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The Landslide Screening Criteria in Hong Kong Considering Rainfall Intensity and Topography

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Abstract: Rain-induced landslides are recognized as one of the most catastrophic hazards on hilly terrains. To develop strategies for landslide risk assessment and management, it is necessary to estimate not only the rainfall thresholds for triggering landslides, but also the topography effects on landslide travel distances. Empirical correlations between the scar area ratios of hillside landslides or channelized debris flows and the maximum rolling rainfall intensities with different periods have been derived. Topographic screening criteria are proposed based on distal elevation of landslides and distance from the nearest building. There are 2383 open hill slope landslides with an area ranging from 10 m^2 to 30 m^2. While the chanelized debris flows with a scar area ranging from 100 m^2 to 200 m^2 take a large proportion. The average values of scar area for the open hillslope and chanelized debris flows are 55.2 and 91.3 m^2, respectively. The average values of horizontal distance for the open hillslope and channelized debris flows are 24.2 and 86.1 m, respectively. There are 1751 open hillslope landslides and 1063 channelized debris flows with crown slope angles ranging from 35° to 40°, which account for the largest proportion. Few landslides have a crown slope angle greater than 65°. The most common distal-end toe angles range is 25 to 30°. Few landslides have a distal-end toe angle greater than 55°. The thresholds of rainfall intensities with durations of 1-, 2-, 4-, 5-, 6-, 8-, 12-, and 24-hr are 77.5, 48.3, 28.1, 22.7, 19.7, 18, 15.2, 8.2 mm/hr, respectively. The landslides with horizontal distances from the nearest buildings <200 m, and distal downslope angles > 20° are likely to lead to direct risks to citizens. The topographic screening criteria considering the distal downslope angle, elevation, and distance from the nearest building are recommended. The study is expected to provide a sound basis for building an early warning system in Hong Kong.

Keywords: Rainfall; landslide consequences; landslide management; risk; proximity; Hong Kong.

1 Introduction

Hilly terrains in subtropical region are prone to rain-induced landslides. For the densely populated cities with hilly terrain, like Hong Kong, even a small landslide may lead to loss of lives or properties of citizens. Hence it is necessary to evaluate the impacts of rainfall intensity and topography on landslide occurrences and magnitudes and therefore to develop landslide screening criteria.

Many studies have been conducted on the relationships between rainfall intensity and landslide occurrences (e. g. Guzzetti et al., 2008; Baum and Godt, 2010). In Hong Kong, the correlations between rainfall and landslides have also been detected (e.g., Finlay et al., 1997; Dai and Lee, 2001; Ko and Lo, 2016; Gao et al., 2018). For instance, Finlay et al. (1997) detected the relationship between the landslide occurrences and the rainfall processes and suggested that the 3-hr rainfall duration could be applied to predict the landslide occurrences. Dai and Lee (2001) revealed the correlations between landslide magnitudes and the cumulative rainfall and found that the maximum rolling 12-hr rainfall is recommended for predicting the landslides. Ko and Lo (2016) proposed a landslide susceptibility method considering the slope angle and the geological condition. Gao et al. (2018) revealed the relationships between natural terrain landslide magnitudes and triggering rainfall based on a large landslide inventory and stated that maximum rolling rainfall with relatively prolonged profiles (4- to 24-h) need to be included.

Studies on predicting landslide runout distances in Hong Kong have also been conducted (e.g., Franks, 1999; Dai and Lee, 2002; Ho and Roberts 2016; Gao et al., 2021). Franks (1999) examined the rainfall-induced landslide events occurred in 1992 and 1993 and determined the topographic factors affecting the occurrences of debris flows. Dai and Lee (2002) conducted statistical analysis on the horizontal distances and the angle of reach of landslides and applied the relations to predict the landslides in Lantau Island. Ho and Roberts (2016) recommended practice and procedures for evaluating the potential natural terrain landslide hazards and proposed alerting criteria. Gao et al. (2021) examined the controlling topographic and geologic factors for travel distances

of open hill slope landslides and channelized debris flows in Hong Kong and found that using the ratio of the horizontal travel distance to fall height alone to estimate the mobility is not suggested.

Further studies to provide screening criteria for estimating the potential landslide risks are still needed. In this study, the open hill slope landslide and channelized debris flow in Hong Kong are analyzed separately. The frequency distributions of the slope angles are depicted. The correlation between the rainfall intensity and the magnitudes of landslides are derived. Two landslide screening criteria are derived.

2 Frequency analysis of historical landslides in Hong Kong

In this study, the frequency distributions of both open hillside landslides and channelized debris flows in Hong Kong are established on the basis of the Enhanced Natural Terrain Landslide Inventory (ENTLI) with 11,622 records in Hong Kong during the period of 1984-2013 (King, 1999; Maunsell-Fugro Joint Venture, 2007). According to the historical records, there were 7296 and 4326 rainfall-induced open hillslope landslides and channelized debris flows, respectively.

The frequency distributions of scar area and horizontal distances for the open hillslope landslides and channelized debris flows are shown in Figure 1. There were 2383 open hill slope landslides with an area ranging from 10 m^2 to 30 m^2. While the chanelized debris flows with a scar area ranging from 100 m^2 to 200 m^2 took a large proportion. The average values of scar area for the open hillslope and chanelized debris flows were 55.24 and 91.33 m^2, respectively.

A total of 2506 open hillslope landslides had a horizontal distance of 10-20 m, and 708 channelized debris flows had a horizontal distance of 100-200 m. About 91% of slope landslides had a horizontal distance below 50 m, and 99% had a horizontal distance below 100 m. About 46% of channelized debris flows had a horizontal distance ranging from 1 to 50 m, and about 76% had a horizontal distance between 1 and 100 m. The average values of horizontal distance for the open hillslope and chanelized debris flows were 24.22 and 86.11 m, respectively.

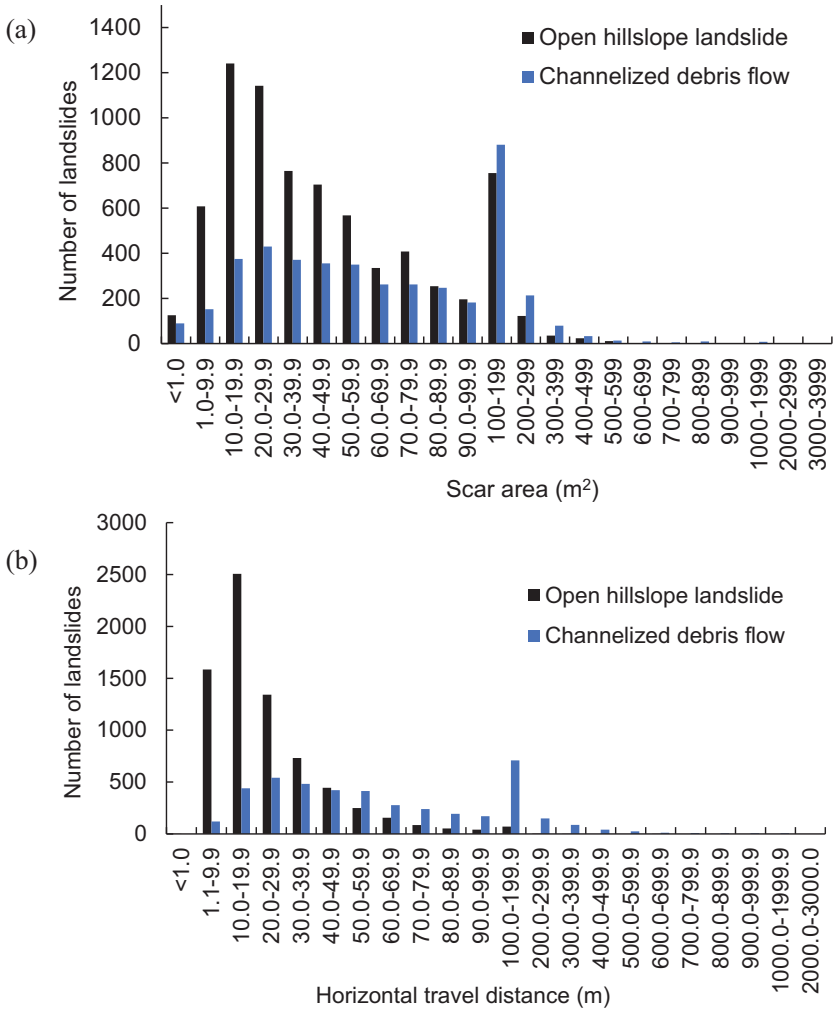

Figure 1. Frequency distributions of (a) scar area and (b) horizontal travel distance of landslides in Hong Kong during 1984-2013.

The slope gradient is recognized as one of the most important factors that greatly affect the stability of the slope (Ho, 2013; Gao et al., 2015; Gao et al., 2016). To quantify the occurrences of open hillslope landslides and channelized debris flows on different slope terrains, the numbers of landslides versus slope gradients, crown slope angles and distal-end toe angles are counted and shown in Figure 2. There are 1751 open hillslope landslides and 1063 channelized debris flows with crown slope angles ranging from 35° to 40°, which accounts for the largest proportion. Few landslides had a crown slope angle greater than 65°.

The most common distal-end toe angles range was 25 to 30°, and in this range, there were 1958 open hillslope landslides and 1092 channelized debris flows, respectively. There were 1794 open hillslope landslides with distal-end toe angles in the range of 30-35°. However, only 638 channelized debris flows had distal-end toe angles in the range of 30-35°. There were also 919 channelized debris flows having a distal-end toe angle between 20-25°. Channelized debris flows tend to be deposited on relatively flat slopes. Few landslides had a distal-end toe angle greater than 55°.

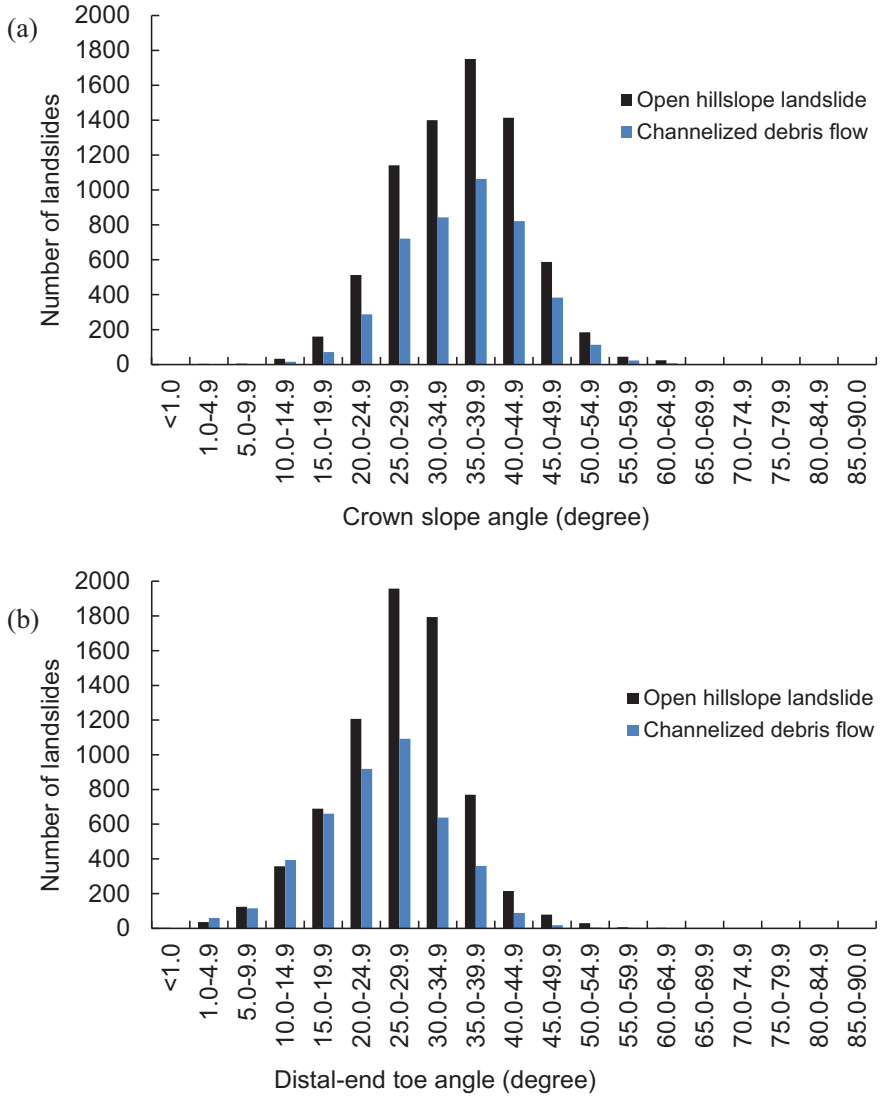

Figure 2. Frequency distributions of (a) crown slope angle and (b) distal-end toe angle of landslides in Hong Kong during 1984-2013.

3 Rainfall thresholds for landslide occurrences in Hong Kong

The rainfall intensity is recorded by the automatic raingauges in Hong Kong. In this study, the maximum rolling 1-hr, 2-hr, 4-hr, 5-hr, 6-hr, 8-hr, 12-hr and 24-hr rainfall in each year during 1984-2013 are adopted to estimate the rainfall threshold. The rainfall intensity (mm/hr) corresponding to the maximum rolling rainfall with different durations can be assumed to follow the power law, and expressed as follows:

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

where D (hour) is the duration ranging from 1 to 24 hours, I is the rainfall intensity (mm/hr) that is calculated by the maximum rolling rainfall divided by its corresponding duration D. α and β are the scale and shape of the power law curve. The spatial variance of the maximum rainfall is not considered in this study.

The total scar areas of both open hillslope landslides and channelized debris flows in each year from 1984 to 2013 can be obtained. The scar area ratio per year can also be computed as the total scar areas divided by the total natural terrain area. The natural terrain area in Hong Kong is about 660 km^2. The scar area ratios are divided into 3 categories, namely, greater than 0.01, between 0.001 and 0.01, and smaller than 0.001. Figures 3(a) and (b) present the rainfall intensity-duration relationships associated with three scar area ratios for open hillslope landslides and channelized debris flows, respectively. If the maximum rolling 24-h rainfall reaches 197.5 mm, the scar area ratios of open hillslope landslides and channelized debris flows may both exceed 0.001. The rainfall intensity corresponding to the maximum rolling 24-hr rainfall is therefore 8.2 mm/hr. Hence, the thresholds of rainfall intensities with durations of 1-, 2-, 4-, 5-, 6-, 8-, 12-, and 24-hr are 77.5, 48.3, 28.1, 22.7, 19.7, 18.0, 15.2, 8.2 mm/hr, respectively.

The threshold from Jibson (1989) is taken as a reference as shown in Figure 3 and the intensity-duration threshold is expresses in Equation (2).

$$I = 41.83 \cdot D^{-0.58} \tag{2}$$

The rainfall intensities thresholds with durations of 1 hr to 8 hr in the study are higher than those predicted by Jibson (1989). According to previous study on landslides in Hong Kong (Gao et al., 2018), the minimum thresholds are identified as 75, 90, 100, 110, 120, 150, 180 and 200 mm for the maximum rolling 1-, 2-, 4-, 5-, 6-, 8-, 12-, and 24-hr rainfall amounts, respectively. These cumulative rainfall amounts are quite similar to the results in this study.

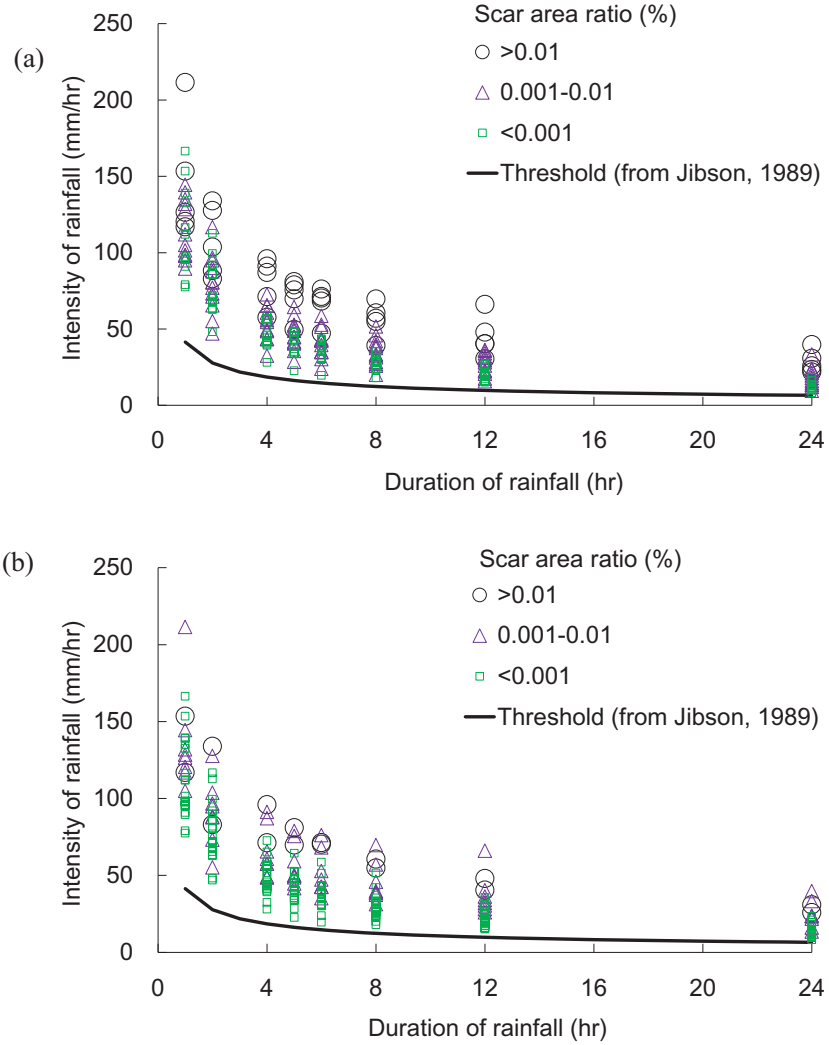

Figure 3. Rainfall thresholds of scar area ratio for (a) open hillslope landslides and (b) channelized debris flow in Hong Kong.

4 Landslide screening criteria considering the topographic factors

A strong dependence of landslide mobility on topography conditions has wide implications on hazard assessment (Ko, 2013; Wong et al., 2006). Empirical classifications of the mobility of natural terrain landslides can be used to assess the potential risks posed by the reactivated landslides. The landslide tail elevations and the distances from nearest buildings are selected as indices. In Hong Kong, the low-lying areas are heavily developed, with elevations commonly lower than 200 m. If a landslide will pose risks to a building depends on its travel distance and the distance from the nearest building. In this study, the mobility of the open hillslope landslides with widths larger than 15 m and channelized debris flows with horizontal travel distances longer than 200 m are analyzed, and it also involves the development of topographic screening criteria and delineation of corresponding mobility zones.

Figure 4 (a) and (b) present the distal angles versus the landslide tail elevations, and the horizontal distances from the nearest building for the selected open hillslope landslides and channelized debris flows, respectively. There are 322 open hillslope landslides with widths larger than 15 m, and the maximum width is up to 47 m. There are 343 channelized debris flows with travel distances longer than 200 m. The landslide tail elevations vary between 0 to 730.0 m, and the horizontal distances from the nearest building range from 4.8 to 2,034.1 m.

According to the frequency distributions of slope angles and travel distances, the topographic screening criteria (boxes in Figure 4) for landslides in Hong Kong are proposed. From Figure 2, about 97% open hillslope landslides and 98% channelized debris flows have crown slope gradients larger than 20°. There are 280 landslides with distal downslope angles > 20° and tail elevations < 200 m, and they are recognized to be suspicious. With reference to Figure 1, more than 99% open hillslope landslides and approximately 92% channelized debris flows have horizontal travel distances shorter than 200 m. The landslides with horizontal distances from the nearest buildings <200 m, and distal downslope angles > 20° are likely to lead to direct risks to citizens. There are 98 landslides in this range (Figure 4 (b)), which is less than the number (280) indicated in Figure 4(a). Though some of the natural terrain landslides with tail elevations lower than 200 m may not affect buildings, they still pose risks to the roads or other infrastructures.

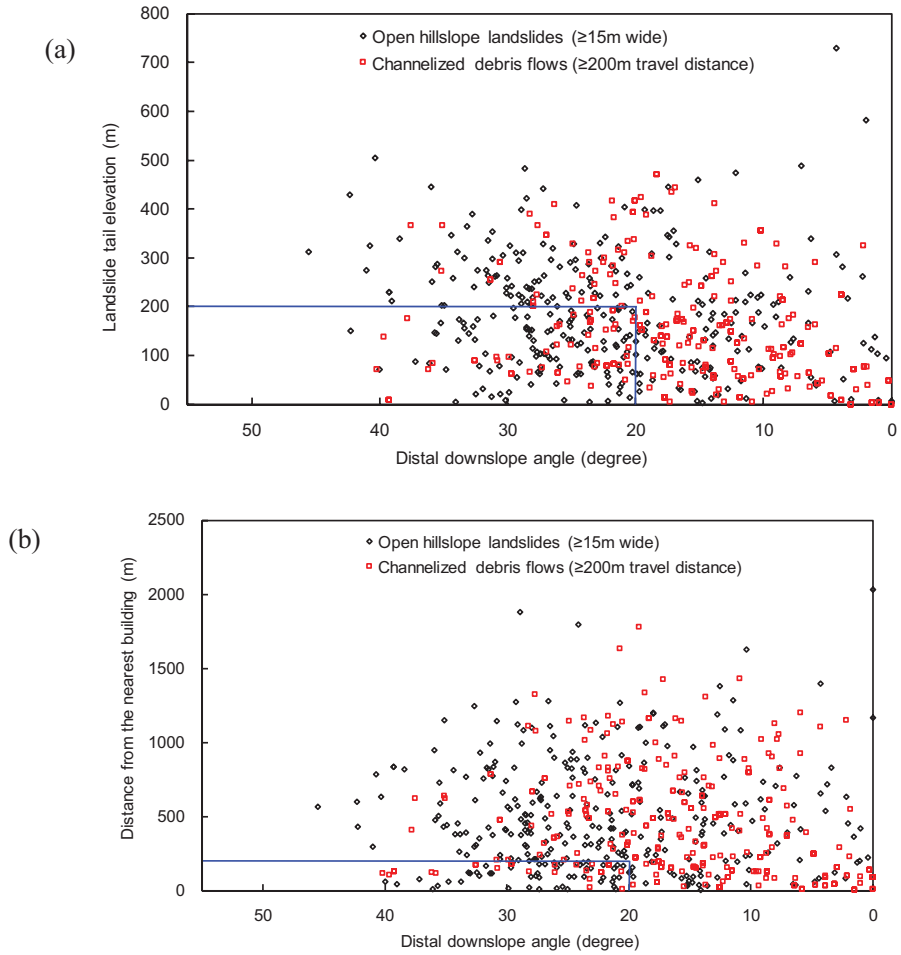

Figure 4. Topographic screening criteria for landslides in Hong Kong based on (a) distal elevation of landslide and (b) distance from the nearest building.

5 Conclusions

In this study, based on a large inventory covering a period of 1984-2013, the frequency distributions of both open hillside landslides and channelized debris flows in Hong Kong are established, and rainfall thresholds for triggering landslides are derived. The average values of scar area for the open hillslope and chanelized debris flows are 55.24 and 91.33 m^2, respectively. The average values of horizontal distance for the open hillslope and channelized debris flows are 24.2 and 86.1 m, respectively. Large proportion of landslides have crown slope angles ranging from 35° to 40°. Few landslides have a crown slope angle greater than 65°. The most common distal-end toe angles range is 25 to 30°. Few landslides have a distal-end toe angle greater than 55°. The thresholds of rainfall intensities with durations of 1-, 2-, 4-, 5-, 6-, 8-, 12-, and 24-hr are 77.5, 48.3, 28.1, 22.7, 19.7, 18, 15.2, 8.2 mm/hr, respectively. The landslides with horizontal distances from the nearest buildings <200 m, and distal downslope angles > 20° are likely to lead to direct risks to citizens. The topographic screening criteria considering the distal downslope angle, elevation, and distance from the nearest building are recommended.

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