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RAINFALL CONDITIONS FOR THE INITIATION OF DEBRIS FLOWS DURING TYPHOON MORAKOT IN THE CHEN-YU-LAN WATERSHED IN CENTRAL TAIWAN

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ABSTRACT

In the August of 2009, Typhoon Morakot brought heavy rainfall and caused several landslides, floods and debris flows in central and southern Taiwan. This work presents the critical rainfall conditions for the initiation of debris flows in the Chen-Yu-Lan watershed of central Taiwan during the action of Typhoon Morakot, where had many severe debris–flows events during the actions of Typhoon Herb in 1996 and Typhoon Toraji in 2001. Thirty-seven debris flow events induced by the heavy rainfalls brought by Typhoon Morakot in the Chen-Yu-Lan watershed were identified by the examination of aerial photographs and field investigations. The rainfall conditions, including the rainfall intensity, the cumulative rainfall, the rainfall intensity-duration curve and the return period of the rainfall, for debris-flows initiation were analyzed and compared with the rainfall conditions of historical debris-flows events in the watershed. The average rainfall intensity that triggered abundant debris flows in the watershed were determined and the relation between the density of debris-flows occurrence and the rainfall characteristics were also presented.

Key words: *rainfall condition, debris flow, Chen-Yu-Lan watershed, Typhoon Morakot*

INTRODUCTION

As a result of heavy rain accompanying typhoons, steep topography, young and weak geological formations, strong earthquakes (25 earthquakes with magnitude greater than 6 on the Richter scale in the 20th century), loose soil, and land development in mountainous terrain, many areas in Taiwan are susceptible to landslides and debris flows (TGRU, 2001; Jan & Chen, 2005; Chen *et alii*, 2009), especially in the study area of the Chen-Yu-Lan watershed in central Taiwan. Many debris-flow events in the watershed have been documented (e.g., Yu & Chen, 1987; Yu, 1997a,b; DPRC, 2000; DPRC, 2001; Lin & Jeng, 2000; Cheng *et alii.*, 2005; Jan & Chen, 2005). The more severe events were those caused by Typhoon Herb in 1996 and Typhoon Toraji in 2001, as indicated in Table 1. On August 7, 2009, a moderate Typhoon Morakot landed on Taiwan. After Morakot landed in the midnight of August 8, almost the entire southern region of Taiwan (Chiayi, Tainan, Kaohsiung, and Pingtung counties) and parts of eastern and central Taiwan (Taitung and Nantou counties) were flooded by record-breaking heavy rain. Massive flooding have destroyed bridges and roads, and submerged many homes forcing residents to evacuate and stay in shelters. Typhoon Morakot brought catastrophic damage in Taiwan, leaving 665 people dead and 34 others missing, and roughly NT$141 billion (US$4.4 billion) in damages. Like previous typhoons events, Typhoon Morakot also caused several debris flows in the the Chen-Yu-Lan watershed.

This study presents the critical rainfall conditions for the initiation of debris flows in the Chen-Yu-Lan

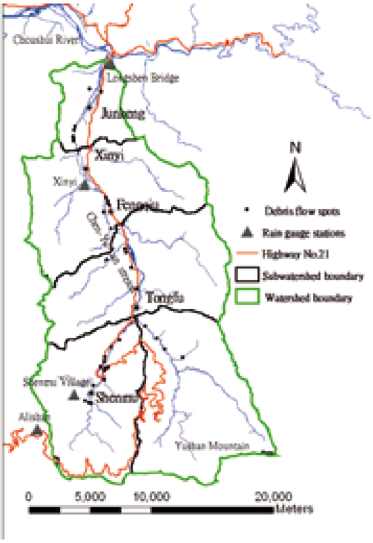

Fig. 1 - Location map of Chen-Yu-Lan watershed, Nantou, Taiwan, and locations of debris-flow gullies analyzed in this paper

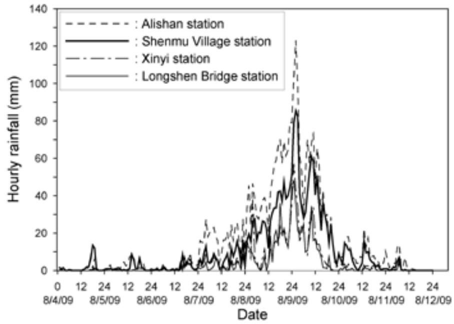

Fig.2 - Hourly rainfall measured at 4 rain-gauge stations in the Chen-Yu-Lan stream watershed during Typhoon Morakot. The maximum hourly rainfall at Alishan rain-gauge station exceeded 100 mm

watershed of central Taiwan during the action of Typhoon Morakot. The rainfall conditions, including the rainfall intensity, the cumulative rainfall, the rainfall intensity-duration curve and the return period of the rainfall, for debris-flow initiation were analyzed and compared with the rainfall conditions of historical debris-flow events in the watershed.

STUDY AREA

The Chen-Yu-Lan watershed is located in Nantou County in central Taiwan, about 12 km east of Chi-Chi, the town closest to the epicenter of the 1999 earthquake. The Chen-Yu-Lan stream is 42 km long with a mean gradient of 4°, and elevations ranging from 310 to 3952 m. The catchment of the Chen-Yu-Lan stream area is 449 km^2 with a mean annual rainfall about 3000 mm. The Chen-Yu-Lan stream follows a major fault, the Chen-Yu-Lan Fault, which is a boundary fault dividing two major geological zones of Taiwan. In addition to the boundary fault separating geological zones, the watershed of the Chen-Yu-Lan stream also contains many other faults, accompanied by fractured zones. Consequently, fractured rock mass prevails over the study area, accounting for enormous landslides and providing an abundant source of rock debris for debris flow (Lin & Jeng, 2000). Since the weak geological condition, heavy rainfall and accompanying frequent earthquakes, debris-flow hazards occur frequently in the watershed. Over ten rainfall events caused numerous debris flows in the past fifteen years. The more severe debris-flow events occurring in the Chen-Yu-Lan watershed were brought by Typhoon Herb in 1996, Typhoon Toraji in 2001 and Typhoon Morakot in 2009. In this paper, 37 debris flows brought by Typhoon Morakot within the Chen-Yu-Lan stream watershed were identified by the examination of aerial photographs and field investigations, as shown in Figure 1.

RAINFALL BROUGHT BY TYPHOON MORAKOT

Typhoon Morakot formed early on August 2, 2009 as a tropical depression over the Pacific Ocean about 1,000 km east of the Philippines. It then moved west towards Taiwan, and landed on August 7 near Hualien city, eastern Taiwan. After Morakot landed in the midnight of August 8, almost the entire southern region of Taiwan (Chiayi, Tainan, Kaohsiung, and Pingtung Counties) and parts of Taitung County and Nantou County were flooded by heavy rain. Hourly rainfall measured at 4 rain-gauge stations, including Longshen Bridge, Xinyi, Shenmu Village, and Alishan, in the Chen-Yu-Lan stream watershed during Typhoon Morakot were collected. Locations of these rain-gauge stations covering the downstream and upstream of the watershed were indicated in Figure 1. The largest rainfall record appears near headwaters of the Chen-Yu-Lan watershed at the Alishan station and the smallest one appears at downstream of the watershed at the Longshen Bridge station. An hourly rainfall exceeding 60 mm persisted for 13 hours from 15:00 on August 8 to 4:00 on August 9, 2009 at Alis-

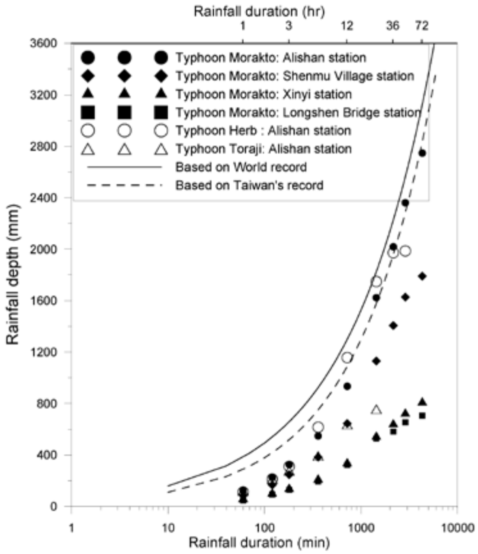

Fig. 3 - Rainfall magnitude-duration graph for Typhoon Morakot at 4 rain-gauge stations in the Chen-Yu-Lan stream watershed. For comparison, maximum rainfall magnitude-durations relations in Taiwan and the corresponding world are shown

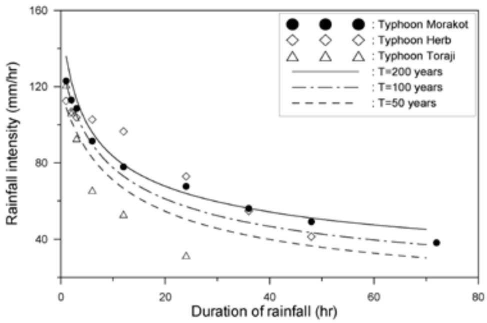

Fig. 4 - Rainfall intensity-duration graphs for Typhoons Morakot, Toraji, and Herb at Alishan station. For comparison, the corresponding relations for various return periods T are also shown

han station (Fig. 2). The maximum rainfall intensity, 123 mm/hr, appears at 1:00 to 2:00 on August 9.

The maximum 1-hour, 12-hour, 24-hour, 48-hour, and 72-hour rainfall at Alishan station were 123mm, 935mm, 1,624mm, 2,361mm, and 2,747mm, respectively, as shown in Figure 3. The cumulative rainfall in three days is up to 2,500 mm, exceeding the average annual rainfall in Taiwan. The previous 48-hour (2280 mm) records in Taiwan were broken. The new 48-hour rainfall records in Taiwan approach the world records (2,490 mm)(TGRU, 2001). Figure 4 shows the rainfall intensity-duration graphs for Typhoons Morakot, Toraji and Herb at Alishan station. For comparison, the corresponding relations for various return periods T (WRAT, 2001) are also shown. The estimated return periods form 10-hour to 40-hour rainfall at Alishan station during Typhoon Morakot approached 200 years. This record-breaking rainfall is believed to play a major role in triggering debris flows.

PROPERTY LOSS CAUSED BY DEBRIS FLOWS

The design codes of culverts, bridges, and riverbanks in mountainous area consider floods with a recurrence interval of 50 years. The maximum rainfall return period brought by Typhoon Morakot in the Chen-Yu-Lan stream watershed exceeded the design standard of 50 years. The extreme amount of rain triggered enormous debris flows and severe flooding. The consequence caused several river embankments damaged, bridges crashed, houses buried, and numerous sections damaged along Highway Route 21. For example, the flood in the Chen-Yu-Lan stream caused Soshan Bridge crashed and Highway Route 21 broken, and over 20 houses damaged. The Longhwa elementary school built near the riverbank of the Chen-Yu-Lan stream was almost destroyed by flood. In Shenmu and Tongfu villages, Xinyi Township, over 20 houses were buried by debris flows or washed away by floods.

The rainfall produced by Typhoon Morakot, peaking at 2,747 mm in three days, surpassing the previous record of 1,736 mm set by Typhoon Herb in 1996. However, the casualties caused by Typhoon Morakot were much lighter than those by Typhoon Herb in 1996, because many structural and non-structural countermeasures against debris flows were made after 1996. There was no death in this Morakot event but 21 deaths in Typhoon Herb in the Chen-Yu-Lan watershed. Especially, the non-structural countermeasures for the planning of evacuation routes and shelters and education of hazard prevention have been conducted in mountainous villages. Many mountainous villages have conducted debris-flow disaster prevention and evacuation practices to enhance inhabitants' hazard-mitigation knowledge and emergency-response swiftness as well as their familiarity with evacuation routes and shelters.

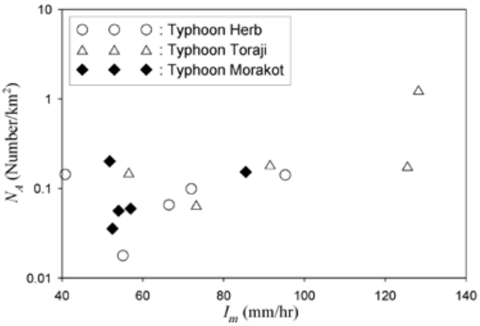

Fig. 5 - Relationship between the occurrence density of debris flows and maximum rainfall intensity in the Chen-Yu-Lan watershed

RAINFALL CONDITIONS FOR TRIGGERING DEBRIS FLOWS

THE RELATION BETWEEN DEBRIS-FLOWS OCCURRENCE DENSITY AND RAINFALL CHARACTERISTICS

Most debris flows caused by Typhoon Morakot generally occurred at the time of the maximum hourly rainfall intensity Im in the Chen-Yu-Lan watershed. Similar results also found in the watershed for abundant debris flows caused by Typhoon Herb and Typhoon Toraji. In order to understand the rainfall characteristics for triggering numerous debris flows, the relationship between the maximum rainfall intensity I_m and a parameter named debris-flow occurrence density *NA* were analyzed.

The debris-flow occurrence density *NA* is defined as the number of debris flows per unit area, i.e. *NA=N / A*. In the study area, the watershed can be viewed as consisting of five subwatersheds as shown in Figure 1. The average rainfall characteristics, such as the hourly rainfall and the maximum rainfall intensity, in each subwatershed area A was computed at the centroid point of A using the reciprocal-distance-squared method (Chow *et alii*., 1988; Wei & McGuinness, 1973) from two adjacent rain-gauge stations. The number of debris-flow gully *N* in each subwatershed area A was also determined. The relationship between the occurrence density of debris flow *NA* and maximum hourly rainfall Im at each subwatershed area in the Chen-Yu-Lan watershed was shown in Figure 5. The results showed that the value of *NA* has an increasing tendency with increasing in I_m,, especially when I_m exceeds 60 mm/hr. High rainfall intensity has a high probability to trigger high occurrence density of debris flows.

INITIATION THRESHOLD OF DEBRIS-FLOWS

Rainfall characteristics that are often considered to affect the triggering of debris flows are rainfall duration, rainfall intensity, and cumulative rainfall (Caine, 1980; Keefer *et alii*., 1987; Wieczorek, 1987). The characteristics of rainfall intensity and rainfall duration for debris-flow gullies in the watershed are discussed in this paper. Because not each gully has a local rain gauge to record the hourly rainfall or cumulative rainfall, the rainfall at an ungauged point was computed using the reciprocal-distance-squared method; that is, the influence of the rainfall at a gauged point on the computation of rainfall at an ungauged point is inversely proportional to the distance between the two points (Chow *et alii*., 1988; Wei & McGuinness, 1973). Hydrometeorological thresholds of debris-flow initiation can be defined by the rainfall intensity versus rainfall duration relation (Caine, 1980; Keefer *et alii*., 1987; Wieczorek, 1987; Jan & Chen, 2005). In the Chen-Yu-Lan watershed, the maximum return periods of rainfall brought by Typhoons Herb, Toraji, and Morakot were over 100 years in the Chen-Yu-Lan watershed. These typhoons caused numerous debris flows and severe properties damages in the watershed. A rainfall intensity-duration formula for abundant debris-flows initiation threshold based on a lower bound of the rainfall data in the Chen-Yu-Lan watershed from Typhoons Herb, Toraji, and Morakot, is plotted in Figure 6 as a Line A and can be expressed as

$$I_A = 70\,D^{-0.5} \qquad (1)$$

where I_A is the average rainfall intensity (mm/hr) and D is the continuous rainfall duration (hr). Equation (1) reveals that the average rainfall intensity that triggered abundant debris flows were at least 14 mm/hr for duration 24 hr, 10 mm/hr for 48 hr and 8 mm/hr for 72 hr. The abundant debris-flows initiation threshold are also compared with the initiation thresholds based on a lower bound of the rainfall triggered at least one debris flow before and after the 1999 earthquake, shown in Figure 6 as a Line B and a Line C, respectively.

The thresholds of the Lines B and C are notably less than those identified for abundant debris flows. The initiation threshold for abundant debris-flows, Eq. (1), is around one to four times of that for at least one debris-flow before the 1999 earthquake, Line B. Figure 6 also finds that the 1999 earthquake significantly lowered the threshold of the rainfall amount required to trigger debris flows, especially after the earthquake

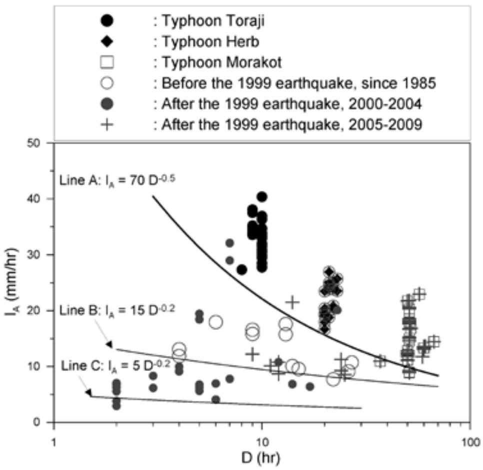

Fig. 6 - Empirical relations between average rainfall intensity and duration for initiation thresholds of debris flows in the entire Chen-Yu-Lan watershed

Date	Locations	Trigger	Damage
1996 07/31 ~ 08/01	Over 30 significant debris flows occurred in Feng-Chiou, Tong-Fu, Dong-pu, Shen-Mu Villages, etc. in Xinyi Township, and Jyun-Keng, Sin-Shan, Shang-An Villages, etc. in Shuei-Li Township, Nantou County.	Typhoon Herb	21 deaths, 6 injured, over 40 houses destroyed, over 40 ha fruit orchard damaged, significant damage to roads, dams, river regulation works, and other properties. (Lin and Jeng, 2000; Cheng et al.,2005; Jan and Chen, 2005)
2001 07/29 ~ 07/30	Over 100 debris flows occurred in Feng-Chiou, Tong-Fu, Shen-Mu Villages, etc. in Xinyi Township, and Jyun-Keng, Sin-Shan, Shang-An Villages, etc. in Shuei-Li Township, Nantou County.	Typhoon Toraji	19 deaths, over 30 missing and 70 houses destroyed, significant damages to dikes, roads, bridges and buildings. (Cheng et al.,2005; DPRC, 2001)

Tab. 1 - Significant debris flow events occurred in the Chen-Yu-Lan watershed

five years, 2000-2004. Apparently, the earthquake caused an abundant supply of loose material to accumulate on hillslopes and in stream channels, and thus, material moved more easily than previously under light rains following the earthquake.

CONCLUSIONS

Typhoon Morakot brought heavy rainfall fall with maximum hourly rainfall of 123mm and maximum cumulative rainfall of 2361 mm in 48 hours at Alishan rainfall station where near the headwater of the Chen-Yu-Lan watershed. The return periods of maximum hourly rainfalls from 10-hour to 40-hour rainfall approached the 200 years and the breaking cumulative rainfall of 2361 mm in 48-hour approached the world records. This record-breaking rainfall plays a major role in triggering abundant debris flows in the Chen-Yu-Lan watershed. Thirty-seven debris flows triggered by Typhoon Morakot in the watershed were collected and investigated. Most debris-flow gullies occurred at the time of peaking hourly rainfall. The occurrence density of debris-flow gully *NA* depends on the maximum rainfall intensity I_m, and *NA* increases with increasing in Im. A rainfall intensity-duration formula for abundant debris-flows initiation threshold based on rainfall data in the Chen-Yu-Lan watershed from Typhoons Herb, Toraji, and Morakot was presented (Eq. (1)). The average rainfall intensity that triggered abundant debris flows were at least 14 mm/hr for duration 24 hr, 10 mm/hr for 48 hr and 8 mm/hr for 72 hr. The initiation threshold for abundant debris-flows is around one to four times of that for at least one debris-flow before the 1999 earthquake. The study results also showed the non-structural countermeasures for the planning of evacuation routes and shelters and education of hazard prevention can efficiently reduce the casualties caused by debris flows.

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