Rainfall-based landslide susceptibility analysis for natural terrain in Hong Kong

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ABSTRACT

Steep natural terrain in Hong Kong, combined with deep weathering profile and high seasonal rainfall, is highly susceptible to rain-induced, shallow landslides. With over 35 years of practice in landslide risk management, Hong Kong has progressively built up a series of important databases that facilitate conducting state-of-the-art research and development works on landslides. Amongst others, there is a dense network of raingauges that provides state-of-the-art rainfall records, a high-resolution inventory of historical landslides and a LIDAR-based digital terrain model for natural terrain. This paper will firstly discuss the previous landslide susceptibility map for natural terrain in Hong Kong, and then present a new territory-wide rainfall-based landslide susceptibility analysis for natural terrain that takes cognizance of effect of slope angle. The year-based susceptibility model correlates landslide density with normalized maximum rolling 24-hour rainfall for eight different slope angle classes. The potential applications of the outcomes of the landslide susceptibility analysis will also be discussed.

Keywords: rainfall, landslide, susceptibility

1 INTRODUCTION

Hong Kong faces a unique long-term slope safety problem due to its dense urban development in a hilly terrain combined with high seasonal rainfall. Its slope engineering practice and landslide risk management have evolved in response to experience and through continuous improvement initiatives and technology advances. The application of state-of-the-art slope engineering practice and quantified landslide risk management has reduced landslide risk to an as low as reasonably practicable level that meets the needs of the public and facilitates safe and sustainable developments. One of the recent initiatives undertaken as part of the continuous efforts to enhance landslide risk management is the development of a rainfall-based landslide susceptibility model for natural terrain in Hong Kong.

Steep natural terrain in Hong Kong, combined with deep weathering profile and high seasonal rainfall, is highly susceptible to rain-induced, shallow landslides. Following its establishment in 1977 as a central body to regulate slope safety and geotechnical engineering in Hong Kong, the Geotechnical Control Office (renamed Geotechnical Engineering Office (GEO) in 1991) has progressively developed an integrated slope safety system that serves to manage landslide risk in a holistic manner through an explicit risk-based approach and strategy. There are four key strategic components and a number of major initiatives and tasks under the system (Chan & Lau 2008 and Malone 1998). Amongst others, the GEO has with time built up a series of important databases that are essential and instrumental to undertaking state-of-the-art research and development work related to landslides.

This paper will firstly discuss the previous landslide susceptibility map for natural terrain in Hong Kong, and then present a new territory-wide rainfall-based landslide susceptibility analysis for natural terrain that takes cognizance of effect of slope angle. The potential applications of the outcomes of the landslide susceptibility analysis will also be discussed.

2 DATA

2.1 Rainfall

The GEO, together with the Hong Kong Observatory (HKO), has installed 110 automatic raingauges across Hong Kong since the early 1980s. Wong et al (2013) gave a detailed account of the GEO raingauge system. The existing network comprises 88 GEO and 22 HKO automatic raingauges with an average density of 10 km²/gauge. The raingauges are monitored automatically and real-time rainfall data from the GEO raingauges are transmitted to the GEO Control Centre at a five-minute interval via a General Packet Radio Service network and Metro Ethernet network services. Data transmission and data sharing between HKO and GEO are carried out by means of
dedicated leased lines. The raingauges provide a reasonably good spatial and temporal coverage of rainfall records across the territory. Using the five-minute rainfall data, year-based normalized maximum rolling 24-hour rainfall across Hong Kong was quantified and related to landslide occurrence. Year-based normalized maximum rolling 24-hour rainfall at a location is equal to the maximum rolling 24-hour rainfall in a year divided by the mean annual rainfall (1977 to 2006) at the same location (Chan et al 2012).

2.2 Slope angle

Lately in the early 2010s, the GEO completed a multi-return airborne Light Detection and Ranging (LIDAR) survey for the whole territory of Hong Kong. Wong (2007) summarized the capability of using multi-return airborne LIDAR for high-precision and virtual-deforestation over-ground survey. In essence, the technique allows landslide geomorphology to be interpreted and landslide maps to be produced to a resolution that cannot otherwise be achieved by using conventional aerial photographs.

The technical requirements of the airborne LIDAR survey in Hong Kong were sampling interval at 1.3 m, and horizontal and vertical data accuracies at 0.3 m and 0.13 m respectively. The survey results were used to develop a 0.5 m-grid DEM for the whole territory of Hong Kong. For global assessments, a 5 m-grid DEM has been prepared by resampling from the 0.5 m-grid DEM. The 5 m-grid DEM were also converted into a 5 m-grid slope angle model.

2.3 Landslides

In the mid 1990s, the GEO began compilation of an inventory of historical natural terrain landslides (known as Natural Terrain Landslide Inventory (NTLI)) (King 1999). Natural terrain landslides were identified based on aerial photograph interpretation (API) using high-flight aerial photographs (taken at 8,000 feet or above). There were about 30,000 landslides in the NTLI. In 2005, the GEO commenced a two-year project on enhancement of the NTLI (known as Enhanced Natural Terrain Landslide Inventory (ENTLI)). Natural terrain landslides in the ENTLI were identified from API using the available low-flight (taken at less than 8,000 feet) aerial photographs, which provided great improvement in both resolution and temporal coverage. The high-flight aerial photographs are only taken once a year while the low-flight aerial photographs are taken more frequently for different parts of Hong Kong. The high-resolution ENTLI contains about 100,000 natural terrain landslides, which are over three times of those in the NTLI. The natural terrain landslides in the ENTLI are categorized into recent and relict landslides. Recent and relict landslides are different types of landslide features. While recent landslides are visible landslide incidents identified from aerial photographs since 1924, relict landslides are only morphological features that give an indication of past landslide activities.

3 PREVIOUS LANDSLIDE SUSCEPTIBILITY MAP

The first territory-wide landslide susceptibility map in Hong Kong (Fig. 1) was prepared in 1998, based on correlation of landslide density (landslides/km²) and landslide frequency (landslides/km²/year) with slope angle and geology (Evans & King 1998). Both recent and relict landslides were considered in working out the landslide density of each terrain unit. Five susceptibility classes were defined: very low, low, moderate, high and very high with landslide densities varying from <10 to >100 landslides per km² corresponding to frequencies varying from 0.1 to >1 landslide/km²/year. Insights from the landslide susceptibility analysis, which highlight the limited resolution of the susceptibility analysis for direct application, have been summarized by Wong (2003).

The landslide susceptibility map was updated in 2014 using the latest 5 m-grid slope angle model and ENTLI. The methodology to prepare the map is the same as the one previously adopted. Slope angles derived from the 5 m-grid slope angle map greatly improved the reliability of the terrain data. Natural terrain landslides were obtained from the ENTLI up to the year 2009. The higher resolution of the inventory provided larger number of natural terrain landslides, even after taking into consideration the recognition factors of the relict landslides. The range of landslide frequencies that corresponds to the five susceptibility classes increases by an order of magnitude (i.e. previously from 0.1 to >1 landslide/km²/year and now from <1 to >10 landslide/km²/year).

The updated susceptibility map has the same limited resolution as the previous susceptibility map. To overcome the limitation, a new territory-wide rainfall-based landslide susceptibility analysis was developed that correlates rainfall and landslide density with slope angle.

![Fig. 1. An extract of the first territory-wide landslide susceptibility map in Hong Kong.](image-url)
4 NEW RAINFALL-BASED SUSCEPTIBILITY ANALYSIS

Lately in 2014, a new susceptibility analysis was carried out. It considered landslide densities on natural hillsides for the years between 1985 and 2006, plus 2008 (i.e. a total of 23 years) within which year-based contours of normalized maximum rolling 24-hour rainfall were available. In the analysis, landslide density was correlated with the normalized maximum rolling 24-hour rainfall, with effect of slope angle taken into account. The following are the main steps of work of the susceptibility analysis undertaken on a GIS platform:

(a) Extract from the ENTLI natural terrain landslides between 1985 and 2006, plus 2008 (a total of 23 years).
(b) Group the normalized maximum rolling 24-hour rainfall into six classes of rainfall intensity: I: 0.025-0.10, II: 0.10-0.15, III: 0.15-0.20, IV: 0.20-0.25, V: 0.25-0.30, and VI: 0.30-0.35.
(c) Group the slope angles of natural terrain in the slope angle map (5 m-grid) into eight slope angle classes: <15°, 15°-20°, 20°-25°, 25°-30°, 30°-35°, 35°-40°, 40°-45° and >45°.
(d) Identify the corresponding rainfall class and slope angle class for each natural terrain landslide based on its year of occurrence and location.
(e) Count for each combined class of rainfall intensity and slope angle the total number of natural terrain landslides and the corresponding total hit area of natural terrain (km²) for the 23 years.
(f) Calculate for each combined class of rainfall intensity and slope angle the year-based natural terrain landslide density (no./km²).

Fig. 2 shows the year-based rainfall-landslide correlation for the eight slope angle classes. The following key observations are noted:

(a) In Fig. 2, the y-axis represents a true probable range of landslide density. Year-based landslide density <0.001 no./km² is not physically possible as in any one year, the number of landslides would definitely be greater than 1 (Note: Natural terrain area is about 660 km². For a landslide density of 0.001 no./km², number of landslides is equal to 0.66.)

(b) Fig. 2 also shows that landslide density increases with the normalized maximum rolling 24-hour rainfall and slope angle (up to the class of 40°-45°), which is reasonable.
(c) Only 2% of the natural terrain area is greater than 45°. For majority of the natural terrain area, landslides occur mostly on slopes between 30° and 45°, irrespective of rainfall (Fig. 3). A lower landslide density is observed for slopes greater than 45° probably because it is composed of stiffer soils, or rock outcrops.
(d) Different portions of natural terrain hit by the same rainfall intensity would have different levels of landslide density, depending on their corresponding slope angle class. Similarly, different portions of natural terrain that belong to the same slope angle class would also have different levels of landslide density, depending on their corresponding rainfall intensity. Effects of rainfall and slope angle on landslide occurrence are now inter-related.
(e) The year-based correlation, taking cognizance of effect of slope angle, is able to achieve an overall resolution of four to five orders of magnitude in terms of landslide density (Fig. 4).
(f) It is also noted in Fig. 4 that natural terrain landslides are highly sensitive to rainfall. The resolution achieved in terms of landslide density spans two to three orders of magnitude between the lowest and highest rainfall classes, for one slope angle class. Comparatively, natural terrain landslides are less sensitive to slope angle as there is less than an order of magnitude coverage in landslide density between 30° and 45° (i.e. the most probable range of slope angles for landslide occurrence).

5 DISCUSSION

The purpose of the model is to make approximate territory wide predictions of the scale of landslide impacts for anticipated precipitation events, in order to provide information necessary for emergency preparedness and planning purposes. The model is one of the few substantial attempts to introduce rainfall intensity as a predictor in a statistical manner. Rainfall is rarely considered in landslide susceptibility analyses carried out elsewhere, as usually adequate rainfall data is neither available nor reliable, which renders relating rainfall to landslide occurrence difficult, if not impossible. However, landslides are very sensitive to rainfall and if rainfall is not considered in a susceptibility analysis, any direct application of the results of the susceptibility analysis would not be very accurate and may mislead important risk-based decision making.

6 CONCLUSIONS

A new territory-wide rainfall-based landslide susceptibility analysis was carried out that correlates rainfall to landslide occurrence, with effect of slope angle considered. This is possible largely because of the availability of abundant high-resolution rainfall data, which is unique world-wide. The outcomes of the susceptibility analysis indicate that landslide occurrence is highly sensitive to rainfall. It is therefore crucial to consider rainfall in the susceptibility analysis so as to achieve meaningful results.

This paper presents a year-based model. A storm-based model taking into account the effect of geology would also be developed for direct application in predicting number of natural terrain landslides that would occur in a rainstorm. The model may also be used in undertaking global analysis, for example, global quantitative risk assessment and priority ranking. However, the resolution and reliability of the model are not yet sufficient to support direct application for site-specific hazard assessments and risk-based decision making.

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