend of variation of the prolonged effect were studied.

2 LANDSLIDES CAUSED BY CHI-CHI EARTHQUAKE

The Chi-Chi earthquake struck central Taiwan on September 21, 1999, with a local magnitude of 7.3, and a moment magnitude of 7.6. The earthquake was triggered by thrusting action of the Chelungpu fault with a fault rupture length of 105 km. Strong ground motions were recorded with the maximum peak horizontal ground acceleration of about 1 g, and the maximum peak vertical ground acceleration of 0.7 g. The distribution of the peak horizontal ground acceleration along with the locations of Chelungpu fault and epicenter were as shown in Figure 1 (Lin et.al. 2009). The earthquake induced extensive landslides covering a total area of more than 8,600 ha. and more than 30,000 cases of land-slides were mapped from SPOT satellite images and aerial photos taken after the earthquake. The data were carefully screened to be consistent with the topographic variations of landslides (Lin and Tung, 2004), and 31,702 cases were identified. The distribution of landslide events is as shown in Figure 2. Comparing Figures 1 and 2, the landslide distribution correlated with intensities of ground motion well and decreased with increasing distance to the epicenter and Chelungpu fault. The landslides induced by the Chi-Chi earthquake were mainly shallow landslides with steep slope angles, which composed about two third of the landslides based on the site reconnaissance as shown in Figure 3 (Lin, et.al. 2000).

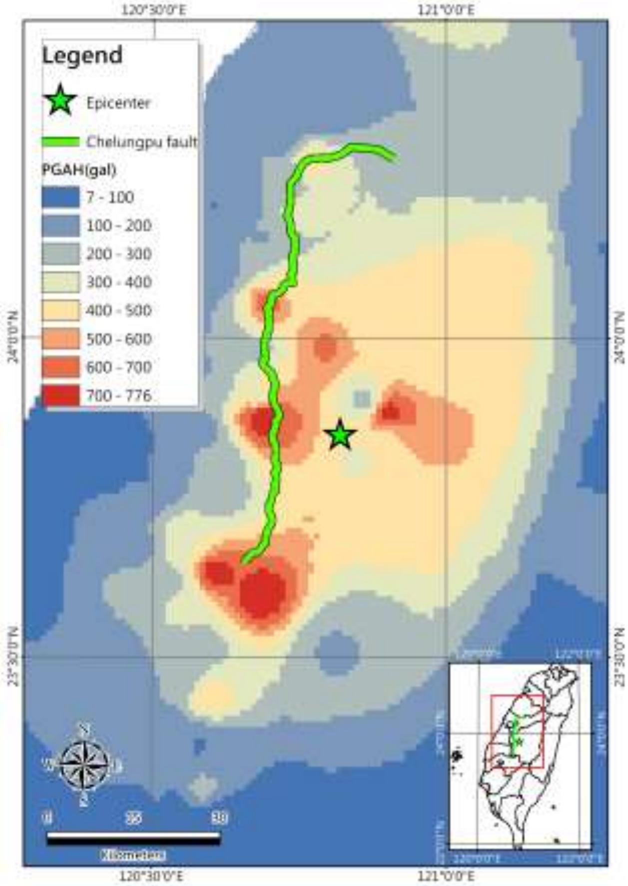

Fig. 1. Distribution of horizontal peak ground acceleration, epicenter, and Chelungpu fault.

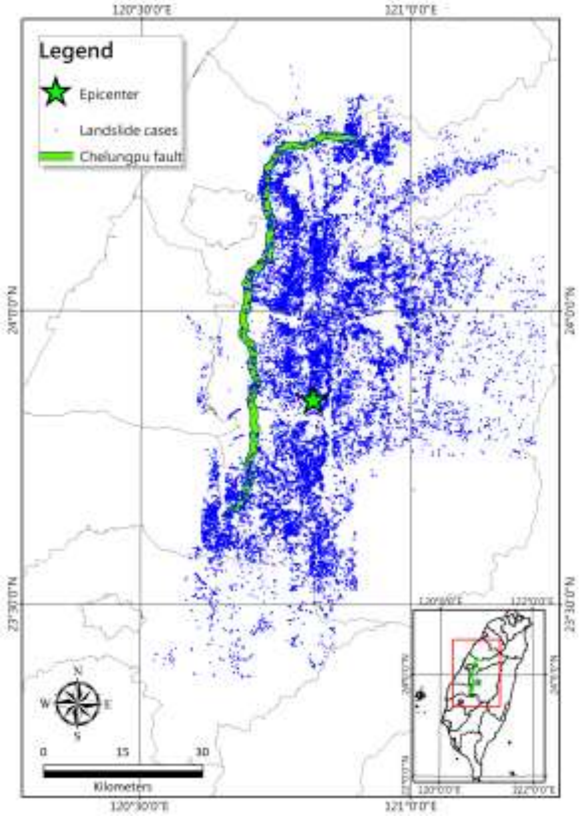

Fig. 2. Distribution of landslide events induced by Chi-Chi earthquake.

The shallow landslide on a steep slope was the typical characteristic of landslide failure induced by seismic motion (Lin, et.al. 2000, Miles and Keefer, 2000). The ground motion and landslide ratio decreased with increasing distance to the epicenter and fault. However, the abrupt ground ruptures and the near field effects were very significant, and both lead to exceptionally high values of ground acceleration especially in the vertical direction, which would affect the stability of slope severely (Lin, et.al. 2009a). The ground accelerations of each landslide event were computed by interpolation of the ground motion records from the neighboring strong motion stations. The distributions of the peak vertical and horizontal ground acceleration of the landslide events are as shown in Figure 4 with the threshold peak acceleration in horizontal and vertical of about 100 and 70 gal, respectively. The number of landslides increases rapidly with increasing peak ground acceleration as shown in Figure 4. It appeared that the intensity of ground motion might be the most important factor for causing landslides, and the vertical ground acceleration has a more significant effect than the horizontal ground acceleration.

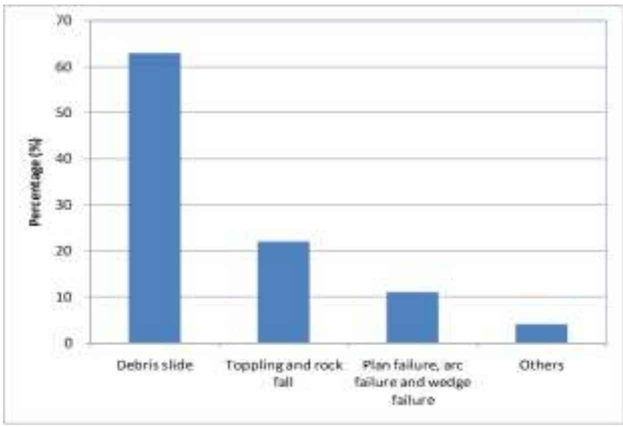

Fig. 3. Distribution of different types of slope failure caused by the Chi-Chi earthquake.

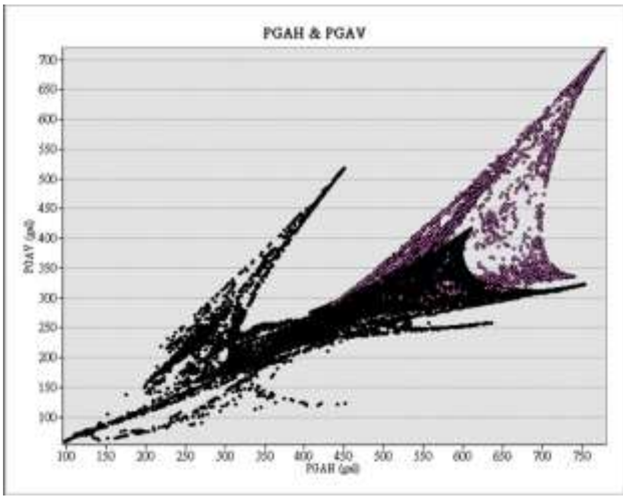

Fig. 4. Distributions of peak horizontal versus peak vertical ground accelerations of landslide caused by the Chi-Chi earthquake.

3 LANDSLIDES CAUSED BY TYPHOON MORAKOT

Typhoon Morakot approached Taiwan since August 6 and made a landfall on midnight of August 7 at Hua-Lien City of eastern Taiwan as shown in Figure 5. The Typhoon moved slowly and carried tremendous amount of rainfall. The rainfall started from August 5 to 11. In addition to the rainfall accompanying typhoon, the monsoon system from southwest direction was drawn in, dumping a tremendous amount of rainfall in southern Taiwan from August 8 to 9. The maximum accumulated rainfall recorded from August 5 to10 was at the A-Li-Shan station with a total accumulated rainfall of 3059.5mm. The distribution of the accumulated rainfall from August 6 to 11 is as shown in Figure 6. The figure shows that a very high amount of rainfall concentrated in southern Taiwan, which was induced by the monsoon system. Such tremendous amount of rainfall caused severe landslides and debris flow hazard in the southern area (Lin, et.al. 2009b). A total number of 1,349 landslide hazard cases and 46 debris flow hazard cases were reported by the Soil and Water Conservation Bureau with most of the hazard

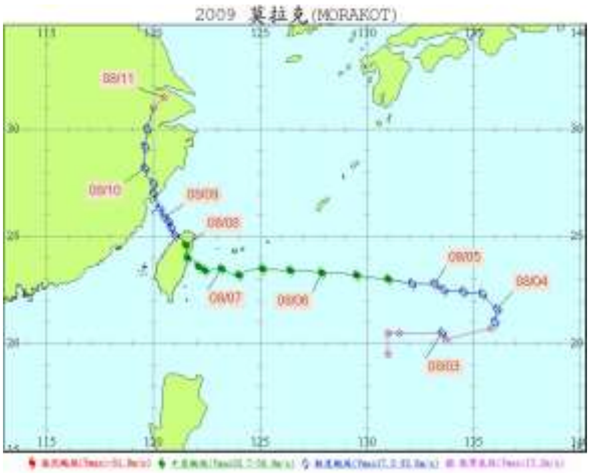

Fig. 5. Path record of typhoon Morakot, 2009, (from CWB, 2009).

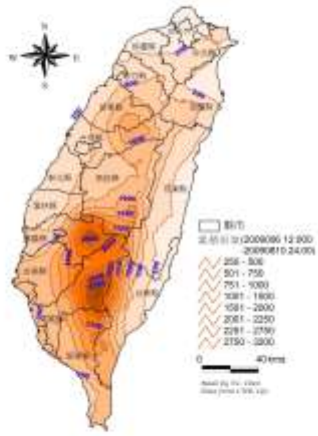

Fig. 6. Distributions of accumulated rainfall from August 6 to11 carried by typhoon Morakot (Chen, et.al. 2009).

located in southern Taiwan. The Central Geological Survey utilized the FORMOSAT-2 satellite images to map the landslides induced by typhoon Morakot, and a total of 45,123 landslide cases were mapped covering an area of 56,350 Ha. The distribution of the mapped landslides with the accumulated rainfall of typhoon Morakot is as shown in Figure 7, and the distribution of mapped landslides with the maximum rainfall intensity is as shown in Figure 8. From the figures, the

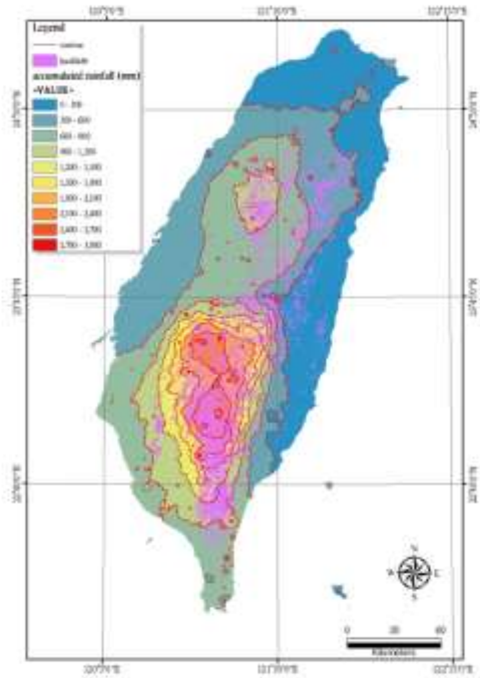

Fig. 7. Distributions of landslides versus accumulated rainfall of typhoon Morakot (landslide data from CGS, 2009).

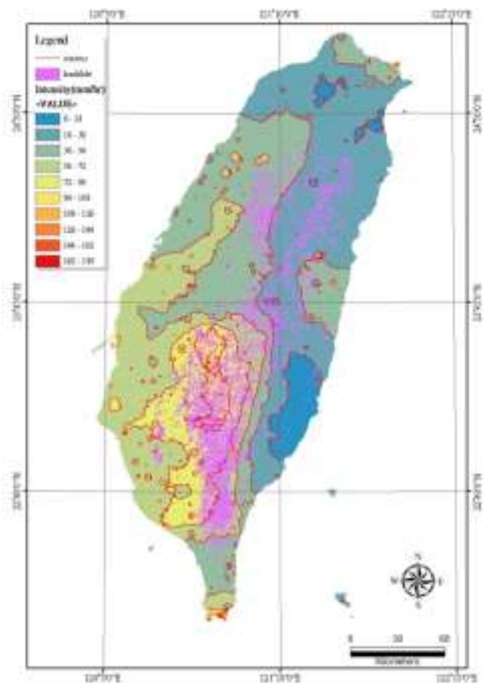

Fig. 8. Distributions of landslides versus the maximum rainfall intensity of typhoon Morakot (landslide data from CGS, 2009).

distribution of landslides focused heavily in the southern Taiwan where tremendous amount of rainfall had been recorded. In both figures, the distribution of landslides appears to decrease with decreasing accumulated rainfall and rainfall intensity. The accumulated rainfall correlated with landslide distribution better than the rainfall intensity; however, the types of landslide movement were not discriminated. It is noted that the landslides caused by typhoon Morakot are more severe and cover a much larger extend than that of Chi-Chi earthquake, because the number of landslide cases and extend of affected areas caused by typhoon Morakot were much larger than those by Chi-Chi earthquake.

4 LONG-TERM EFFECTS OF THE CATASTROPHIC EVENTS

Immediately after the Chi-Chi earthquake, the reactivations of the landslides were very significant, which also induced severe debris flow hazard. In 2001 typhoon Toraji caused severe landslide and debris flow hazard, and in 2004 typhoon Minduli again caused severe landslide and debris flow hazard in central Taiwan. In both events, it was found that many of the landslides occurred in Chi-Chi earthquake were reactivated and even enlarged, which often induced secondary debris flow hazard. In order to look into the long-term effects of the Chi-Chi earthquake, the time series remote sensing images of three river basins being affected by the Chi-Chi earthquake as shown in Figure 9 were collected. The remote sensing images of different resolutions as listed in Table 1 were calibrated and landslides were mapped for significant events. The resulting landslide ratios of the three river basins computed in the selected significant events are listed in Table 2. From Table 2, the landslide ratios increased in the first event after the Chi-Chi earthquake in all three basins. It is speculated that the strong motions of the earthquake would have caused fissures and cracks developed in the slopes, which then developed into landslides during the subsequent severe rainfall events. The percentage of reactivation larger than 100 suggested the enlargement of the reactivated landslide. The landslides reactivated in all three basins remained at a ratio of more than 70 % depending on the amount of rainfall in each event. A close examination of the May River watershed until typhoon Morakot, 2009, suggested the percentage of the reactivated landslide remained at a very high level until 2006, and then gradually decreased until the data of typhoon Morakot in 2009. However, the amount of rainfall in May river basin by typhoon Morakot was actually lower than other previous event. The scar and location of the reactivated landslide displayed a cascading effect, and gradually moved toward the down-slope direction and into the river channel (Lin and Chiang, 2015). This is illustrated by a field case in the May river basin in Figure 10. For the field case shown in Figure 10, the landslide was observed first in 1996 triggered by typhoon Herb, and subsequently triggered by the

Chi-Chi earthquake. The landslide triggered by Chi-Chi

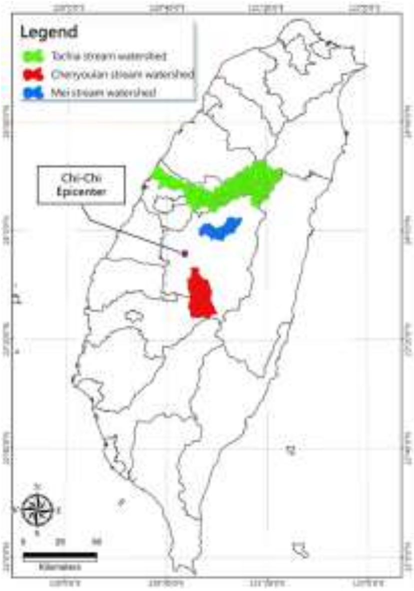

Fig. 9. Locations of three river basins affected and epicenter of Chi-Chi earthquake.

Table 1. Time series of remote sensing images data.

year	date of image	event	source	resolution (m)
1989			aerial photos	1
1996	7/29~8/1	Typhoon Herb		
1998	June		SPOT-1	10
1998	June		aerial photos	1
1999	9/21	Chi-Chi EQ		
1999	Oct.		SPOT-1	10
2001	7/28~7/31	Typhoon Toraji		
2001	Oct.		SPOT-1	10
2002	Jan.		aerial photos	0.5
2004	6/28~7/3	Typhoon Miduli		
2004	July		SPOT-5	5
2004	July		aerial photos	0.5
2006	6/8~6/10	6/9 torrential rainfall		
2006	June		SPOT-5	5
2008	9/11~9/16	Typhoon Sinlaku		
2008	Oct.		FORMOSAT-2	4
2009	8/5~8/10	Typhoon Morakot		
2009	Sep.		FORMOSAT-2	2
2009	Sep.		aerial photos	0.25

Table 2. Variations of landslide ratios of the three river basins with time series events.

Triggering event	Ta-Chia river watershed	Chen-You-Lan river watershed	May river watershed
Chi-Chi EQ, 1999	0.48%	2.46%	3.39%
Toraji, 2001	1.63%	3.95%	5.73%
% of reactivation	100	87.8	129.50
accumulated rainfall, mm	480	634	353
Mindule, 2004	3.19%	4.83%	4.28%
% of reactivation	195.83	63.82	77.10
accumulated rainfall, mm	1658.5	1418	985.5
6/9 Torrential Rainfall, 2006	-	-	5.05%
% of reactivation	-	-	101.47
accumulated rainfall, mm	792	-	788
Sinlaku, 2008	-	-	2.91%
% of reactivation	-	-	53.69
accumulated rainfall, mm	1158	686	966
Morakot, 2009	-	-	2.07%
% of reactivation	-	-	25.07
accumulated rainfall, mm	-		678.5

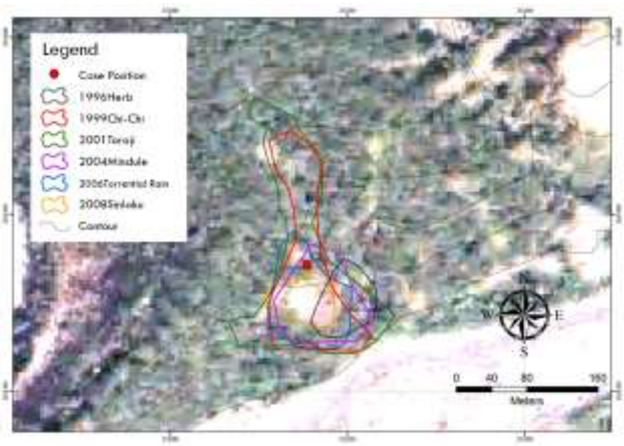

Fig. 10. A field landslide case traced from 1996 to 2008.

earthquake was significantly closer to the up-slope direction. Subsequently the landslide reactivated in

2001, and enlarged toward the up-slope direction. Starting 2004 until 2008, the reactivated landslide gradually moved toward the downslope direction and decreased in size, suggesting a cascading effect with decreasing influences. It appeared that the reactivation of landslides gradually reduce to the condition before the Chi-Chi earthquake with decreasing scale. However, a prolong effect of landslide reactivation is still significant in May river basin until typhoon Morakot, 2009, with a reactivation ratio of 25%. The initial catastrophic landslides and subsequent reactivations have caused severe and continuous debris transportation affecting the basin and downstream areas even after 10 years.

The southern Taiwan was struck severely by landslide and debris flow hazard induced by typhoon Morakot in 2009. For years following typhoon Morakot, it was found that a significant number of landslides and debris flow have been reactivated in areas struck severely by the typhoon. The landslide scars of two sub-basins in Kaoshiung City, southern Taiwan, were mapped using time-series aerial photos, FORMOSAT-2, and SPOT-5, -6, -7 satellite images of significant events since 2005 before typhoon Morakot until 2014. The locations of two sub-basins are as shown in Figure 11. The resulting landslide ratios of the two sub-basins computed in the selected significant events are as listed in Table 3. From Table 3, the landslide ratios remained at a quite low level until 2008, and increased drastically immediately after typhoon Morakot to about 10%, which was a very high value. It was found that the landslide ratios remained at a high level after typhoon Morakot and then decreased gradually but remained at a much higher landslide ratio compared to that before typhoon Morakot until 2014. The variations of landslide ratio of the two sub-basins in time series of significant events from 2005 to 2014 are as shown in Figure 12, and the long-term trend can be observed

Fig. 11. Location of two sub-basins in Kaoshiung City.

Table 3. Variations of landslide ratios of the two sub-basins with time series events.

Image	Number of Landslides		Landslide Ratio (%)		Event / Date
Date	Namashia	Liuguey	Namashia	Liuguey	
2005	149	477	0.50	2.22	Torrential Rain 2005. Typhoon Haitang 2005.
2006	719	1,567	0.83	2.53	Torrential Rain 2006. Typhoon Bilis 2006.
2007	437	1,409	0.94	2.94	--
2008	633	1,460	0.89	2.75	Typhoon Sanpa 2007.
2009	47	265	0.34	1.40	Typhoon Kalmaegi 2008.
2010	2,427	3,626	10.97	10.82	Typhoon Morakot 2009.
2011	2,430	3,202	11.00	10.62	Typhoon Fanapi 2010.
2012	1,120	2,325	7.00	8.84	Torrential Rain 2012.
2013	834	763	6.67	4.63	Typhoon Kongrey/ 2013.
2014	357	1,040	4.39	5.76	Typhoon Matmo 2014.

clearly with a drastic increase of landslide ratio after the typhoon Morakot and then gradually decrease with time. With the landslides mapped for the two sub-basins in time series, the reactivated landslide ratios from the previous event were determined for each event. The variations of ratio of landslide reactivated from previous event along with event year are plotted in Figure 13. Figure 13 shows that the ratios of landslide reactivated from previous event ranged from 20~50% before typhoon Morakot. However, only 2~8% of

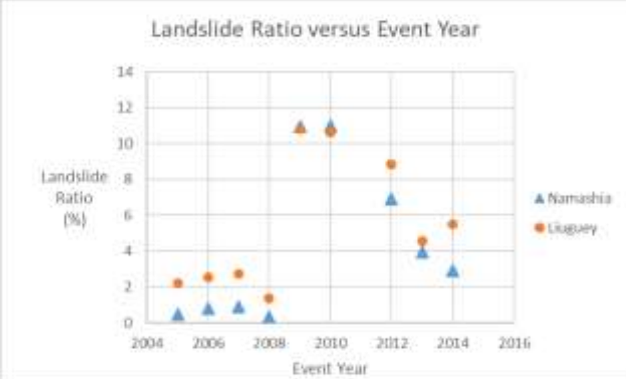

Fig. 12. The variations of landslide ratio of the two sub-basins in time series of significant events.

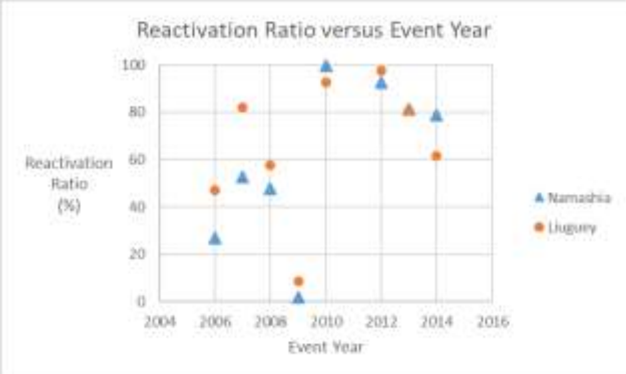

Fig. 13. The variations of landslide reactivation ratio of the two sub-basins in time series of significant events.

landslides were reactivated during typhoon Morakot, which suggested that most of the landslides were newly triggered by typhoon Morakot. In addition, the reactivation ratios were very high for the events after typhoon Morakot until 2014, suggesting a prolong effect of landslide caused by typhoon Morakot. The continuous erosion in the up-stream slopes and debris mass transportation toward the down-stream areas were observed in field following the initial landslides caused by typhoon Morakot. Field investigations revealed that extensive landslides were reactivated and large quantities of debris mass did not transport all in one time. The remaining debris volumes on the slopes often caused further hazard of debris flow or debris transportation in the basin when heavy rainfall occurred (Lin, et.al. 2014, Lin, et.al. 2017).

5 DISCUSSIONS

Results of the follow-up study of the landslide recurrences of three river basins in central Taiwan in years after Chi-Chi earthquake suggested that the landslides induced by the Chi-Chi earthquake have been repeatedly activated by the subsequent rainfall events. This long-term effect appeared to decrease gradually but still being quite significant after 10 years in the May River basin. In addition, severe ground erosion in the up-stream slopes and tremendous amount of debris transportation have been observed in the field following the landslide evolution. Such condition often results in significant topographic variations and secondary hazard, which causes damages to infrastructures and difficulties for reconstruction. Figure 14 illustrates this condition with top photo taken on April, 2000, and bottom photo taken on September, 2008. In Figure 14, the gas station in May river basin has been repeatedly struck by landslides and accompanying debris flow from 2000 to 2008, and significant topographic variations were observed.

A similar situation also occurred in areas severely affected by landslides caused by typhoon Morakot. The prolong effects are as shown in Figure 13 with high reactivation ratios until 2014 in this study. The repeatedly occurrences of landslides and accompanying debris flows after typhoon Morakot have caused severe erosion of the up-stream slope and tremendous amount of debris transportation. This condition again resulted in severe topographic variations and secondary hazard, which causes damages to infrastructures and difficulties for reconstruction as observed in field.

Fig. 14 Photos taken on April, 2000(top), and on September, 2008(bottom), showing repeated damages caused by debris transportation down-stream by landslides and debris flows.

6 CONCLUSION

In this study, for both catastrophic events causing severe landslides, the prolonged effects were observed with significant landslide reactivations accompanying tremendous amount of debris transportation. A continuous transportation of tremendous amount of debris mass was observed in the affected areas of both events, which affected the downstream areas and causing topographic variations and difficulties in reconstruction. It is suggested that the catastrophic events such as the Chi-Chi earthquake and typhoon Morakot both released tremendous amounts of energy, and thus could cause prolonged effects on stabilities of slopes. Continuous monitoring and study of the time series evolution of landslides and debris transportation would be essential for evaluation and mitigation of the influences of such catastrophic events on landslide disasters.

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