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Increase in basin sediment yield from landslides in storms following major seismic disturbance

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ABSTRACT

The landslide area along the Tachia River catchment of central Taiwan was investigated using the remote sensing images of various typhoon and earthquake events taken from 1996 to 2004 and the sediment discharge measured at hydrometric stations. Our findings indicate that 88% of the coseismic landslides triggered by the 1999 Chi-Chi earthquake were first-time occurrences. After the Chi-Chi earthquake, 59% of the landslide area was reactivated during typhoon Toraji and 66% during typhoon Mindulle. The landslides prone to reactivation were on the formations with closely spaced discontinuities. It is suggested that further rock-mass defects in the formations were added or opened by the earthquake, and that the landslide areas continued to extend until the end of 2004. Post-1999 rainstorms delivered large amounts of colluvial sediment into the main channel, leading to a 2-fold increase in post-seismic sediment discharge while the precipitation was only half that of the pre-earthquake rate.

1. Introduction

The 1999 Chi-Chi earthquake (M_W=7.6) resulted in huge landslides along the eastward central highway in the Tachia River catchment of central Taiwan, with 1.5 million m^3 of earth driven from broken slopes (DGH, 2000). On July 2, 2004, typhoon Mindulle released 1300 mm of precipitation in 3 days on central Taiwan, causing a huge hazardous debris flow in the Tachia River catchment. The 20 million m^3 of debris deposition and >10 m aggradation in the main channel indicate that an abundance of rock debris had been driven into the river channel from the slopes (WRA, 2004).

The coseismic landsliding was used to probe into such that the magnifying effect of seismic shaking on the hilltop would trigger the occurrence of rock fracture and landsliding (Keefer, 1984; Geli et al., 1988; Khazai and Sitar, 2003). The threshold of rainfall to generate landslides has lowered significantly since the 1999 Chi-Chi earthquake in the Chenyoulan River of central Taiwan. Some of the pertinent studies have focused on the effect of the landsliding distribution on steeper slope (Iverson et al., 1997; Chen et al., 2006), and examined the difference between landslides triggered by typhoon and those by earthquake, respectively (Keefer et al., 1987; Lin et al., 2003; Chen, 2006; Lin et al., 2008).

The debris originally banked up on the slopes was driven into the river channel, and the subsequent sediment discharge into the river reveals the erosion condition of the upstream catchment (Hartshorn et al., 2002; Fuller et al., 2003; Dadson et al., 2003). This study attempts to probe the landsliding and investigate the relationship between sediment transfer and landslide by analyzing the effect of 1996 typhoon Herb, 1999 Chi-Chi earthquake, 2001 typhoon Toraji and 2004 typhoon Mindulle in the Tachia River catchment. The Tachia River catchment is an appropriate area to test the seismic effect of the 1999 Chi-Chi earthquake, and this case study would provide several experiences of the sustained landsliding investigation and sediment estimation to regard as the reference of catchment management. Last, by studying the characteristics of landsliding and how the landsliding debris responds to sediment transfer in the downstream channel, the study also provides information to assess hazard risk and the future benefit of reconstruction.

2. Study area

The 410 km^2 study region is between the Techi and Ma-An Dam in the Tachia River catchment (Fig. 1a). The Tachia River, 120 km in length, is the major river in central Taiwan, and draining an area of 1200 km^2. The elevation within this area ranges between 360 m and 3600 m, with slopes ranging between 30° and 50°.

The annual average precipitation is 2300 mm in the Tachia River catchment, with 70% of the precipitation concentrated in the period from April to August (Central Weather Bureau, 2006). The monthly

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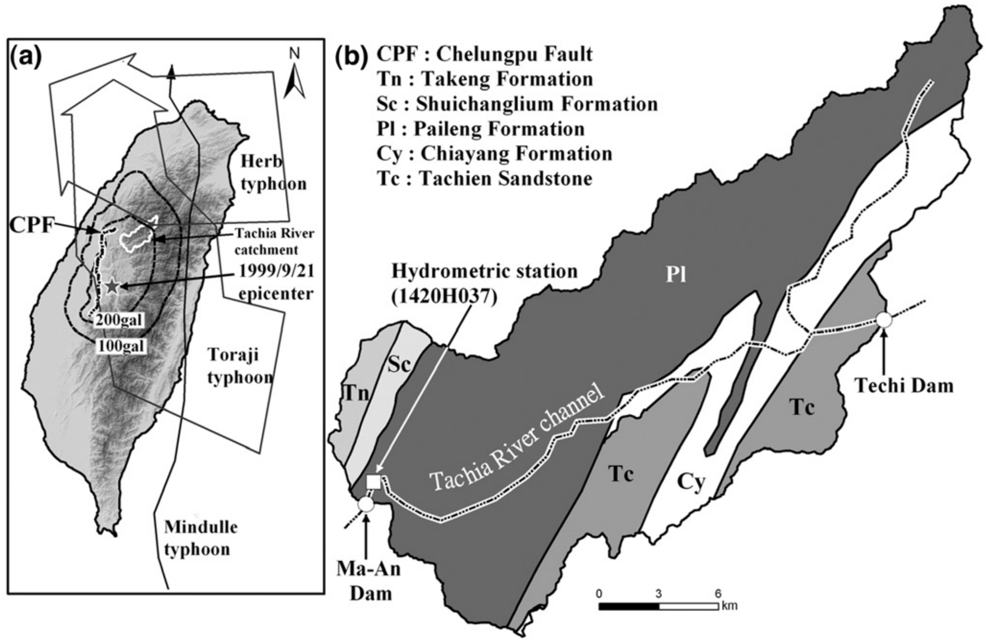

Fig. 1. (a) The location of the study area within Taiwan, the epicenter of the 1999 Chi-Chi earthquake, and the tracks of typhoons. The study area in central Taiwan is east of the Chelungpu Fault (CPF), which is the main fault of the 1999 Chi-Chi earthquake. The star indicates the epicenter of the 1999 Chi-Chi earthquake. The contour line, whose unit is gal, is the peak ground-acceleration distribution of the 1999 Chi-Chi earthquake. The arrow regions indicate the track width of the storms (wind velocity$>$17.1 m s^{-1}) of typhoons Herb and Toraji. The storm diameter of typhoon Mindulle was greater than the length of Taiwan (around 394 km). When the center of typhoon Mindulle passed Taiwan, the area of storm covered entire Taiwan. (b) Distribution of rock formations in the study area along the Tachia River. Area between the Ma-An Dam and the Techi Dam: 410 km^2, of which 62% is in Paileng Formation, 17% is in Chiayang Formation, 16% is in Tachien Sandstone, 3% is in Shuichanglium Formation, and 2% is in the Takeng Formation. Square means the location of the hydrometric station (1420H037).

average precipitation in the period from September to the coming January is less than 100 mm, and the monthly average precipitation in the period from May to August is more than 300 mm. Among the cumulative precipitations during the duration of several typhoons, the cumulative precipitation during 2004 typhoon Mindulle, 1157 mm in 4 days, is largest. Besides, the cumulative precipitation during 1996 typhoon Herb is 667 mm in 3 days and the amount during 2001 typhoon Toraji is 369 mm in 2 days. The maximum daily precipitation is 560 mm during 1996 typhoon Herb; the second is 434 mm during 2004 typhoon Mindulle.

Over the interval 1979–2005, the annual average flow discharge in the Tachia River was 1434 million m^3 (WRA, 2005). 66% of the flow discharge was concentrated in the wet season from May to September, and monthly average flow discharge in the wet season was 190 million m^3. In the winter season from October to the following March, the monthly average flow discharge, 61 million m^3, was just one-third of that in the wet season.

3. Geological setting

The Tachia River catchment traverses 3 geological regions, including the Western Foothills, the Hsuehshan Range and the Backbone Range of the Central Range in Taiwan. The Shuichanglium Formation, Paileng Formation, Chiayang Formation, Tachien Sandstone and the Neogene clastic deposition outcrop in this study area, in the middle reaches of Tachia River (Fig. 1b). The main orientation of formations includes strikes of N15°–40°E with southward dips of 20°–70° and strikes of N10°–30°E, with northward dips of 40°–80°. There are 4 faults, with strikes of N20°E distributed in this study area. The orientations of 4 main discontinuities are strikes of N70°–80°E with southward dips of 50°–70°, strikes of N60°–80°E with northward dips of 40°–60°, strikes of N10°–50°W with southward dips of 40°–80° and strikes of N30°–60°W with northward dips of 60°–80° (Chen and Petley, 2005).

The study area is east of the Chelungpu fault, and 10 km away from the rupture of the 1999 Chi-Chi earthquake. The peak ground acceleration of the Chi-Chi earthquake in the Tachia River catchment ranged from 150 gal to 260 gal, and decayed eastwardly.

4. Study method

The study applied 3 kinds of methods, including 70 sets of rock uniaxial compressive test (UCS), landslide mapping, and estimation of sediment discharge. Landslides were mapped from 10 and 20 m resolution SPOT satellite images, and were rechecked with high-resolution 1:5000 aerial photos. Then the landslides smaller than 400 m^2 were deleted to make sure that the resolution of mapping landslides would reach at least 20 m×20 m. From the landslide mapping, we determined landslide ratios (defined as the ratio of landsliding area to the total area analyzed), new generation ratios, L_{NR} (defined as the ratio of new landslide area to the total landslide area after the event), and reactivated ratios, L_{RR} (defined as the ratio of reactivated landslide area to landslide area before the event) during each typhoon and the Chi-Chi earthquake. The hydrometric data, including regular daily flow discharge, irregular flow discharge and sediment concentration measured from station 1420H037, were used to estimate sediment discharge by the average methods and the rating-curve methods (Cohn, 1995).

5. Rock strength

According to the classification scheme of the International Society for Rock Mechanics (ISRM, 1981), the averagely measured numbers of the discontinuities within the sandstone of Takeng Formation and the shale of Shuichanglium Formation are 8.6 m^{-3} (numbers of discontinuities per cubic meters of rock mass) and 6.8 m^{-3}, respectively, that is, medium rock-mass quality. The average measured numbers of

Table 1
The uniaxial compressive strength of each formation in the study area

Formation	Mean (MPa)	Maximum (MPa)	Minimum (MPa)	Strength classification of ISRM
1. Takeng Formation sandstone	50	37	68	R_3
2. Paileng Formation sandstone	110	17	183	R_5
3. Paileng Formation shale	66	32	94	R_4
4. Chiayang Formation sandstone	129	37	165	R_5
4. Chiayang Formation slate	19.5[a]			R_2
5. Tachien Sandstone	137	105	176	R_5

R_2: very weak rock; R_3: median rock; R_4: strong rock; R_5: very strong rock (ISRM, 1981).
[a] Data referred to Public Construction Commission, Taiwan, 2001.

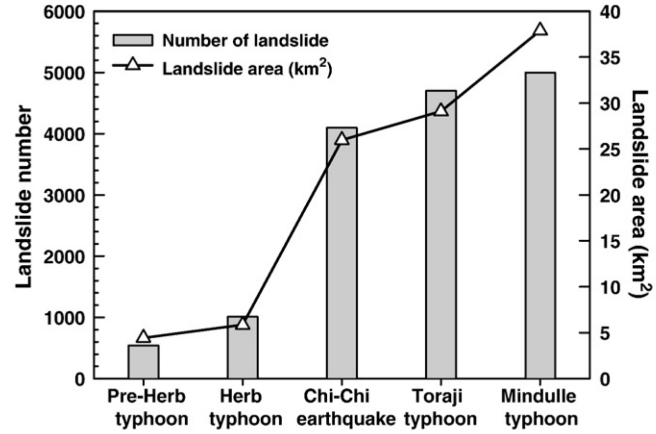

Fig. 2. Both landslide number and area appear to increase significantly after the Chi-Chi earthquake.

discontinuities within the sandstone of Paileng Formation, Chiayang Formation and Tachien Sandstone were over 10 per cubic meter, and rock mass within these formations has a smashed structure.

Results of uniaxial compressive strength tests of formations within the Tachia catchment show that the sandstones within the Paileng, and Chiayang Formations and the Tachien Sandstone (average UCS values of 110, 129 and 137 MPa, respectively) can be classed as very strong rocks; the weakest lithology is slate in the Chiayang Formation (USC 19.5 MPa) (Table 1).

6. Landsliding

To comprehend the landslide changes during the typhoons and the earthquake, and to discriminate the disturbed areas for each event, the new generation ratio (L_{NR}) is applied to represent how large an area was affected after the event. The reactivated ratio (L_{RR}) is applied to represent how this large area, which was repeatedly disturbed in the former event, reactivated in the later event.

The value of coseismic L_{NR} triggered by the Chi-Chi earthquake is 88%, which is higher than the L_{NR} triggered by typhoon Herb, 64%, and the values of L_{NR} triggered by typhoon Toraji and Mindulle are 47% and 49%, respectively. Rock-mass shattering on hillslopes has been reported from the epicentral areas of other large earthquakes (Harp and Jibson, 1996), and the effect of seismic acceleration resulted in the changes of the normal and shear stresses in the hillslopes (Geli et al., 1988). These coseismic effects would result in lowering of the landsliding threshold. Additionally, the values L_{RR} for typhoon Herb, Chi-Chi earthquake, typhoon Toraji and typhoon Mindulle are 47%, 51%, 59% and 66%, respectively.

The increase of L_{RR} after the Chi-Chi earthquake indicates that the reactivated landslide area is extending and the landslide distribution in the Tachia River catchment is still effected by the Chi-Chi earthquake (Table 2). The landslide area post-Chi-Chi earthquake is 4 times greater than that triggered by typhoon Herb. Although, the landslide number triggered by typhoon Toraji and Mindulle increased moderately, the landslide area was still extending, 1.5 times more than the post-Chi-Chi earthquake landslide area.

The landslide ratios for landsliding events triggered by typhoon Herb, Chi-Chi earthquake, typhoon Toraji and typhoon Mindulle are 1.7%, 10.8%, 11.1% and 13.5%, respectively, based on the landslide analysis conducted within 36 sub-catchments at Tachia River catchment (Fig. 2). Therefore, the landslide ratios appear to be increasing (Table 3). Among these 4 events, the average L_{NR} of sub-catchments for the Chi-Chi earthquake, 90.4%, is highest, and average values of L_{NR} for typhoon Toraji and Mindulle, 51.3% and 48.5%, stay at around 50%. The values of L_{RR} of these 36 sub-catchments within Tachia River catchment for typhoon Herb, Chi-Chi earthquake, typhoon Toraji and typhoon Mindulle are 40%, 43.4%, 55.8% and 61.3%, and the increasing L_{RR} indicates that landslides continued extending the area that had been disturbed during the fore-event.

Despite the landslide ratio triggered by the Chi-Chi earthquake, each formation shows a positive linear correlation (R^2=0.94) with uniaxial compressive strength, which appears that formations with higher UCS seemed prone to be disturbed by seismic ground shaking and result in higher landslide ratio (Fig. 3a). We still prefer to attribute this appearance to that coseismic landslide is prone to act in formations with high discontinuities density. The landslide ratio has weak correlation with the density of discontinuities in each formation (Fig. 3b). High discontinuities density in Paileng, Chiayang Formations and Tachien Sandstone is the major factor to cause high landslide ratios.

To examine the influence of slope on the area disturbed by landsliding, the distribution of landslide area with slope angle was examined throughout the Tachia catchment. The slope-area disturbed by landsliding shows an evident peak at 45° (Fig. 4a). The high peak is thought to reflect the maximum stable gradient of mountain slopes (Burbank et al., 1996). The slopes ranging from 30° to 60° were seriously disturbed by landsliding. 25.4 km^2 of the coseismic landsliding area, with slope ranging from 30° to 60°, is 4.6 times more than 5.5 km^2 of the landsliding area triggered by typhoon Herb, with slope ranging from 40° to 50°. The phenomenon was more obvious after the Chi-Chi earthquake.

The distribution of the landslide area with elevation of landsliding head scarp was also examined (Fig. 4b). The average elevations of landsliding triggered by the Chi-Chi earthquake, typhoon Toraji, and Mindulle were 1360±3.6 m, 1475±3.3 m, and 1540±3.3 m,

Table 2
The results of landslide analysis in the various events

Event	Number	Landslide area (km^2)	Reactivated area (km^2)	New generation area (km^2)	Reactivated ratio (%)	New generation ratio (%)
Pre-typhoon Herb	543	4.43	–	–	–	–
Typhoon Herb	1010	5.86	2.10	3.76	47	64
Chi-Chi earthquake	3935	25.97	3.01	22.96	51	88
Typhoon Toraji	4482	29.10	15.41	13.69	59	47
Typhoon Mindulle	4847	37.89	19.24	18.66	66	49

Table 3
Landslide statistics for 36 sub-catchments in the Tachia River study area

Event	Landslide ratio (%)	New generation ratio (%)	Reactivated ratio (%)
Typhoon Herb	0–6.6 (1.7)	0–100 (62.8)	0–79.4 (40.0)
Chi-Chi earthquake	0.2–41.8 (10.8)	70.6–100 (90.4)	0–95.5 (43.4)
Typhoon Toraji	0.5–37.2 (11.1)	16.7–91.2 (51.3)	16.5–78.9 (55.8)
Typhoon Mindulle	0–53.9 (13.5)	0–85.5 (48.5)	0–84.8 (61.3)

"( )" means the average.

respectively. Further, Fig. 4b shows that more and more areas, whose elevations are higher than 1000 m, were disturbed by landsliding. It would mean that more and more landsliding area became near to the crest, and distant from the river channel.

The coseismic peak ground acceleration during the Chi-Chi earthquake ranged from 150 gal to 260 gal along the Tachia River catchment (Lee et al., 1999). The 83% landslide area is within the area where PGA ranges from 210 gal to 240 gal, and the landform within this range is a steep gorge with 30°–70° slopes and fragmentary formations (Fig. 5). The low landslide ratio where the PGA value was higher than 240 gal, is due to the fact that the total land area in this range of PGA was only 69.7 km^2, i.e. 17% of study area. In central Taiwan, 74% landslide triggered by the Chi-Chi earthquake occurred in the region with PGA is >200 gal (Khazai and Sitar, 2003). The increasing L_{RR} for typhoon Toraji and Mindulle indicates that formations disturbed by seismic shaking are prone to be destabilized by subsequent rainstorms after the Chi-Chi earthquake. Indeed, in the following 5 years, the roughly 50% landslides within the region of 210–240 gal coseismic shanking were reactivated by rainstorms (Fig. 6).

7. Sediment discharge in the Tachia River

To estimate the annual sediment discharge, 4 estimation approaches were applied (direct average method (E_{AVG}), monthly weighted average method (E_{MWA}), usual rating-curve method (E_{RC}), and non-parametric rating-curve method (E_{SM})). These 4 estimation methods determined that E_{AVG} is 0.70±0.05 Mt year^{-1}, E_{MWA} is 0.59±0.04 Mt year^{-1}, E_{RC} is 0.19±5.26% Mt year^{-1}, and E_{SM} is 0.33±6.06% Mt year^{-1} (Fig. 7). Among these 4 methods, the estimation value of average method is somewhat higher than that of rating-curve method. Further, the E_{AVG} is highest, and E_{RC} is lowest.

Dadson (2004) suggests that monthly weighted average method is applicable to estimate the river sediment discharge on Taiwan Island; however, Kao et al. (2005) consider that sediment discharge on Taiwan Island is dominated by the quantity of flow discharge, and regard estimation by the rating-curve method as more accurate. In this study, the estimation values exhibit a specified relation between monthly weighted average method and non-parametric rating-curve method (Fig. 8), and the estimation result of monthly weighted average method, 0.59±0.04 Mt year^{-1} is about twice that of non-parametric rating-curve method, 0.33±6.06% Mt year^{-1}.

The transfer of sediment is dominated by transport-limited conditions, so the discharge of sediment is controlled by the discharge of river flow (Hovius et al., 2000). In this study, around thirty measured flow discharge data and sediment-concentration data per year can be used to build an annual rating curve, and the formula can be written as follows,

$$Q_S = \kappa Q_W^b$$

where Q_W means the flow discharge in unit of m^3 s^{-1}, Q_S means the sediment discharge in unit of ton, and κ and b are the coefficients of the power-law regression equation. The daily average flow discharge can be put into the equation of rating curve to obtain daily sediment discharge, and the annual sediment discharge can be calculated by summing the daily sediment discharge. Additionally, the hourly flow discharge also can be put into the equation of rating-curve equation to estimate the sediment discharge during a typhoon.

The rating curves, built by all measured data in the period of 1979–2003, were used to compare the difference in the ratio of unit sediment discharge before and after the Chi-Chi earthquake. The estimation equations of rating curve prior to seismic and post-seismic can be written as follows,

$$Q_{S\ \text{prior to seismic}} = \kappa_1 Q_{W\ \text{prior to seismic}}^{b_1}$$

$$Q_{S\ \text{post-seismic}} = \kappa_2 Q_{W\ \text{post-seismic}}^{b_2}$$

$$\Delta\kappa = \frac{Q_{S\ \text{post-seismic}}}{Q_{S\ \text{prior to seismic}}}$$

where $\Delta\kappa$ is the ratio of Q_S post-ground shanking to Q_S prior to ground shanking. The post-earthquake sediment discharge is greater than that prior to seismic when a $\Delta\kappa > 1$.

The rising regression lines for rating curve in the period of 2000 to 2003 illustrate the increase of sediment discharge with the same flow discharge as compared to prior to earthquake (Fig. 9a). It reveals that more material was readily available after the Chi-Chi earthquake than before. The year-by-year increasing $\Delta\kappa$ also means that unit sediment discharge post-earthquake is much higher than that prior to earth-quake. The variability of $\Delta\kappa$ expresses that in the Tachia River the unit

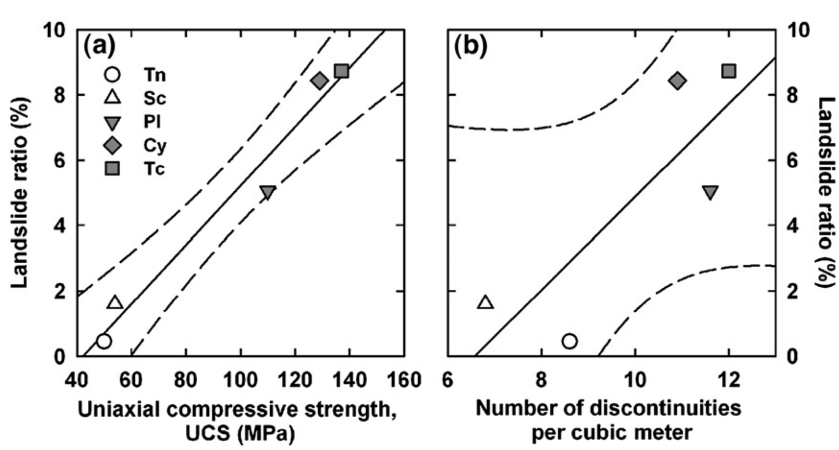

Fig. 3. (a) Landslide ratio shows a positive linear correlation (R^2=0.94) with uniaxial compressive strength. The dashed lines indicate 95% confidence limits. (b) The landslide ratio is weakly correlated (R^2=0.66) with the density of discontinuities in each formation. The dashed lines indicate 95% confidence limits.

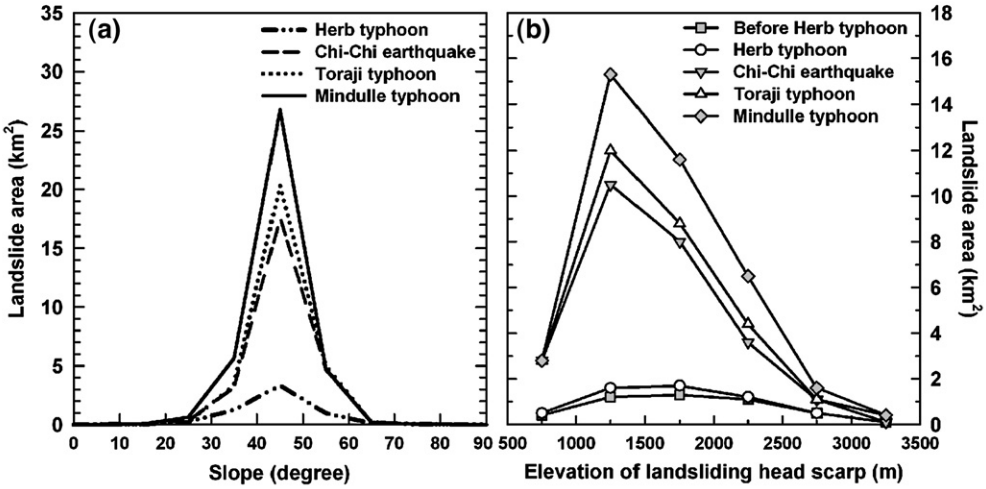

Fig. 4. (a) Distribution of landslide area in the study area by slope angle in each typhoon and the Chi-Chi earthquake. (b) Distribution of landslide area in the study area by elevation of landsliding head scarp in each typhoon and the Chi-Chi earthquake.

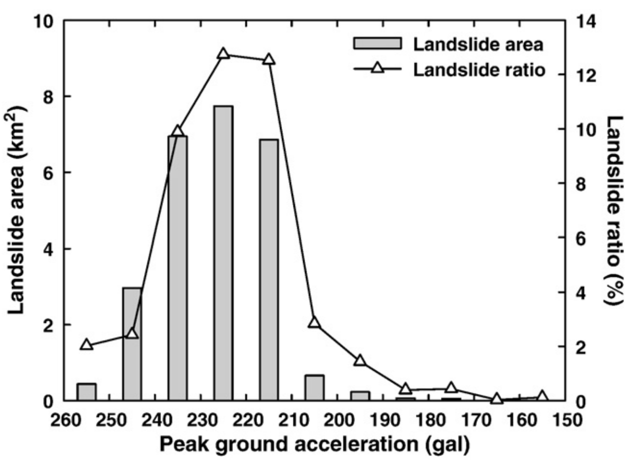

Fig. 5. Distribution of landslide area in the study area by peak ground acceleration in the Chi-Chi earthquake. The ground-acceleration scale is reversed in the figure to match the west to east attenuation in shaking intensity across the study area. Most of the landslide area lies within 210–240 gal, but this does not include topographic amplification effects.

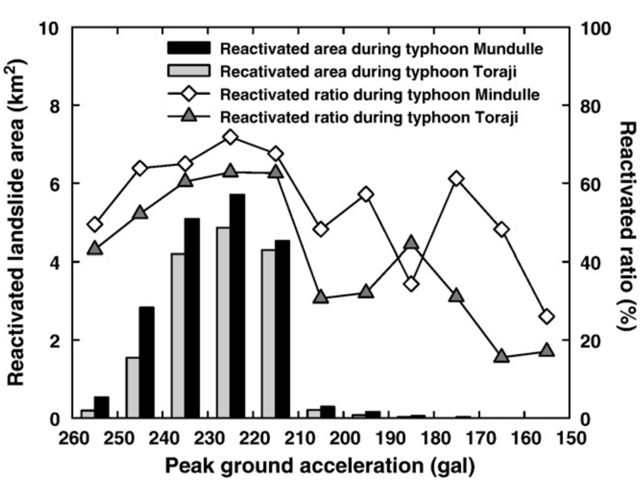

Fig. 6. The relationship between the reactivated landslide area and peak ground acceleration during the events of typhoons Toraji and Mindulle.

sediment discharge post-Chi-Chi earthquake is about 2 times greater than that prior to earthquake when flow discharge is less than 100 m^3 s^{-1}; moreover the unit sediment discharge post-Chi-Chi earthquake is 4 times greater than that prior to earthquake when flow discharge is higher than 10 m^3 s^{-1} (Fig. 9b). In addition, as discussed earlier (Section 6 Landsliding), we reason that the increase in the ratio of unit sediment discharge after the earthquake arises because the landslide debris was moved progressively over time, nearer to and into the river channel. Thus more and more material could be deposited into the channel year by year to become river sediment.

To understand the change of sediment discharge in the period of typhoon post-Chi-Chi earthquake, the hourly data of measured flow discharge is used to estimate the sediment discharge for typhoons Herb and Toraji by the non-parametric rating-curve method. The precipitations during typhoons Herb and Toraji were 667 mm and 369 mm, respectively and the total flow discharges for these two typhoons were 196 million m^3 for the former and 107 million m^3 for the latter. The hours of flow discharge higher than 1000 m^3 s^{-1} were 20 h for typhoon Herb and 7 h for typhoon Toraji. Further, the maximum hourly sediment discharges during typhoon Herb and Toraji are 520 tons, with 12,809 tons of total sediment discharge, and 3128 tons, with 34,497 tons of total sediment discharge, respectively.

The precipitation and total flow discharge during typhoon Herb are 1.8 times greater than those during typhoon Toraji, and the maximum of hourly flow discharge during typhoon Herb is also higher than that during typhoon Toraji. However, the maximum of hourly sediment discharge during typhoon Herb is only 1/6 of that during typhoon Toraji, and the total sediment discharge during typhoon Herb is less than half of that during typhoon Toraji. The 4-fold increase in area of landslide disturbance from the Chi-Chi earthquake resulted in increased material being carried downstream by subsequent typhoon Toraji. It also meant that sediment movement in Tachia River increased after the earthquake. The sediment discharge from typhoon Toraji totaled 34,500 tons, about 20% of the 2001 sediment discharge of 176,500 tons, indicating that the annual sediment yield of the Tachia catchment is dominated by large events such as typhoons and earthquakes.

8. Discussion

Our investigation found that a major part of the sediment-concentration data was higher than the regression line of the rating curve when the flow discharge was higher than 100 m^3 s^{-1} in the period 1979 to 2003. This phenomenon appears to lead to under-estimation of the sediment discharge by the rating-curve method. In

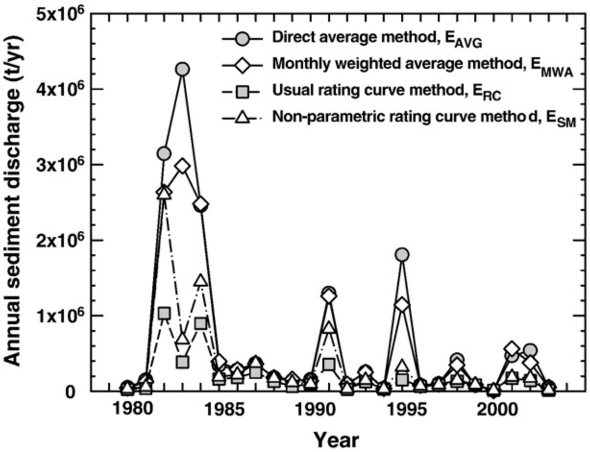

Fig. 7. Estimation of sediment discharge by four different methods.

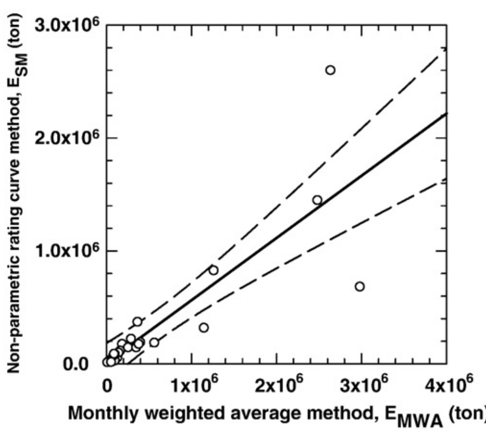

Fig. 8. The relationship between the monthly weighted average method (E_{MWA}) and the non-parametric rating-curve method (E_{SM}) displays a positive correlation (R^2 = 0.69). The dashed lines indicate 95% of confidence interval. The solid line is the best fit to the data, of the form $E_{\mathrm{SM}} = 0.56 E_{\mathrm{MWA}}$, obtained with a least-squares loss function.

general, to estimate the annual sediment discharge by the rating-curve method, the measured data needs to be random and representative (Cohn, 1995).

Among the total 784 sets of measured sediment-concentration data in the periods of 1979 to 2003, we took 150 sets of measured data having flow discharge higher than 100 m^3 s^{-1} to estimate the sediment discharge by building a rating curve and also set up another rating curve by using a total of 784 sets data. The sediment discharge, estimated by the rating curve which was built from the measured data with flow discharge > 100 m^3 s^{-1}, exhibited a 14-fold increase over that estimated by the rating curve built from all 784 sets of measurements.

The estimation of sediment discharge is based on around 30 measurements taken over a year, i.e. in the order of 2–3 sets of sampling per month. The data were analyzed in four different ways to estimate the annual discharge of sediment. As seen in Fig. 7, the different methods resulted in some variation in the annual estimations, but we consider that averaging all the results obtained over the year gives a realistic figure for the annual discharge. For an individual event or short period, however, in order to obtain a more accurate determination, the discharge of sediment was estimated using the rating-curve method, which is based on samples taken close to the event and the hourly flow discharge.

In addition, difficulties in access to the remote hillslopes, and inability to determine proportions of debris coming from landslide sources versus from stable areas, prevented us from studying the precise sources of sediment and their relationships to landsliding. However, we believe that most of the material in the channel came from landslides, because there were a lot of boulders and colluvial debris in gullies and on the river bed. We could not afford the expense or the time to use high-resolution digital topographic models to determine sediment fluxes between landslides and the river channel.

9. Conclusion

The new generation ratios of landslide (L_{NR}) for consequent rainstorms post-1999 Chi-Chi earthquake hold steady at about 50%, indicating that the earthquake continues to affect landsliding in the subsequent typhoon events. The reactivated ratios of landslide, which rose to 66% after 2004 typhoon Mindulle, also indicate that more than half of the old landslides persist in unstable conditions.

Slope ranging from 30°–60° were greatly disturbed by landsliding, respectively after the Chi-Chi earthquake, and the locations of new landslides progressively migrated closer to the topographic crests of slopes in successive events from 1999 to 2004. It meant that the enlargement of seismic wave on the top of hills results in the increase of the topographic elevation of disturbed area, and more landslides being found near the crest.

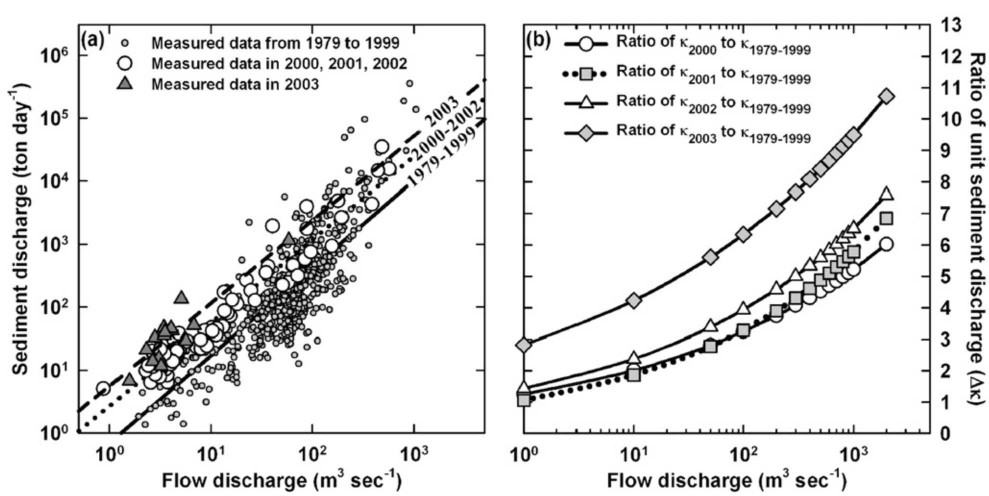

Fig. 9. (a) Variation in sediment discharge with flow. Symbols differentiate sediment-rating curves by year since the earthquake. Solid line is the least-squares fit to the logarithms of the data from 1979 to 1999. Dotted line is the fit to the logarithms of date from 2000 to 2002. Dashed line is the least-squares fit to the logarithms of the data of 2003. (b) The diagram reveals the ratio of unit sediment discharge increasing significantly after the 1999 Chi-Chi earthquake.

The average annual sediment discharge of the Tachia River catchment in the period of 1979–2002 was 0.33–0.70 million tons. The progressive increasing of the ratios of the unit sediment discharges after the Chi-Chi earthquake to that prior to the Chi-Chi earthquake reveals that post-earthquake unit sediment discharge increases and the amount of the landsliding debris driven into the river channel also increased year by year after 1999. The sediment discharge during 2001 typhoon Toraji is twice that during 1996 typhoon Herb, although the precipitation and flow discharge during typhoon Toraji are less than those during typhoon Herb. The increase in sediment concentration after the Chi-Chi earthquake indicates that significantly more sediment was made available to the Tachia River through the seismic shanking. The sediment discharge in the Tachia River is dominated by torrential typhoon; about 20% of annual sediment discharge in 2001 was carried downstream in 2 days in typhoon Toraji.

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