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Modeling the spatial occurrence of shallow landslides triggered by typhoons

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ABSTRACT

Many shallow landslides in Taiwan are triggered by typhoons (tropical cyclones) during the summer months. Each typhoon produces a different rainfall distribution, depending on its track and position and the atmospheric conditions. This study investigated whether the additional rainfall data in a landslide susceptibility model can improve its performance in predicting typhoon-triggered landslides, and whether information on past typhoon events, combined with an event-based landslide inventory, can help predict landslides triggered by a typhoon. To answer these questions, the study adopted a method that integrates rainfall data with the critical rainfall model (a landslide susceptibility model based on geoenvironmental factors) to derive a logistic regression model for predicting landslide occurrence. Results of a back analysis of landslides triggered by nine typhoons from 2001 to 2009 reveal that, by including rainfall data, the integrated method performs better than the critical rainfall model in the average overall accuracy rate (0.78 vs. 0.45) and the average modified success rate (0.75 vs. 0.68). Our preliminary results also suggest that it is possible to predict landslides triggered by a typhoon by using a catch-all model developed from all other typhoon events in an inventory, or a group model developed from other typhoon events of similar rainfall characteristics in an inventory. This study opens up a new research direction in analyzing rainfall-triggered landslides in Taiwan and elsewhere.

1. Introduction

Landslides occur on slopes that are predisposed to failure under the influence of gravity. Slope failures can be fostered by a range of geoenvironmental factors including lithology, soils, land use, and morphological conditions (e.g., slope, aspect, curvature, and drainage area). Landslides can be triggered by earthquakes, intense storms, human activities, or a combination of these factors. Therefore, to better understand landsliding, both the triggering and predisposing factors must be considered (Crosta, 1998; Borga et al., 2002; Tarolli et al., 2011).

This study focuses on shallow landslides triggered by typhoons (tropical cyclones) at watershed level. The predisposing and triggering factors for typhoon-triggered landslides have different characteristics. Geoenvironmental factors are quasi-static because changes in slope, aspect, and curvature are so gradual that they can be considered as constant (Dai and Lee, 2003). In contrast, each typhoon, controlled by its track and position and the atmospheric conditions, produces a different spatial distribution of rainfall amounts. How to decipher useful information from these rainfall distributions and to use them for predicting typhoon-triggered landslides is the fundamental question for this study.

A variety of methods for employing rainfall information in landslide prediction have been proposed in the literature. They are briefly reviewed here in terms of their relevance to this study. The traditional method is empirical rainfall thresholds. Based on historical data, the method relates landslide initiation to minimum rainfall thresholds of intensity and duration (e.g., Campbell, 1975; Caine, 1980; Larsen and Simon, 1993; Guzzetti et al., 2004; Baum et al., 2005; Chen et al., 2007). Rainfall thresholds at local and regional levels may also consider geologic, lithological, or land use characteristics in addition to rainfall factors (Tiranti and Rabuffetti, 2010; Peruccacci et al., 2012). Taiwan's Soil and Water Conservation Bureau, for example, issues debris flow warnings when the cumulative rainfall reaches between 250 and 550 mm, depending on the watershed to which the warning is issued. The method of rainfall thresholds can predict the general timing of landslide initiation (e.g., within hours), but it cannot predict landslide locations.

Rainfall data can be coupled with physically-based models for predicting landslides. In some cases, the coupled models are designed for real-time landslide early warning systems in which a physically-based model given the input of time-varying rainfall data can predict the location and timing of landslides (e.g., Baum et al., 2008; Montrasio et al., 2011; Rossi et al., 2013). In other cases, the coupled models are used to simulate landslide occurrence and its impacted areas (e.g., Chiang et al., 2012). These models are event-based because the rainfall input is specific to a particular event.

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Rainfall factors can be combined with geoenvironmental factors in statistical models for predicting landslide locations (e.g., Dai and Lee, 2003). This is one type of landslide susceptibility analyses (Guzzetti et al., 2005) as it includes rainfall in addition to a set of geoenvironmental factors as instability factors. Lee et al. (2008), for example, included maximum hourly rainfall, rolling 24-h rainfall, and total rainfall with geoenvironmental factors in discriminant analysis to build a landslide susceptibility model. Because the model is developed using rainfall factors specific to a rainfall event, it cannot be deployed for predicting landslides triggered by a different event.

The integrated method proposed by Chang and Chiang (2009) combines rainfall data with a physically-based landslide susceptibility model to derive a statistical model for landslide prediction. Instead of using maximum 24-h rainfall directly, their method first calculates the difference between the maximum 24-h rainfall and a physically-based rainfall threshold and then uses it and rainfall duration as explanatory variables in logistic regression. They reported that the integrated model performed better than a physically-based model in predicting landslides triggered by two typhoon events in northern Taiwan.

Taiwan experiences, on average, four to five typhoons every year (Chiang and Chang, 2011). A review of the typhoon database maintained by Taiwan's Central Weather Bureau (CWB) reveals that the spatial distribution of rainfall amounts is different for each typhoon (http://rdc28.cwb.gov.tw/data.php). Can the addition of typhoon rainfall data improve the performance of a landslide susceptibility model in its prediction? Can we also combine the information on past typhoon events and an event-based landslide inventory for predicting landslides triggered by a typhoon? To answer these questions, this study adopts the integrated method (Chang and Chiang, 2009) for an analysis of landslides triggered by nine typhoons from 2001 to 2009. The research design of this study offers a chance to test the transferability of the integrated method through the first question and to apply the integrated method in a different type of landslide susceptibility analysis through the second question. The role of typhoons in landslides and landslide erosion in Taiwan has received much attention lately (Chang et al., 2007; Chiang and Chang, 2011; Chen et al., 2011; Keijsers et al., 2011; Chiang et al., 2012; Huang and Montgomery, 2012; Chen et al., 2013). We hope that this study can provide additional insights into landslides triggered by typhoons.

2. Study area

The 2868 km^2 Kaoping watershed is located within the slate belt of the Western Foothills in southern Taiwan (Fig. 1). The elevation ranges from the highest peak of the Central Mountain Range at 3952 m a.s.l. to the basin outlet at 25 m a.s.l. The average slope derived from a 40 m digital elevation model (DEM) is 26.4°. Ninety percent of annual precipitation (~2800 mm) falls in the wet season (May to September) (Water Resource Agency, 2008). The geologic maps published by Taiwan's Central Geological Survey show that the lithology in the watershed comprises Paleozoic to Mesozoic black schist and green schist, Eocene to Oligocene schist and phyllite, Miocene argillite, Pleistocene terrace deposits and alluvium, and Modern alluvium (Fig. 1). According to the 2007 land use map from Taiwan's Ministry of the Interior, 76% of the study area is forested: mixed forest, broad-leaf forest, and bamboo forest account for 65%, 8%, and 3%, respectively. The remaining 24% consists of cultivated fields, built-up areas, landslides, and others.

According to Wu and Kuo (1999), when a typhoon crosses northern Taiwan, it can bring heavy rainfall in southern Taiwan, including our study area, due to south-westerly flows. Therefore, the Kaoping watershed experiences frequent landslides and debris flows, which have been covered in several recent studies (Chiang et al., 2012; Chen et al., 2013; Mondini et al., 2013).

3. Material and methods

3.1. Critical rainfall model

As Chang and Chiang (2009) did, we used the critical rainfall as a threshold for assessing landslide occurrence: if a location has a higher observed rainfall value than the critical rainfall, it has a chance of having a landslide. The critical rainfall is derived from a model that combines the factor of safety (*FS*) and steady-state hydrologic models to delineate areas prone to landsliding due to surface topographic effects on hydrologic responses (Montgomery and Dietrich, 1994; Pack et al. 1998; Claessens et al., 2007a,b). The critical rainfall, Q_{cr} [mm day^{-1}], which represents the condition $FS = 1$, or the threshold separating landsliding ($FS < 1$) and non-landsliding ($FS > 1$), can be computed by:

$$Q_{cr} = T\sin\theta\left(\frac{b}{a}\right)\left(\frac{\rho_s}{\rho_w}\right)\left[1-\frac{(\sin\theta - C)}{(\cos\theta\tan\phi)}\right] \tag{1}$$

where T is saturated soil transmissivity [m^2 h^{-1}]; a is the upslope contributing drainage area [m^2]; b is the unit contour length (the grid resolution) [m]; ρ_s is wet soil bulk density [g cm^{-3}]; ρ_w is the density of water [g cm^{-3}]; θ is the local slope angle [°]; ϕ is the effective angle of internal friction of soil [°]; and C is the combined cohesion term [−], made dimensionless relative to perpendicular soil thickness h [L] and defined as:

$$C = (C_r + C_s)/(h\rho_s g) \tag{2}$$

where C_r is root cohesion [N m^{-2}], C_s is soil cohesion [N m^{-2}], and g is the gravitational acceleration constant (9.81 m s^{-1}). Landsliding is predicted to occur in a unit area if the steady-state rainfall is greater than the critical rainfall.

Critical rainfall values calculated from Eq. (1) are bounded by unconditionally stable and unstable areas. Unconditionally stable areas are areas predicted to be stable even when saturated and satisfy:

$$\tan\theta \leq \left(\frac{C}{\cos\theta}\right) + \left(1-\frac{\rho_w}{\rho_s}\right)\tan\phi. \tag{3}$$

Unconditionally unstable areas are areas predicted to be unstable even when dry. They can exist in a very small area percentage in the landscape, usually along stream channels. Typically, unconditionally unstable areas are characterized by steep slopes and no soil and root cohesion. In equation form, unconditionally unstable areas satisfy:

$$\tan\theta > \tan\phi + \left(\frac{C}{\cos\theta}\right). \tag{4}$$

This study estimated soil thickness h using a slope-dependent function included in a report of the Central Geological Survey (2009). Derived from 73 field samples in the study area with an R^2 of 0.813, the function has the following form:

$$\ln(h) = 1.4356 - 0.454 \cdot \theta. \tag{5}$$

From the same report, we derived three soil physical characteristics: ρ_s, T (the product of conductivity k and soil depth h), and C for different geological formation units within the study area (Table 1). Finally, a 40-m DEM was used to calculate local slope angle θ and upslope contributing drainage area a. The 40-m raster also became the basis for calculating the critical rainfall.

3.2. Rainfall data

This study dealt with nine typhoons from 2001 to 2009 that impacted the study area (Table 2). The selection of these typhoons was primarily based on the availability of pre- and post-event satellite images.