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THE VARIABILITY IN TIME OF THE OCCURRENCE CONDITIONS OF DEBRIS FLOW AFTER CATASTROPHIC TYPHOONS AND EARTHQUAKES: A THEORETICAL EXPLANATION WITH EXPERIMENTAL TESTS

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ABSTRACT

In Taiwan, large and often catastrophic typhoons and earthquakes are both factors to trigger serious landslides in mountains. The presences of large amounts of sediments due to the landslides increase the occurrence of debris flow. Base on post-event data, the threshold of debris flow occurrence decreases soon after an earthquake indicating a fast recovery. A relationship of debris flow occurrence from Egashira (1997) is applied, which shows fine sediment plays an important role with debris-flow development and occurrence. In this paper, a series mobile-bed experiments were done to access the influence of the concentration change from upstream discharge with fine/ coarse particle. Two variables were recorded in the experiment, which were depth-ratio (sediment layer depth/ total depth), and the sediment discharge. With comparison with theoretical relationship, the result shows the occurrence condition varied with the ratio of fine sediment.

Key words: debris flow occurrence, fine sediment, typhoons, earthquakes, rainfall threshold

INTRODUCTION

The ML 7.3 Chi-Chi Earthquake (23.85°N, 120.81°E) that occurred on 21 September 1999 was the largest earthquake on the island of Taiwan for the past hundred years. In central Taiwan (a region of around 2,400 km^2), over 20,000 landslides (Wang, 2000) of approximately 113 km^2 in total area were triggered by the earthquake (Hung, 2000; Lin, 2003, 2006). Sediment generated by these landslides was deposited on slopes and riverbeds. In the following typhoon seasons, heavy rainfalls readily mobilized the sediment material and caused debris flows.

The significant increase in debris flow frequency following the Chi-Chi earthquake and the strong effect of rainfall on the generation of debris flows prompted a re-evaluation and subsequent lowering of the rainfall threshold for a valid debris-flow warning system (Lin, 2003; Shieh, 2004; Chen, 2006; Shieh, 2009). Consequently, government and engineers became increasingly interested in quantifying and better understanding the variability in rainfall triggering of debris flows.

The variation in the rainfall threshold for debris

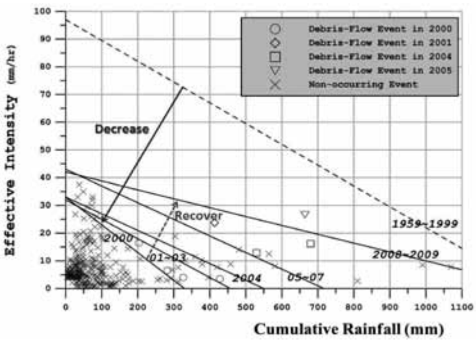

Fig. 1 - The rainfall threshold from 1999 ~ 2009

flow triggering after the earthquake was analysed by surveys in the earthquake area. Riverbed deposits, particle-size distributions, and sediment concentrations were monitored continuously at the field site between 1999 and 2009. During the 10-year study period, the data show that the rainfall threshold for debris flow activity was remarkably decreased just after the Chi-Chi Earthquake, but gradually recovering with time (Fig. 1).

In Fig. 1, the effective intensity means the max effective rainfall intensity during a typhoon, and the cumulative rainfall means the total rainfall during the event. Each point in Fig. 1 means one event. The reason for the variation is due to the fine particles increased rapidly due to landslides triggered by the earthquake. The fine sediment caused the flow density to increase, and lowered the debris flow triggering criteria. With time, rainfall caused debris flows and transported fine particles downstream, the flow density decreased, and the rainfall threshold is recovering gradually over time (SHIEH, 2009).

To investigate the variation in the rainfall threshold for debris flow triggering, a move-bed experiment was set and theory of mechanics of debris flow occurrence by EGASHIRA *et alii* (1989) was modified in this paper.

METHODOLOGY

MECHANICS OF DEBRIS FLOW OCCURRENCE

EGASHIRA *et alii* (1989) developed constitutive equations of debris flow. These results have been applied to a wide range of mass flows from debris flows to the flow within general bed-loads, and the results have been rational. From the theory, a debris flow occurrence condition could be derived as a simple equation, such as (1). Fig. 2 presents a schematic model of such a debris flow.

In Fig. 2, hs is the sediment layer depth, ht, is total depth), u (z) is the velocity profile in z-axis, c (z) is the

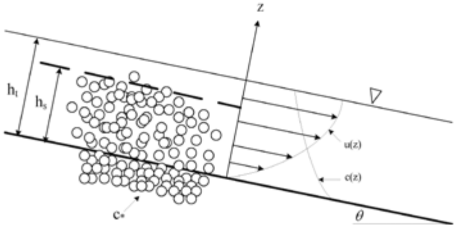

Fig.2 Schematic model of debris flow

concentration profile, c(z) is the concentration of the river bed, and θ is the slope of the river bed.

The depth-ratio of the moving sediment layer to depth of flow, h_s / h_t, is indicative of the type of sediment movement on or above the bed. When hs is similar to the diameter of the particles, transport is dominantly within the bed-loads. Conversely, when h_s / h_t is greater than 0.8, the water and sediment are almost completely mixed, which indicates the occurrence of a debris flow. Between these two types, it is a type of motion referred to as sediment-laden flow (EGASHIRA, 1989, 1991, 1992 & 1997). EGASHIRA (2008) derived this ratio from his model, which can be presented as the following equation.

$$\frac{h_s}{h_t} = \frac{1}{\left(\frac{\sigma}{\rho_w} - 1\right) \cdot \bar{c}_s} \cdot \frac{\tan\theta}{(\tan\phi - \tan\theta)} \qquad (1)$$

where $\bar{c}_s$ is the depth-averaged concentration of the moving sediment layer, σ is the density of sediment, ρ_w is the density of water, and ϕ is the friction angle of sediment. This relationship can be applied to the continuum between debris flow and flow within bed loads. According to the post-Chi-Chi-earthquake monitoring results, multiple landslides contributed new sediments. The new sediment contained a greater proportion of fine particles and therefore the density of flow increased rapidly because of the fine particles in suspension. So, in the above relationship, the density of water including the suspended matter, ρ_m can be used instead of ρ_w . Therefore, the original equation can be modified as follow:

$$\frac{h_s}{h_t} = \frac{1}{\left(\frac{\sigma}{\rho_m} - 1\right) \cdot \bar{c}_s} \cdot \frac{\tan\theta}{(\tan\phi - \tan\theta)} \qquad (2)$$

With parameters setting, the relationship between depth-ratio and riverbed gradient can be plotted (Fig. 3). The figure shows that when the density of flow increases, the depth-ratio of the moving sediment layer to the flow depth also increases. For example, when ρ_w is 1.0 and the riverbed gradient is 6°, the depth-ratio is 0.5. The flow type is sediment-laden flow only. When ρ_m increases to 1.3, however, the depth-ratio reaches 0.8 and the type of flow is a debris flow. Furthermore, note that the lowest possible riverbed gradient for de-

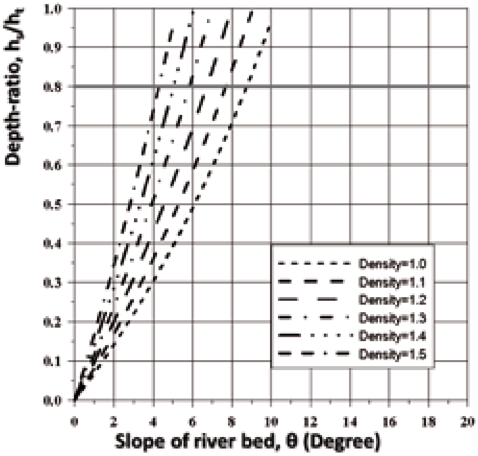

Fig. 3 - The relationship between depth-ratio and river-bed gradient

bris flow decreases as the density of flow increases. In Fig.3, when m ρ_m increases to 1.5, a debris flow can occur with a gradient as low as 4o. The result shows that the increase of flow density not only lowers the moving criteria for debris flows, but also increases the distance of debris flow traveling.

	D	ρ	φ
Coarse sand	1.2	2530	32.6
Fine sand	0.1	2570	28.3

D: size of sand (mm); ρ: Density (kg/m^3); φ: Inter-friction angle (°)

Tab. 1 - Character of sediment

	Q_{sc}	Q_{sf}	R	ρ_m
Case0	21	0		1
Case1	21	4	5.3 : 1	1.02
Case2	21	8	2.6 : 1	1.03
Case3	21	12	1.8 : 1	1.04
Case4	21	20	1.1 : 1	1.07
Case5	21	48	1:2.3	1.16

Qsc: discharge of coarse sand (cm^3/sec); Qsf: discharge of fine sand (cm^3/sec); R: Ratio between the two types of sand

Tab. 2 - Upstream Condition of experiment

EXPERIMENT SETTING

Base on the theory, a series mobile-bed experiments were done to access and vaildate the relationship of water density and debris flow occurrence. To change m ρ_m , two size particles were selected. For the rough one, which is assumed as main part of sediment movement, the size is 10 mm. On the other hand, a fine particle which is 0.1 mm, is select for the change of water density. Tab.1. is the parameter of sands. For the channel, a 4.0 meter channel was selected, and the slope of the channel could reach 12° (Fig. 4). In the upstream end, water and sediment (both fine and coarse sand) could be supplied for different discharge. A dam with 10 cm was placed at the downstream of the channel to catch the flow material.

To change the flow density m ρ_m , the upstream boundary was set as six different sediment supplies. The discharge of water and rouse sediment was fix, and the discharge of fine sediment was set from 0.0 to 48 cm^3/s. Tab. 2 shows the input condition. The fine sediment ratio range from zero to two times of the coarse sediment, and the change of water density range, from 1.0 to about 1.2.

In order to understand the phenomenon, two variables were recorded, the depth-ratio and the sediment discharge. To measure the depth-ratio, a high-speed camera was used and located near the end of the flume (Fig. 4). Video speeds of 300 fps and 600 fps was selected for video recording. The sediment discharge was measured by collecting the sand at the downstream end of the flume. In all case, the following variables were held const: slope of channel: 12°; discharge of water: 410 cm^3/sec.

The process of the experiments is description as fallows:

1. Discharge of water and coarse sand were released.
2. When the space of the dam is filled with the sediment and the variation of bed is steady, the fine sands would were added.
3. When the bed was near equilibrium, the flow was recorded with camera, and sediment was collected at the downstream end of the flume.
4. The depth-ratio was defined by each recorded frame. Then the sediment discharges of coarse/fine sand were calculated after a particle- size analysis.
5. The experiments were repeated for 3 runs of each case.

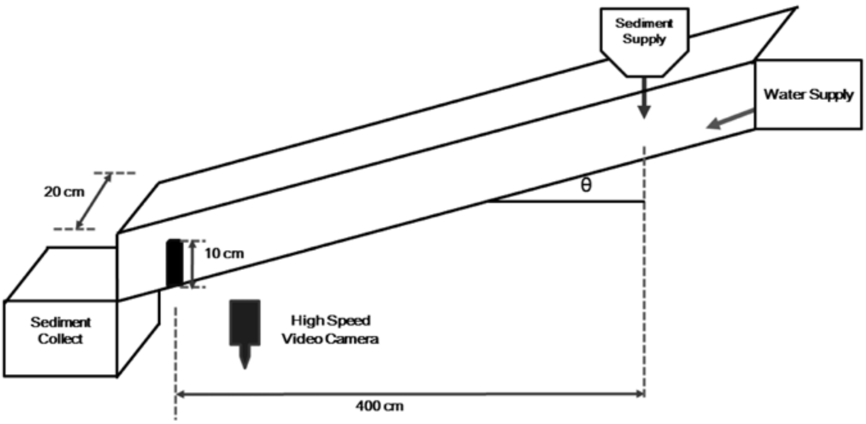

Fig. 4 - Schematic diagram of the experiment al laboratory flume

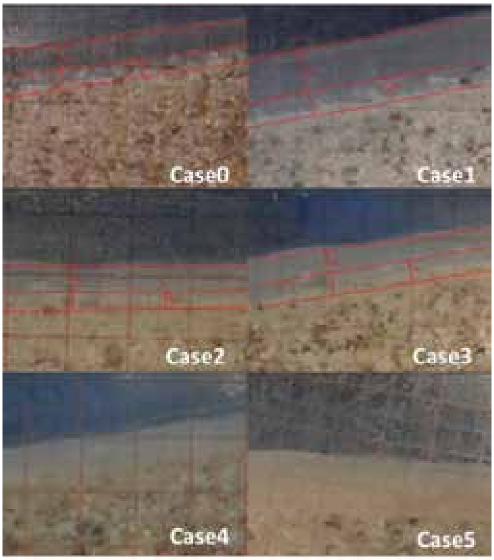

Fig. 5 - Depth-ratio recorded in each case

	hs/ht(Run1)	hs/ht(Run2)	hs/ht(Run3)	hs/ht (AVG)
case0	0.45	0.43	0.41	0.43
case1	0.44	0.47	0.46	0.46
case2	0.48	0.48	0.47	0.48
case3	0.51	0.52	0.48	0.50
case4	0.5	-	-	0.50
case5	-	-	-	-

"-" means the depth-ratio is hard to defined

Tab. 3 - Depth-ratio in each case for different runhs/ ht(Run1)

EXPERIMENT RESULT AND ANALYSIS

EXPERIMENT RESULT

Accord the experiment setting, the flow depth of water is about 1 cm to 2 cm. Fig. 5 shows the image took for depth-ratio analysis for Case0 ~ Case5 in the figure, the size of grid is 5 mm.

In case0, the water density didn't change, so the depth-ratio is well recorded. With fine sand increasing, the depth-ratio got increased. But in Case5, it is very hard to define the hs and the depth-ratio. Tab.3 shows the defined depth-ratio of each experiment. "-" is the table means the value couldn't be defined by the recorded flame.

Fig.6 shows the average data of each case, and also thearison with theoretical line or relationship. The experimental data plot very close to the theoretical line. So with fine sediment increasing, the bed-load transform to debris flow gradually

On the other hand, the sediment volume was record. Tab. 4 provides the result of the sediment transportation. The input and output value of coarse/ fine sediment were listed in Tab. 4.

It shows the variation of discharge of coarse sand would increase with the increasing of fine sand. In Case0 and Case1, the discharge of coarse sand is equilibrium, but increasing in Case 2 ~ Case4. In Case 5, the coarse sand discharge is almost same with Case4. The discharge of fine sediment was almost at equilibrium in each case. Fig.7 is draw According to the data in Tab.4 to show the trend of sediment discharge. This result could explan the increse of fine sediment would result in more coarse sediment movement.

	Qsc (Input)	Qsf (Input)	Qsc (Output)	Qsf (Output)
Case0	21	0	22	0
Case1	21	4	26	6
Case2	21	8	32	9
Case3	21	12	46	11
Case4	21	20	42	18
Case5	21	48	42	49.5

Unit of the sediment discharge is cm3/sec

Tab. 4 - Sediment Discharge in each case

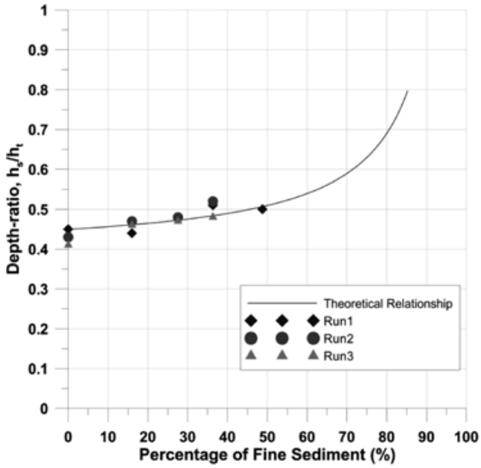

Fig. 6 - Comparison between experiment data with theoretical relationship

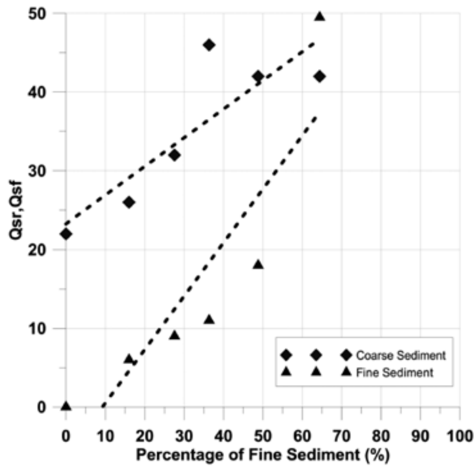

Fig. 7 - Sediment discharge change with percentage of fine sediment

DISCUSSION AND CONCLUDING REMARKS

There was a significant variation of debris flow occurrence after 921 Earthquake in Taiwan. Shieh (2009) proposed the fine sediment played an important role with the variation. After a catastrophic earthquake or typhoon, the large availability of sediment due to landslides would lower the triggering rainfall threshold. Then the threshold then increases in time due to the washing out of the finer sediments provided by mass transport.

This paper tries to reproduce the theoretical variation of debris flow occurrence with laboratory experiments. According to a modified theory from Egashira *et alii* (1989), the variation is supported due to the change of water density. When the density increases to 1.5, a debris flow could take place at a slope of 4°.

Through the experiment results, the depth-ratio of sediment would increase with increasing density with a constant slope. There are same trend by sediment discharge analysis, the discharge increasing with the increasing density. These both explain the decrease of debris flow occurrence with the fine sediment increasing. With comparing the sediment movement in a watershed after earthquake, the variation of debris flow occurrence condition could have a preliminary understanding.

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