Construction of 3D Rainfall Threshold Surface for Debris Flow Warning

Chien-Yuan Chen and Ho-Wen Chen

Abstract—**Rainfall-induced debris flow caused by climate change has recently become a threat to human life worldwide. Types of rainfall characteristics, namely, high rainfall intensity for a short duration, high accumulated rainfall for a long duration, and postseismic effects were investigated to build a 3D rainfall threshold surface for debris flow warning. Rainfall parameters including effective accumulated rainfall, intensity, and duration were investigated in the 3D analysis. The construction of a 3D rainfall threshold surface enhances knowledge on the rainfall characteristics that initiate debris flows. Rainfall monitoring in consideration of different rainfall characteristics can improve predictions of debris flow and thus facilitate the issue of timely warnings.**

***Index Terms*—Debris flow, warning, 3D, rainfall threshold.**

I. Introduction

Climate-change-triggered torrential-rainfall-induced debris flow has recently become a threat to human life worldwide. Natural disaster-induced accidents increased in 2005 as a result of the sequenced intense typhoons Haitang (July), Matsa (August), and Longwang (September) hitting Taiwan. Additionally, typhoons brought severe wind, floods, landslides, and debris flows from Bilis (July, 2006), Sepat (August, 2006), and Krosa (October, 2006), and from Kalmaegi (July, 2008), Sinlaku (September, 2008), and Jangmi (September, 2008).

Typhoon Morakot landed Taiwan on 7-10 August, 2009, bringing heavy rainfall and serious floods in southern Taiwan. The typhoon-induced disasters were attributed to its slow velocity, which led to long rainfall duration and high rainfall intensity [1]. Rainfall from Typhoon Marakot triggered numerous debris flows in southern Taiwan in 2009. Fig. 1 shows some debris flow disasters after Typhoon Morakot in southern Taiwan in 2009. In all, 398 residents were buried by a dam-breach-induced debris flow in Shaolin Village when Typhoon Morakot struck Taiwan [2]. Fig. 2 Shows debris flow blockages resulting in a stream that scoured the lower terrace of Longhua Elementary School in Nantou County [3].

Typhoon Morakot was an extreme rainfall event exceeding a 200 yr recurrence amount at many rain gauge stations causing severe floods, landslides and debris flows in southern Taiwan [4]. A high-precision real-time rainfall monitoring system for debris flow warning is urgently required for disaster prevention and mitigation in Taiwan.

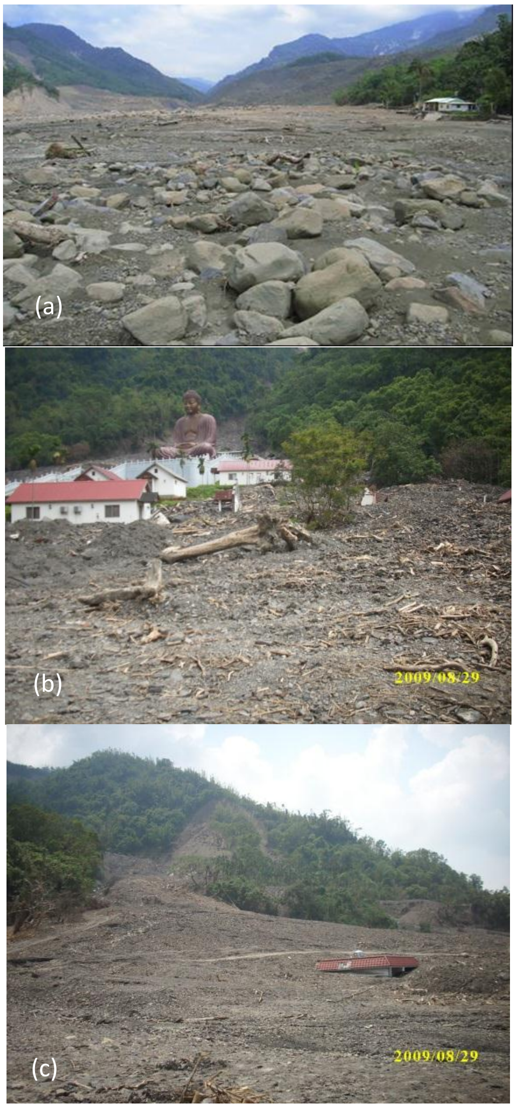

Fig. 1. Debris flow disasters after Typhoon Morakot in southern Taiwan in 2009 (a) debris masses buried Shaolin Village, (b) debris buried farm, (c) debris buried hot spring village.

Taiwan has 1705 debris-flow-prone creeks [5]. After Typhoon Herb in 1996, only 485 debris-flow-prone creeks were present. The number of debris-flow-prone creeks increased after the M_L 7.3 Chi-Chi earthquake in Taiwan in 1999. Postseismic landslides resulted in up to 1420 creeks being prone to debris flow in 2001 during typhoons Toraji and Nari. Torrential rains from Typhoon Marakot abruptly increased the number of debris-flow-prone creeks to 1503. The number has been continually increasing in recent years (Fig. 3).

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Fig. 2. Debris flow blockages resulting in a stream that scoured the lower terrace of Longhua Elementary School in Nantou County [3].

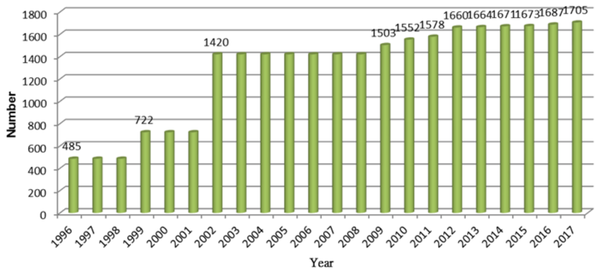

Fig. 3. Statistical analysis of the number of debris-flow-prone creeks in Taiwan.

Rainfall monitoring is the main methodology for debris flow warning. Early and precise rainfall monitoring could provide sufficient time for emergency evacuation of residents. The most commonly used rainfall parameters for debris flow monitoring include (effective) accumulated rainfall, duration, and intensity. The commonly used combinations of debris flow thresholds include accumulated rainfall–intensity [6]–[7] and intensity–duration [8]–[12]. However, no studies have used a spatial threshold surface for debris flow warning.

Table 1 lists the available rainfall threshold equations based on rainfall intensity and duration. The rainfall threshold equation for debris flow and landslide warning is expressed in the following form:

$$I = \alpha D^{-\beta} \tag{1}$$

where parameters α and β are constant.

TABLE I: RAINFALL THRESHOLD EQUATIONS BY RAINFALL INTENSITY AND DURATION

Equation	Type	Reference
$I=14.82D^{-0.39}$	Shallow landslide and debris flow	[13]
$D=0.9/(I-0.17)$	Debris flow	[14]
$I=30.53D^{-0.57}$	Debris flow and landslide	[15]
$I=91.46D^{-0.82}$	Landslide	[16]
$I=12(1/D+0.07)$	Soil slips and debris flow	[17]
$I=63/D+6.05$	Debris flow	[18]
$I=12.45D^{-0.42}$	Landslide	[19]
$I=0.82D^{-0.19}$	Landslide	[20]
$I=73.9D^{-0.79}$	Landslide	[21]
$I=2.2D^{-0.44}$	Shallow landslide and debris flow	[22]
$I=6.61D^{-0.77}$	Debris flow	[23]
$I=2.18D^{-0.26}$	Shallow landslide	[24]
$I=25.96D^{-0.24}$	Debris flow	[25]
$I=0.45D^{-0.09}$	Mudflow	[26]
$I=52.86D^{-0.45}$	Landslide, debris flow, and rock slide	[27]
$I=2.63D^{-0.3}$ (summer) $I=3.64D^{-0.28}$ (fall)	Debris flow	[28]
$I=2.97D^{-0.41}$(5% threshold)	Shallow landslide and debris flow	[29]
$I=3.99D^{-0.65}$ (1% exceedance probability)	Debris flow	[30]

II. STUDY AREA AND METHODOLOGY

Taiwan is located at the intersection of the Eurasian plate and Philippine plate. Thus, it has a fragile geological condition and is prone to frequent earthquakes. Moreover, the topography of Taiwan is characterized by mountains with an elevation of approximately 3000 m and short rivers (Fig. 4). Taiwan is also located on the track of typhoons and is prone to torrential rains brought by the typhoons.

Data from documented debris flows were collected to construct a 3D threshold surface for debris flow warning (Fig. 4). The data set comprises 61 postseismic debris flows from 1999 to 2001 [6], 11 landslides and debris flows in 2008, and 38 landslides and debris flows in 2009 [31]. The different periods of debris flows represent various debris flow triggering conditions, including postseismic effects, high rainfall intensity for a short duration, and high accumulated rainfall for a long duration. The three most commonly used rainfall parameters, effective accumulated rainfall ($A_{c\text{-}eff}$), rainfall duration (D), and average rainfall intensity (I_{avg}), were used for constructing the 3D rainfall threshold surface. Statistical computations for constructing the surface were performed using R [32].

The effective accumulated rainfall ($A_{c\text{-}eff}$) is defined as follows [31]:

$$\underline{A_{c\text{-}eff}} = \alpha_1 d_1 + \alpha_2 d_2 + \ldots + \alpha_{14} d_{14} = \sum_{t=1}^{14} \alpha_t d_t, \quad \alpha_t = 0.5^{t/T} \tag{2}$$

where α_t is the empirical attenuation coefficient, d_t (mm) is the daily rainfall in t days, and T is the half-life (1 day herein). The average rainfall intensity (I_{avg}) is defined as follows:

$$I_{avg} = A_{c\text{-}eff} / D \tag{3}$$

III. RESULTS AND DISCUSSION

An analysis of the postseismic debris flow revealed that debris flows were initiated at a low rainfall intensity in Taiwan. The average rainfall intensity was suggested to be used for improving the monitoring efficiency [6]. The optimal regression and lower level of equations for the surface can be represented as follows (Fig. 5):

$$I_{avg} = 29.11 + 0.034A_{c\text{-}eff} - 0.6D \ (r^2 = 56\%, \text{ for } I_{avg}, A_{c\text{-}eff}, \text{ and } D > 0) \quad (3)$$

$$I_{avg} = 20.26 + 0.02A_{c\text{-}eff} - 0.63D \ (\text{-2.5\% lower level}) \quad (4)$$

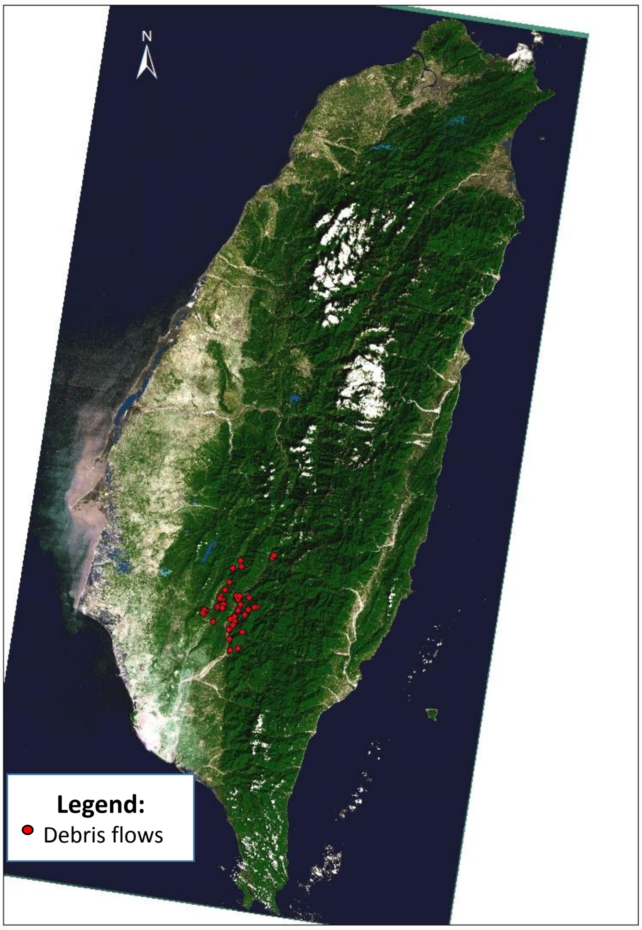

Fig. 4. Study area and site locations of initiated debris flows in 2008-2009 in Taiwan.

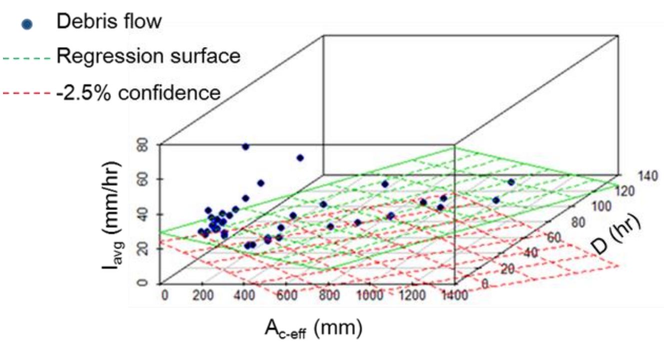

Fig. 5. 3D rainfall threshold surface for postseismic debris flows.

Debris flows were initiated by rainfall at a high intensity for a short duration during Typhoon Kalmegi in 2008. The optimal regression and lower level of equations for the surface can be represented as follows (Fig. 6):

$$I_{avg} = 58.35 + 0.098A_{c\text{-}eff} - 5.73D \ (r^2 = 97\%, \text{ for } I_{avg}, A_{c\text{-}eff}, \text{ and } D > 0) \quad (5)$$

$$I_{avg} = 52.27 + 0.08A_{c\text{-}eff} - 6.6D \ (\text{-2.5\% lower level}) \quad (6)$$

Debris flows were initiated by high accumulated rainfall for a long duration during Typhoon Morakot in 2009. The optimal regression and lower level of equations for the surface can be represented as follows (Fig. 7):

$$I_{avg} = 22.34 + 0.024A_{c\text{-}eff} - 0.55D \ (r^2 = 93\%, \text{ for } I_{avg}, \mathbf{A_{c\text{-}eff}}, \text{ and } D > 0) \quad (7)$$

$$I_{avg} = 20.26 + 0.02A_{c\text{-}eff} - 0.63D \ (\text{-2.5\% lower level}) \quad (8)$$

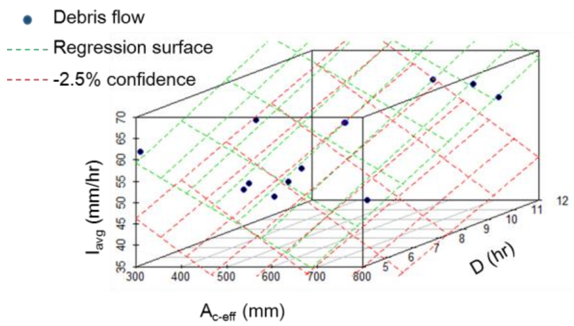

Fig. 6. 3D rainfall threshold surface for debris flows induced by rainfall at a high rainfall for a short duration after Typhoon Kalmegi in 2008.

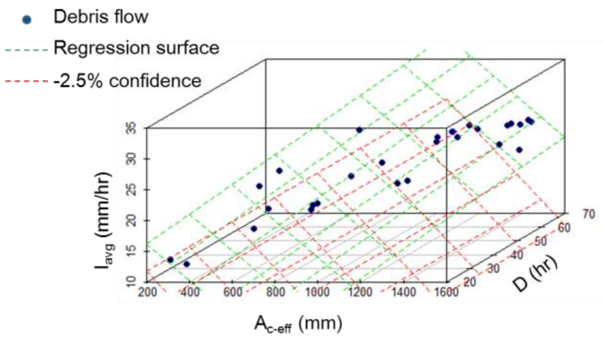

Fig. 7. 3D rainfall threshold surface for debris flows induced by high accumulated rainfall for a long duration after Typhoon Morakot in 2009.

The three events evaluated using the rainfall threshold surface exhibited notable differences (Fig. 8). The postseismic debris flows had the lowest threshold surface. Debris flows that occurred after Typhoon Morakot in 2009 exhibited a middle threshold surface under high accumulated rainfall for a long duration. Typhoon Kalmegi-induced debris flows in 2008 had the highest threshold surface under a high rainfall intensity for a short duration. The different rainfall threshold surfaces suggest that rainfall characteristics must be considered in monitoring rainfall-induced debris flows.

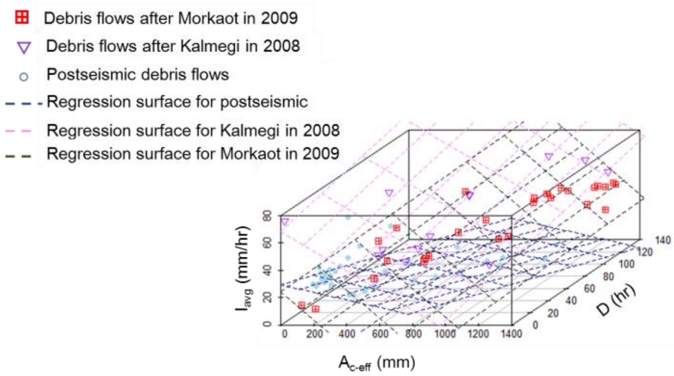

Fig. 8. Comparisons between rainfall threshold surfaces for debris flow warning.

IV. Conclusion

Debris flow warning is an economic and effective strategy for disaster prevention and mitigation. An effective warning model can provide sufficient time for emergency evacuation. The 3D rainfall threshold surface constructed using the effective accumulated rainfall, intensity, and duration provides enhanced spatial information on the initiation of debris flows. The results obtained using various threshold surfaces reveal that various rainfall characteristics, such as high rainfall intensity for a short duration, and high accumulated rainfall for a long duration, and postseismic effects, must be considered in monitoring and issuing warnings for rainfall-induced debris flows.

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