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Scenarios of Large-Scale Landslides and Debris Flows under Extreme Rainstorms

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Rainfall-induced landslides and debris flows can cause great losses of both human lives and properties, especially on Hong Kong Island where the density of population is high and landslide and debris flow are active. In the changing climate, the frequency of the occurrence of landslides and debris flows is on a growing trend. Therefore, it is important to simulate possible scenarios of landslides and debris flows under extreme weather conditions. The objective of this paper is to simulate future landslides and debris flows on Hong Kong Island considering the influence of climate change. In this paper, a physically-based models are implemented. The slope stability analysis is conducted and the movement traces and locations of landslides are predicted to determine the initiation locations of debris flows under three reference rainstorms (i.e. 44%, 65% and 85% of the 24-h probable maximum precipitation, PMP). Then debris flows initiated at indicated locations are predicted. With the increase of rainstorm magnitude, the landslide and debris flow magnitudes grow dramatically. Also, many debris flows can occur simultaneously and merge under extreme storms, posing much greater threat to people's lives and properties.

Keywords: Landslide, debris flow, rainstorm, natural hazard.

1 Introduction

Landslides and debris flows often occur under extreme storms (e.g., Staley et al. 2013, Tiranti et al. 2014), which can cause great damage to infrastructures and loss to people's lives and properties. Due to climate change, the frequency of extreme storms is becoming larger and larger in Hong Kong according to the 24-h PMP (probable maximum precipitation) updating study by AECOM (2017). This means that rainfall-induced landslides and debris flows will occur more frequently. These hazards can be very destructive when occurring on Hong Kong Island, which has a hilly terrain with 30% of the land steeper than 30°, and is densely populated. Currently landslide mitigation measures are often based on rainfall of a return period of ten years (GEO 2011); it is necessary to evaluate the impact of landslides and debris flows on Hong Kong Island under weather conditions much severer than ten-year return period rainfall in order to make new mitigation policy.

Rainfall-induced slope failures have been studied by many researchers (e.g., Dai and Lee 2002; Ko and Lo 2016). Dai and Lee (2002) conducted a logistic regression analysis to evaluate the slope stability on Lantau Island in Hong Kong. Ko and Lo (2016) developed a rainfall-based model to assess the landslide susceptibility in Hong Kong and established correlations between landslide density and slope angle and lithology. Gao et al. (2017a,b) evaluated landslide scenarios on western Hong Kong Island and developed correlations between magnitude of landslides and rainfall intensity. In this paper, a physically-based distributed cell model developed by Chen and Zhang (2014) is adopted for slope stability analysis because of its capability of catchment-scale analysis.

With sufficient source materials provided by slope failures, debris flows can be triggered more easily. King (2013) conducted a detailed study on the 1990 Tsing Shan debris flow. Cui et al. (2013) studied debris flows triggered by rainfall in Qingping Town, China. Chen and Zhang (2015) proposed a physically-based model (EDDA 1.0) to predict likely debris flows. Predicting debris flows in large scale is conducted in this study with EDDA 1.0.

This paper aims to predict potential landslides and debris flows over the entire Hong Kong Island under extreme rainfall conditions. Physically-based models are implemented to simulate landslides and debris flows. Three extreme rainfall conditions are considered in this paper, i.e. 44%, 65%, and 85% of 24-h PMP. Slope failure analysis is conducted first; given the deposition locations and landslide volumes, debris flow analysis is conducted. Finally, the maximum debris flow velocity and depth under various storm conditions are predicted.

2 Description of the study area

The study area covers the entire Hong Kong Island with an area of 78.59 km^2. The peak elevation is 551.7 m. The slope angle obtained with the built-in tool on GIS (Geographical Information System) platform ranges from 0° to 67°. The bedrocks are mostly granite rocks and volcanic rocks. Most of the granite rocks is located at the northeastern part and the south part of Hong Kong Island. Due to the subtropical weather, the bedrock experiences weathering from time to time. The superficial deposits can be classified into volcanic deposits and granite deposits.

3 Methodology

In this paper, a two-step procedure is adopted. Slope failure simulation is conducted first to get the initiation locations and volumes of debris flows; then the debris flow dynamics is simulated. The detailed procedure is as follows:

- Discretization of the study area and assignment of soil or rock parameters to each cell according to the properties of the cell.
- Interpolation and definition of extreme rainfall scenarios.
- Infiltration analysis, slope stability analysis, and landslide movement and volume prediction.
- Analysis of debris flow dynamics.

3.1 *Extreme rainfall scenarios*

In this study, PMP is used to represent the storm magnitude. The 7 June 2008 rainstorm is used for validation and verification; the magnitude of this storm corresponds to approximately 29% of the 24-h PMP. Three severe rainfall scenarios are selected in this study: 44% of the 24-h PMP, which is the rainfall data recorded at rain gage N19; 65% of the 24-h PMP, which corresponds to the maximum precipitation in the history of Hong Kong; 85% of the 24-h PMP, which takes the local moisture maximization into account. The rainfall is assumed to be uniformly distributed over the study area, and the spatial variability is not considered.

3.2 *Slope stability analysis*

Generally, there are two mechanisms of rainfall-induced slope failure: the build-up of positive pore water pressure and the dissipation of matric suction during the infiltration process (e.g., Zhang et al. 2011, Collins and Znidarcic 2014). Therefore, it is necessary to conduct infiltration analysis first. The Richards equation is adopted here to analyze the process:

$$\frac{\partial}{\partial z^*}\left(k\frac{\partial \psi}{\partial z^*}\right)+\frac{\partial k}{\partial z^*}\cos\beta=\frac{\partial \theta}{\partial t} \tag{1}$$

where k is the permeability; ψ is the pore-water pressure head; z^* is the layer thickness as described by Chen and Zhang (2014); β is the slope angle; t is time; θ is the volumetric water content.

An infinite slope stability analysis model is adopted here. For a fully saturated soil slope, the factor of safety F_s is calculated after Brunsden and Prior (1984):

$$F_s=\frac{\tan\phi'}{\tan\beta}+\frac{c'-\psi(Z,t)\gamma_w\tan\phi'}{\gamma_s z'\sin\beta\tan\beta} \tag{2}$$

where c' and ϕ' are the effective cohesion and friction angle, respectively; γ_w and γ_s are the unit weights of water and soil, respectively.

If the soil is unsaturated, matric suction will be present, and F_s is expressed based on the extended Mohr-Coulomb failure criterion (Fredlund et al. 1978) as:

$$F_s=\frac{\tan\phi'}{\tan\beta}+\frac{c'-\psi(Z,t)\gamma_w\tan\phi_b}{\gamma_s z'\sin\beta\tan\beta} \tag{3}$$

where ϕ_b is the friction angle associated with the matric suction.

Finally, the movement of landslides is predicted. The correlation between H/L and landslide volume V is proposed by Corominas (1996):

$$Log(H/L)=-0.047-0.085\log(V) \tag{4}$$

where H is the elevation difference between the landslide scar and deposition location; L is the distance between the two locations; V ($\times10^3$ m^3) is the landslide volume.

Through the above analysis, the landslide location, trace, deposition area and volume can be obtained. Given such information, the initiation location and volume of debris flow can be determined. In this study, the debris flows are assumed to initiate at the landslide deposition areas.

3.3 *Debris flow analysis*

In this study, each debris flow is assumed to initiate from a single slope failure at its source. An integrated model EDDA 1.0 (Erosion-Deposition Debris flow Analysis) proposed by Chen and Zhang (2015) is adopted. The governing equations include mass conservation of the debris flow [Eq. (5)], mass conservation of the solid phase [Eq. (6)], momentum conservation [Eq. (7)], and the change of bed elevation [Eq. (8)].

$$\frac{\partial h}{\partial t}+\frac{\partial(hv_x)}{\partial x}+\frac{\partial(hv_y)}{\partial y}=i\left[C_{v*}+(1-C_{v*})s_b\right] \tag{5}$$

$$\frac{\partial (C_v h)}{\partial t} + \frac{\partial (C_v h v_x)}{\partial x} + \frac{\partial (C_v h v_y)}{\partial y} = iC_{v*} \tag{6}$$

$$\frac{\partial v_x}{\partial t} + v_x \frac{\partial v_x}{\partial x} = g[-\mathrm{sgn}(v) S_{fx} - \frac{\partial (z_b + h)}{\partial x}] - \frac{v_x \{i[C_{v*} + (1 - C_{v*}) s_b]\}}{h} \tag{7}$$

$$\frac{\partial z_b}{\partial t} = i \tag{8}$$

where h and v are the flow depth and velocity, respectively; i is the erosion (>0) or deposition (<0) rate; C_v and C_{v*} are the volumetric sediment concentration of the mixture and the erodible bed, respectively; s_b is the degree of saturation of the erodible bed; s_f is the flow resistance slope; and z_b is the bed elevation.

4 Validation with historical records

According to the ENTLI (Enhanced Natural Terrain Landslide Inventory) records, there were 37 landslide and 6 debris flow incidents in 2008 over the entire Hong Kong Island. The total landslide volume is estimated to be 11,700 m³, and the landslide volume that turned into debris flows is estimated to be 4,400 m³ according to the width and length of the landslide scars recorded in the ENTLI. The validation summary is listed in Table 1.

Table 1. Model validation

	Estimated volume of slope failure (m³)	Estimated volume of debris flow (m³)	Remarks
The 2008 rainstorm	11,700	4,400	The total number of landslides and channelized debris flows are 37 and 6 respectively, while the actual number and volume could be larger since many small-scale landslides and debris flows were not included in the database.
Simulated results	21,000	7,000	The total landslide volume and debris flow volume are slightly larger than the observed values.

5 Prediction of landslides and debris flows under extreme storms

In this paper, three scenarios of extreme rainstorms are simulated, i.e. 44%, 65%, and 85% of the 24-h PMP. As expected, a large number of landslides and debris flows can be triggered under extreme rainstorms. Figure 1 shows the landslide scars, traces, and deposits under (a) 29%, (b) 44%, (c) 65%, and (d) 85% of the 24-h PMP. Table 2 summarizes the maximum travel distance, maximum flow depth and velocity, affected area of the predicted debris flows under each rainfall scenario.

(a) (b)

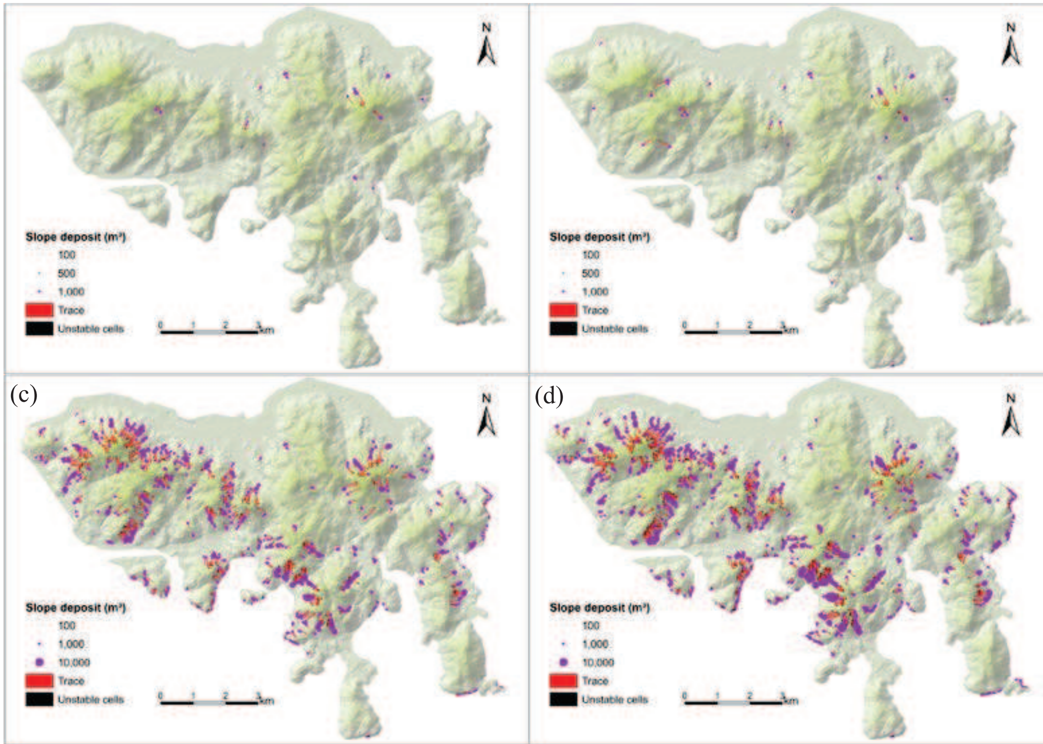

Figure 1. Landslide scenarios under storms of (a) 29% PMP, (b) 44% PMP, (c) 65% PMP, (d) 85% PMP.

Table 2. Increased debris-flow impact with storm magnitude

Storm magnitude (of 24-h PMP)	29%	44%	65%	85%
Total soil deposit volume (10^3 m^3)	21	57	1124	1838
Assumed initial debris volume (10^3 m^3)	7	19	371	607
Maximum travel distance (m)	690	700	790	880
Maximum flow depth (m)	3.9	3.9	7.2	7.3
Maximum flow velocity (m/s)	3.3	3.3	3.9	4.3
Total volume (10^3 m^3)	13	30	433	679
Affected area (10^3 m^2)	23.8	94.5	643.8	827.5
Affected area/terrain area (%)	0.03	0.12	0.82	1.05

From the simulated results, the magnitude of landslides and debris flows increases moderately with the storm magnitude initially when the rainfall intensity is relatively small. With the increase of rainfall intensity, the magnitude grows abruptly from 44% of PMP to 65% PMP. However, when the rainfall intensity increases further to 85% PMP, the magnitude of landslides and debris flows increases only by about1.6 times in terms of total volume.

6 Conclusions

Large-scale landslides and debris flows under extreme rainfall conditions are simulated in this study. A two-step simulation scheme is adopted: a slope failure analysis is conducted first, followed by a debris flow analysis based on the predicted landslide results. The model is validated with the historical records of the June 2008 rainstorm. Although the total volume is slightly overestimated, it is within a reasonable range since small-scale landslides and debris flows in remote areas are not included in the database. Under the three extreme rainfall scenarios, the hazard intensity increases moderately initially, and increases abruptly from 44% to 65% of the PMP, and slows down as the rainfall intensity continues to increase.

This study is a two-step study, and the landslide and debris flow hazards are simulated separately. In the future, an integrated full-process analysis should be conducted.

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