Terrain-based Landslide Frequency Map for Natural Terrain in Hong Kong

GEO Report No. 340

F.W.Y. Ko

Geotechnical Engineering Office
Civil Engineering and Development Department
The Government of the Hong Kong Special Administrative Region

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Prepared by:

Geotechnical Engineering Office,
Civil Engineering and Development Department,
Civil Engineering and Development Building,
101 Princess Margaret Road,
Homantin, Kowloon,
Hong Kong.

Preface

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W.K. Pun
Head, Geotechnical Engineering Office
December 2018

Foreword

This report details the methodology adopted to develop the terrain-based landslide frequency map for natural terrain in Hong Kong.

The map was produced by Ms Florence W.Y. Ko under the supervision of Mr Y.K. Shiu. Mr W.K. Ho provided technical support to the data computation using GIS technology. The Drafting Unit of the Standards and Testing Division assisted in formatting this report. Colleagues in the GEO and practitioners in the geotechnical industry provided constructive comments on the draft version of this TN. All contributions are gratefully acknowledged.

H.W. Sun
Chief Geotechnical Engineer/Standards & Testing

Abstract

This report details the methodology adopted to develop the terrain-based landslide frequency map for natural terrain in Hong Kong. The landslide frequency map is a digital map produced using GIS technology and shows, for every grid of 5 m x 5 m on the natural terrain, annual theoretical landslide frequency. Derivation of the annual theoretical landslide frequency and key features of the map are discussed. Part-prints of the map for some commonly known areas are also presented for reference.

Contents

List of Tables

List of Figures

1 Introduction

This report details the methodology adopted to develop the terrain-based landslide frequency map for natural terrain in Hong Kong. The landslide frequency map is a digital map produced using GIS technology based on the rainfall-based landslide susceptibility model (Lo et al, 2015) and shows, for every grid of 5 m x 5 m on the natural terrain, annual theoretical landslide frequency. Section 2 provides a brief summary of the rainfall-based landslide susceptibility model. Derivation of the annual theoretical landslide frequency and key features of the map are discussed in Sections 3 and 4 respectively. Part-prints of the map for some commonly known areas are presented in Section 5 for reference. The digital map is currently for internal use by the Geotechnical Engineering Office to support the review of landslide susceptibility of natural terrain.

2 Rainfall-based Landslide Susceptibility Model

A new territory-wide rainfall-based landslide susceptibility model was developed in 2014 that correlates rainfall and landslide density with slope angle and solid geology (Lo et al, 2015). The year-based susceptibility model correlates landslide density with normalized maximum rolling 24-hour rainfall. Twenty-four terrain units, comprising eight classes of slope angle and three classes of solid geology were considered. For each terrain unit, a year-based correlation between normalized maximum rolling 24-hour rainfall and landslide density was obtained. Based on the year-based rainfall and landslide data, the correlation for sedimentary area was assumed to be the same as that for volcanic area, both of which were in turn taken as three times that of intrusive area.

Global adjustment factors were adopted to transform the year-based correlation to the storm-based correlation. Figure 2.1 shows the storm-based correlation for intrusive area and that for volcanic and sedimentary areas is presented in Figure 2.2.

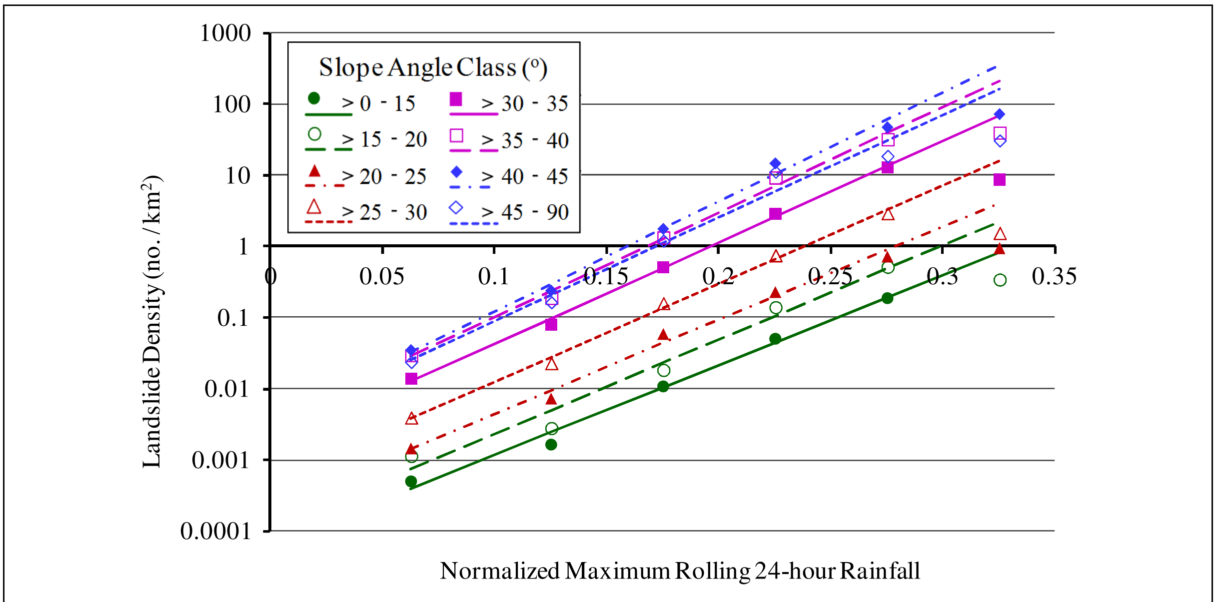

Figure 2.1 Storm-based Correlation for Intrusive Area

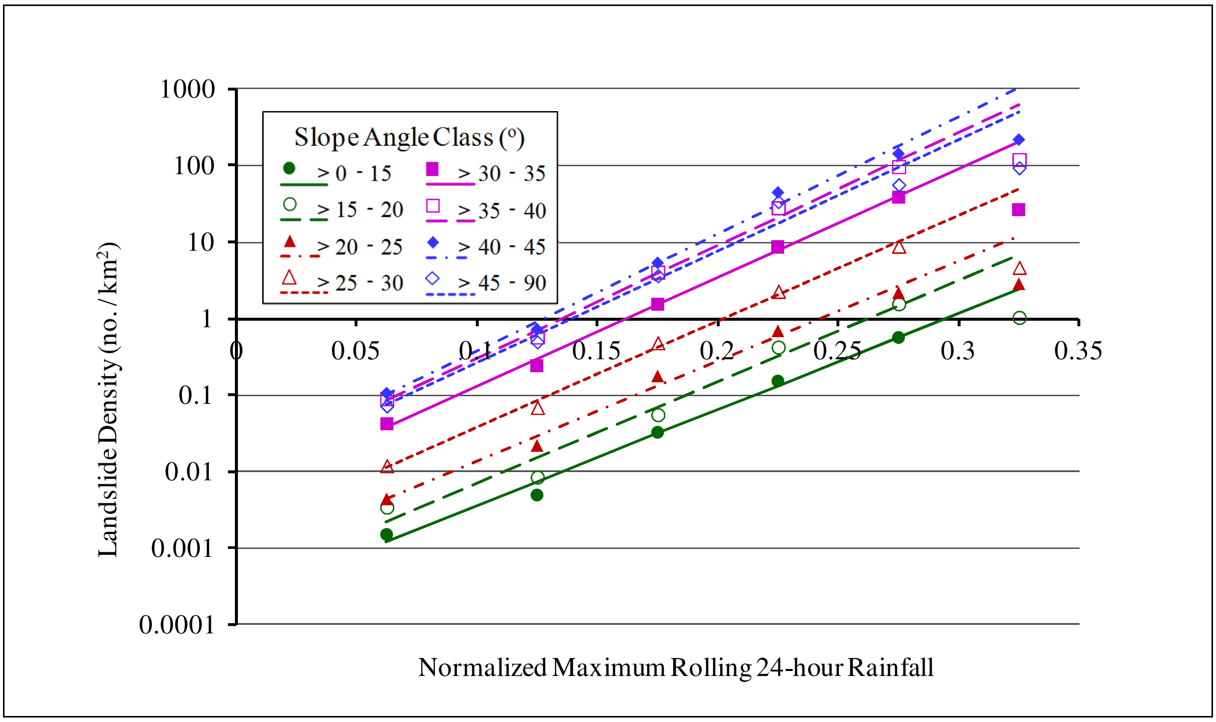

Figure 2.2 Storm-based Correlation for Volcanic and Sedimentary Areas

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 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. Details regarding the estimation of the return periods were explained in Tables D.2 and D.3 of Ko (2005). The number of landslides that would likely occur at a given rainfall scenario was derived from the rainfall-landslide density correlation (Ko, 2005). The annual theoretical landslide frequency was therefore calculated by coupling the mean annual frequency of occurrence of rainfall with the rainfall-landslide density correlation for the four rainfall scenarios.

The same methodology was used in deriving the annual theoretical landslide frequency for the landslide frequency map. The rainfall-landslide density correlation (*ibid.*) was however updated with the rainfall-based landslide susceptibility model (Lo et al, 2015). Table 3.1 shows the mean annual frequency of occurrence of rainfall as adopted in Wong et al (2006) and Table 3.2 summarizes the derivation of the annual theoretical landslide frequency, for the four storm-based rainfall scenarios.

Table 3.1 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 3.2 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 3.1).
(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*, based on the rainfall-based landslide susceptibility model (see Table 3.3).
(3) *A* is the plan area of a 5 m x 5 m grid (in km^2).

Table 3.3 Storm-based Landslide Densities

Storm-based Landslide Density (no./km^2)			Rainfall Scenario			
			A	B	C	D
Attribute Group	Intrusive	< 15°	0.0004	0.0050	0.0912	0.8013
		> 15 - 20°	0.0007	0.0107	0.2270	2.2430
		> 20 - 25°	0.0014	0.0203	0.4157	4.0039
		> 25 - 30°	0.0038	0.0619	1.4893	16.1805
		> 30 - 35°	0.0125	0.2198	5.8396	68.3484
		> 35 - 40°	0.0281	0.5495	16.4435	210.3794
		> 40 - 45°	0.0329	0.7192	24.4545	344.3304
		> 45°	0.0253	0.4714	13.3535	163.9530
	Volcanic and Sedimentary	< 15°	0.0012	0.0151	0.2735	2.4040
		> 15 - 20°	0.0022	0.0321	0.6810	6.7290
		> 20 - 25°	0.0043	0.0608	1.2470	12.0117
		> 25 - 30°	0.0115	0.1857	4.4679	48.5414
		> 30 - 35°	0.0374	0.6593	17.5189	205.0451
		> 35 - 40°	0.0843	1.6486	49.3306	631.1383
		> 40 - 45°	0.0986	2.1577	73.3636	1032.9911
		> 45°	0.0758	1.4143	40.0606	491.8591

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:

$$F_{T,ij} = F_a D_{a,ij} A + F_b D_{b,ij} A + F_c D_{c,ij} A + F_d D_{d,ij} A \qquad (3.1)$$

There are altogether 16 attribute groups in the landslide susceptibility model, arising from the eight slope angle classes (i.e. < 15°, > 15 - 20°, > 20 - 25°, > 25 - 30°, > 30 - 35°, > 35 - 40°, > 40 - 45° and > 45°) and two solid geology classes (i.e. intrusive and volcanic-cum-sedimentary). The annual theoretical landslide frequency for each grid of each attribute group 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 3.1. 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.

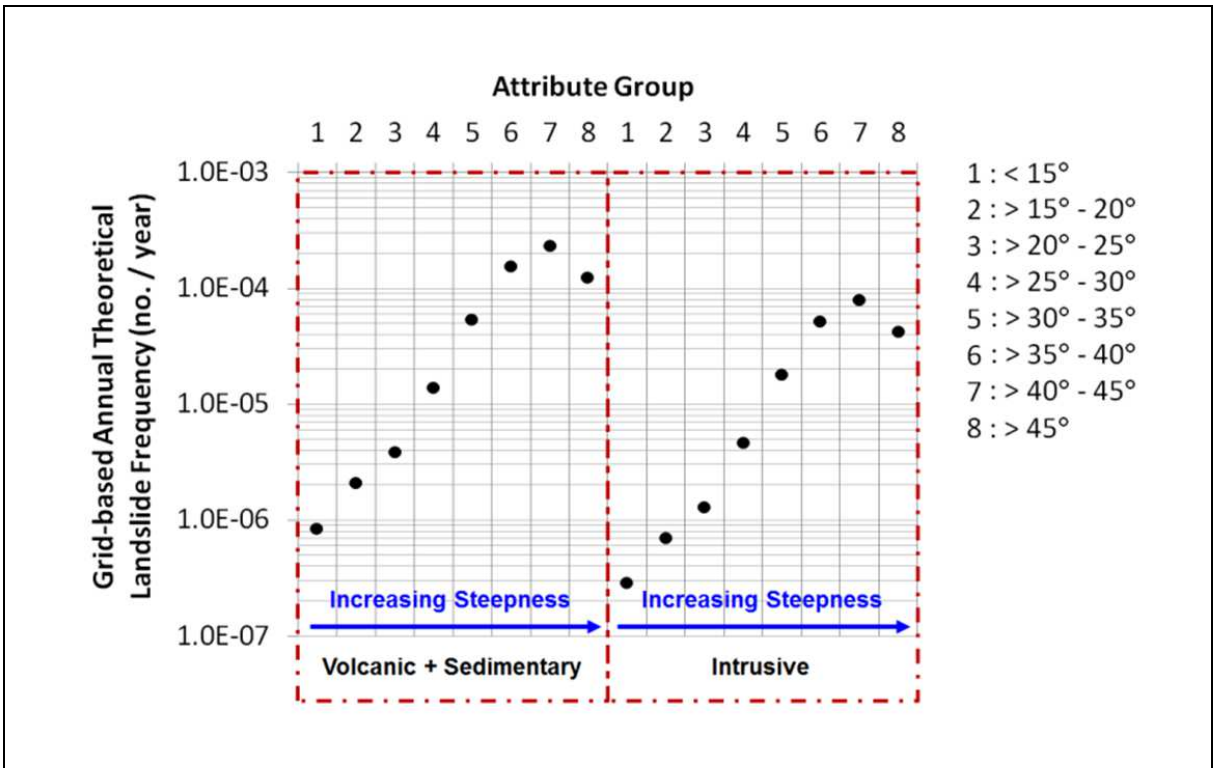

Figure 3.1 Annual Theoretical Landslide Frequency according to Attribute Groups

4 Terrain-based Landslide Frequency Map

The terrain-based landslide frequency map is a digital map produced by firstly coupling the slope angle and solid geology maps (Lo et al, 2015) and then assigning each grid its annual theoretical landslide frequency using GIS technology. It shows, for every grid of 5 m x 5 m on the natural terrain, the annual theoretical landslide frequency. In the map, the annual theoretical landslide frequency for the 16 attribute groups are shown in five different colours that represent their relative levels of terrain susceptibility to landslide. Yellow and light blue grids represent terrain with above-average susceptibility. Dark blue grids represent terrain with average susceptibility. Light green and dark green grids represent terrain with below-average susceptibility (see Table 4.1).

Figure 4.1 shows a typical map layout and legend. Figures 4.2 to 4.6 present the map for the Shek Pik, Tai O, Tung Chung, Mid-levels and Pak Sin Leng areas. The locations of the crowns of the recent natural terrain landslides are overlaid on the map for reference.

Table 4.1 Susceptibility Class and Colour Codes of Grid-based Annual Theoretical Landslide Frequency

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

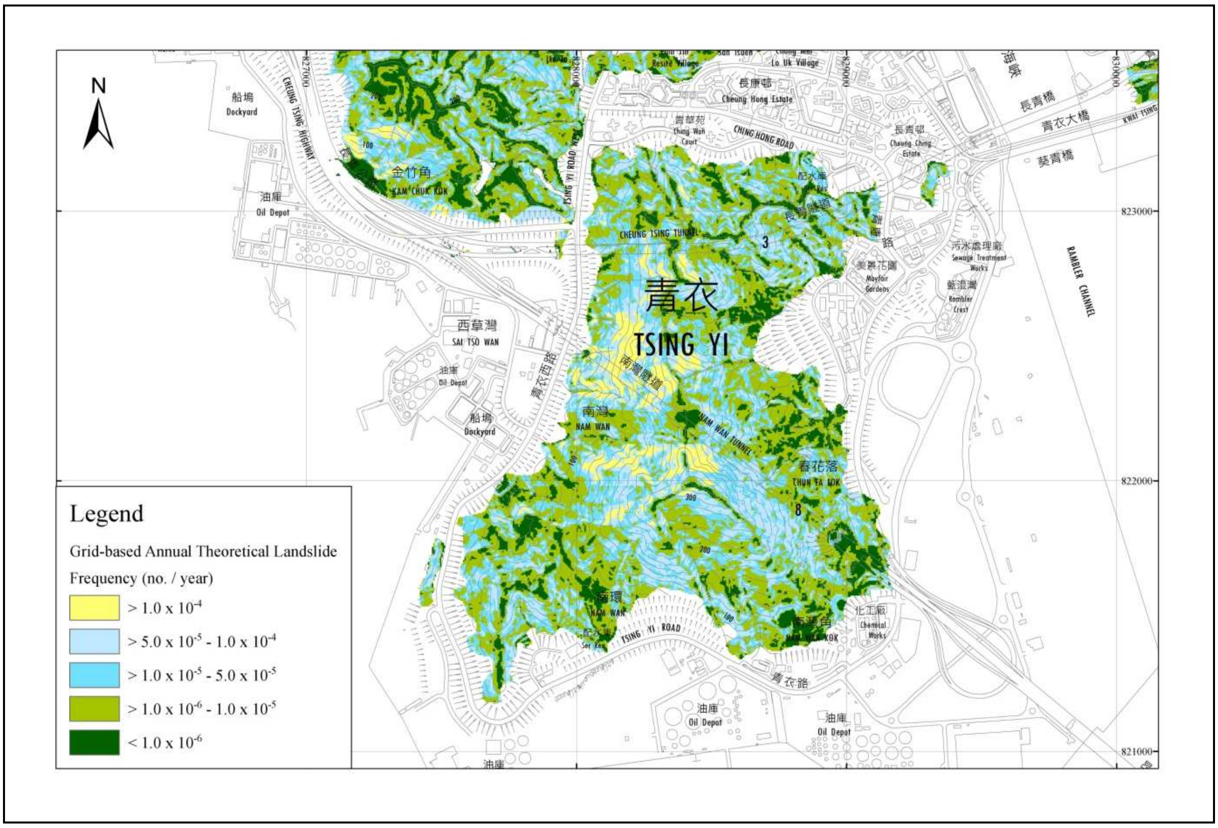

Figure 4.1 Typical Map Layout and Legend

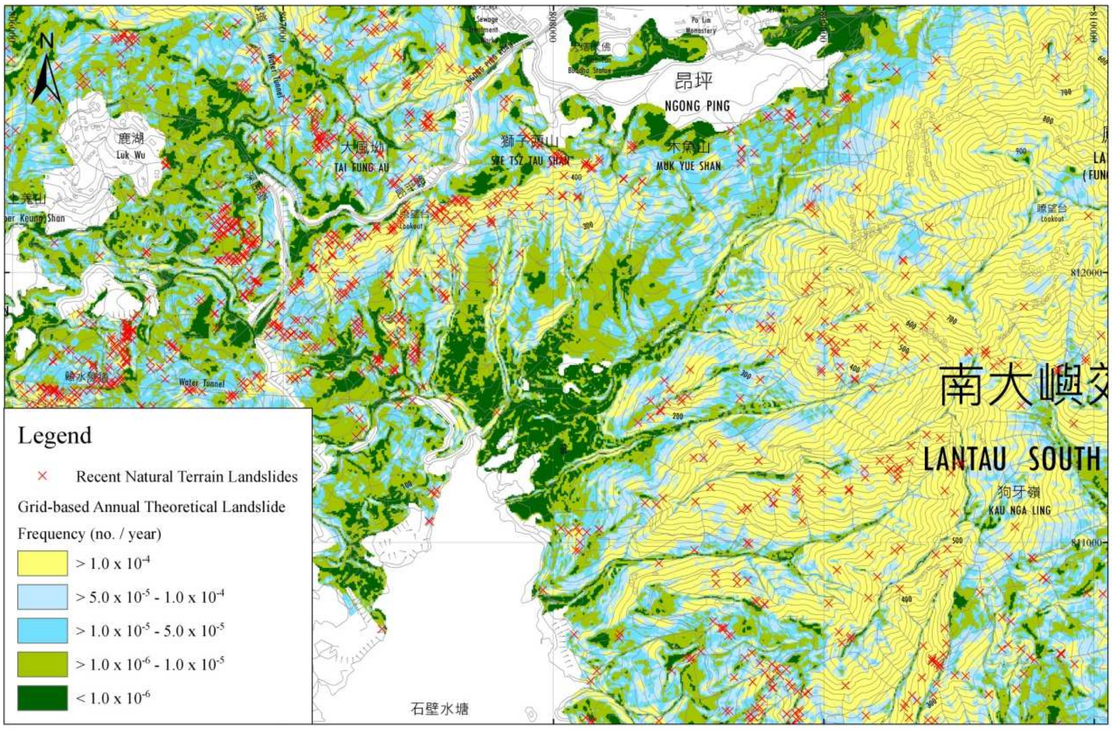

Figure 4.2 Map for Shek Pik Area

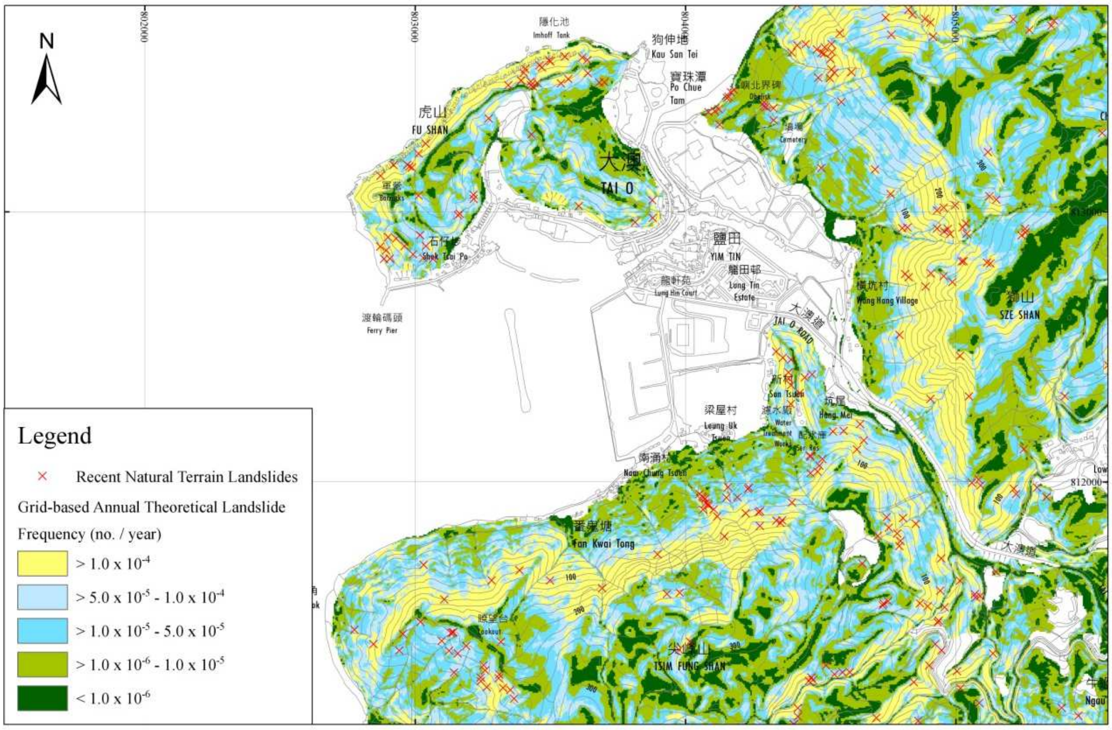

Figure 4.3 Map for Tai O Area

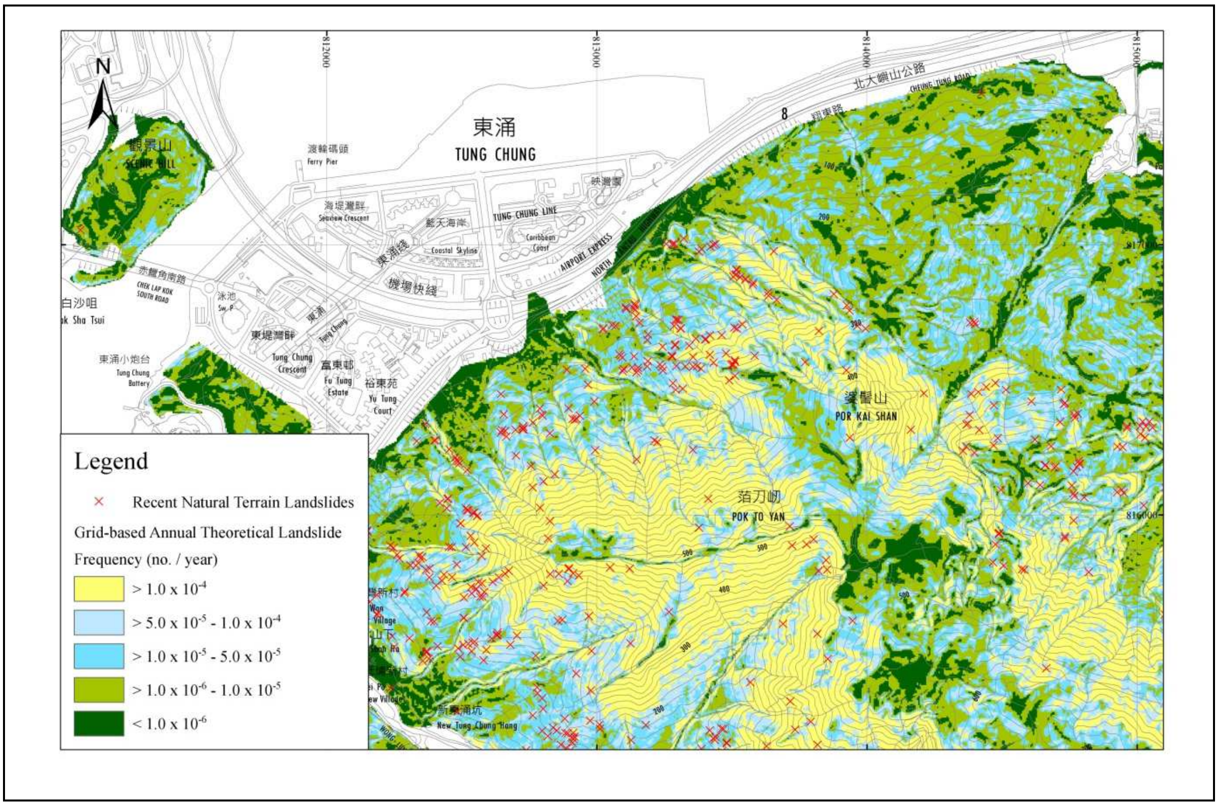

Figure 4.4 Map for Tung Chung Area

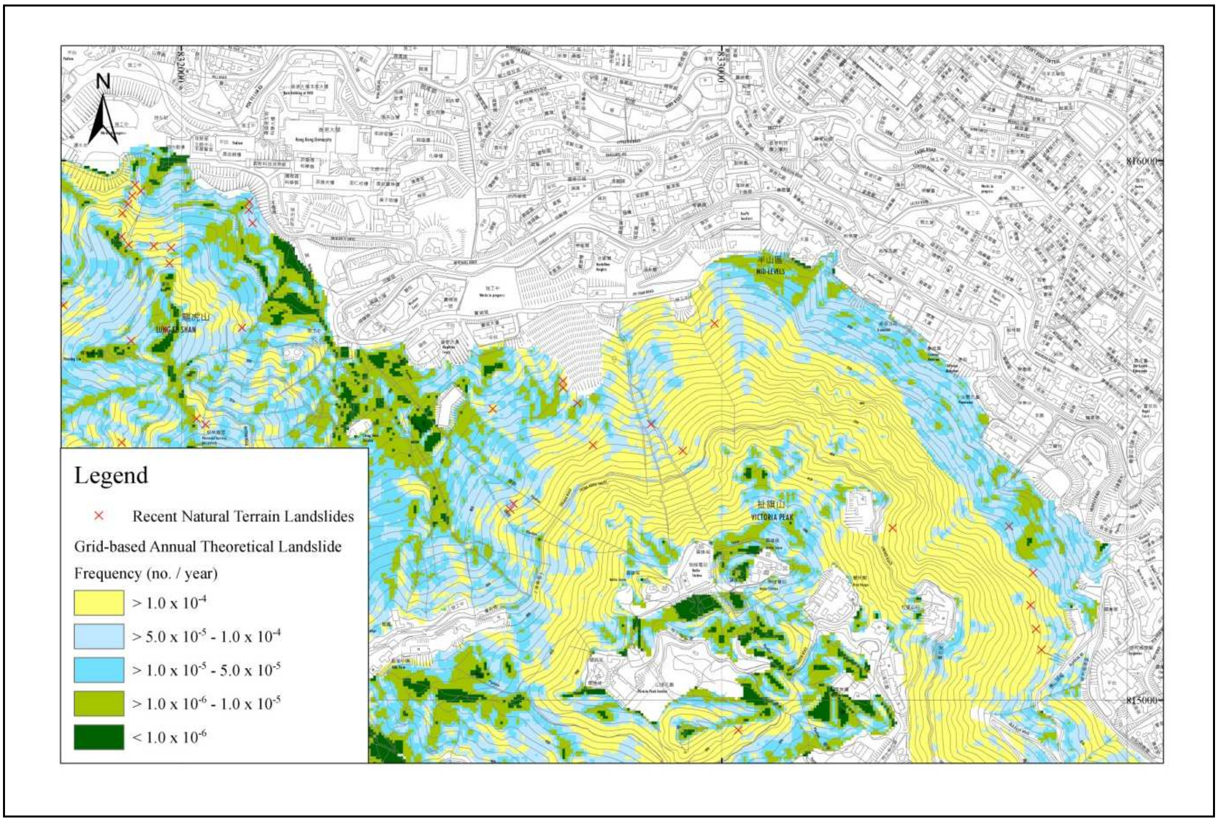

Figure 4.5 Map for Mid-levels Area

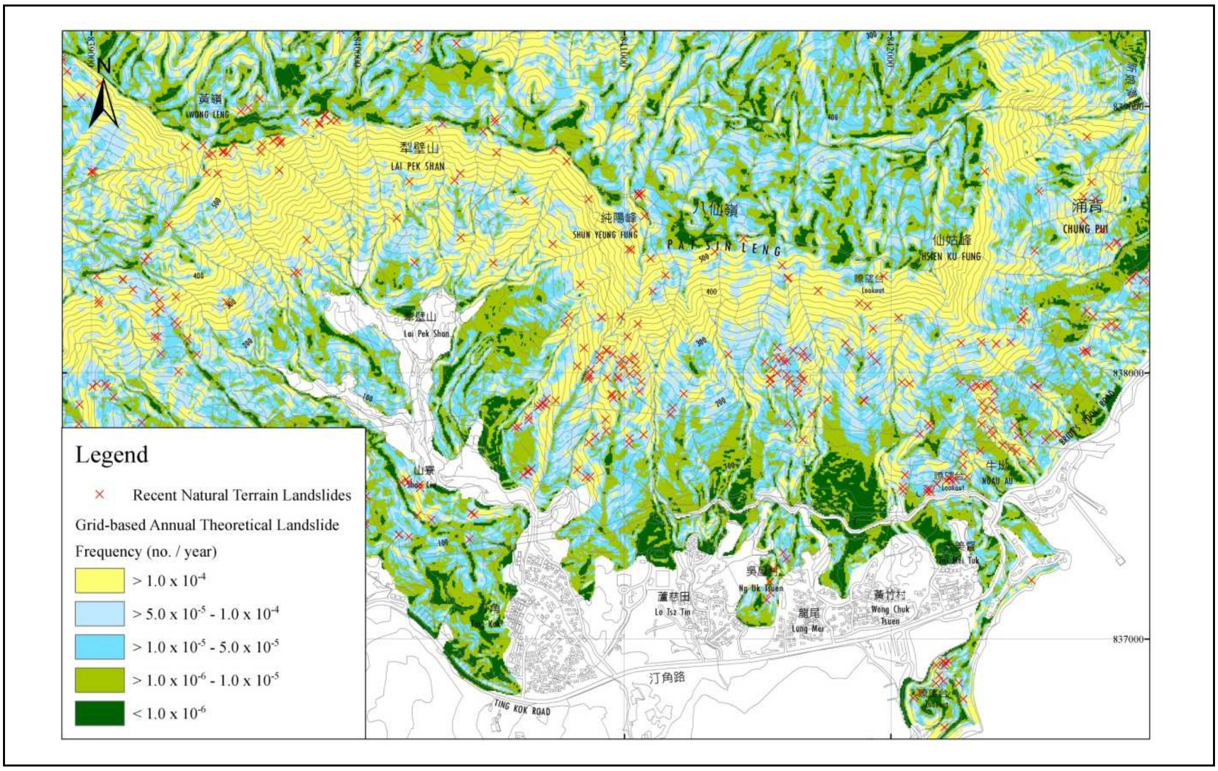

Figure 4.6 Map for Pak Sin Leng Area

5 Key Observations

The landslide frequency map was built on the findings of the rainfall-based landslide susceptibility analysis. The analysis assessed average 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.

In terms of benchmarking with actual terrain response, the landslide frequency map shows a good match between terrain susceptibility and actual occurrence of landslides for areas that have previously been hit by severe rainfall events. The same observation is less obvious for areas that have not been previously tested to the same. This is the result of sharing of landslide response across the entire terrain of the same attribute group, for a given rainfall scenario.

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. The slope gradients, which is based on the results of air-borne Light Detection and Ranging (LiDAR) survey conducted in 2010, represent the post-failure gradient at the landslide location. Nevertheless, Figure 3.1 shows that slopes of angles larger than 35° are most susceptible to landslides, which is consistent to field observations. 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.

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 fills the gap in the current practice of hazard evaluation, which refers largely to record of past landslides, and opens up the source of potentially problematic 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.

It should be noted that the rainfall-based landslide susceptibility model would be further enhanced to take into consideration the effect of relict landslides on recent landslide activities. In connection with this, the landslide frequency map would be updated to incorporate the significant findings in due course. The technical details involved in identifying relict landslides as a new attribute considered in the rainfall-based landslide susceptibility model would be discussed in a separate report.

6 Conclusions

The digital landslide frequency map building on the findings of the rainfall-based landslide susceptibility analysis has been produced using GIS technology. It is currently for internal use by the Geotechnical Engineering Office to support the review of landslide susceptibility of natural terrain in Hong Kong.

7 References

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