A Landslide Frequency Map for Natural Terrain in Hong Kong
Carte de fréquence des glissements de terrain pour le relief naturel à Hong Kong

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ABSTRACT: Landslides from natural hillsides could result in serious consequence to life and property in Hong Kong due to its dense urban development in a hilly terrain combined with high seasonal rainfall. The problem is chronic due to an ever-increasing population, slope degradation, encroachment of more urban development on steep hillsides and potential impact of extreme rainfall, which could become more frequent and more severe due to climate change. Over the past 35 years, Hong Kong has maintained continual slope safety efforts through a suite of landslide risk management tools to reduce and contain landslide risk within an as low as reasonably practicable level that meets the needs of the public and facilitates safe and sustainable developments. The slope engineering practice and landslide risk management have evolved in response to experience and through continuous improvement initiatives and technology advances. In this paper, the recent development in landslide susceptibility analysis for natural terrain in Hong Kong is introduced that resulted in a territory-wide rainfall-based landslide susceptibility model. Coupling the mean annual frequency of occurrence of a credible range of rainfall scenarios in Hong Kong, the model enabled the development of a high-resolution territory-wide natural terrain landslide frequency map. The performance of the map was evaluated against historical landslide data that is independent of the training data set. The benefits and implications of the map are discussed in the context of overall landslide risk management. Potential applications of the map in Hong Kong are also presented.

RÉSUMÉ : Les glissements de terrain des collines naturelles pourraient avoir des conséquences graves pour la vie et les biens à Hong Kong en raison de son développement urbain dense dans un terrain vallonné combiné à de fortes précipitations saisonnières. Le problème est chronique en raison de la croissance de la population, de la dégradation des pentes, de l'empiètement d'un développement plus urbain sur les pentes escarpées et de l'impact potentiel des précipitations extrêmes, qui pourraient devenir plus fréquentes et plus graves en raison des changements climatiques. Au cours des 35 dernières années, Hong Kong a maintenu des efforts constants en matière de sécurité des pentes grâce à une série d'outils de gestion du risque de glissements de terrain pour réduire et contenir les risques de glissements de terrains à un niveau aussi bas que raisonnablement réalisable et répondant aux besoins du public. Les pratiques d'ingénierie des pentes et la gestion des risques de glissements de terrain ont évolué en fonction de l'expérience et des initiatives d'amélioration continue et des progrès technologiques. Dans le présent article, le développement récent de l'analyse de susceptibilité aux glissements de terrain pour les terrains naturels à Hong Kong a été mis en place, ce qui a entraîné un modèle de susceptibilité aux glissements de terrain à l'échelle du territoire. En couplant la fréquence annuelle moyenne de l'apparition d'une gamme crédible de scénarios de précipitations à Hong Kong, le modèle a permis l'élaboration d'une carte à haute résolution de la fréquence des glissements de terrain naturel à l'échelle du territoire. La performance de la carte a été évaluée en fonction des données historiques sur les glissements de terrain qui sont indépendantes de l'ensemble de données d'entraînement. Les avantages et les implications de la carte sont discutés dans le contexte de la gestion globale des risques de glissements de terrain. Les applications potentielles de la carte à Hong Kong sont également présentées.

KEYWORDS: Landslide frequency, high-resolution analysis, rainfall, slope angle, bedrock geology, Hong Kong

1 INTRODUCTION

Landslides from natural hillsides could result in serious consequence to life and property in Hong Kong due to its dense urban development in a hilly terrain combined with high seasonal rainfall. The problem is chronic due to an ever-increasing population, slope degradation, encroachment of more urban development on steep hillsides and potential impact of extreme rainfall, which could become more frequent and more severe due to climate change. Over the past 35 years, Hong Kong has maintained continual slope safety efforts through a suite of landslide risk management tools to reduce and contain landslide risk within an as low as reasonably practicable level that meets the needs of the public and facilitates safe and sustainable developments.

The assessment of landslide susceptibility is one of the key components in natural terrain landslide hazard assessment (Corominas et al, 2014; Hungr, 2016). However, without taking into account the dynamic triggering factors, such as rainfall, most of the susceptibility analyses result in relative landslide susceptibility between different parts of the hillside instead of landslide frequency. A new territory-wide rainfall-based landslide susceptibility model was developed by Ko & Lo (2016) which adopts rainfall, slope angle and simplified lithology as the causal factors. With the key triggering factor, rainfall, explicitly considered in the susceptibility model, it has the ability to predict the number of landslides that may occur given a rainfall condition. The landslide frequency of natural hillsides in Hong Kong has been assessed by coupling the landslide susceptibility model with the frequency of occurrence of various rainfall intensities. The results are presented as a landside frequency map at a territory-wide scale on the GIS platform. This paper presents the methodology adopted to develop the landslide frequency map for natural terrain in Hong Kong. Evaluation of the performance of the map is also discussed.

2 RAINFALL-BASED LANDSLIDE SUSCEPTIBILITY MODEL

Natural terrain occupies about 60% of the land and much of it is steeply sloping and mantled by weak saprolitic or residual soils, or colluvial deposits derived from past landslide and erosion processes. While Hong Kong’s natural hillsides have experienced a long history of landscape evolution, they remain highly susceptible to rain-induced landslides as they are subject to continual degradation. Field investigations have revealed that failures typically occur within one to two meters of the surface mantle, where erosion pipe holes, dilation and partial infilling of relict discontinuities, and localized tension cracks are often observed. Under this condition, a large number of shallow landslides can be triggered by heavy rain (Wong, 2009).

A new territory-wide rainfall-based landslide susceptibility model was developed which adopts rainfall, slope angle and simplified lithology as the causal factors (Ko & Lo, 2016). 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.

In essences, the susceptibility model correlates landslide density with normalized maximum rolling 24-hour rainfall. Sixteen attribute groups, comprising eight classes of slope angle (i.e. < 15°, ≥ 15 - 20°, ≥ 20 - 25°, ≥ 25 - 30°, ≥ 30 - 35°, ≥ 35 - 40°, ≥ 40 - 45° and ≥ 45°) and two classes of simplified solid geology (i.e. intrusive and volcanic-cum-sedimentary) were considered. For each attribute group, a set of year-based and storm-based correlations between normalized maximum rolling 24-hour rainfall and landslide density was obtained. Landslides that occurred in the 23 years between 1985 and 2006, plus 2008 were used as the training data set.

Figure 1 shows the storm-based correlation for intrusive area and that for volcanic-cum-sedimentary areas is presented in Figure 2.

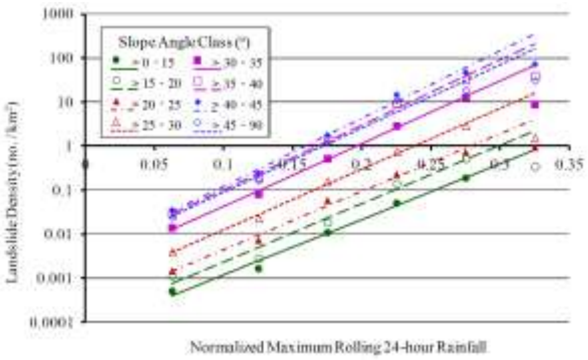

Figure 1. Storm-based Correlation for Intrusive Area.

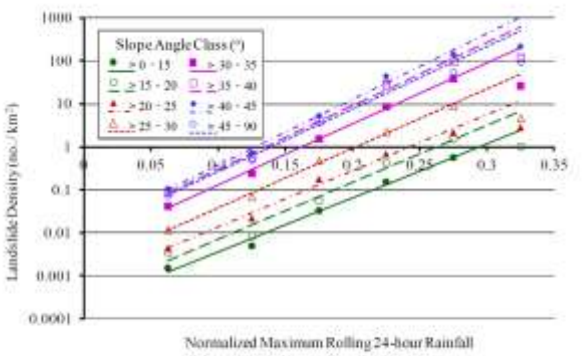

Figure 2. Storm-based Correlation for Volcanic-cum-Sedimentary Areas.

3 ANNUAL THEORETICAL LANDSLIDE FREQUENCY

An annual theoretical landslide frequency (in the unit of no./year) is the expected number of landslides that would likely occur in a year given the mean annual frequency of occurrence of rainfall. It was first adopted in Hong Kong by Wong et al (2006) as one of the components considered in calculating the hazard frequency in the global landslide risk assessment for natural terrain in Hong Kong.

In Wong et al (2006), four probable storm-based rainfall scenarios were considered, and their corresponding mean annual frequency of occurrence were calculated as the reciprocal of their return periods (Table 1). Details regarding the estimation of the return periods were explained in Ko (2005).

The number of landslides that would likely occur at a given rainfall scenario was derived from the rainfall-based susceptibility model (Ko & Lo, 2016). By coupling the mean annual frequency of occurrence of rainfall of each rainfall scenarios with the predicted number of landslides, the corresponding annual theoretical landslide frequency can thus be determined (Table 2).

Table 1. Rainfall Scenarios and Mean Annual Frequency of Occurrence of Rainfall.

Rainfall Scenario	Normalized 24-hour Rainfall	Mean Annual Frequency of Occurrence
A	<= 0.10	F_a = 1/1.23 = 0.8130
B	> 0.10 and <= 0.20	F_b = 1/2.09 = 0.4785
C	> 0.20 and <= 0.30	F_c = 1/16.46 = 0.0608
D	> 0.30 and <= 0.35	F_d = 1/281.81 = 0.0035

Table 2. Derivation of Annual Theoretical Landslide Frequency.

Rainfall Scenario	Normalized 24-hour Rainfall	Theoretical Landslide Frequency (no./year)
A	<= 0.10	$F_a D_{a,ij} A$
B	> 0.10 and <= 0.20	$F_b D_{b,ij} A$
C	> 0.20 and <= 0.30	$F_c D_{c,ij} A$
D	> 0.30 and <= 0.35	$F_d D_{d,ij} A$

Notes: (1) F_a, F_b, F_c and F_d are mean annual frequency of occurrence of rainfall for storm-based rainfall scenarios A, B, C and D respectively (see Table 1).
(2) $D_{a,ij}$, $D_{b,ij}$, $D_{c,ij}$ and $D_{d,ij}$ are storm-based landslide density for rainfall scenarios A, B, C and D respectively, and for a grid of 5 m x 5 m of slope angle class i and solid geology class j.
(3) A is the plan area of a 5 m x 5 m grid (in km²).

The annual theoretical landslide frequency for each 5 m x 5 m grid of slope angle class i and solid geology class j in the landslide frequency map is $F_{T,ij}$, which is calculated as:

$$F_{Tij} = F_a D_{aij} A + F_b D_{bij} A + F_c D_{cij} A + F_d D_{dij} A \quad (1)$$

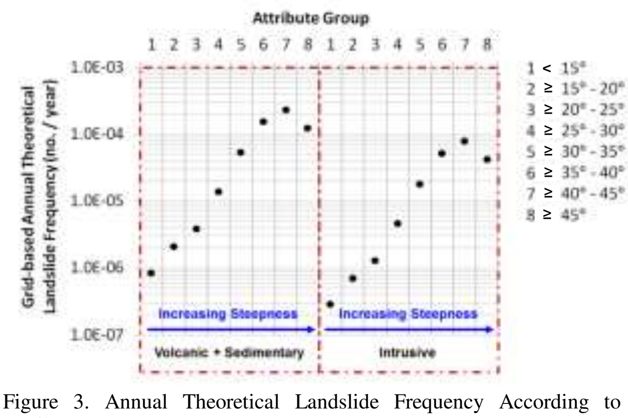

Figure 3. Annual Theoretical Landslide Frequency According to Attribute Groups.

The annual theoretical landslide frequency for each grid of the 16 attribute groups ranges from the highest value of 2.3 x

10^{-4} no./year to the lowest value of 2.8 x 10^{-7} no./year. The annual theoretical landslide frequency according to their corresponding attribute groups is shown in Figure 3. The grid-based average value of the annual theoretical landslide frequency for all the natural terrain in Hong Kong is 3.3 x 10^{-5} no./year.

4 TERRAIN-BASED LANDSLIDE FREQUENCY MAP

A terrain-based landslide frequency map was compiled based on the annual theoretical landslide frequency. The map is a digital map on a GIS platform showing the annual theoretical landslide frequency for every grid of 5 m x 5 m on the natural terrain. The chosen 5 m by 5 m resolution appears to be an appropriate scale for the present analysis. This grid size is comparable with the scale of majority of the natural terrain landslide source areas. In the map, the annual theoretical landslide frequencies are categorized into five classes to represent their relative levels of terrain susceptibility to landslide, each shown in a different colour (Table 3). Figure 4 shows a typical map layout. The area distribution of the five susceptibility classes is summarized in Table 4.

Table 3. Susceptibility Classes and Colour Codes of Grid-based Annual Theoretical Landslide Frequency.

Susceptibility Class	Colour Code*	Grid-based Annual Theoretical Landslide Frequency (no./year)
I	Yellow	> 1.0 x 10^{-4}
II	Light Blue	> 5.0 x 10^{-5} - 1.0 x 10^{-4}
III	Dark Blue	> 1.0 x 10^{-5} - 5.0 x 10^{-5}
IV	Light Green	> 1.0 x 10^{-6} - 1.0 x 10^{-5}
V	Dark Green	≤1.0 x 10^{-6}

** The colour codes are adopted in the coloured version of the landslide frequency map on GIS platform*

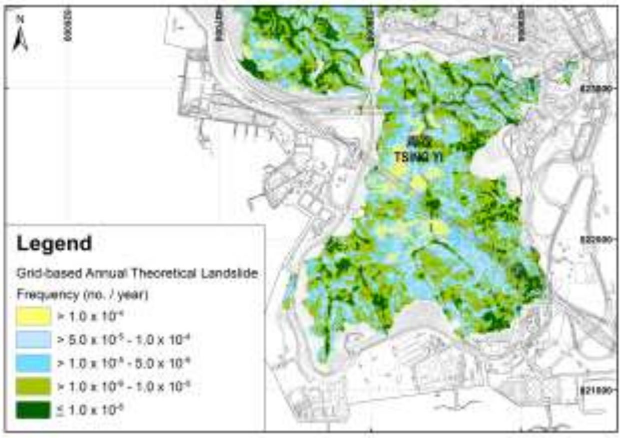

Figure 4. Typical Map Layout and Legend.

Table 4. Area Distribution of Susceptibility Classes

Susceptibility Class	Area (km^2)	Percentage Area
I	75.2	11.4%
II	113.9	17.3%
III	149.1	22.7%
IV	218.2	33.2%
V	101.5	15.4%

5 VALIDATION

The performance of the landslide frequency map was evaluated using accuracy statistics and the receiver operating characteristic (ROC) curves. Frattini et al. (2010) provided a detailed review on the use of these techniques.

Recent landslides occurred before 1985 were used to evaluate the landslide frequency map. They were not included in developing the rainfall-based landslide susceptibility model and hence, are statistically independent of the natural terrain landslide frequency map.

5.1 *Accuracy Statistics*

In this technique, accuracy is assessed by comparing the presence and absence of landslides (observed data) within attribute groups that are predicted as relatively stable (predicted positive) and unstable (predicted negative) based on a binary classification of susceptibility (model results). This classification requires a cutoff value of susceptibility that divides the predicted negative terrains (susceptibility less than the cutoff) and predicted positive terrains (susceptibility greater than the cutoff). The comparison of observed data and model results reclassified into two classes is represented through contingency tables. An example of a generic contingency table is shown in Table 5. Accuracy statistics assess the model performance by combining correctly and incorrectly classified positives and negatives.

Susceptibility classes I and II in the natural terrain landslide frequency map (corresponding to areas with an above-average theoretical landslide frequencies) were classified as predicted positive and classes III, IV and V as predicted negative (corresponding to areas with an average theoretical landslide frequencies or below).

Table 5. Contingency Table Used for Landslide Model Evaluation.

		Observed	
		Positive	Negative
Predicted	Positive	True Positive (TP)	False Positive (FP)
	Negative	False Negative (FN)	True Negative (TN)
		Sensitivity = TP / (TP + FN)	Specificity = TN / (FP + TN)

5.2 *Receiver Operating Characteristic Curves*

In this technique, the susceptibility classes are arranged from the highest to the lowest. By considering a range of possible cutoff values, pairs of sensitivity and (1–specificity) are derived and plotted with the former on the y-axis and latter on the x-axis. The area under the curve (AUC) can be used as a metric to assess the overall quality of a model: the larger the area, the best the performance of the model over the whole range of possible cutoffs. A value of 0.5 indicates a random result, a value approaching 1.0 indicates good prediction. As compared to the contingency table, The application of ROC curves do not require a priori cutoff value and the performance of a landslide susceptibility map is assessed throughout the entire range of cutoff values.

5.3 *Results*

Table 6 gives the contingency tables that compare the presence and absence of landslides within the predicted positive and negative attribute groups. There are about 78% of recent landslides fall within susceptibility classes I and II in the landslide frequency map. About 71% of pixels of susceptibility classes III, IV and V have no landslides.

The ROC curve of the map is shown in Figure 5. The value of AUC achieved is 0.80. It shows that there is a higher degree of agreement between observed data and model results. The results indicate that the map is consistent with the observed data to give reasonable prediction of both landslide occurrence and non-occurrence considering the entire possible range of cutoff values.

Table 6. Validation Results Using Accuracy Statistics.

		Observed	
		Positive	Negative
Predicted	Positive	5846	83139914
	Negative	1693	206235535
		Sensitivity = 77.54%	Specificity = 71.27%

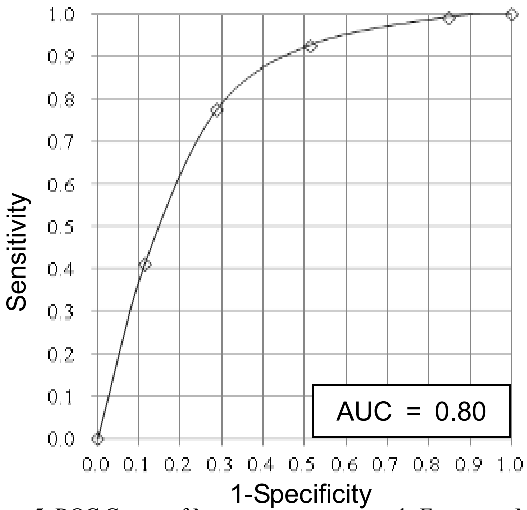

Figure 5. ROC Curves of Natural Terrain Landslide Frequency Map.

6 KEY OBSERVATIONS

The landslide frequency map was built on the findings of the rainfall-based landslide susceptibility analysis. The analysis provides the expected landslide response to rainfall for each of the 16 groups of terrain, in terms of theoretical landslide density. In other words, landslide response is shared across the entire terrain of the same attribute group, for a given rainfall scenario. For terrain in the same attribute group, areas with and without past rainfall experience have the same terrain susceptibility. As a result, terrain susceptibility as indicated in the landslide frequency map is independent of past rainfall experience.

As it is independent of past rainfall experience, the landslide frequency map has a predictive strength on the potential of landslide occurrence for a given rainfall scenario in the future, which may be calculated based on the theoretical landslide frequency. At a global scale, it is useful in various applications such as quantitative risk assessment and identification and priority ranking of potentially vulnerable natural hillsides. The map should however not be used for terrain evaluation and assessment at site-specific scale because of a lack of adequate resolution to duly account for site-specific terrain conditions. It may however be a useful supplementary reference.

Accuracy statistics and ROC curve were applied to evaluate the performance of the natural terrain landslide frequency map against historical landslides. The results show that the map is highly consistent with the observed data for both presence and absence of landslides.

It should be noted that areas of rock outcrops and cliffs are not delineated in the landslide frequency map. As rock outcrops and cliffs generally fall into the slope angle class "> 45°", it is probable that they appear as yellow or light blue areas on the map, although shallow natural terrain landslides in Hong Kong seldom occur on such terrain. Nevertheless, rock outcrops and cliffs constitute only a very small portion of the natural terrain area and the reliability of the map is therefore not affected in a practical sense.

7 CONCLUSIONS

The digital landslide frequency map building on the findings of the rainfall-based landslide susceptibility analysis was produced using GIS technology. It is a useful reference tool in various applications related to the overall landslide risk management in Hong Kong.

8 ACKNOWLEDGEMENTS

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9 REFERENCES

Corominas, J., Van Westen, C., Frattini, P., Cascini, L., Malet, J.P., Fotopoulou, S., Catani, F., Van Den Eeckhaut, M., Mavrouli, O., Agliardi, F. and Pitilakis, K. 2014. Recommendations for the quantitative analysis of landslide risk. *Bulletin of engineering geology and the environment*, 73(2), 209-263.

Frattini, P., Crosta, G. and Carrara, A. 2010. Techniques for evaluating the performance of landslide susceptibility models. *Engineering Geology*, 111, 62-72.

Hungr, O. 2016. A review of landslide hazard and risk assessment methodology. *Proceedings of the 12th International Symposium on Landslides*, Naples, Italy, 3-27.

Ko, F.W.Y. 2005. *Correlation between Rainfall and Natural Terrain Landslide Occurrence in Hong Kong (GEO Report No. 168).* Geotechnical Engineering Office, Hong Kong.

Ko, F.W.Y. and Lo., F.L.C. 2016. Rainfall-based landslide susceptibility analysis for natural terrain in Hong Kong - A direct stock-taking approach. *Engineering Geology,* 215 (2016), 95-107.

Wong, H.N., Ko, F.W.Y. and Hui, T.H.H. 2006. *Assessment of Landslide Risk of Natural Hillsides in Hong Kong (GEO Report No. 191).* Geotechnical Engineering Office, Hong Kong.

Wong, H.N. 2009. Rising to the challenges of natural terrain landslides. *Proceedings of the HKIE Geotechnical Division Annual Seminar 2009*, Hong Kong, 15–53.