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INITIATION OF HILLSLOPE DEBRIS FLOW AFFECTED BY CHI-CHI EARTHQUAKE, TAIWAN

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ABSTRACT: A reconnaissance was conducted to hillslope debris flows (HDF) which affected by Chi-Chi earthquake and Typhoon Morakot. Historical PGA and cumulative - and intensity rainfalls at debris-flows initiation time were studied to figure out the initiating characteristic of debris flows. Result shows that the earthquake related HDF not only initiation in high PGA region but also in moderate PGA region (100 to 250 gal). As PGA increasing, the triggering cumulative - and intensity rainfalls of HSDF are decreasing. Shocking by Chi-Chi earthquake, rock mass developed dense cracks enhancing landslide potential and stored the material for the circumstance of HSDF.

Key Words: hillslope debris flows, Chi Chi earthquake, rainfall

INTRODUCTION

Taiwan is situated at the juncture zone of the Euro-asia Continental Plate and the Philippine Sea Plate with a northwest tectonic movement of the Philippine Sea Plate. As the consequences of the tectonic actions, the Central Mountain Range as well as the Coastal Mountain Ranges are produced, and the prevailing geological formations and structural patterns align approximately parallel to the longitudinal axis of the island. The topography and geological conditions are highly related to the tectonic activity, where the mountain area composes about 77% of the whole area with highly fractured geological conditions. As the results of the tectonic activity, Taiwan is among the most active seismic districts in the world.

During the 1999 Chi-Chi earthquake, extensive slope failures were triggered by the earthquake in central Taiwan. Among those, numerous of hillslope debris flows were triggered by Typhoon Toraji and Typhoon Nari. Those hillslope debris flows were identified that affecting by Chi-Chi earthquake. Been heavy and intense rainfall, Typhoon Morakot attacked Taiwan during August 6 to August 10 in 2009, 10 years after the earthquake, which brought the worst record to the history of Meteorology in south Taiwan. More than 3,000 mm of precipitation was accumulated including 1,500 mm of rainfall collected in one day and up to 130 mm/hr in intensity in the mountainous area. (Chen et al., 2009)

A reconnaissance was conducted to hillslope debris flows (HDF) which were affected by Chi-Chi earthquake and Typhoon Morakot. PGA and cumulative- and intensity rainfalls on hillslope debris flows were studied to figure out the initiating characteristic of the debris flows.

CHI-CHI EARTHQUAKE AND TYPHOON MORAKOT EVENTS

(1) The Chi-Chi earthquake

The Chi-Chi earthquake struck central region of Taiwan on September 21, 1999, with a moment magnitude of 7.6, had caused severe ground failures and loss of lives and properties. The earthquake was triggered by the faulting action of the Chelungpu fault, with a fault rupture length of 105 km. The Chelungpu fault is a shallow thrust east-dipping fault which moved westward. The focal depth of the earthquake was only 8 km, which meant a tremendous amount of energy was released near the ground surface. The maximum peak horizontal ground acceleration recorded was about 1 g, and the maximum peak vertical ground acceleration recorded was 0.7 g. The PGA contour of motion caused by the main shock is shown in Fig. 1.

The Chi-Chi earthquake caused extensive slope failures in central Taiwan from Miao-Li County to Jai-Yi County. The Soil and Water Conservation Bureau surveyed the landslides based on aerial photos and SPOT satellite images taken before and after the earthquake. More than 21,900 items of ground surface variation involving a total area of more than 8,600 hectares were identified. The distributions of the documented ground surface variations are shown in Fig. 1.

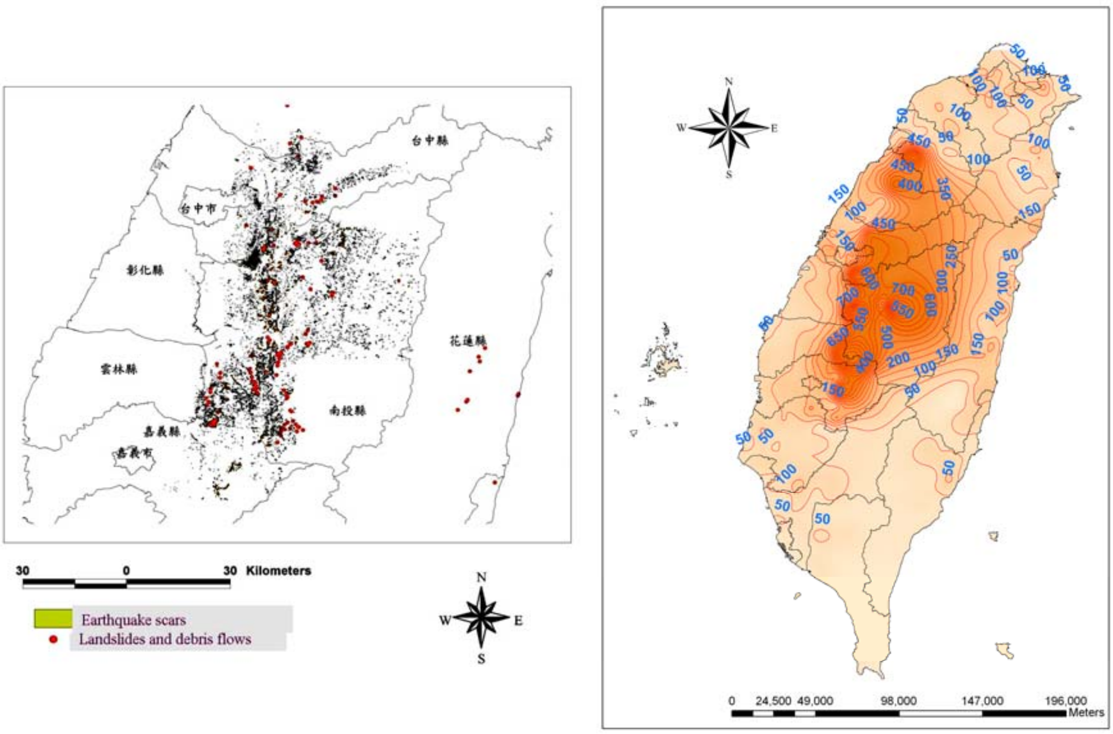

Fig. 1. Distribution of the PGA and ground surface variations after Chi-Chi earthquake in central Taiwan.(Lin et al., 2002)

(2) The Typhoon Morakot

Typhoon Morakot attacked Taiwan during the days of August 6 to August 10 in 2009, which brought the worst record to the history of Meteorology in south Taiwan. More than 3,000 mm of precipitation was accumulated including 1,500 mm of rainfall collected in one day and up to 130 mm/hr in intensity in the mountainous area. The maximum intensity and accumulation rainfall are shown in Fig.2 and Fig. 3.

The high-intensity and –accumulation event caused flooding and triggered ten thousands of soils slips, debris flows and large, complex landslides. Total area of landslide is more than 60,000 ha and more than 500 victims were killed. (Chen et al., 2009; Lin et al., 2011)

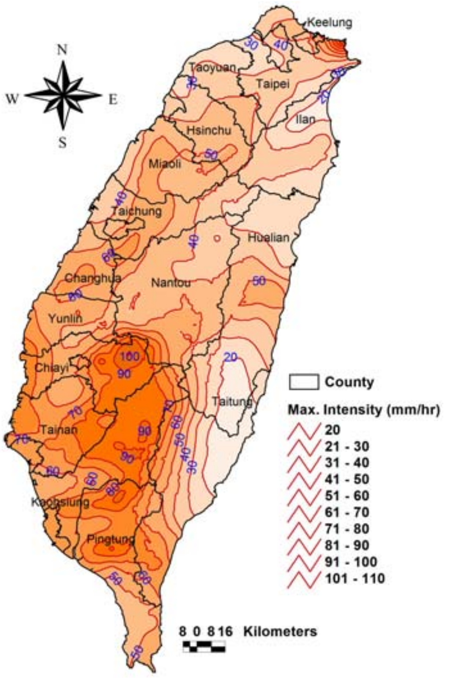

Fig. 2 Maximum rainfall intensity in Typhoon Morakot (Chen et al., 2009)

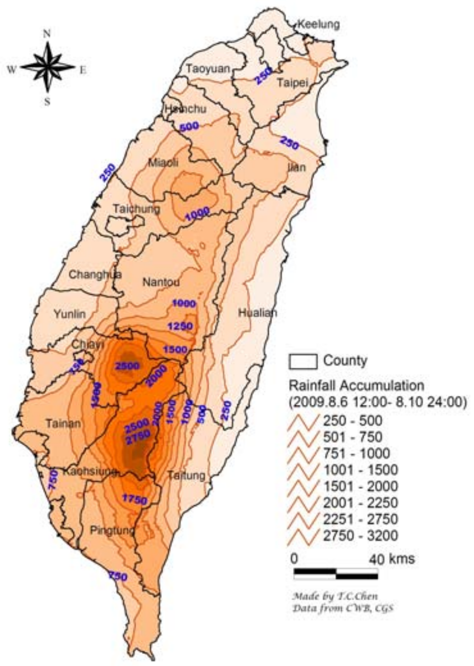

Fig. 3 Accumulated rainfall in Typhoon Morakot (Chen et al., 2009)

Most landslide hazards occurred during the period from the afternoon of 8 August to early morning of 9 August as the rainfall intensity rose. Soil and Water Conservation Bureau documented 1349 landslide hazards including more than 100 debris flow cases. The landslide area identified using FORMOSAT II satellite images by Central Geological Survey is more than 50000 hectares. (Lin et al., 2011)

Kaoping River, the major river in south Taiwan for 171 km in length and 3285 square km in basin, was severe damaged in Typhoon Morakot. A reconnaissance was conducted shown the sever slope failure and debris flows were triggering during the typhoon. 60 stream debris flows and 29 hillslope debris flows were documented. Stream type debris flows were recognized and mitigated by official authority before typhoon mostly; oppositely few hillslope type debris flows were detected from authority hence causing serious hazard to community and residents.

Fig. 4 illustrated the distribution of identified severe landslide cases with accumulated rainfall. Observing Figure 2, it was found that the locations of severe landslide and debris flow hazards are consistent with high accumulated rainfall area (as shown in Fig. 5). (Lin et al., 2011)

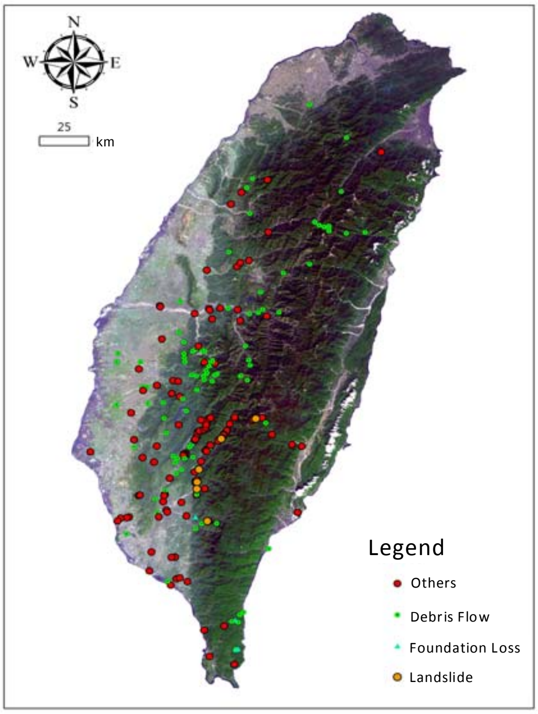

Fig. 4 Locations of hazards and types (Lin et al., 2011)

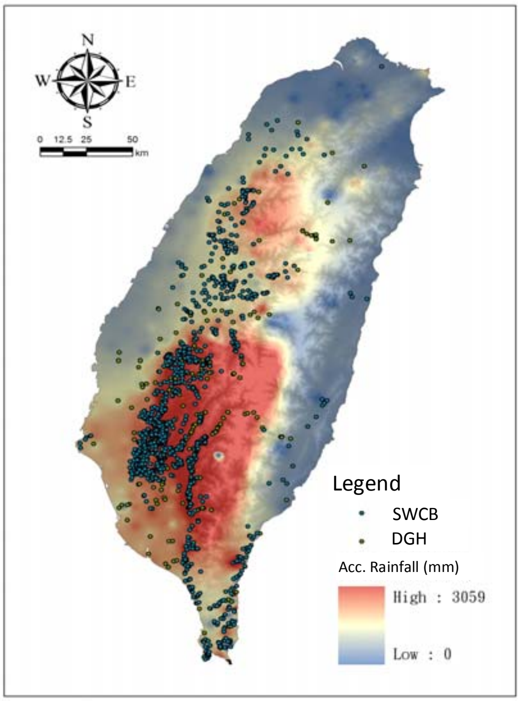

Fig. 5 The distribution of landslide hazards with rainfall from August 5 to 10, 2010 overlaid with topography. (Lin et al., 2011)

DISTRIBUTION OF HILLSLOPE DEBRIS FLOW

A reconnaissance on hillslope debris flows affected by Chi-Chi earthquake and Typhoon Morakot was conducted. More than 80 hillslope debris flows were documented in the events. The investigation is shown in following.

(1) Occurrence of a hillslope debris flow

Hillslope debris flow (HDF) originating on steep slopes have the short gully length, small watershed and the narrow shape of the watershed of the topographic characteristics and gully length is related to watershed area. (Lin et al., 2000)

Hillslope debris flows (Brunsden 1979) are one of the most common geomorphic phenomena in mountainous areas. A shallow landslide evolves s into a debris flow (Bathurst et al, 1997). They have been described as the “rapid mass movement of blocky, mixed debris of rock and soil by flow of wet, lobate mass”, as “the downslope flow of debris mixed with a minor, yet significant, amount of water” (Innes 1983). Brunsden (1979) pointed out that they typically occur on slopes with abundant nonconsolidated sediments, steep gradients, scarce plant cover, and no previous rills or incised channels. Scars develop at the rupture area, and a tongue develops with lateral levees ending in a frontal lobe with imbricated, nonsorted clasts (Johnson and Rodine 1984). The earthquake and typhoon related HDF are shown as Fig. 6 and Fig.7.

Fig. 6 HDF in Moi-Li after Chi-Chi earthquake.

Fig. 7 Lui-Que HDF in Typhoon Morakot.

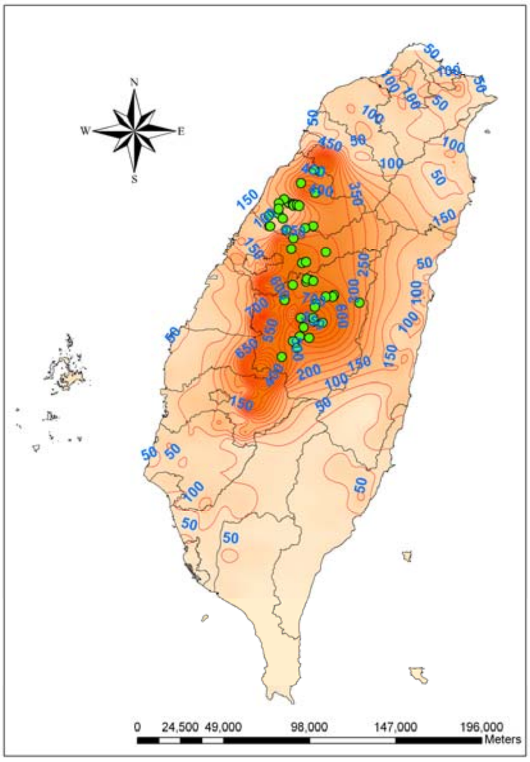

Fig. 8 The Distribution of HDF of the two typhoon events in a year after Chi-Chi earthquake.

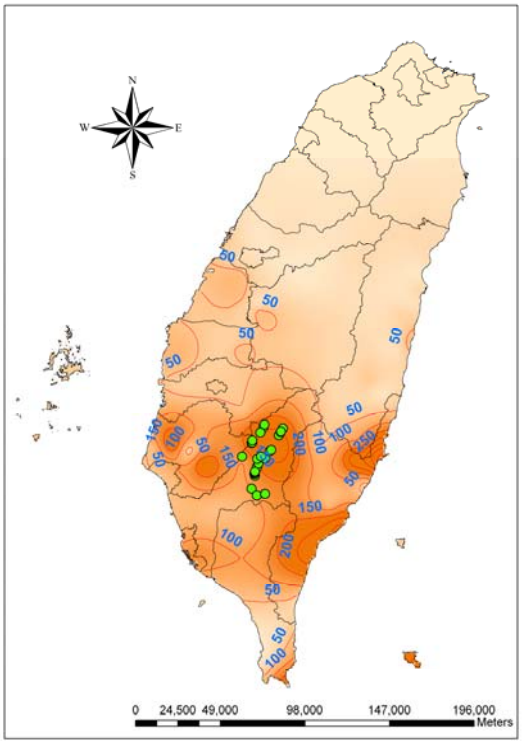

Fig. 9 Total 29 cases HDF cases were documented in Typhoon Morakot and the maximum PGA of south Taiwan in last decade.

(2) The hillslope debris flow after Earthquake event

The reconnaissance was conducted in two typhoon events in a year after Chi-Chi earthquake. The

Distribution of HDF is shown in Fig. 8. The Locations of HDF are around in major earthquake affected area, region of PGA 150 gal to 800 gal, in central island. About 80% of 50 HDF is located in the region of PGA large than 200 gal. Half of HDF were distributed in sedimentary rock; the others were in metamorphic rock. Documented data of each HDF included watershed area, stream length, average slope, landslide area, initiation time, surround rainfall gauge records of HDF, and so on. The small and shallow landslides were mostly found in the HDF catchment as referring to Fig. 1.

(3) The hillslope debris flow of Typhoon event

The reconnaissance was also conducted in Typhoon Morakot event, 10 year after Chi-Chi earthquake. The Locations of HDF are in Kaoping River, the major river in south Taiwan, where was minor affected, PGA lower than 50 gal, by Chi-Chi earthquake. 30 HDF were documented in this typhoon event, the distribution of HDF is shown in Fig. 9. Because the consideration of earthquake effect, we collect the earthquake PGA record in the region and surround area in last decade. Fig.9 shows the distribution of PGA, contour is range from 100 gal to 250 gal in Kaoping River. About 20% of HDF is located in the region of PGA large than 200 gal. 30% of HDF were distributed in sedimentary rock; the others were in metamorphic rock. Same data was documented for each HDF included initiation time, rainfall gauge records. The small and shallow landslides were also found in the HDF catchment. despite its landslide area larger than earthquake event.

- ***The triggering rainfall of hillslope debris flow***

Hours rainfall records of three typhoon events, overall gauges in Taiwan Island, were collected and developed in a database for the HDF triggering rainfall determination. We surveyed the HDF initiation times by investigation in field, News records, and reports of government agent and considered with the geomorphic factors and rainfall history. The effective rainfall composed of antecedent and present rainfall was introduced to character the triggering rainfall of HDF. The calculation of rainfall Intensity I (mm/hr) and effective accumulation P (mm) at the most possible initiation moment of HDF are illustrated in Fig. 10. There are 74 cases out of the 80 HDF cases (~ 92 %) related to high intensity rainfall with rainfall intensity exceeding 30 mm/hr. Most of Chi-Chi earthquake relating HDF cases (~ 48 %) with the effective accumulation >400 mm, oppositely, the effective accumulation are higher than 400 mm for most of Typhoon Morakot cases.

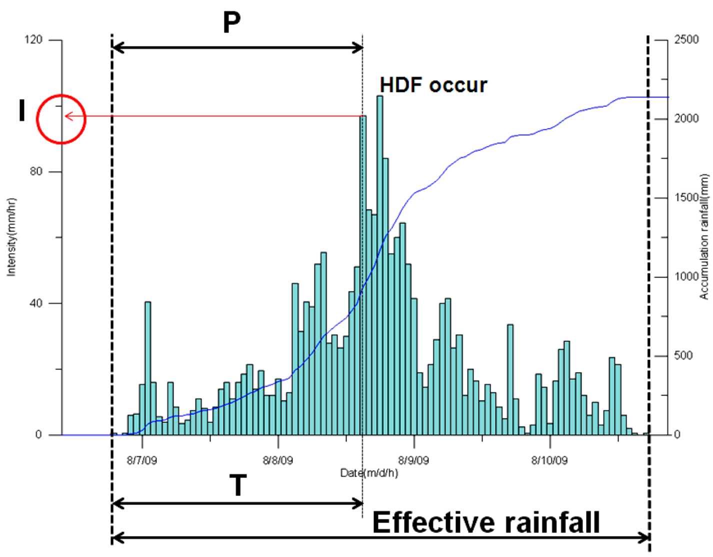

Fig.10 The schematic of trigging intensity and effective accumulation rainfall

(1) Intensity I – PGA

As shown in figure 11, the HDF location distributes from 100 gal to 800 gal in Chi-Chi earthquake events, the HDF is rare in the region of PGA lower than 100 gal. There are 14 cases out of the 50 HDF cases (~ 28 %) in which PGA between in 100 to 250 gal (Level 5 earthquake intensity of CWB). It point out the potential of HDF not only initiation in high PGA region but also in moderate PGA region, the HDF potential area for disaster mitigation seen be considered to spread to the regions of PGA 100 gal and up. The threshold of HDF triggering intensity decreased, as earthquake's PGA increased. The lowest triggering intensity of is about 20 mm/hr in which PGA was 208 gal. HDFs located in the region lower than 200gal have a tendency towards higher triggering intensity, oppositely the one in high PGA region tend to lower triggering intensity.

It also showed in the figure, the HDF location distributes from 100 gal to 250 gal in Typhoon Morakot events, the HDF is also rare in the region of PGA lower than 100 gal. There are total 29 cases HDF cases in which the maximum PGA lower than 250 gal, included the Chi-Chi earthquake event, in last decade. There are not clear tendency on PGA and intensity because the HDF are also influenced by effective accumulation rainfall. Most of HDF triggering intensity was higher than 35 mm/hr despite 3 cases of effective accumulation more than 1000 mm.

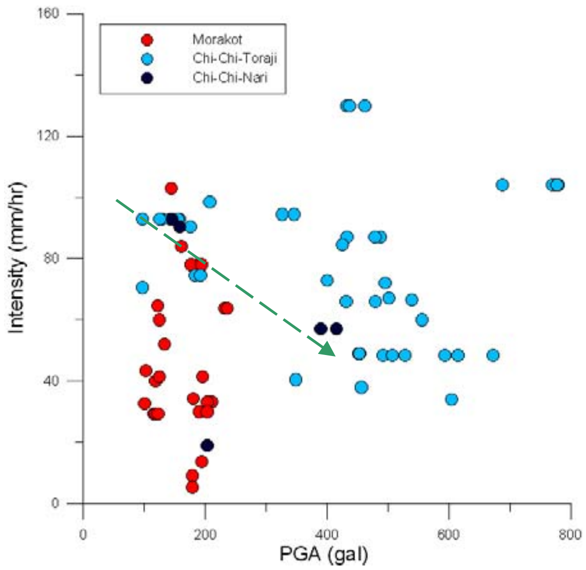

Fig. 11 The distribution on the triggering rainfall intensity and PGA of HDFs

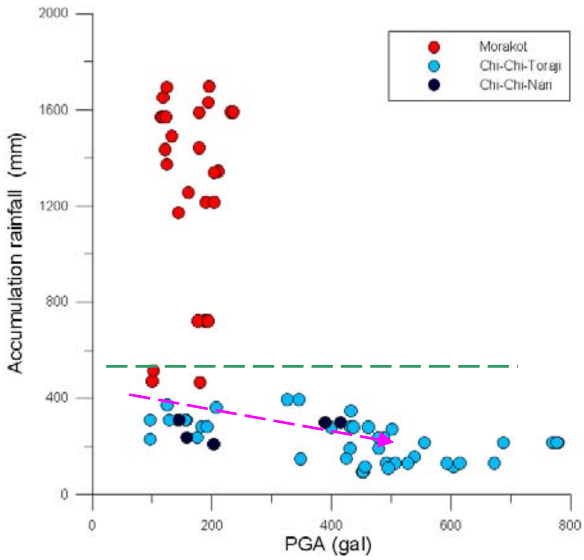

Fig. 12 The distribution on the triggering effective accumulation and PGA of HDFs

(2) Effective accumulation P - PGA

The figure 12 illustrated the 400 mm of effective accumulation rainfall seen to a bound between Chi-Chi earthquake and Typhoon Morakot events. Overall HDF related to Chi-Chi earthquake was low than effective accumulation 400 mm, the lower effective accumulation P is 95 mm and 29 cases out of the 50 HDF cases (~ 58 %) in which P lower than 250 mm, in small to moderate rainfall scale. The HDF has a tendency towards the threshold of HDF earthquake's PGA increased, the triggering lower effective accumulation P decreased.

The HDF located lower than 300gal has a tendency towards the triggering P was higher 200 mm, oppositely the one in high PGA region tend to lower triggering P. In contrast, most of HDF located in high triggering accumulation region, there are 23 cases out of the 29 HDF cases (~ 79 %) in which P was higher than 1000 mm.

Fig. 13 shows the distribution of triggering intensity and effective accumulation of HDF. Two groups are observed in the figure, the earthquake related group shows a tendency to74% of HDF's intensity higher than 50 mm/hr despite there were lower accumulation rainfall; in contrast, only 59% of Typhoon's HDF that the intensity was lower than 50 mm/hr but the P was higher than 1000 mm mostly. It also demonstrates the difference of HDF related to earthquake and typhoon.

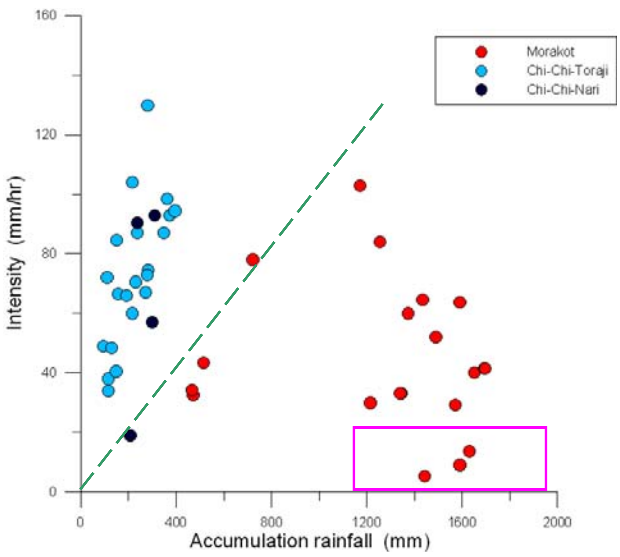

Fig. 13 The magnitude of HDF of Chi-Chi earthquake and Typhoon Morakot related

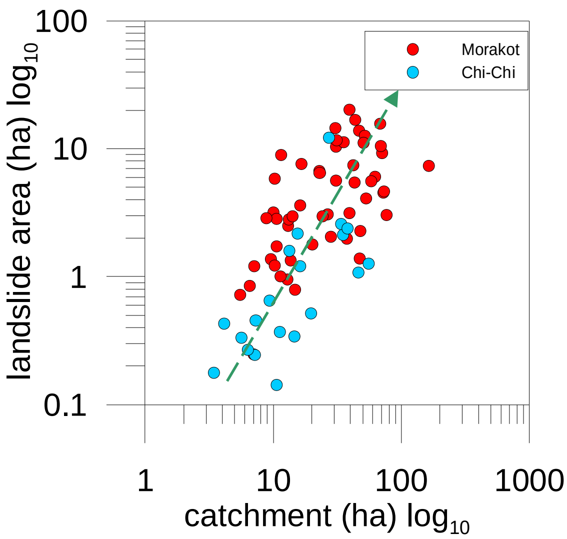

Fig. 14 The catchment and landslide area on two types HDFs

(3) Magnitude of hillslope debris flow

The magnitude for HDF was difference influenced by the factor, the earthquake related HDF tends to small landslide area, and the typhoon related HDF is tending large landslide magnitude. Fig. 14 showed the catchment and landslide area on two types HDF, there is a tendency towards the landslide area increasing with the catchment increased. The catchment of earthquake HDF range from 3.4 to 56 ha with the landslide area from 0.14 to 12 ha. The catchments were range from 10 to 165 ha with the landslide area from 1 to 20 ha. 75% of earthquake HDF case is landslide area small than 2 ha, in contrast, it is only 12 % did for the typhoon case.

CONCLUSIONS

Hydrological and geomorphic characteristics study focuses on earthquake and Typhoon Mprakot related types of hillslope debris flow, and cumulative- and peak intensity rainfalls on debris-flows were studied by spatial analysis to figure out the initiating characteristic of debris flows. We conclude the results as following: :

(1) The earthquake related HDF not only initiation in high PGA region but also in moderate PGA region (100 to 250 gal, Level 5 earthquake intensity of CWB), the HDF potential area for disaster mitigation seen be considered to spread to the regions of PGA 100 gal and up. The threshold of HDF triggering intensity decreased, as earthquake's PGA increased.

(2) The 400 mm of effective accumulation rainfall seen to a bound between Chi-Chi earthquake and Typhoon Morakot events. There is a tendency towards the threshold of HDF earthquake's PGA increased, the triggering lower effective accumulation decreased.

(4) There are not clear tendency on PGA and intensity for HDF in Typhoon Morakot, those HDF are also influenced by effective accumulation rainfall. Most of HDF triggering intensity was higher than 35 mm/hr but strongly influence by the higher effective accumulation rainfall.

(5) Two groups are observed in the figure, the earthquake related group shows a tendency to74% of HDF's intensity higher than 50 mm/hr despite there were lower accumulation rainfall; it also demonstrates the difference of HDF related to earthquake and typhoon.

(6) The magnitude for HDF was difference influenced by the factor, the earthquake related HDF tends to small landslide area, and the typhoon related HDF is tending large landslide magnitude.

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