The establishment of rainfall thresholds for debris slide in Taiwan — with the combination of multivariate analysis and the I-R index

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ABSTRACT

Catastrophic landslides and debris slides triggered by intense typhoons such as Typhoon Morakot (2009) occurred more frequently in the recent years, and caused many casualties and economic loss in Taiwan. For the purpose of reducing the damage resulted from geological hazards, this study collects landslide inventories which contain the information of occurrence time, location, magnitude, rainfall intensity, accumulated rainfall and tries to establish the rainfall threshold for debris slide. This study adopts the concept of risk matrix, combining the magnitude (landslide ratio of slope units) and the possibility of occurrence (historical disaster records) to set up the warning thresholds. Critical rainfall thresholds are build up according to the R_{24} (24 hours accumulated rainfall, as long-term rainfall) and I_3 (3 hourly mean rainfall intensity, as short-term rainfall) of historical disasters. Validation with recent typhoon event shows the threshold can forecast the landslides in 2~9 hours in advance which may be enough for the evacuation. An early-warning system is also built and the results can be applied to regional land-use planning and disaster prevention.

Keywords: landslide warning, debris slide, landslide susceptibility, rainfall threshold

1 INTRODUCTION

Debris slide is the slide of weathered materials on the slope which can be considered as shallow landslide. The rainfall thresholds for the debris slide had been well discussed and concluded in the past (Hung et al., 2001; Guzzetti et al., 2007). These thresholds can mainly classified into 5 categories including intensity-duration (Brunetti et al., 2010; Zhou et al., 2014), accumulated rainfall-duration (Martelloni, 2011; Vessia et al., 2014), accumulated rainfall (Corominas and Moya, 1999; Bell and Maud, 2000), intensity-accumulated rainfall (Hong et al., 2005) and accumulated rainfall-accumulated rainfall (Osanai et al., 2010; Turkington et al., 2014).

However, the rainfall thresholds may overestimate or underestimate if the magnitude of landslide didn't taking into consideration. Thus, the aim of this study is trying to combine the magnitude of landslide and the method of evaluating rainfall thresholds as well as the concept of risk matrix to establish the rainfall thresholds for slope unit in Taiwan. This work also explores the relationship between the landslide and

rainfall characteristics and finds that 3 hours mean rainfall intensity and 24 hours accumulated rainfall are the most dominant parameter, thus, the I_3 - R_{24} threshold are established and validated for the purpose of further applications. Finally, with the connection of real-time rainfall data (QPESUMS, Quantitative Precipitation Estimation and Segregation Using Multiple Sensor), a landslide evaluation system is also established for the purpose of early warning.

2 STUDY AREA

Taiwan is located at the western Pacific Ocean, the convergent plate boundary zone of Philippine Sea plate and Eurasian plate. There are hundreds of faults and folds in the 36,000 km² area because of the tectonic activity. Typhoons and monsoons bring lots of rainfall which is estimated 2,500 mm, even more than 3,000 mm in mountainous areas every year (Hsu, 2013). As a result, the exhumation rate in Taiwan is about 3 to 6 mm/year (Dadson et al., 2003), mainly are caused from the landslide process. On the other hand, the population in Taiwan is about 2.3 millions, high population density

and the frequent nature disasters make Taiwan one of the countries that most exposed to multiple hazards (Dilley et al., 2005).

This study divided Taiwan into 4 main regions including the northern, the central, the southern and the eastern Taiwan (Fig.1). These areas are the most populated as well as facing the threat of landslide.

Fig. 1. Regions of study area.

3 METHOD

The aim of this study is trying to establish the rainfall thresholds for the debris slide, thus, the landslide must be interpreted firstly to build up the landslide inventory. After that, field investigation is needed to check the results of interpretation, the mechanism and the geological condition of each landslide. The occurrence time of landslides is crucial information when establishing the rainfall thresholds, therefore, this research also visit the village chief and the resident around the landslide to record the data demanded. With occurrence time, accumulated rainfall and the rainfall intensity can be calculated. Combining the results of landslide susceptibility and the historical landslide cases, the rainfall thresholds hereby can be established and an early-warning system can also build for the sake of reducing the loss of life and wealth.

3.1 Landslide inventory and field investigation

Landslides can be interpreted through the usage of remote sensing images such as aerial photos or satellite images according to the texture, shape and topographical characteristics of landslide (Asselenand and Seijmonsbergen, 2006; Moine et al., 2009; Mondini et al., 2011; Stumpf and Kerle, 2011; Martha et al., 2012; Razak et al., 2013). This study follows the rules proposed by Soeters and Van Westen (1996) and uses SPOT image (resolution: 2.5 m x 2.5 m) before and after 16 typhoon events for the interpretation of landslides induced by heavy rainfall. Field investigation is needed for the validation of interpretation (Fig. 2). The detailed information such as mechanism, lithology, geological structure, joint, strength of rocks, depth of landslide should also record for further analysis.

Fig. 2. Landslide interpretation and the picture took during the field investigation.

3.2 Records of occurrence time of landslide and the Landslide Disasters Database (LDD)

Rainfall conditions that induced landslides are key data while applying the empirical method to establish the rainfall thresholds for debris slide (Guzzetti et al., 2007, 2008; Brunetti et al., 2010). A total 949 cases which contain the information of occurrence time of landslide are collected during the field investigation (Fig. 3). Besides, for the purpose of conserving these valuable records and providing for further analysis, a Landslide Disasters Database was built (Fig. 4). This database consists of 4 parts: (1) basic data, such as location, occurrence time, typhoon event, area, geological condition, geomorphological condition; (2) map, which shows the location of landslide; (3) pictures of the investigation, highlighting important features; (4) attached files of reports on the landslide. The database benefits government collecting landslide cases systematically.

Fig. 3. Flowchart of recording the occurrence time of landslide during field investigation.

Fig. 4. Landslide Disasters Database (LDD) which helps collecting landslide cases systematically.

3.3 Analysis of rainfall data

Based on the occurrence time of each landslide, rainfall data was collected and analyzed to understand the rainfall condition. In Taiwan, both high intensity and long duration rainfall events can cause severe disasters (Chen et al., 2006; Wu et al., 2011; Wei et al., 2014; Lee et al., 2015), thus, this study uses 3-hours mean rainfall intensity (I_3) as short-term rainfall index and 24-hours accumulated rainfall (R_{24}) as long-term index (Liao et al., 2010). The definition of a rainfall

event is as followed: A rainfall event is started when the hourly rainfall is greater than 4 mm and comes to the end when the rainfall is continuously lower than 4 mm for 6 hours. Fig. 5 shows the method for calculating the rainfall indexes. If the landslide is occurred at i hour, I_3 is the mean value of the rainfall within i , $i-1$, $i-2$ hours and R_{24} is the summation of the rainfall within i to $i-23$ hours.

Fig. 5. Rainfall indexes used in the study.

3.4 Slope unit

For the purpose of the application in disaster prevention, this study uses slope unit as mapping unit (Guzzetti et al., 1999; Xie et al., 2004; Fig. 6). Slope unit is a kind of mapping unit that based on the features of geomorphology such as ridges and river valleys. Each slope unit can be given a unique number and the government can issued a warning toward a specific slope during the rainfall event. This will also lift the efficiency of evacuation.

Fig. 6. (a) Grid-based mapping unit and (b) slope unit-based mapping unit (Xie et al., 2004). Slope unit can lift the efficiency of disaster mitigation during rainfall events.

3.5 Landslide susceptibility analysis

Logistic regression method is applied in this study to evaluate the susceptibility of each slope units

(Guzzetti et al., 1999; Ayalew and Yamagishi, 2005, Cheng et al., 2013). Geological, topographical and triggering factors such as lithology, strength of rock, gradient, height of slope, rainfall intensity and accumulated rainfall are considered to develop landslide susceptibility model (Fig. 7). Validation is also performed with landslide inventory to verify the model.

Fig. 7. The flowchart of developing landslide susceptibility model.

3.6 Rainfall threshold for debris slide

Logistic regression method is applied in this study to calculate the susceptibility of each slope units. It is found that when the susceptibility of the slope unit is higher, the landslide ratio of the slope unit (landslide area within a slope unit divided by the area of slope unit) is also greater. According to this phenomenon, slope units are categorized into Type I (high susceptibility and landslide ratio of slope unit is greater than 0.2), Type II (moderate susceptibility and landslide ratio is between 0.1 to 0.2), Type III (low susceptibility and landslide ratio is lower than 0.1), and the rainfall thresholds for each type are setup separately.

After analyzing more than 900 cases, 3 hours mean rainfall intensity and 24 hours accumulated rainfall are chosen as the index for establishing rainfall thresholds for debris slide (Wei et al., 2015). Historical records of landslides are plotted in the diagram (Fig. 8.), and the ellipse is used to determine the envelope of historical cases according to the distribution of data. The parameter a and b of ellipse are set according to the slope of regression line by applying least square method. The thresholds are determined according to the percentage of historical cases that included by the envelope, i.e. the 90% threshold includes 90% of the historical cases. It means that if the rainfall condition exceeds this threshold, the probability of occurring landslides is extremely high.

This study also takes the magnitude of landslide into consideration and gives the warning signal with the concept of hazard matrix (Fig. 9.). The magnitude of landslide is classified into 3 categories according to the landslide ratio of slope units mentioned in the first paragraph in this section. If the landslide magnitude (the landslide ratio of the slope unit) is giant and the probability of occurrence is high, it is assigned as red signal which means high danger; on the other hand, if

the magnitude (the landslide ratio of the slope unit) is small and the probability is low, it is assigned as green signal which means general condition.

Fig. 8. Establishing rainfall thresholds by adopting I_3 and R_{24} as index to evaluate the probability of occurring landslides under different rainfall conditions.

		Possibility of occurrence			
		High	Moderate-High	Moderate	Low
Magnitude	Giant	Type I High danger	Moderate-High (~60%) High danger	Moderate (~30%) Moderate danger	Low (<30%) Low danger
		Type II High danger	Moderate danger	Low danger	General condition
	Small	Type III Moderate danger	Low danger	General condition	General condition

Fig. 9. Setting of warning signals combining the magnitude, the possibility of occurrence and the concept of risk matrix.

4 RESULTS AND VALIDATIONS

4.1 Results

Taiwan was divided into 4 main regions (Fig. 1.) and the preliminary rainfall threshold for each magnitude in each region was established (Fig. 10.). These thresholds also reflect the complexity and the difference of geology and climate in each region. For example, the northern Taiwan is mainly consisting of volcanic and metamorphic rocks while the southern Taiwan is mainly sedimentary and metamorphic rocks, but the MAP (mean annual precipitation) is higher in southern Taiwan, thus it shows a slightly higher threshold to induce new landslide in southern Taiwan.

Fig. 10. Preliminary rainfall thresholds in Taiwan. There are 4 main regions and 3 main types of magnitude in each region.

4.2 Validation

Validations are performed with landslide cases during the Typhoon Matmo, July, 2014. It is showed that newly occurred landslides can be forecasted 2 to 9 hours in advanced with red or orange signal according to the snake line in the graph (Fig. 11.), providing valuable information for the disaster prevention. It is also find that for the existing landslides, it may re-occur during the yellow signal period. This phenomenon implies that there is a much lower threshold for the pre-existing landslides. Two ways may solve this problem: one is establishing another threshold for the pre-existing landslides and another is lowering the threshold for warning (i.e. announcing warning when the signal turns to yellow). However, more cases for the validation are still needed before taking into practice.

Fig. 11. Validations of the rainfall thresholds show that newly occurred landslides can be forecasted 2 to 9 hours in advanced, providing valuable information for disaster prevention.

5 RAINFALL-INDUCED LANDSLIDE EARLY WARNING INFORMATION SYSTEM (RILEWIS)

A real-time warning system is built for the purpose of early warning (Fig. 12.). This system is connected with real-time rainfall data. As the rainfall increases, the system can calculate the snake line immediately (shown as in Fig. 11.) and provide the information of the stability of slopes (Fig. 13.).

Fig.12. The Rainfall-induced Landslide Early Warning Information System (RILEWIS) is connected with real-time rainfall data and providing the information of the stability of slopes.

Fig.13. The warning signal of each slope unit is calculated automatically according to the rainfall. As rainfall increases, the signal will turn to orange or red indicating that the possibility of failure is higher.

6 CONCLUSIONS

This study classifies landslide magnitude into 3 categories and establishes the rainfall threshold separately. The combination of magnitude, possibility of occurrence and the concept of risk matrix can setup warning signals in a more intuitional way for the decision of evacuation. Preliminary validation shows that the results is acceptable and can be used for further test on landslide forecasting. An early-warning system is also built to connect the real-time rainfall data and calculating the warning levels immediately for the purpose of disaster prevention and may increase the response time for evacuation.

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