Territory-wide Rainfall-based Landslide Susceptibility Analysis

GEO Report No. 364

F.L.C. Lo, R.P.H. Law & F.W.Y. Ko

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

[Blank Page]

Territory-wide Rainfall-based Landslide Susceptibility Analysis

GEO Report No. 364

F.L.C. Lo, R.P.H. Law & F.W.Y. Ko

This report was originally produced in May 2015
as GEO Special Project Report No. SPR 1/2015

First published, December 2022

Prepared by:

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

Preface

In keeping with our policy of releasing information which may be of general interest to the geotechnical profession and the public, we make available selected internal reports in a series of publications termed the GEO Report series. The GEO Reports can be downloaded from the website of the Civil Engineering and Development Department (http://www.cedd.gov.hk) on the Internet.

Raymond WM Cheung
Head, Geotechnical Engineering Office
December 2022

Foreword

This report presents a new territory-wide rainfall-based landslide susceptibility analysis for natural terrain that takes cognizance of the effects of slope angle and solid geology.

The study was carried out by Mr Frankie L.C. Lo and Dr Raymond P.H. Law under the supervision of Ms Florence W.Y. Ko and myself. Technical Officer, Mr W.K. Ho, provided valuable technical support in the spatial analyses using Geographic Information System. The Drafting Unit of the Standards and Testing Division assisted in formatting this report. All contributions are gratefully acknowledged.

Y.K. Shiu
Chief Geotechnical Engineer/Standards & Testing

Abstract

The previous landslide susceptibility map for natural terrain in Hong Kong has its limitations for direct application, such as in predicting number of natural terrain landslides in a rainstorm and undertaking global analysis, for example, global quantitative risk assessment and priority ranking. To overcome the limitations, a new territory-wide rainfall-based landslide susceptibility analysis was developed that correlates rainfall and landslide density with slope angle and solid geology. 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. Global adjustment factors were recommended to transform the year-based correlation to the storm-based correlation. Storm-based correlation based on normalized maximum rolling 4-hour and 24-hour rainfalls was also developed using the same methodology.

For the time being, the new susceptibility model would be applied in predicting number of natural terrain landslides in a rainstorm and 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 at this stage.

Contents

List of Tables

List of Figures

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. This is made possible through the long-term investment in compiling a series of important databases that are essential and instrumental to undertaking state-of-the-art research and development work related to landslides.

This report first discusses the previous landslide susceptibility map for natural terrain in Hong Kong and its limitations, and then presents a new territory-wide rainfall-based landslide susceptibility analysis for natural terrain that takes cognizance of the effects of slope angle and solid geology.

2 Data

2.1 Rainfall

The Geotechnical Engineering Office (GEO), together with the Hong Kong Observatory (HKO), has installed 124 automatic raingauges across Hong Kong since the early 1980s. The existing network comprises 88 GEO and 36 HKO automatic raingauges with an average density of 10 km^2/gauge (Figure 2.1). Each GEO raingauge station consists of a tipping bucket rainfall measuring unit and a data logger (with an internal modem) powered by solar energy. The raingauges are monitored automatically. Prior to 2015, real-time rainfall data of the GEO raingauges were transmitted to the receiving servers at 5-minute intervals via a General Packet Radio Service network and Metro Ethernet network services. Now, real-time rainfall data of the GEO raingauges are transmitted to the receiving servers at 1-minute intervals via mobile phone network. The raingauges provide a reasonably good spatial and temporal coverage of rainfall records across the territory. For past rainstorms, the five-minute rainfall data was used to quantify year-based normalized maximum rolling 24-hour rainfall and combined 4-hour and 24-hour rainfalls across Hong Kong, which were then related to landslide occurrence [Note: Year-based normalized maximum rolling 24-hour rainfall (or combined 4-hour and 24-hour rainfalls) at a location is equal to the maximum rolling 24-hour rainfall (or combined 4-hour and 24-hour rainfalls) in a year divided by the mean annual rainfall (1977 to 2006) at the same location (Chan et al, 2012)]. Figure 2.2 shows the contours of the year-based normalized maximum rolling 24-hour rainfall over the natural terrain area in 2008 as an example.

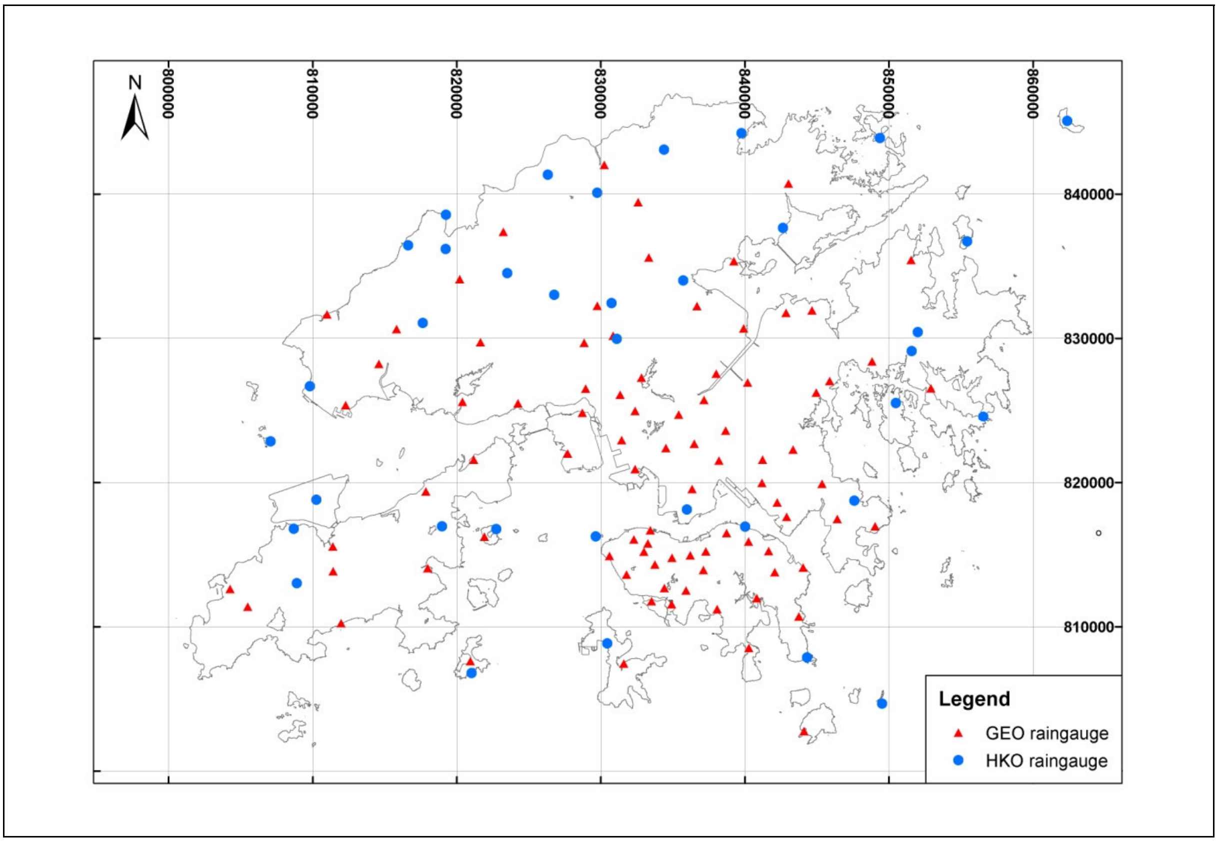


Figure 2.1 Locations of GEO and HKO Automatic Raingauges

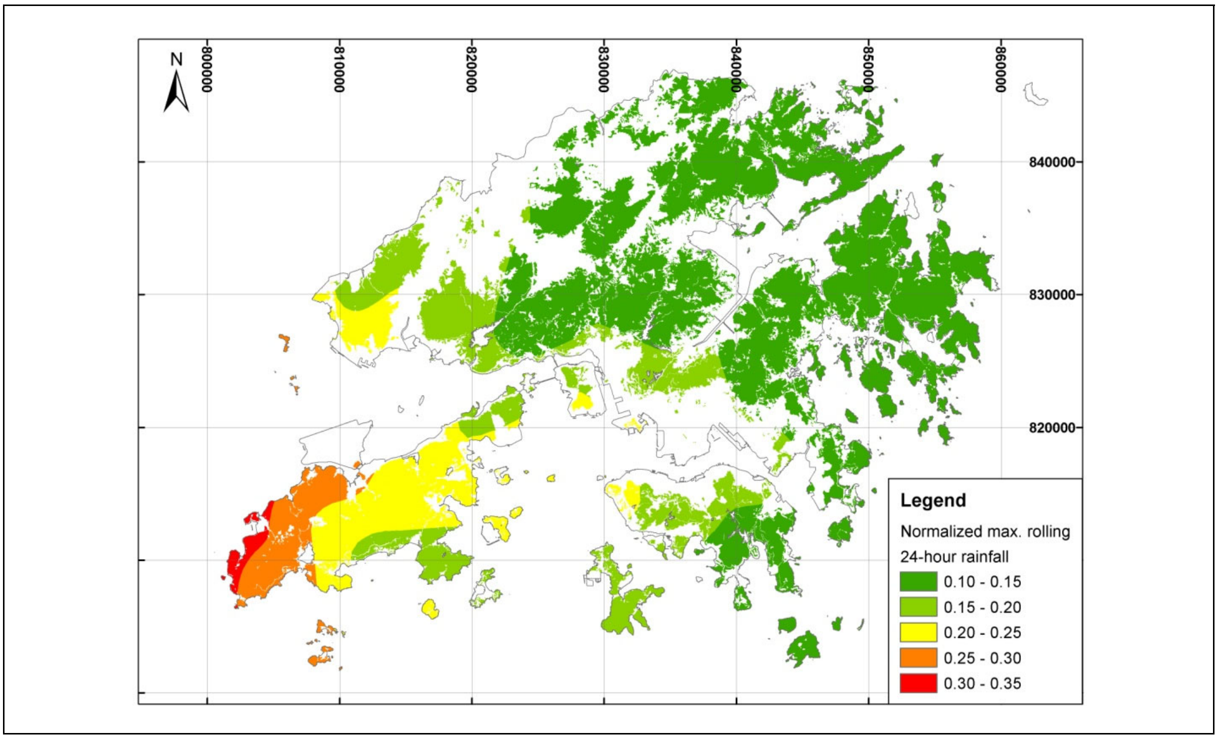


Figure 2.2 Contours of the Year-based Normalized Maximum Rolling 24-hour Rainfall over the Natural Terrain Area in 2008

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. An example of the 5 m-grid slope angle map is shown in Figure 2.3. The distribution of natural terrain area according to slope angle classes is shown in Figure 2.4.

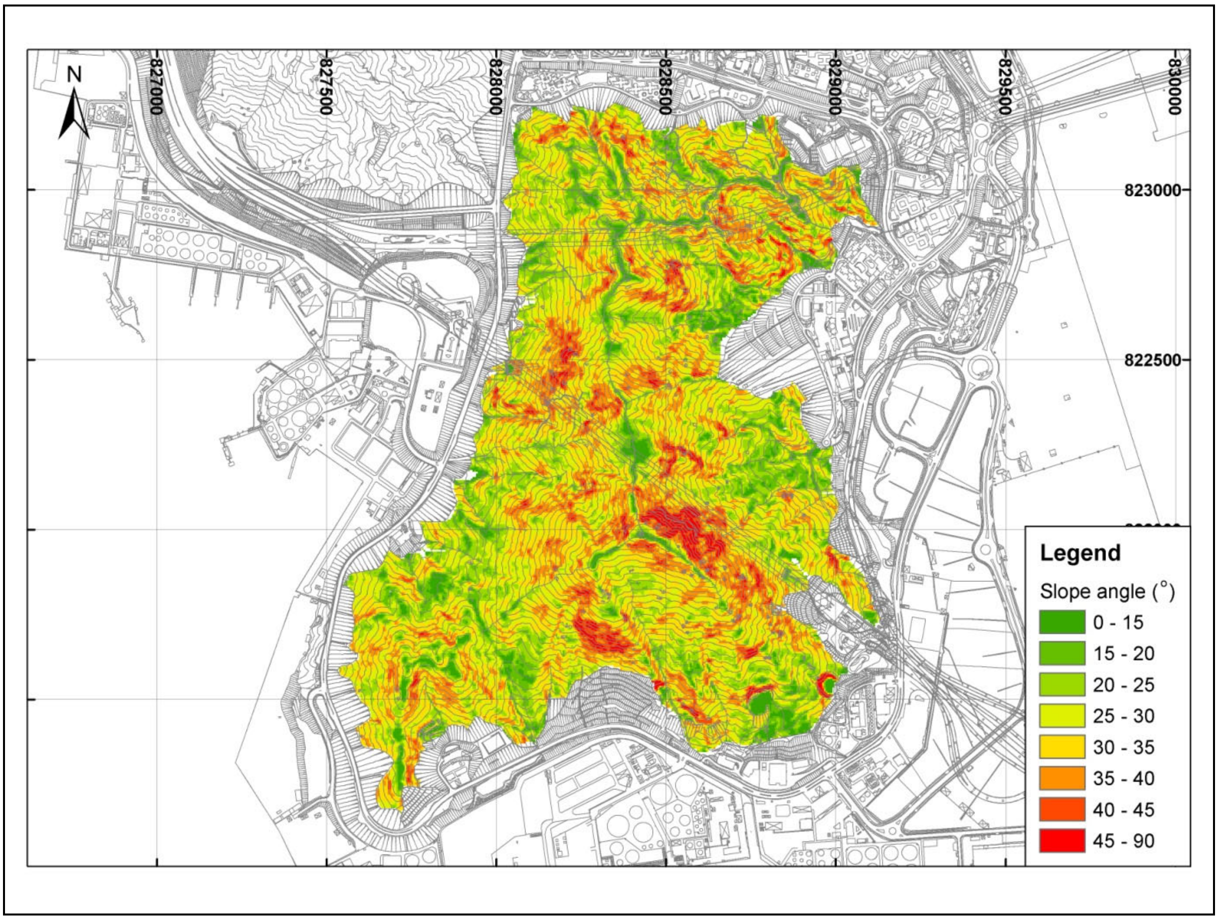


Figure 2.3 An Example of the 5 m-grid Slope Angle Map

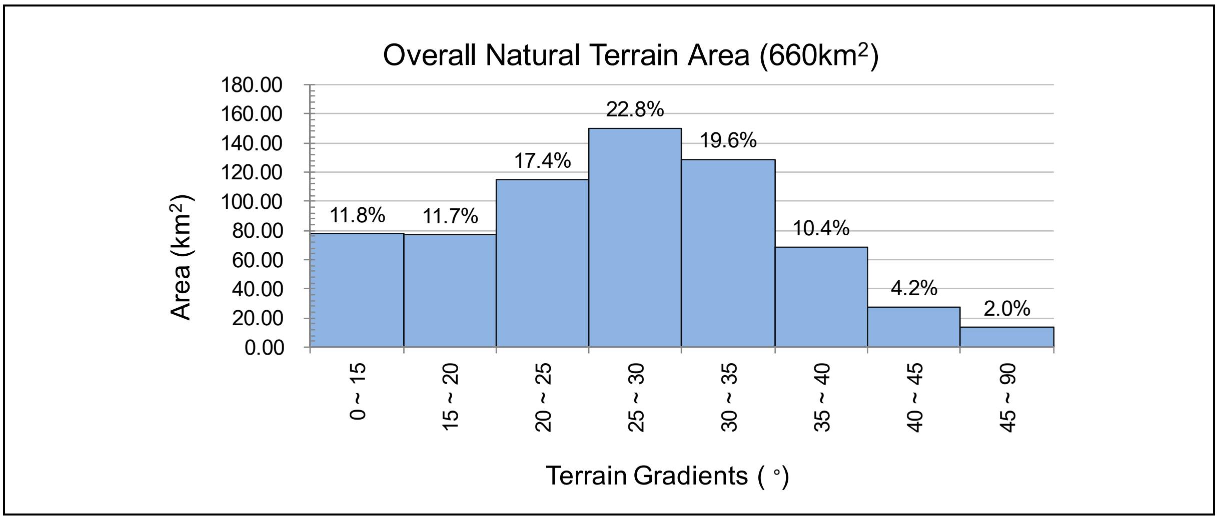


Figure 2.4 Distribution of Natural Terrain Area according to Slope Angle Classes

2.3 Solid Geology

Sewell et al (2000) summarized the history and development of the set of fifteen 1:20,000-scale geological maps and six accompanying memoirs in Hong Kong. For the purpose of global assessments, the complex solid geology of Hong Kong as shown in the 1:20,000 geological maps was simplified to three main groups: intrusive, volcanic and sedimentary (Figure 2.5).

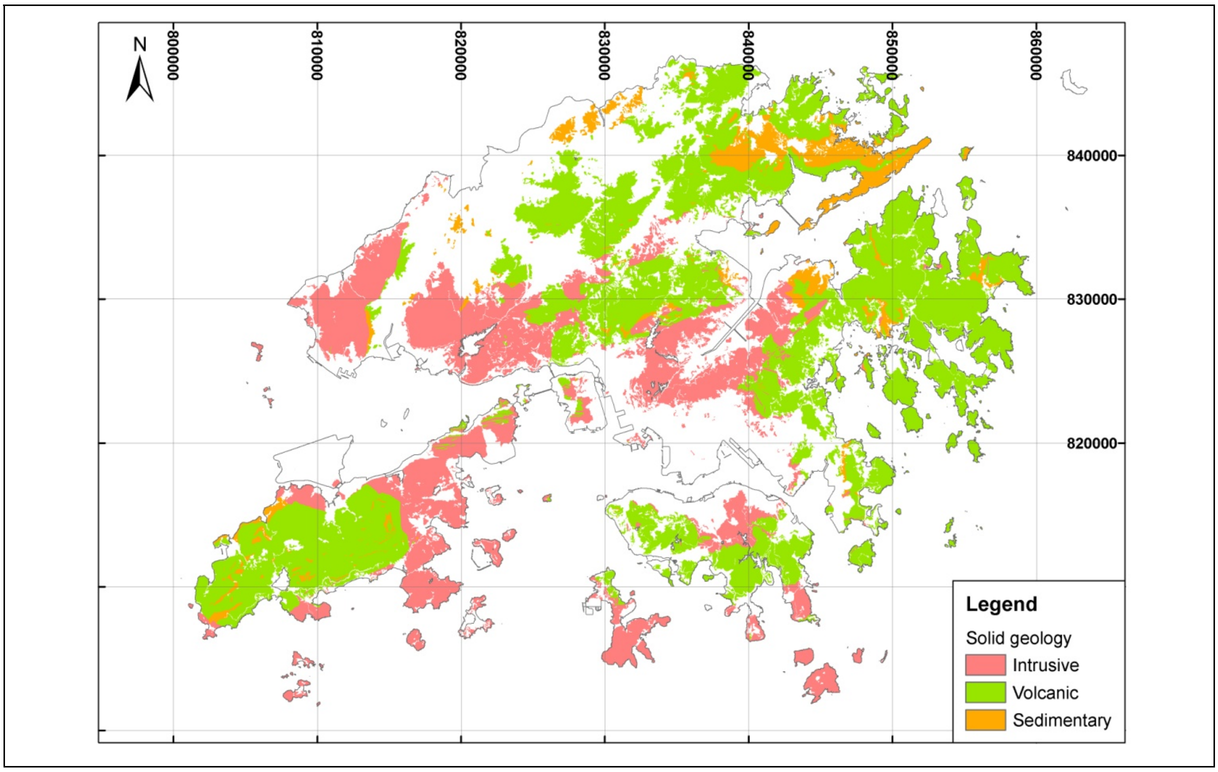


Figure 2.5 The Simplified Solid Geology of Hong Kong

2.4 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. Recent landslides in the ENTLI are further classified into three types, namely, channelized debris flow, open hillslope landslide and coastal landslide. Recognition factors of the relict landslides are recorded in the ENTLI as 80%, 50% and 10%. Other key landslide features, such as length and width, elevation of landslide crown and trail and runout distance are also recorded in the inventory. Figure 2.6 illustrates the recent and relict landslides on a particular natural hillside in Hong Kong.

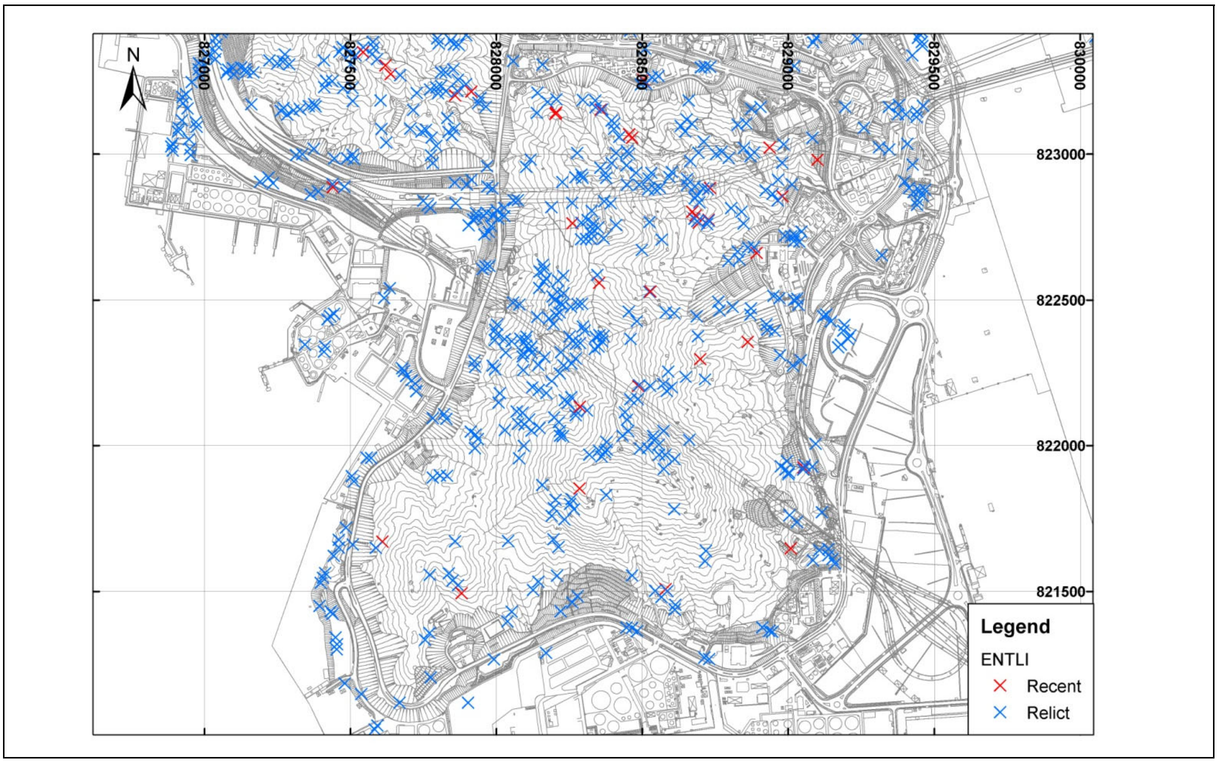


Figure 2.6 Recent and Relict Landslides on a Particular Natural Hillside in Hong Kong

3 Previous Landslide Susceptibility Map

The first territory-wide landslide susceptibility map in Hong Kong (Figure 3.1) was prepared in 1998, based on correlation of landslide density (landslides/km^2) and landslide frequency (landslides/km^2/year) with slope angle and geology (Evans & King, 1998). Five susceptibility classes were defined: very low, low, moderate, high and very high with landslide densities varying from < 10 to > 100 landslides per km^2 corresponding to frequencies varying from 0.1 to > 1 landslide/km^2/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).

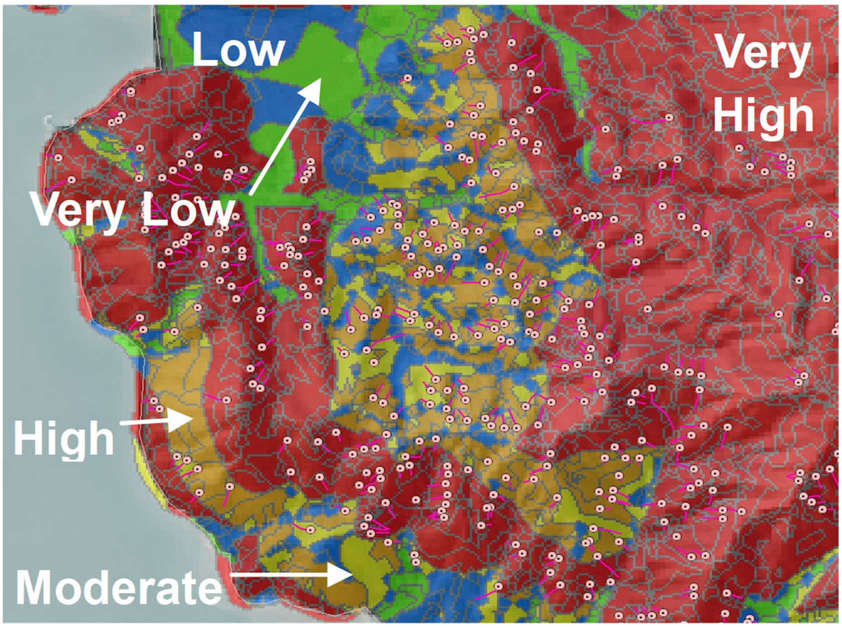


Figure 3.1 An Extract of the First Territory-wide Landslide Susceptibility Map in Hong Kong

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/km^2/year and now from < 1 to > 10 landslide/km^2/year).

Both susceptibility maps have the following limitations:

(a) The resolution achieved in terms of landslide frequency, which spans about one order of magnitude between the least and most susceptible zones, is very limited for practical use. As a comparison, it is not difficult to achieve resolution better than three to four orders of magnitude in consequence assessment with the use of a generic consequence model.

(b) Natural terrain landslides are far sensitive to short-duration, intense rainfall than terrain characteristics, such as slope angle. If rainfall is not considered, the outcome would not be very accurate. For example, in year 2000, many landslides were found on hillsides of “medium” and “low” susceptibility classes but few landslides occurred on hillsides of “very high” and “high” susceptibility classes, when the heavy rainstorm mainly hit natural terrain areas of “medium” and “low” susceptibility classes.

(c) The susceptibility analysis considers both recent and relict landslides at equal weight. However, recent and relict landslides are different types of landslide features as discussed in Section 2.4. The number of relict landslides observed does not give a full picture of the number of past landslides. Combining them together for quantitative analysis may be misleading.

(d) But if only recent landslides are taken into consideration, the observation period of recent landslide activities would be too short as compared with the long-term landslide triggering period. As natural terrain landslides are very sensitive to short-duration intense rainfall, the short observation period of recent landslide activities would not be adequate to average out rainfall effect.

To overcome the limitations, a new territory-wide rainfall-based landslide susceptibility analysis was developed that correlates rainfall and landslide density with slope angle and solid geology.

4 New Rainfall-based Landslide Susceptibility Analysis

4.1 Year-based Analysis

The analysis considers 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 is correlated with the normalized maximum rolling 24-hour rainfall, with effects of slope angle and solid geology 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.

(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) Group the solid geology of natural terrain in the 1 : 20,000 geological map into three classes: intrusive, volcanic and sedimentary.

(e) Identify the corresponding rainfall class, slope angle class and solid geology class for each natural terrain landslide based on its year of occurrence and location.

(f) Count for each combined class of rainfall intensity, slope angle and solid geology the total number of natural terrain landslides and the corresponding total hit area of natural terrain (km^2) between 1985 and 2006, plus 2008 (see Tables 4.1 and 4.2 respectively) (Note: There are $6 \times 8 \times 3 = 144$ combined classes of rainfall intensity, slope angle and solid geology).

(g) Calculate for each combined class of rainfall intensity, slope angle and solid geology the year-based natural terrain landslide density ($no./km^2$) (see Table 4.3).

Figure 4.1 shows the year-based rainfall-landslide correlation for combined intrusive and volcanic areas. Sedimentary-origin landslides are not considered in deriving the correlation given the minor proportion and localized nature of sedimentary area, and the limited amount of data under high rainfall classes. Only 10% of the natural terrain area (which is about $0.1 \times 660 = 66$ km^2) is of sedimentary origin. Others belong to the intrusive (30%) and volcanic (60%) groups. The majority of sedimentary area clusters at north-eastern Hong Kong. Nevertheless, the limited data indicates that, under the same rainfall and slope angle classes, sedimentary area is in general as active as the volcanic area but is more susceptible to landslides than the intrusive area. In this study, the year-based rainfall-landslide correlation for sedimentary area is assumed to be the same as the one for volcanic area.

Figure 4.2 gives the breakdown of calculated landslide densities for intrusive and volcanic areas according to their rainfall and slope angle classes, together with their mean values. In general, landslide densities of volcanic area are higher than those of intrusive area, except for rainfall class I. By analyzing the landslide data for rainfall classes II, III and IV, and for slope angles between 30° and 45°, the landslide density of volcanic area is

Table 4.1 Breakdown of Total Number of Natural Terrain Landslides between 1985 and 2006, plus 2008 according to Rainfall, Slope Angle and Solid Geology Classes

Intrusive		Normalized Maximum Rolling 24-hour Rainfall Class					
		I	II	III	IV	V	VI
Angle Class (°)	0 ~ 15	3	3	4	1	4	0
	15 ~ 20	11	5	5	4	8	0
	20 ~ 25	18	17	26	7	12	0
	25 ~ 30	55	51	60	33	43	0
	30 ~ 35	152	86	185	86	159	2
	35 ~ 40	180	133	319	172	212	0
	40 ~ 45	86	74	187	109	134	0
	45 ~ 90	25	21	51	48	19	0

Volcanic		Normalized Maximum Rolling 24-hour Rainfall Class					
		I	II	III	IV	V	VI
Angle Class (°)	0 ~ 15	4	4	3	3	1	0
	15 ~ 20	5	7	7	7	5	1
	20 ~ 25	12	30	32	20	15	4
	25 ~ 30	51	147	151	86	107	9
	30 ~ 35	162	505	397	292	405	39
	35 ~ 40	181	615	477	450	585	90
	40 ~ 45	84	296	215	273	400	61
	45 ~ 90	32	106	79	95	96	13

Sedimentary		Normalized Maximum Rolling 24-hour Rainfall Class					
		I	II	III	IV	V	VI
Angle Class (°)	0 ~ 15	0	1	0	1	0	0
	15 ~ 20	0	2	1	0	0	1
	20 ~ 25	4	5	6	3	3	3
	25 ~ 30	12	44	7	2	9	3
	30 ~ 35	63	124	52	15	44	9
	35 ~ 40	83	191	50	32	75	14
	40 ~ 45	37	107	35	22	40	9
	45 ~ 90	21	53	6	18	8	5

Table 4.2 Breakdown of Total Hit Area (km^2) between 1985 and 2006, plus 2008 according to Rainfall, Slope Angle and Solid Geology Classes

Intrusive		Normalized Maximum Rolling 24-hour Rainfall Class					
		I	II	III	IV	V	VI
Angle Class (°)	0 ~ 15	272.56	184.81	73.48	23.88	5.15	0.74
	15 ~ 20	267.54	180.40	71.59	23.61	4.73	0.64
	20 ~ 25	411.56	276.73	110.39	36.27	6.77	0.85
	25 ~ 30	566.75	379.98	152.95	48.86	8.64	0.96
	30 ~ 35	518.82	345.54	139.55	41.17	7.02	0.69
	35 ~ 40	263.49	171.96	68.50	18.19	2.78	0.27
	40 ~ 45	93.63	60.10	23.15	5.95	0.78	0.10
	45 ~ 90	40.11	26.51	9.70	2.71	0.30	0.04

Volcanic		Normalized Maximum Rolling 24-hour Rainfall Class					
		I	II	III	IV	V	VI
Angle Class (°)	0 ~ 15	600.85	348.96	88.49	15.80	8.21	0.85
	15 ~ 20	605.75	350.93	90.82	15.43	7.79	0.82
	20 ~ 25	879.16	529.91	135.72	22.76	11.98	1.27
	25 ~ 30	1101.49	697.02	175.99	29.88	16.86	1.94
	30 ~ 35	899.06	584.46	145.48	25.30	14.91	1.66
	35 ~ 40	493.36	318.29	79.56	15.15	9.61	0.86
	40 ~ 45	210.12	133.38	33.98	7.07	4.88	0.32
	45 ~ 90	108.40	69.90	17.22	3.66	2.77	0.17

Sedimentary		Normalized Maximum Rolling 24-hour Rainfall Class					
		I	II	III	IV	V	VI
Angle Class (°)	0 ~ 15	89.10	54.07	12.10	2.13	1.45	0.06
	15 ~ 20	84.42	50.27	10.31	1.73	1.12	0.06
	20 ~ 25	122.22	73.35	13.98	2.38	1.36	0.09
	25 ~ 30	155.32	93.30	16.99	3.09	1.62	0.11
	30 ~ 35	137.19	81.57	13.94	2.89	1.46	0.08
	35 ~ 40	80.65	45.28	7.78	2.04	0.99	0.07
	40 ~ 45	32.95	17.21	3.46	1.04	0.57	0.04
	45 ~ 90	16.58	8.28	1.89	0.60	0.44	0.03

Table 4.3 Breakdown of Year-based Landslide Density (no./km^2) according to Rainfall, Slope Angle and Solid Geology Classes

Intrusive		Normalized Maximum Rolling 24-hour Rainfall Class					
		I	II	III	IV	V	VI
Angle Class (°)	0 ~ 15	0.01	0.02	0.05	0.04	0.78	0.00
	15 ~ 20	0.04	0.03	0.07	0.17	1.69	0.00
	20 ~ 25	0.04	0.06	0.24	0.19	1.77	0.00
	25 ~ 30	0.10	0.13	0.39	0.68	4.98	0.00
	30 ~ 35	0.29	0.25	1.33	2.09	22.65	2.92
	35 ~ 40	0.68	0.77	4.66	9.45	76.37	0.00
	40 ~ 45	0.92	1.23	8.08	18.31	171.98	0.00
	45 ~ 90	0.62	0.79	5.26	17.72	63.92	0.00

Volcanic		Normalized Maximum Rolling 24-hour Rainfall Class					
		I	II	III	IV	V	VI
Angle Class (°)	0 ~ 15	0.01	0.01	0.03	0.19	0.12	0.00
	15 ~ 20	0.01	0.02	0.08	0.45	0.64	1.23
	20 ~ 25	0.01	0.06	0.24	0.88	1.25	3.15
	25 ~ 30	0.05	0.21	0.86	2.88	6.35	4.64
	30 ~ 35	0.18	0.86	2.73	11.54	27.16	23.45
	35 ~ 40	0.37	1.93	6.00	29.70	60.87	105.05
	40 ~ 45	0.40	2.22	6.33	38.60	81.90	189.53
	45 ~ 90	0.30	1.52	4.59	25.94	34.61	78.62

Sedimentary		Normalized Maximum Rolling 24-hour Rainfall Class					
		I	II	III	IV	V	VI
Angle Class (°)	0 ~ 15	0.00	0.02	0.00	0.47	0.00	0.00
	15 ~ 20	0.00	0.04	0.10	0.00	0.00	16.25
	20 ~ 25	0.03	0.07	0.43	1.26	2.20	34.54
	25 ~ 30	0.08	0.47	0.41	0.65	5.57	28.08
	30 ~ 35	0.46	1.52	3.73	5.19	30.13	106.48
	35 ~ 40	1.03	4.22	6.42	15.72	75.73	195.12
	40 ~ 45	1.12	6.22	10.11	21.13	69.96	212.14
	45 ~ 90	1.27	6.40	3.17	29.92	18.11	162.07

on average about three times that of intrusive area. An average ratio of 3 may be used to derive rainfall-landslide correlations for intrusive and volcanic areas respectively as explained later in this report. Ratios obtained using data from other rainfall and slope angle classes were considered not representative and hence not used, for the following reasons. Firstly, natural terrain under rainfall class I is not susceptible to landslides. It has little contribution to the prediction of the landslide number. Secondly, for rainfall classes V and VI, the corresponding hit areas are small (both are less than 5% of natural terrain area for both intrusive and volcanic areas). The amount of data is too little for a meaningful analysis. Furthermore, natural terrain with a slope angle less than 30° when hit by rainfall between rainfall classes II and IV is also not prone to landslides, and only 2% of the natural terrain area is steeper than 45°.

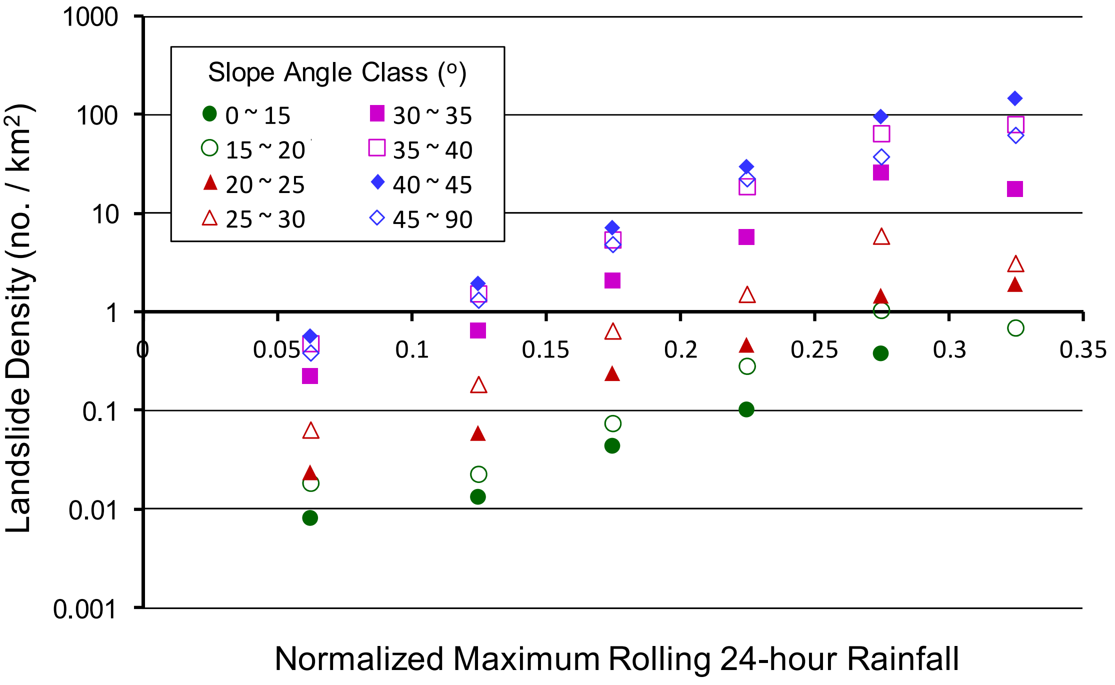


Figure 4.1 Year-based Rainfall-landslide Correlation for Combined Intrusive and Volcanic Areas

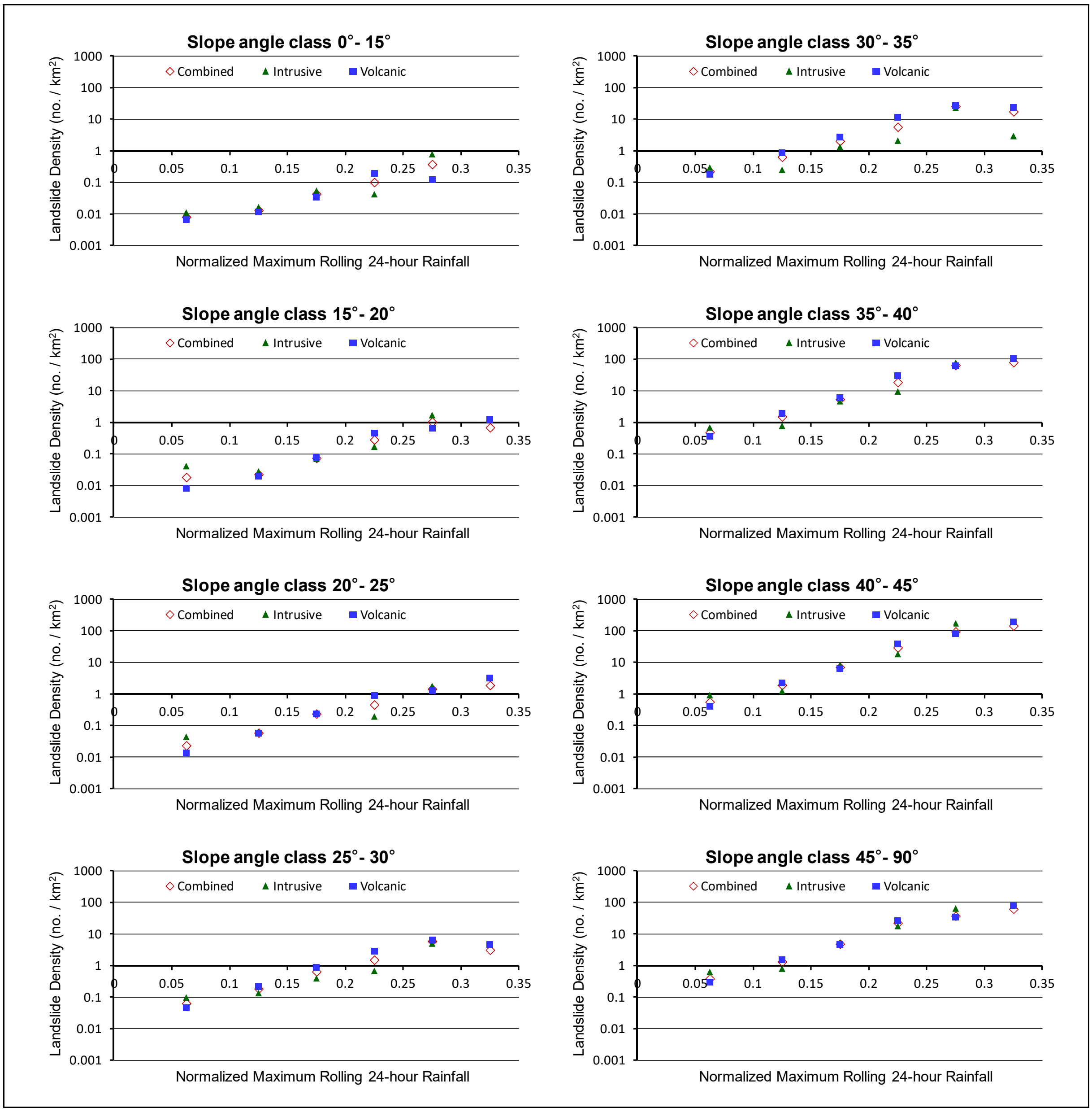


Figure 4.2 Breakdown of Calculated Landslide Densities for Intrusive and Volcanic Areas according to their Rainfall and Slope Angle Classes

4.2 Storm-based Analysis

The year-based rainfall-landslide correlation considers rolling maximum 24-hour rainfall and the total number of natural terrain landslides observed in a year. There are many rainstorms in a year and each rainstorm would result in some landslides. For direct application in predicting number of natural terrain landslides that would occur in a rainstorm, the year-based rainfall-landslide correlation needs to be transformed into a storm-based correlation. This was done by applying an adjustment factor to the year-based landslide densities under each rainfall class. Based on past rainfall records, rainfall in rainfall class IV or above occurs normally once a year. Its year-based and storm-based correlations are therefore equal and the adjustment factor is taken as unity. On the other hand, rainfall class I hits both the intrusive and volcanic areas, on average, eight times a year (i.e. natural terrain area hit by rainfall class I (a total of 111,736 km^2 for 23 years) divided by overall natural terrain area (a total of $657.48 \times 23 = 15{,}122$ km^2 for 23 years) is equal to 8). Rainfall class I hits natural terrain within each slope angle class eight times a year too, as the distribution of natural terrain area hit by rainfall class I in a storm according to slope angle and that of the overall natural terrain are similar (Figure 4.3). An adjustment factor of 8 was therefore applied across the eight slope angle classes to convert the year-based correlation under rainfall class I to its storm-based correlation. For rainfall classes II and III, adjustment factors of four and two were proportionally assigned respectively. Figure 4.4 presents the storm-based rainfall-landslide correlation as derived in this manner. To account for effect of solid geology, landslide susceptibility of volcanic area is taken as three times that of intrusive area, which was derived from the year-based data. With this assumption and together with the year-based hit area ratio between intrusive and volcanic areas (see Equations 4.1 to 4.4), the correlation for intrusive and volcanic areas can be obtained by applying an adjustment factor of 0.5 and 1.5 respectively to the storm-based rainfall-landslide correlation (for combined intrusive and volcanic areas) for each of the eight slope angle classes in Figure 4.4.

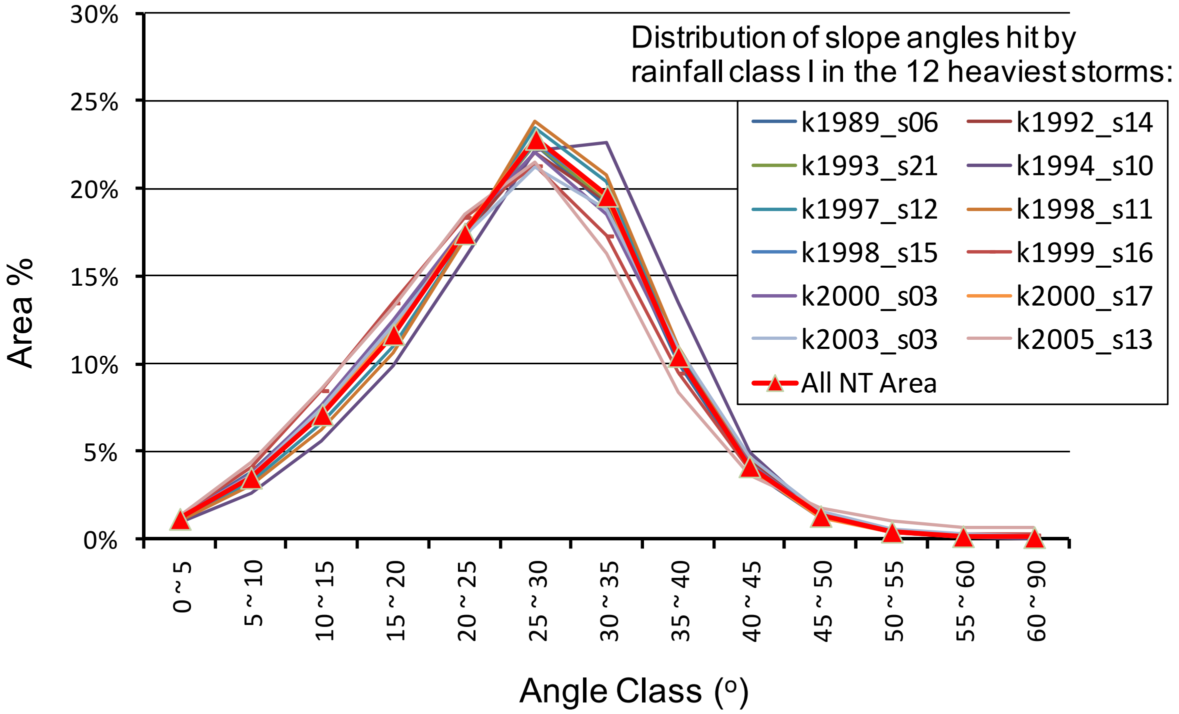


Figure 4.3 Distribution of Natural Terrain Area Hit by Rainfall Class I according to Slope Angle in the 12 Heaviest Storms and that of the Overall Natural Terrain

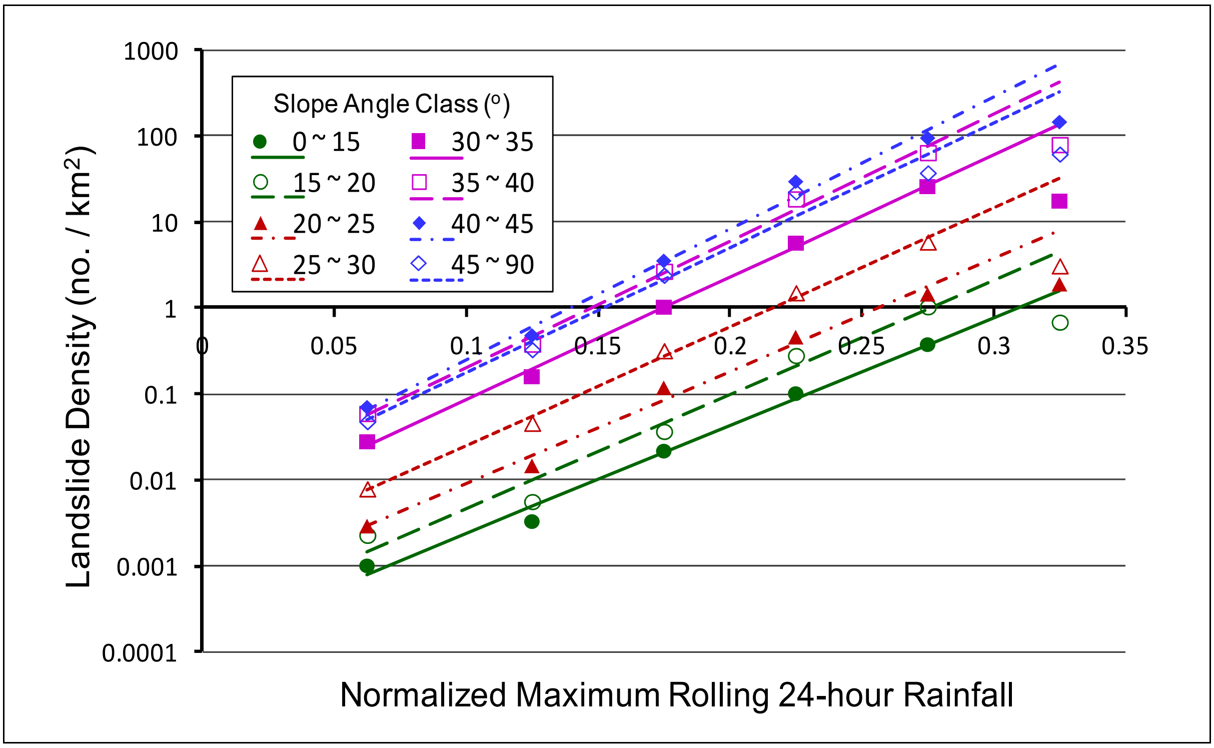


Figure 4.4 **Storm-based Rainfall-landslide Correlation (Based on Normalized Maximum Rolling 24-hour Rainfall)**

$$\frac{D_{\mathrm{VOL}}}{D_{\mathrm{INT}}} = 3 \quad (4.1)$$

$$D_{\mathrm{MEAN}} = \frac{(A_{\mathrm{INT}} D_{\mathrm{INT}} + A_{\mathrm{VOL}} D_{\mathrm{VOL}})}{A_T} \quad (4.2)$$

Substitute Equation 4.1 into Equation 4.2, and express A_{INT} and A_{VOL} in terms of A_T:

$$D_{\mathrm{MEAN}} = \frac{\alpha A_T D_{\mathrm{INT}} + \beta A_T (3 D_{\mathrm{INT}})}{A_T} \quad (4.3)$$

Rearrange Equation 4.3:

$$D_{\mathrm{INT}} = \frac{D_{\mathrm{MEAN}}}{\alpha + 3\beta} \quad (4.4)$$

where D_{VOL} = landslide density for volcanic area under each rainfall-cum-slope angle class

D_{INT} = landslide density for intrusive area under each rainfall-cum-slope angle class

D_{MEAN} = landslide density for combined volcanic and intrusive areas under each rainfall-cum-slope angle class

A_{INT} = area of natural terrain with intrusive origin under each rainfall-cum-slope angle class

A_{VOL} = area of natural terrain with volcanic origin under each rainfall-cum-slope angle class

A_T = total area of natural terrain under each rainfall-cum-slope angle class

αA_T = A_{INT}

βA_T = A_{VOL}

$1/(\alpha+3\beta)$ = 0.5, based on actual hit area data.

There are uncertainties associated with the limitations of data and a number of assumptions have had to be made in deriving the model described above. Further work will be carried out to check and verify the model and if necessary refine it, using data from past and future rainstorms and landslides.

According to Chan et al (2012), both correlations based on normalized maximum rolling 24-hour rainfall and normalized maximum rolling 4-hour and 24-hour rainfalls are used to predict number of natural terrain landslides in a rainstorm. Storm-based rainfall-landslide correlation for combined intrusive and volcanic areas based on normalized maximum rolling 4-hour rainfall and 24-hour rainfalls was therefore also developed using the same methodology and is presented in Figure 4.5. Similarly, the correlations for intrusive and volcanic areas can be obtained by applying an adjustment factor of 0.5 and 1.5 respectively to the storm-based correlation (for combined intrusive and volcanic areas) for each of the eight slope angle classes in Figure 4.5.

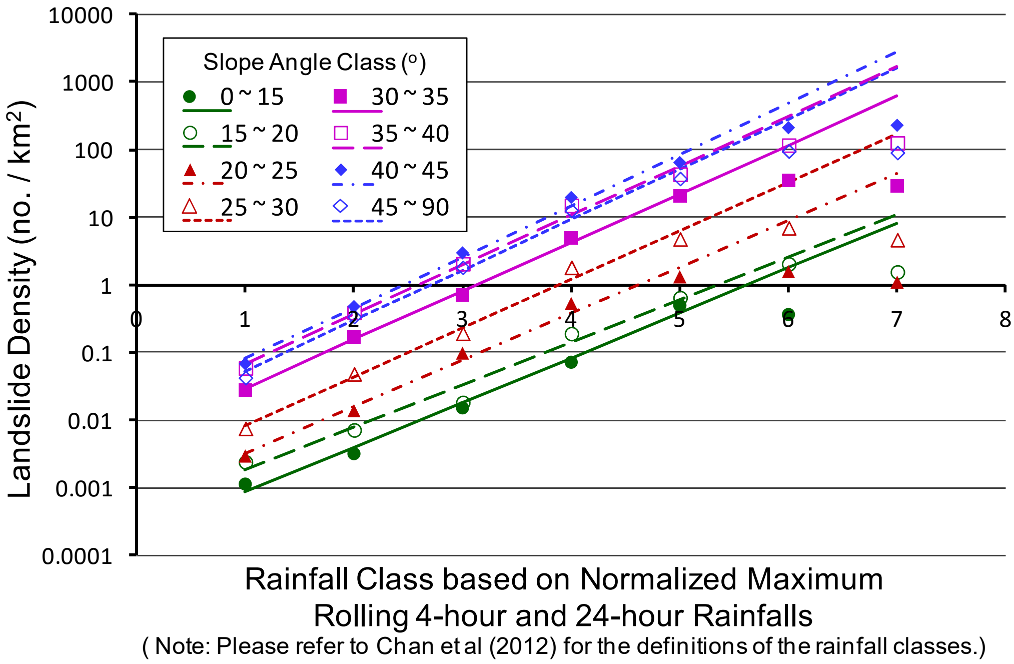


Figure 4.5 Storm-based Rainfall-landslide Correlation (Based on Normalized Maximum Rolling 4-hour and 24-hour Rainfalls)

4.3 Key Findings

The rainfall-based landslide susceptibility model is developed for assessing the susceptibility to landslides of natural terrain in Hong Kong. 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.

According to the outcomes of the new territory-wide rainfall-based landslide susceptibility analysis, the following key observations are noted:

(a) In Figure 4.1, the y-axis represents a genuine range of landslide density. Year-based landslide density < 0.001 no./km^2 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 km^2. For a landslide density of 0.001 no./km^2, number of landslides is equal to 0.66).

(b) Figure 4.1 shows that natural terrain landslide density increases with the normalized maximum rolling 24-hour rainfall (up to rainfall class V for some of the slope angle classes) and slope angle (up to the class of 40° - 45°), which is reasonable. Data for rainfall class VI are derived from two major rainstorms that occurred in 1993 and 2008, both on Lantau Island. They are not considered representative as the corresponding hit areas are small and localized.

(c) Only 2% of the natural terrain area is greater than 45°. For the majority of the natural terrain area, landslides occur mostly on natural terrain sloping between 30° and 45°, irrespective of rainfall and solid geology (Figure 4.6). A lower landslide density is observed for natural terrain that slopes greater than 45° probably because it is rocky or composed of denser soils.

(d) Different portions of natural terrain hit by the same rainfall intensity would have different levels of landslide density, subject to their slope angle and solid geology. Similarly, different portions of natural terrain that belong to the same slope angle and solid geology classes would also have different levels of landslide density, depending on their

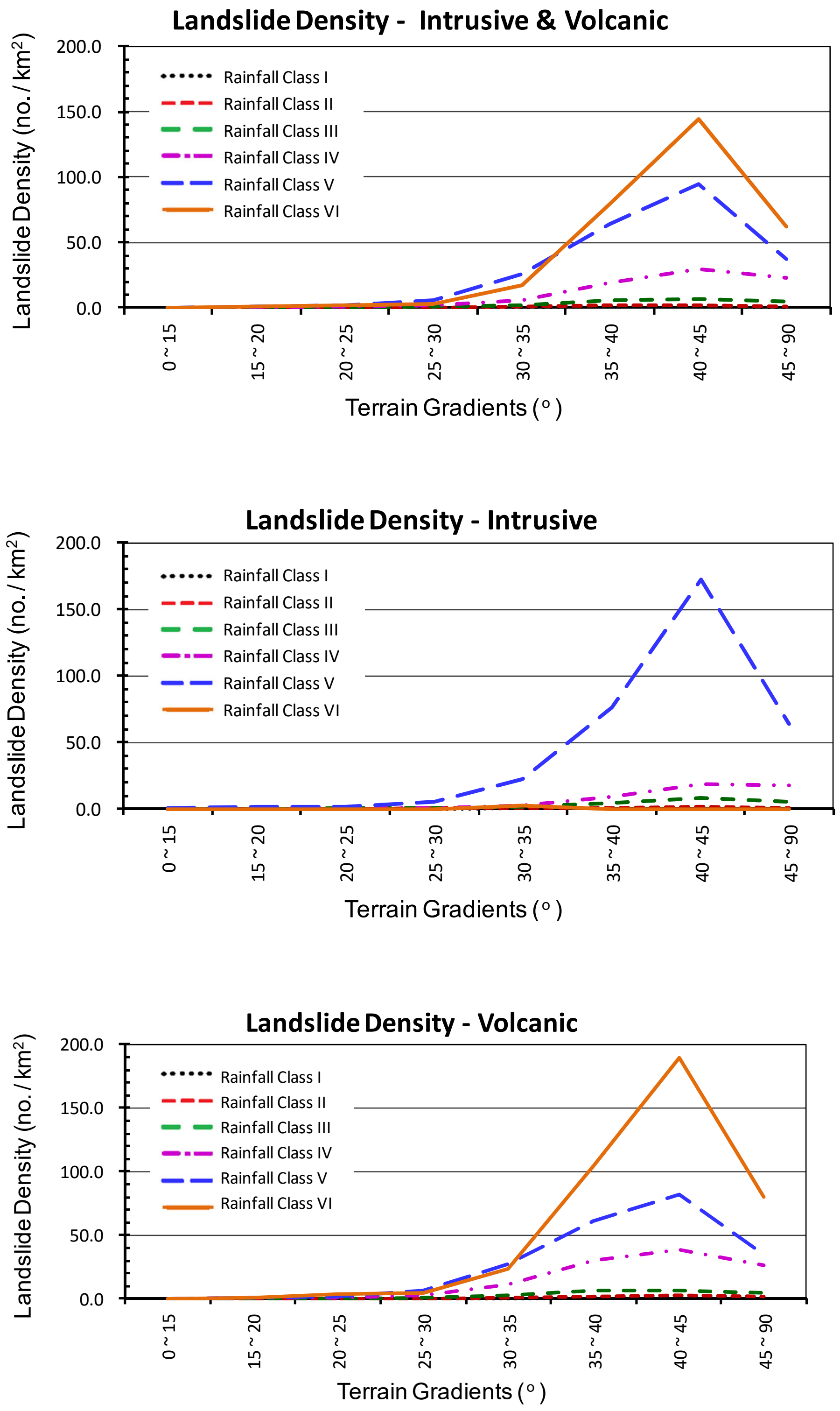
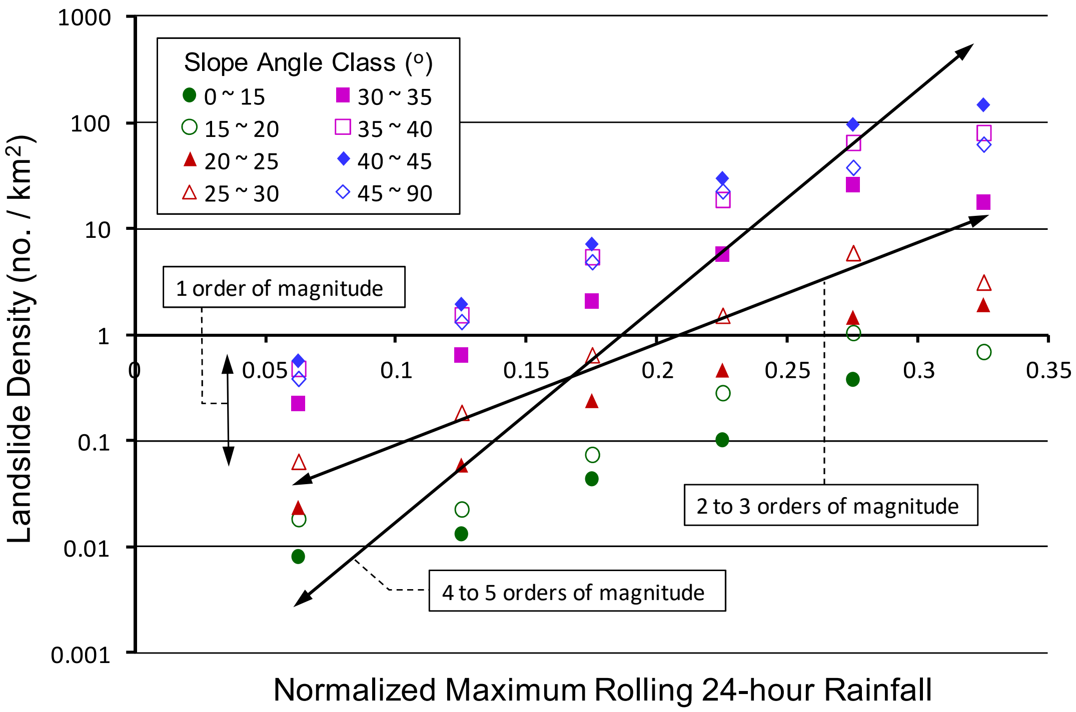


Figure 4.6 Distribution of Landslide Densities According to Rainfall, Slope Angle and Solid Geology Classes

rainfall intensity. Effects of rainfall, slope angle and solid geology on landslide occurrence are now inter-related.

(e) The year-based rainfall-landslide correlation, taking cognizance of effects of slope angle and solid geology, is able to achieve an overall resolution of four to five orders of magnitude in terms of landslide density. Landslide density is directly correlated with the physical basis of landslide occurrence, viz. rainfall, slope angle and solid geology (Figure 4.7).

(f) 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 (Figure 4.7). 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) under one rainfall class (Figure 4.7).



Note: Separate sets of data for intrusive and volcanic areas are not shown for clarity.

Figure 4.7 Relative Sensitivity to Rainfall, Slope Angle and Solid Geology

5 Conclusions

A new territory-wide rainfall-based landslide susceptibility analysis was carried out that correlates rainfall to landslide occurrence, together with the consideration of effects of slope angle and solid geology. 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. For the time being, the new susceptibility model would be applied in predicting number of natural terrain landslides in a rainstorm and 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 at this stage.

6 References

Chan, C.H.W., Ting, S.M. & Wong, A.C.W. (2012). *Development of Natural Terrain Landslip Alert Criteria (Special Project Report No. SPR 1/2012).* Geotechnical Engineering Office, Hong Kong, 68 p.

Evans, N.C. & King, J.P. (1998). *The Natural Terrain Landslide Study: Debris Avalanche Susceptibility (Technical Note TN 1/98).* Geotechnical Engineering Office, Hong Kong, 96 p.

King, J.P. (1999). *Natural Terrain Landslide Study - The Natural Terrain Landslide Inventory (GEO Report No. 74).* Geotechnical Engineering Office, Hong Kong, 127 p.

Sewell, R.J., Campbell, S.D.G., Fletcher, C.J.N., Lai, K.W. & Kirk, P.A. (2000). *The Pre-quaternary Geology of Hong Kong.* Geotechnical Engineering Office, Hong Kong, 181 p. plus 4 maps.

Wong, H.N. (2003). Natural terrain management criteria - Hong Kong practice and experience. *Proceedings of the International Conference on Fast Slope Movements: Prediction and Prevention for Risk Mitigation*, Naples, Italy, vol. 2.

Wong, H.N. (2007). Digital technology in geotechnical engineering. *Proceedings of the Hong Kong Institution of Engineers Geotechnical Division Annual Seminar 2007*, pp 157-168.

GEO PUBLICATIONS AND ORDERING INFORMATION
土力工程處刊物及訂購資料

An up-to-date full list of GEO publications can be found at the CEDD Website http://www.cedd.gov.hk on the Internet under "Publications". The following GEO publications can also be downloaded from the CEDD Website:

i. Manuals, Guides and Specifications
ii. GEO technical guidance notes
iii. GEO reports
iv. Geotechnical area studies programme
v. Geological survey memoirs
vi. Geological survey sheet reports

Copies of some GEO publications (except geological maps and other publications which are free of charge) can be purchased either by:

Writing to
Publications Sales Unit,
Information Services Department,
Room 626, 6th Floor,
North Point Government Offices,
333 Java Road, North Point, Hong Kong.

or

- Calling the Publications Sales Section of Information Services Department (ISD) at (852) 2537 1910
- Visiting the online Government Bookstore at http:// www.bookstore.gov.hk
- Downloading the order form from the ISD website at http://www.isd.gov.hk and submitting the order online or by fax to (852) 2523 7195
- Placing order with ISD by e-mail at puborder@isd.gov.hk

1:100 000, 1:20 000 and 1:5 000 geological maps can be purchased from:

Map Publications Centre/HK,
Survey & Mapping Office, Lands Department,
23th Floor, North Point Government Offices,
333 Java Road, North Point, Hong Kong.
Tel: (852) 2231 3187
Fax: (852) 2116 0774

Any enquires on GEO publications should be directed to:

Chief Geotechnical Engineer/Standards and Testing,
Geotechnical Engineering Office,
Civil Engineering and Development Department,
Civil Engineering and Development Building,
101 Princess Margaret Road,
Homantin, Kowloon, Hong Kong.
Tel: (852) 2762 5351
Fax: (852) 2714 0275
E-mail: ivanli@cedd.gov.hk

詳盡及最新的土力工程處刊物目錄，已登載於土木工程拓展署的互聯網網頁http://www.cedd.gov.hk 的"刊物"版面之內。以下的土力工程處刊物亦可於該網頁下載：

i. 指南、指引及規格
ii. 土力工程處技術指引
iii. 土力工程處報告
iv. 岩土工程地區研究計劃
v. 地質研究報告
vi. 地質調查圖表報告

讀者可採用以下方法購買部分土力工程處刊物(地質圖及免費刊物除外):

書面訂購
香港北角渣華道333號
北角政府合署6樓626室
政府新聞處
刊物銷售組

或

- 致電政府新聞處刊物銷售小組訂購 (電話：(852) 2537 1910)
- 進入網上「政府書店」選購，網址為 http://www.bookstore.gov.hk
- 透過政府新聞處的網站 (http://www.isd.gov.hk) 於網上遞交訂購表格，或將表格傳真至刊物銷售小組 (傳真：(852) 2523 7195)
- 以電郵方式訂購 (電郵地址：puborder@isd.gov.hk)

讀者可於下列地點購買1:100 000、1:20 000及1:5 000地質圖：

香港北角渣華道333號
北角政府合署23樓
地政總署測繪處
電話: (852) 2231 3187
傳真: (852) 2116 0774

如對本處刊物有任何查詢，請致函：

香港九龍何文田公主道101號
土木工程拓展署大樓
土木工程拓展署
土力工程處
標準及測試部總土力工程師
電話: (852) 2762 5351
傳真: (852) 2714 0275
電子郵件: ivanli@cedd.gov.hk