Chapter 4

Enhancing slope safety preparedness for extreme rainfall and potential climate change impacts in Hong Kong

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ABSTRACT

A comprehensive Slope Safety System has been implemented by the Geotechnical Engineering Office (GEO) to manage the landslide risk in Hong Kong. The system has generally proved to be effective in coping with the prevailing landslide problems. However, the more frequent occurrences of extreme rainfall causing serious landslides and major casualties in different parts of the world in recent years have highlighted the impact of extreme rainfall on the community and concerns about the possible effect of climate change on slope safety. The impact of extreme rainfall poses new challenges which need to be addressed from a strategy, policy and technical perspective, as the number, scale and mobility of the corresponding landslides could be unprecedented. To manage the new challenges, a systematic approach was adopted by the GEO to (a) take stock of the relevant climate change studies, (b) identify the nature and scale of the credible extreme landslide events, (c) assess the severity of landslide consequences, (d) evaluate the capacity of emergency management, and (e) examine the scope for improving crisis preparedness as well as system and community resilience. The preliminary findings are presented in this report.

4.1 INTRODUCTION

Hong Kong has a population of 7 million and a small land area of 1,100 km^2, only 15% of which is developed land. The terrain is hilly (with 75% of the land steeper than 15° and 30% steeper than 30°) (See Figures 4.1 and 4.2). The vulnerable setting, comprising dense urban development, a legacy of inadequate geotechnical control before the 1970s, coupled with high seasonal rainfall (24-hour intensity exceeding 300 mm and 1-hour intensity exceeding 70 mm are not uncommon) has given rise to acute landslide problems in Hong Kong.

The Geotechnical Engineering Office (GEO), which was established by the Hong Kong Government in 1977, has implemented a comprehensive Slope Safety System. This embraces a range of initiatives covering policy, strategic, legislative, administrative, technical and procedural frameworks that serve to manage landslide risk in a

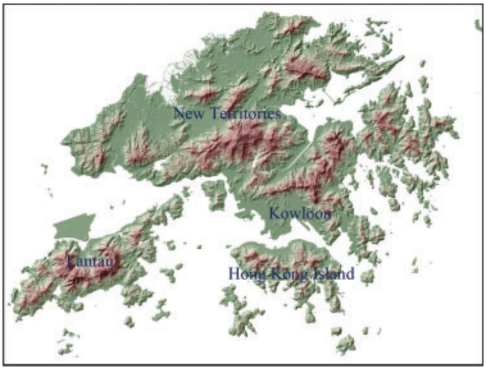


Figure 4.1 Topography of Hong Kong.

Figure 4.2 Aerial view of Hong Kong Island.

holistic manner. Risk management is done through an explicit risk-based approach and strategy. The goals are: (a) to reduce landslide risk to the community through a policy of priority and partnership, and (b) to address public perception and tolerability of landslide risk in order to avoid unrealistic expectations.

The key components of the Slope Safety System are shown in Table 4.1. The risk-based methodology embraces a holistic consideration of the likelihood of landslide hazards and their adverse consequences to reduce the landslide risk posed to existing developments, and to contain the increase in landslide risk associated with new developments. It is a multi-pronged approach involving hazard avoidance and prevention, study and mitigation of risk, public education and warning, and emergency management.

The overall landslide risk in Hong Kong has been substantially reduced over the years, as reflected by Quantitative Risk Assessment (QRA) and significant reduction in landslide fatalities (see Figure 4.3).

4.2 EVOLVEMENT OF SLOPE SAFETY SYSTEM UP TO 2008

The Slope Safety System has been evolving with time to incorporate enhancements arising from improved knowledge and practice.

Hong Kong is not immune from heavy rainfall events, which occur from time to time, either in association with low pressure troughs or in connection with tropical cyclones. The following is a brief account of the severe rainstorms experienced in Hong Kong since the 1960s, up to the late 1990s:

(a) Rainstorm of June 1966 – the rainstorm primarily struck Hong Kong Island and triggered hundreds of landslides and flooding which resulted in 64 fatalities, >2,000 people homeless, >8,600 people temporarily evacuated and >400 houses damaged (Chen, 1969).

(b) Rainstorm of June 1972 – the severe rainstorm caused many significant landslides in various places of Hong Kong, including the landslide disasters at Sau Mau Ping and Po Shan Road which killed more than 130 people.

Table 4.1 Key components of the Hong Kong slope safety system.

Slope Safety System components	*Contribution by each component* – *reduce landslip risk*: *hazard*	*reduce landslip risk*: *consequence*	*address public attitude & perception*
Policing			
-cataloguing, safety screening and statutory repair orders for slopes	✓		
-checking new works	✓	✓	
-slope maintenance audit	✓		
-inspecting squatter areas and recommending safety clearance		✓	
-input to land use planning	✓	✓	
Safety requirements, technical standards and research			
[*e.g. natural terrain hazard study and mitigation, debris mobility, etc.*]	✓	✓	✓
Works projects			
-upgrading existing Government man-made slopes	✓		
-mitigating natural terrain landslide hazards	✓	✓	
Regular slope maintenance			
-routine and preventive slope maintenance	✓		
Education and information			
-slope maintenance campaign	✓		✓
-personal precautions campaign		✓	✓
-slope safety awareness programme	✓	✓	✓
-information services	✓	✓	✓
-landslide warning and emergency services	✓	✓	✓

Note: Regular maintenance of registered Government man-made slopes and natural terrain defence/stabilisation measures are carried out by the responsible Government departments.

(c) Rainstorms of May and August 1982 – over 600 mm of rainfall was recorded within the four days from 28 to 31 May 1982 and more than 520 mm of rainfall from 15 to 19 August 1982. The two intense rainstorms triggered over 1,400 natural terrain landslides and caused serious damage particularly to squatter areas (with over 20 fatalities) (Hudson, 1993; Lee, 1983; Wong *et al.,* 2006).

(d) Rainstorm of November 1993 – over 700 mm of rainfall was recorded in 24 hours over Lantau Island triggering >800 natural terrain landslides and >300 man-made slope failures, which resulted in closure of roads and evacuation of houses (Wong *et al.,* 1997; Wong & Ho, 1995).

(e) Rainstorm of July 1994 – during the heavy rainfall episode from 22 to 24 July, over 600 mm rainfall was recorded at Hong Kong Observatory, together with record-breaking maximum 1-hour, and 24-hour rainfall of 185.5 mm and 954 mm respectively recorded at Tai Mo Shan. This resulted in about reported 200 landslides, 5 fatalities, 4 injuries, closure of roads and evacuations of houses (Chan, 1996).

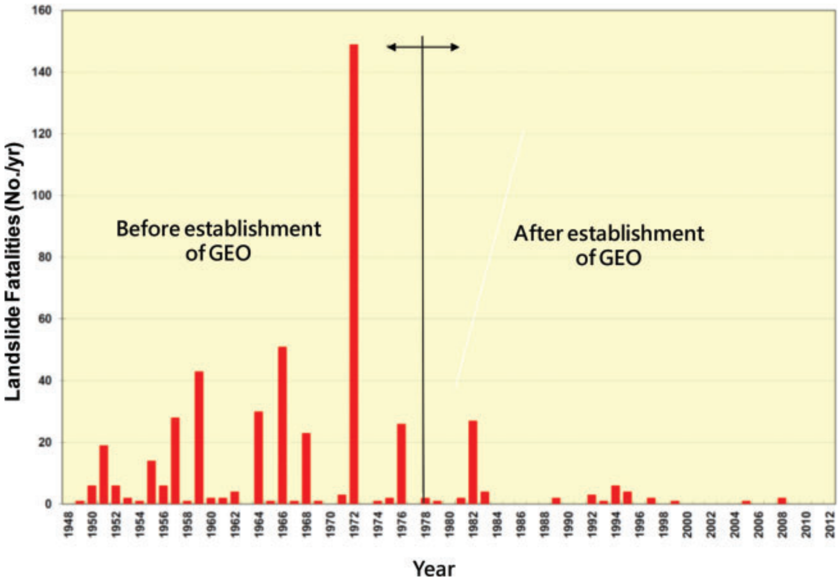


Figure 4.3 Landslide fatalities in Hong Kong since 1948.

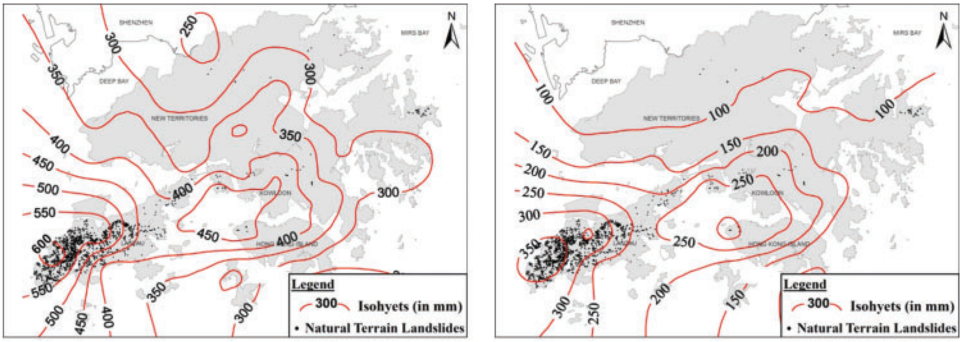
(f) Rainstorm of August 1999 – over 500 mm of rainfall was recorded in 24 hours over the southern part of the New Territories triggering >200 man-made slope failures, which resulted in 1 fatality and permanent evacuation of 3 public housing blocks (Ho *et al.*, 2002).

It is noteworthy that many of the past major rainstorms in Hong Kong were not centred at the most densely populated locations, or that the intensity of the rainstorms that struck the more densely populated locations was not particularly severe. Otherwise, the number of landslides and the casualty rate would have been much higher.

The GEO has been maintaining comprehensive records on reported landslides since the late 1970s. In addition, recent and relict natural terrain landslides have been systematically mapped using the available stock of territory-wide, high-resolution aerial photographs dating back to the 1920s (e.g. to produce a natural terrain landslide inventory that contains >100,000 landslides), together with the use of air-borne Light Detection and Ranging (LiDAR) technology. In addition, Hong Kong has implemented a comprehensive network of automatic raingauges (>100 nos.) that collect and transmit rainfall data at 5-minute interval round the clock since the mid-1980s.

The above data provide essential information for evaluating slope and hillside responses to severe rainfall and form a basis of GEO's Landslip Warning System, landslide QRA, back analysis of landslide debris mobility, rainfall-landslide correlations for man-made slopes and natural terrain respectively, etc.

The high quality landslide data, together with lessons learnt from the study of serious landslides under GEO's systematic landslide investigation programme, has



(a) Maximum rolling 24-hour rainfall distribution (b) Maximum rolling 4-hour rainfall distribution

Figure 4.4 Maximum rolling rainfall distributions for the 7 June 2008 rainstorm.

contributed to enhancing the technical understanding of actual slope and hillside performance.

The impact of extreme rainfall was previously assessed by the GEO, albeit in a rather rudimentary manner based on the knowledge and data available at the time. In 2000, GEO undertook a preliminary examination of its landslide emergency preparedness by reference to a severe rainstorm corresponding to 80% of the Probable Maximum Precipitation (PMP). The corresponding landslide scenario was taken to be 650 reported landslides, comprising 430 man-made slope failures and 220 natural terrain landslides affecting existing developed areas (Sun *et al.*, 2001). In 2006, the risk posed by natural hillsides was quantified using QRA techniques, under which the risk scenario of an extreme rainstorm was considered by reference to the prevailing rainfall-landslide relationship at the time. It was assessed that the risk associated with such extreme rainfall would contribute about 30% of the overall risk posed by natural hillsides (Wong *et al.*, 2006).

Focused R&D work on natural terrain landslides, together with the development and application of digital technology, has culminated in the Hong Kong Government launching an expanded retrofitting programme for slopes affecting existing buildings and infrastructure (Development Bureau, 2007). This expanded programme, known as the Landslip Prevention and Mitigation Programme, involves mitigation of the risk posed by vulnerable natural terrain catchments pursuant to the 'react to known hazard' policy, upgrading of substandard Government man-made slopes, and safety screening of private man-made slopes.

4.3 THE SEVERE RAINSTORM IN JUNE 2008

Hong Kong experienced a very severe rainstorm in June 2008, which primarily struck Lantau Island. It resulted in widespread natural terrain landslides, with many large scale and mobile failures.

The maximum rolling 4-hour and 24-hour rainfall recorded for the rainstorm were 384 mm and 623 mm respectively (see Figure 4.4). An estimate using the available rainfall records of the corresponding raingauges in that area in the last two decades reveals

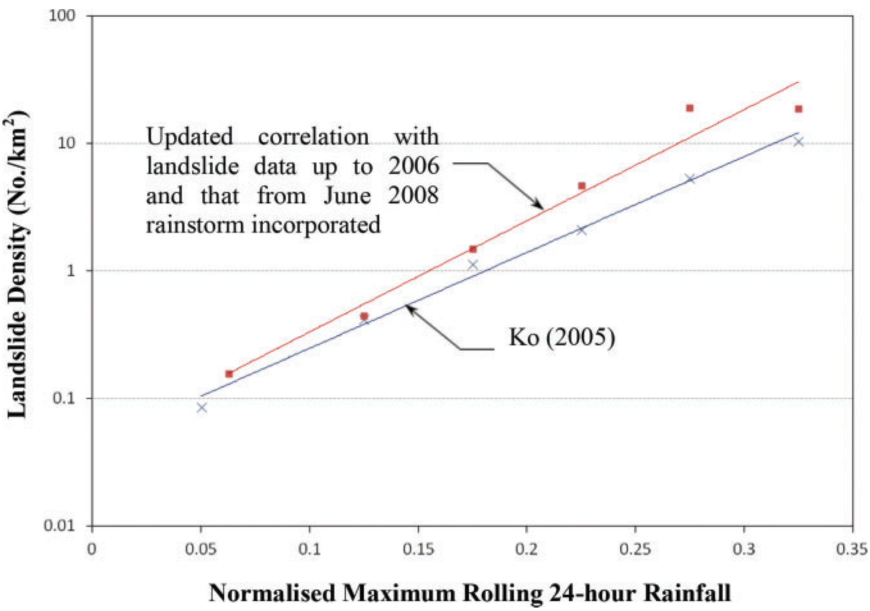


Figure 4.5 Year-based rainfall-natural terrain landslide correlation based on normalised maximum rolling 24-hour rainfall (Chan *et al.*, 2012).

that the statistical return period of such 4-hour and 24-hour rainfall may be of the order of 1,000 and 200 years respectively. This was probably the most severe rainstorm since rainfall record began in Hong Kong in 1885, as corroborated by the significant response of natural hillsides in terms of occurrence of rain-induced landslides.

The June 2008 rainstorm resulted in widespread natural terrain landslides (some 2,400 nos. on Lantau Island). The landslides caused serious disruptions to the communities (e.g. sole road access cut off, water supply to some local villages was cut off, large scale evacuation needed, the trunk road to the Hong Kong International Airport was shut down for several hours by debris flows and flooding, etc.), and major difficulties in respect of the response and recovery operations rendering Government's emergency response system on the verge of breakdown.

Due to the significant residual risk that might exist following natural terrain landslides (e.g. presence of tension cracks, overhanging boulders, loose debris or debris dams on drainage lines), the ability to deploy sufficient experienced staff to undertake timely inspections of failed hillsides that are close to developed areas, in order to establish the hillside condition and the necessary follow-up actions, has proved to be an important element of the landslide emergency system.

The landslides that occurred in 2008 were studied extensively and the technical insights were summarised by Wong (2009). In essence, the number, scale and mobility of natural terrain landslides under such intense rainfall conditions were unprecedented.

The rainfall-landslide response reinforces the key observation made in the past studies that the density of natural terrain landslides in Hong Kong increases exponentially with normalised rainfall intensity (Figure 4.5). It is noteworthy that the landslide

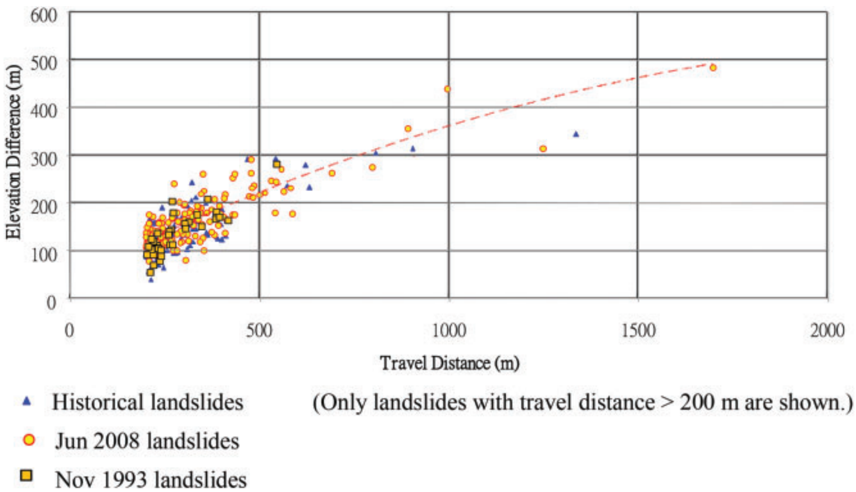


Figure 4.6 Mobility of June 2008 channelised debris flows and historical long-runout landslides.

Figure 4.7 Example of long runout June 2008 debris flow (Shek Pik Reservoir).

density in the June 2008 rainstorm was higher than that projected from the correlation with normalised 24-hour rolling rainfall based on the previous data from several decades of 'recent' landslide data. The mobility of landslide debris (Figures 4.6 and 4.7) and the scale (i.e. volume) of the 2008 landslides were also observed to have increased significantly as compared with that in the landslide inventory up to that time.

All in all, the data from a relatively short time window (i.e. of several tens of years for natural terrain landslides) are liable to under-represent the effects of extreme rainfall. In light of the severe rainstorm of June 2008, the corresponding rainfall-landslide correlation was duly updated, as presented below.

The torrential rain in June 2008 fell largely on Lantau Island, the largest outlying island and one of the sparsely populated areas in Hong Kong, hence it could be regarded as a near-miss event. The consequences could have been much more serious had the 2008 rainstorm hit the more densely developed urban areas of Hong Kong.

4.4 CONSIDERATION OF EXTREME RAINFALL EVENTS

According to the Intergovernmental Panel on Climate Change (IPCC), extreme weather refers to "the occurrence of a value of a weather or climate variable above (or below) a threshold value near the upper (or lower) ends of the range of observed values of the variable" (IPCC, 2012). The US National Oceanic and Atmospheric Administration (NOAA) echoes that by the following: "… charts the occurrence of specific extreme events over time since 1910. In most cases, extreme events are defined as lying in the outermost ("most unusual") ten percent" of a place's historical data (where analyses are done at national and regional scales, and "Climatic extremes are an important component of a location's climatology and are used for quality controlling meteorological observations, setting engineering limits, and helping authorities to develop climate-related safety plans, among other things" (NOAA, 2014). In essence, 'extreme event' may be taken to refer to rare and adverse condition at the extremities of the relevant historical or statistical distribution at national/regional scale.

The above highlights the important observation that an extreme event could be a natural phenomenon given the natural and intrinsic variability of the weather system. As such, extreme events would need to be considered irrespective of whether climate change prevails or not. Climate change is liable to render extreme rainfall events more frequent, as well as more intense.

In so far as landslide risk management is concerned, the extreme events that need to be considered are those which would bring about many sizeable and/or mobile landslides (either due to rainfall or earthquake). Such extreme landslide scenarios are characterised by widespread landslides which could impact on developed areas and lead to serious loss of life and damage to buildings, infrastructure and essential services. Around the globe, catastrophic landslides induced by extreme rainfall causing serious casualties have been reported increasingly in recent years. For example, the landslide at Xiaolin village during the passage of Typhoon Morakot in Taiwan in 2009 killed more than 400 people; the rain-induced landslides in Brazil in 2011 caused more than 900 fatalities; the debris flow in Gansu in 2010 led to more than 1,400 fatalities; the torrential rain in South Korea in 2011 brought about more than 30 landslide-related fatalities; Tropical Storm Washi brought flash floods and severe landslides, resulting in 1,010 fatalities in the Philippines in 2011; Severe Typhoon Wipha struck eastern Japan in 2013 and caused more than 40 landslide-related fatalities, etc. Hong Kong was not immune from extreme rainfall events. The occurrence of widespread natural terrain landslides during the June 2008 rainstorm, which involved many large-scale and mobile failures, has emphasised the critical need to address extreme rainfall events in a more rigorous manner.

The more frequent occurrences of extreme rainfall causing serious landslides and major casualties around the world in recent years have highlighted the real threat of the potential impact of extreme rainfall on community and concerns about the possible effect of climate change on slope safety. The impact of extreme rainfall poses new challenges which need to be addressed from a strategic, policy and technical perspective, given that the number, scale and mobility of the corresponding landslides could be unprecedented.

To address the acute challenges of more frequent occurrences of extreme rainfall, a systematic approach has been adopted by the GEO as follows:

(a) to take stock of the relevant climate change and rainfall studies,
(b) to identify the key component of risk and the nature and scale of credible extreme landslide events,
(c) to assess the severity of the landslide consequences,
(d) to evaluate the capacity of emergency management, and
(e) to examine the scope for improving crisis preparedness, as well as system and community resilience in respect of slope safety.

4.4.1 Climate change and rainfall studies

4.4.1.1 Globally observed changes in extreme rainfall and future projections

The United Nations Intergovernmental Panel on Climate Change (IPCC) released its Fifth Assessment Report of Working Group I (WGI AR5) in 2013, reaffirming the observed and unequivocal warming of the Earth's climate due to the human-caused increases in atmospheric concentration of greenhouse gases (IPCC, 2013). Apart from the warming atmosphere, one of the many responses of the climate system to the enhanced greenhouse warming is an increase in tropospheric water vapour (Santer *et al.*, 2007; Wentz *et al.*, 2007), and hence an increase in the availability of precipitable water for extreme rainfall events. There is also evidence of an intensifying water cycle over the last 50 years (Durack *et al.*, 2012). Hence, a warmer atmosphere holding more moisture can lead to notable changes in the frequency and intensity of extreme precipitation events (Kharin *et al.*, 2007; O'Gorman *et al.*, 2009; Lenderink & Meijgaard, 2010). Although precipitation changes are less spatially coherent than temperature changes, studies have shown that where sufficient data are available, there have been statistically significant increases in the number of heavy precipitation events in more regions than there have been statistically significant decreases (Figures 4.8 (a) and (b)).

IPCC's latest projections of future climate are based on the climate model data contributed to the Coupled Model Intercomparison Project Phase 5 (CMIP5) from various modelling centres/groups around the world. Although the science of climate modelling has advanced significantly in the last few decades, limitations in climate models still exist. For instance, there are small-scale physical, biological and chemical processes which cannot be fully described by mathematical equations. These processes are approximated by the so-called "parameterisations" within the climate models. Different climate models have different but equally plausible numerical representations of the climate system, with different strengths and weaknesses. Such a diversity is considered a healthy aspect by the climate modelling community. Although the collection of

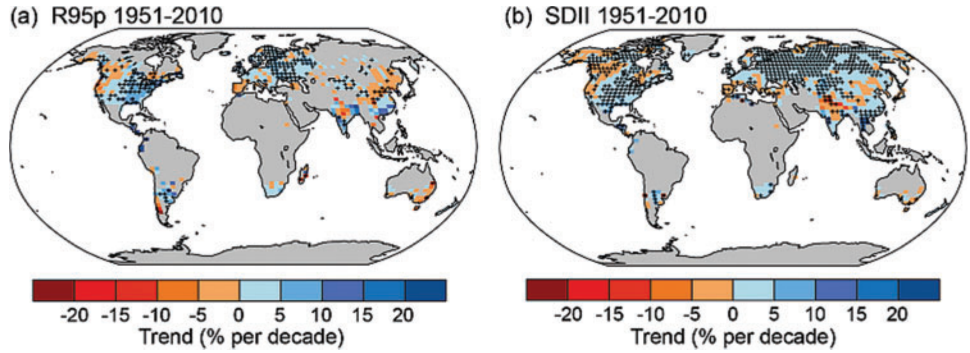


Figure 4.8 Trend in (a) the annual amount of precipitation from days above the 95th percentile (R95p) and (b) the daily precipitation intensity (SDII) during 1951–2010. Grey areas indicate incomplete or missing data. Black plus signs indicate statistically significant trends (IPCC, 2013).

CMIP5 model data is not meant to be a systematic or comprehensive sampling of possible future climate, it does provide a range of plausible climate projections as well as a basis for assessing the uncertainties in the projections. The "multi-model" approach is now a standard technique used by the climate science community to assess projection of a specific climate variable.

In WGI AR5, the climate projections are computed according to four new greenhouse gases concentration scenarios with different target radiative forcing at the top of the atmosphere at the end of the 21st century, namely Representative Concentration Pathway RCP2.6, RCP4.5, RCP6.0 and RCP8.5. A higher radiative forcing corresponds to a higher trajectory of greenhouse gases concentration in the 21st century and hence stronger warming on Earth. Although all these scenarios are plausible in principle, the latest observations have a strong indication that the world is likely to be tracking along the trajectory of RCP8.5 scenario in terms of carbon dioxide emission and that the RCP2.6 scenario seems rather unlikely (Figure 4.9). Under the RCP8.5 scenario (i.e. high concentration scenario), most land regions on Earth would experience an increase in extreme rainfall for the rest of this century (Figures 4.10 (a) and (b)).

4.4.2 Observed changes in extreme rainfall over China and future projections

A number of studies detected changes in annual precipitation as well as extreme precipitation frequency and intensity in China in the last few decades (e.g. Zhai *et al.*, 1999; Gong & Wang, 2000; Wang & Zhou, 2005; Zhai *et al.*, 2005; Zhang *et al.*, 2009; Lu *et al.*, 2010). Zhai *et al.* (2005) reported that, for the period of 1951–2000, the total precipitation in China as a whole had little trend but there were distinctive regional and seasonal patterns of trends. For instance, the annual precipitation as well as the frequency of extreme precipitation events has increased significantly over western China, the Yangtze River valley, and the southeastern coast. Over Guangdong, there was an increasing trend in annual precipitation during 1961–2006, though statistically insignificant (Composing team for Assessment Report on Climate Change of

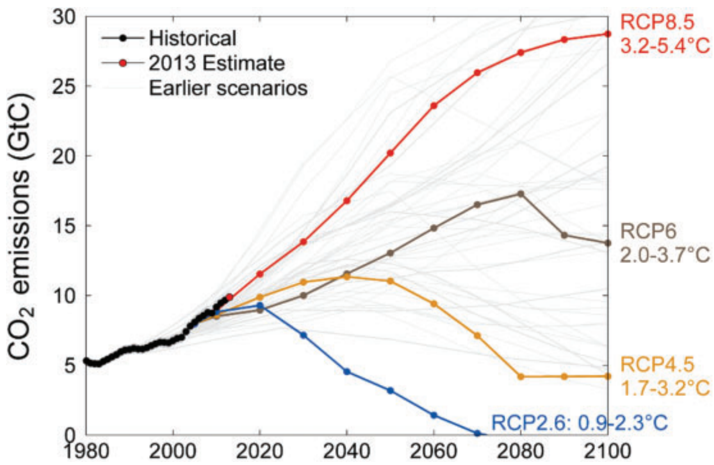


Figure 4.9 Observed emissions and emissions scenarios (image source: Global Carbon Project).

Guangdong, 2007). The number of rain days over southern China had a decreasing trend but the precipitation intensity increased significantly during 1961–2008 (Wu *et al.*, 2011). The frequency of heavy precipitation (40 mm per hour) increased from 1.3 times per year in the 1960s to 1.8 times per year in recent years (Composing team for Assessment Report on Climate Change of Guangdong, 2007).

Using 19 climate models, Sun & Ding (2009) projected an increase in summer (June–August) rainfall over southern China due to the increase in atmospheric water vapour under a warming climate and the presence of an anticyclone over western Pacific and South China Sea which enhances water vapour transport. Kitoh *et al.* (2013) found that, over the East Asian region, the daily precipitation intensity and seasonal (May–September) maximum 5-day precipitation total would increase under the RCP4.5 and RCP8.5 scenarios. Chen (2013) and Zhou *et al.* (2014) also found an intensification of precipitation over southern China under these two scenarios. Zhou *et al.* (2014) projected that the proportion of heavy precipitation in annual precipitation and maximum daily rainfall would increase over southern China. These changes can be attributed to intensification of the East Asian monsoon circulation (Kitoh *et al.*, 2013), and more unstable atmosphere over southern China (Chen, 2013).

4.4.3 Observed changes in extreme rainfall in Hong Kong

The rainfall trend in Hong Kong is generally consistent with that in southern China. In the last 60 years or so (1947–2013), Hong Kong's annual precipitation exhibited an increasing trend of 36 mm/decade, though statistically insignificant. On the analysis of the past trend in extreme rainfall in Hong Kong, Wong & Mok (2009) found that the return periods of short-duration extreme rainfall events had decreased significantly from the year 1885 to 2009. For example, the return period of hourly rainfall of 100 mm or more shortened from 37 years in 1900 to 18 years in 2000, indicating that such heavy rainfall events have become more frequent.

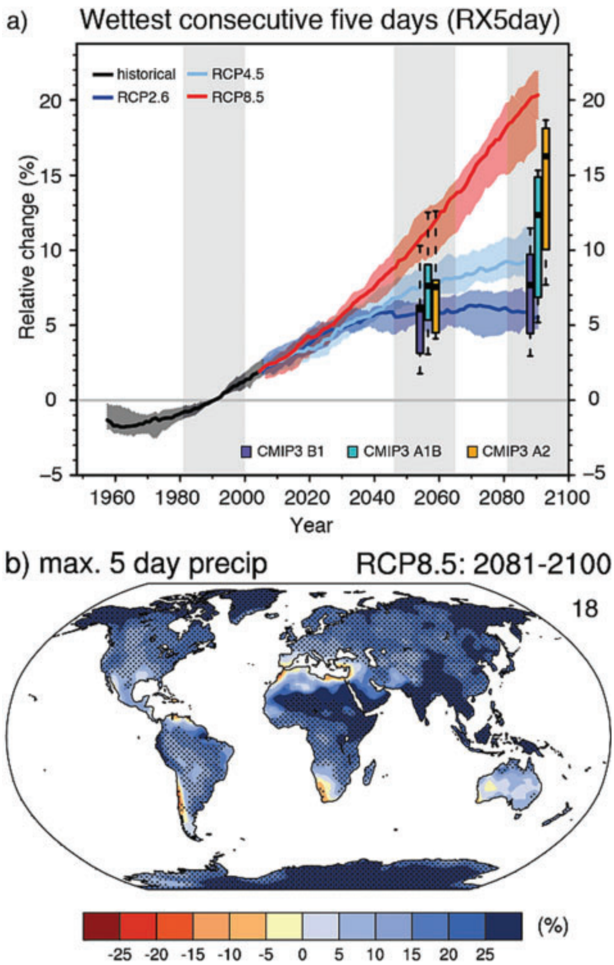


Figure 4.10 (a) Projected global average percent changes (relative to 1981–2000) over land regions in the annual maximum five-day precipitation accumulation (RX5day) for the RCP2.6, RCP4.5 and RCP8.5 scenarios. Shading in the time series represents the interquartile ensemble spread (25th and 75th quantiles). The box-and-whisker plots show the interquartile ensemble spread (box) and outliers (whiskers) of projections from 11 CMIP3 model simulations of the SRES scenarios A2 (orange), A1B (cyan) and B1 (purple) averaged over the periods 2046–2065 and 2081–2100. (b) Projected percent change of RX5day over the 2081–2100 period (relative to 1981–2000) in the RCP8.5 scenario. Stippling indicates statistical significance at the 5% level (IPCC, 2013).

The maximum hourly rainfall record of the Hong Kong Observatory Headquarter has been broken several times since 1885 and the time interval between new records is getting shorter. In particular, the record was broken three times since 1966. The latest record of 145.5 mm was set on 7 June 2008, breaking the previous one by a wide margin of 30 mm (Figure 4.11).

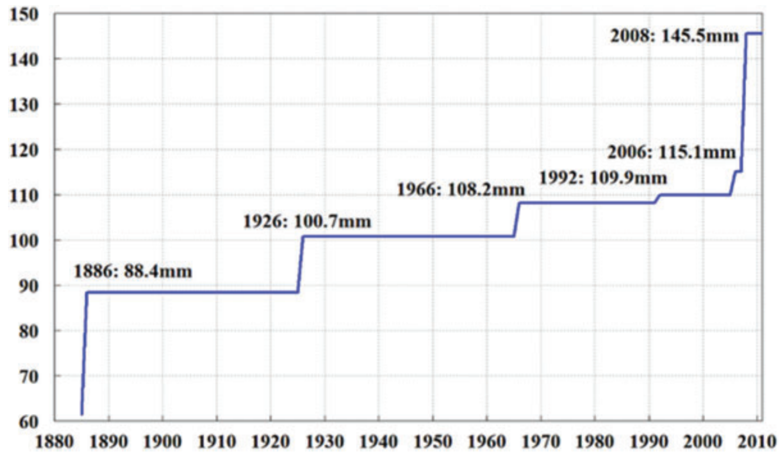


Figure 4.11 Maximum hourly rainfall recorded at Hong Kong Observatory.

4.4.4 Downscaling strategy in climate projection

To obtain rainfall projection for a small area like Hong Kong, either dynamical or statistical downscaling of global climate models (GCM), which are normally of coarse spatial resolution (e.g. 200 km × 200 km), should be performed. Dynamical downscaling involves a regional climate model (RCM) of a finer resolution (typically 50 km), which uses GCM output as boundary conditions to produce projections at a finer scale. This approach is physics-based and its results are dynamically consistent. Since this technique is very computationally demanding, it is not uncommon to see RCM using only one GCM as input (Gao *et al.*, 2013), rendering the uncertainty of the projection difficult to assess. Generating a large ensemble of projections based on a single GCM and a single RCM to assess the uncertainty is possible but could be very expensive (e.g. the UKCP09 project producing climate projections of a scale down to 25 km grid squares for the UK cost about £11 million, http://ukclimateprojections.metoffice.gov.uk/22681). The inclusion of an RCM inevitably introduces further model uncertainty to the projection (Rowell, 2006). In addition, the precipitation output from an RCM is still subjected to bias and usually cannot be used to support hydrological model without bias correction (Piani *et al.*, 2010; Wang & Chen, 2014). Even if bias-correction is carried out, the resolution of an RCM may still be inadequate to capture local forcings of the scale of a few kilometres (Murphy, 1999).

Statistical downscaling develops statistical relationships between large-scale predictors and local-scale predictands, and assumes that these relationships will still hold in future climate. Climate projection for a specific area can then be obtained using GCM output as predictors. This technique is far less computationally demanding but its performance is comparable to dynamical downscaling (Murphy, 1999). The same downscaling procedures can be applied to an ensemble of GCMs and hence a range of possible climate projections could be obtained.

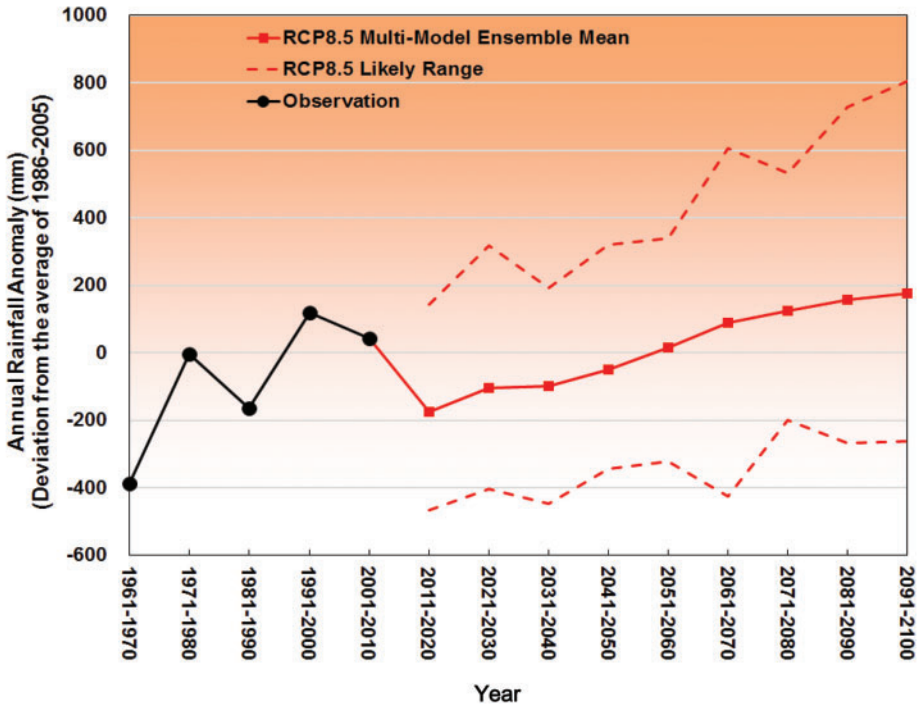


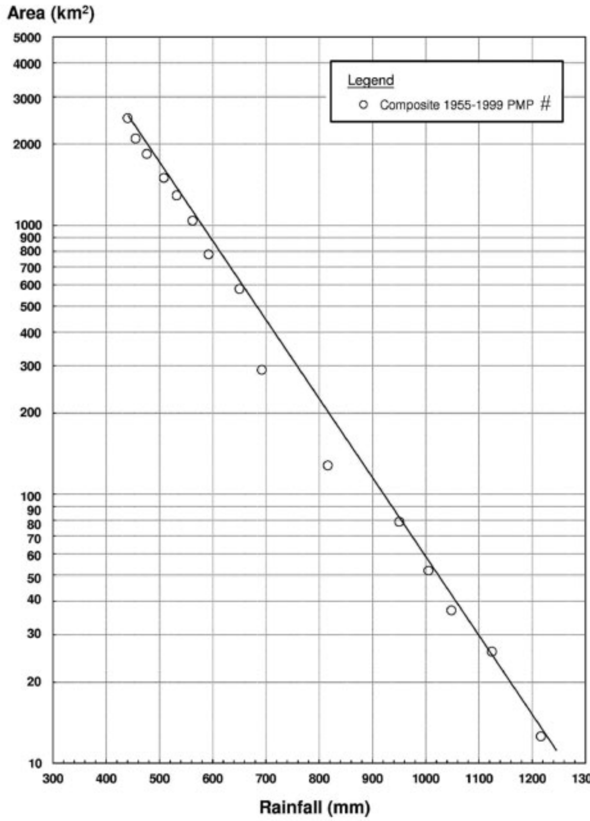
Figure 4.12 Past and projected annual rainfall anomaly of Hong Kong under the RCP8.5 scenario.Likely range refers to the region embraced by the 5th and 95th percentiles of the multi-model ensemble.

4.4.5 Rainfall projections for Hong Kong in the 21st century

Since the publication of the Third Assessment Report of IPCC, the Hong Kong Observatory (HKO) has conducted climate projection studies using the technique of statistical downscaling. Subsequent to the release of WGI AR5, the HKO is now working on the update of the climate projections for Hong Kong. The HKO utilised monthly data of 25 CMIP5 models and employed multiple linear regression to project the rainfall changes in Hong Kong in the 21st century. Under the RCP8.5 scenario, the number of extremely wet years (annual rainfall >3,168 mm) is expected to increase from three in 1885–2005 to about 12 in 2006–2100 (with a likely range of 5 to 20). The corresponding annual rainfall in late 21st century is expected to increase by about 180 mm compared to the 1986–2005 average (with a likely range of −250 mm to +800 mm) (Figure 4.12).

4.4.6 Recent update of Probable Maximum Precipitation (PMP) estimate for Hong Kong

PMP refers to the theoretical upper limit of the amount of rain that can fall according to hydro-meteorological principles in a given time duration over a given area, with no



"Composite 1955-1999 PMP" refers to composition of the controlling points on the PMP which come from different rainstorms in the period of 1955 to 1999

Figure 4.13 Previous 24-hour PMP estimates for Hong Kong (HKO, 1999).

allowance made for long-term climatic trends (WMO, 2009). PMP is commonly used in reservoir and dam engineering and is hence familiar to the engineering profession. It may be adapted in the present context to serve as a yardstick or index for benchmarking the severity of extreme rainfall events to be considered for landslide impact assessment and emergency preparedness planning purposes. The use of the storm transposition technique (see below), which considers all the severe rainstorms actually observed in the neighbouring meteorologically similar regions, can add some realism and confidence to the assessed PMP.

The PMP for Hong Kong was first derived in 1968 for waterworks developments by the HKO (Bell & Chin, 1968). In 1998, the GEO and HKO collaborated on a study to update the 24-hour PMP using the moisture maximisation approach, see Figure 4.13 (HKO, 1999). This was used by the GEO in the early 2000s to develop possible extreme landslide event scenario to serve as a benchmark for reviewing the adequacy of the Government's landslide emergency preparedness measures (Sun *et al.*, 2001).

The GEO, with technical support by the HKO and various other Government departments and tertiary institutes, commissioned a study in 2011 to further update the 24-hour PMP estimates. In this third-generation update, the storm separation technique (viz. the Step Duration Orographic Intensification Factors (SDOIF) Method) was adopted. The rainfalls for each selected rainstorm are decomposed into two components (i.e. convergence component and local orographic component respectively) to facilitate the transposition analysis. A statistical approach was adopted to estimate the orographic factors (denoted as orographic intensification factors) by examining the geographical variation of historical annual maximum rainfalls of the corresponding duration. The associated rainstorm survey covered various meteorologically similar areas in the region, including Taiwan, Guangdong, Guangxi, Hainan, Fujian and Zhejiang. Following a detailed review of the severity of the storms and data availability and quality, four major rainstorms in Taiwan (viz. Herb in 1996, Aere in 2004, Haitang in 2005 and Morakot in 2009) were selected for transposition analysis.

By accounting for the orographic intensification factors of Taiwan (to eliminate the orographic effect), the isohyets of the above four rainstorms were converted into the convergence components. Then the convergence components of these four rainstorms were generalised to elliptical-shaped isohyets with an aspect ratio of 1.6 to establish the so-called "generalised convergence component". The generalised convergence component was then multiplied by orographic intensification factors of Hong Kong to take into account the local orographic effect. The results were further adjusted by a moisture maximisation factor (WMO, 2009) to produce the PMP estimate. The merging of the generalised convergence component and the orographic intensification factors was subjected to different orientations of the generalised convergence component and different relative positions of the convergence component to Hong Kong in order to ascertain the worst combination (see Figure 4.14).

The findings are given in AECOM & Lin (2014). The Depth-Area-Duration curve of the updated PMP estimate is shown in Figure 4.15, while the isohyets of the updated PMP estimates are given in Figure 4.16. The updated PMP for 10 km^2 has increased from 1,250 to 1,510 mm (i.e. 21% increase), whilst for 100 km^2 the updated PMP has increased from 930 mm to 1,350 mm (i.e. 45% increase), as compared with the 1999 PMP (denoted as PMP_{1999}).

By definition, the PMP estimates do not explicitly consider or fully account for the potential impact of climate change. AECOM & Lin (2014) have attempted to investigate the impact of climate change on the PMP estimates for Hong Kong through a literature review (e.g. studies on impact of climate change on PMP, extreme rainfalls and tropical cyclone activities in North Pacific, etc.), and a trend analysis of the related climate parameters that affect the PMP estimates. Based on the trend analysis, the time series of monthly average sea surface temperature in July and August in the relevant areas (i.e. the sea to the south-east of Hong Kong) shows a statistically significant increasing trend from 1961 to 2010 with a confidence level of 95%. However, the time series of annual maximum persisting 12-hour dew point temperature at the HKO does not show an increasing trend from 1961 to 2010. AECOM & Lin (op. cit.) opined that the uncertainties involved are too high to quantify the projection of extreme rainfalls, potential changes in the amount of precipitable water and the relationship between extreme rainfalls and PMP. As a result, they concluded that it was not credible to quantify the impact of climate change on the PMP in Hong Kong in

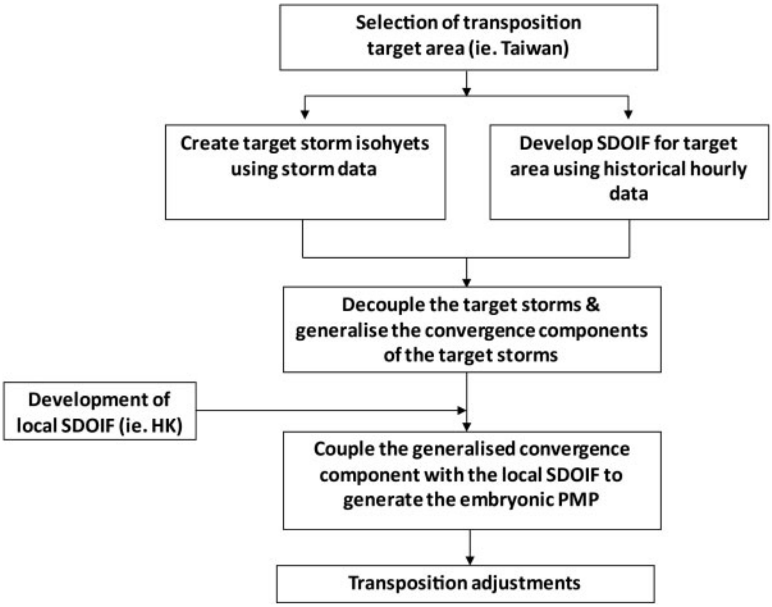


Figure 4.14 Storm transposition via SDOIF Method.

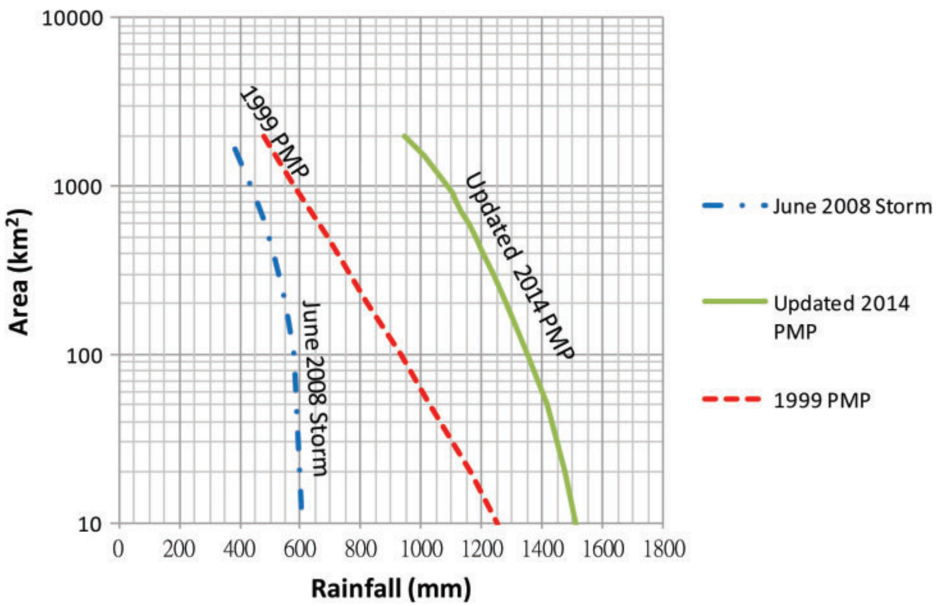


Figure 4.15 Depth-Area-Duration curves for updated 24-hour PMP for Hong Kong.

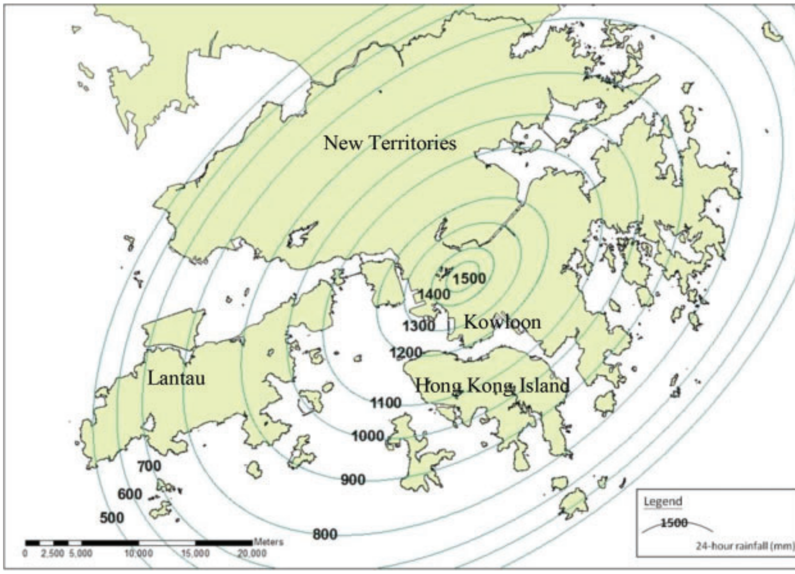


Figure 4.16 Isohyets of 24-hour rainfall of a hypothetical rainstorm corresponding to 2014 PMP estimate.

the 21st century with sufficient confidence based on the currently available data and technical-knowhow.

4.4.7 Geological evidence on relationship between landslide activity and climate change

Apart from the empirical correlation between rainfall and landslides, a more scientific approach may be adopted to study the potential effect of climate change by reference to the geological record which contains evidence of how the Earth's climate has changed over hundreds of millions of years. This evidence includes direct and proxy data for the ocean and atmosphere. The GEO has embarked on a programme of systematically dating ancient debris fan deposits by quantitative means with a view to studying the potential relationship between landslide activity and climate change.

The approach entails (a) reviewing past and present studies on palaeo-climate relevant to the Pearl River Delta region, (b) acquiring numerical age data (using a combination of techniques comprising optically stimulated luminescence (OSL), radiocarbon dating and cosmogenic nuclide surface exposure) on ancient coastal debris fan complexes, together with their characterisation and interpretation, and (c) integrating these data with the results of previous dating studies by GEO on ancient deep-seated sizeable landslides (volumes ranging from 700 m^3 to 850,000 m^3, most of which had ages of the order of tens of thousands of years) in Hong Kong. This is intended to provide a basis for projecting the possible response of the landscape to the estimated climatic and environmental changes, including the probable landslide characteristics under these scenarios.

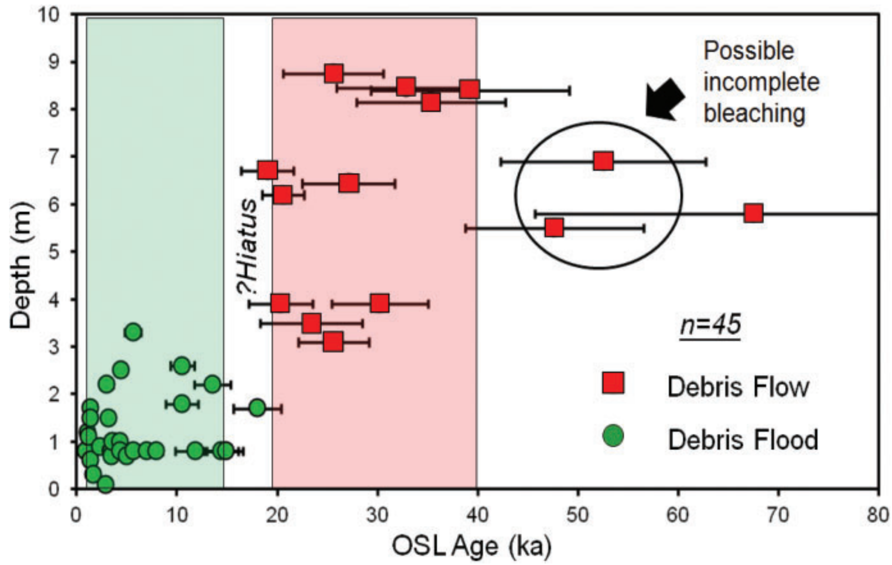


Figure 4.17 Age-depth relationship of debris samples taken from sites at West Lantau (Sewell *et al.*, 2013).

Studies of Hong Kong's palaeo-climate have made reference to various proxies including microfossil diatom evidence, pollen evidence, speleothem data, heavy metal contamination, carbon isotopes in vegetation, pulses of organic carbon, high resolution sea surface temperature, together with response of geochemical proxies to monsoon intensification. The dating of the ancient debris fans revealed that the fan complexes on Lantau Island typically consisted of multiple overlapping debris deposits. It was found that clast-supported debris flood deposits generally overlie older, matrix-supported debris flow deposits. The ages for the debris flood deposits range from 14,000 to 1,000 years old, with an average thickness of 1 to 2 m, whereas the ages for the debris flow deposits range from 20,000 and 40,000 years old, with an average thickness of 2 to 3 m. There appears to be an apparent hiatus at around 14,000 yr BP, as suggested in the boreholes by a change in decomposition grade and debris characteristics (see Figure 4.17).

The available age dating data from sizeable relict landslides suggest the following pulses of deep-seated landslides: 3.5–8 ka, 11–17 ka, 26–31 ka and 47–59 ka, with an apparent increased frequency of sizeable landslides post-Last Glacial Maximum (LGM) corresponding to sea level rise and monsoon intensification (see Figure 4.18). There is no obvious neotectonic connection, but this cannot be entirely ruled out.

The available information points to the possibility of a period of intense landslide activity during the early Holocene, coincident with the rapid rise in sea level and elevated temperatures (Sewell & Campbell, 2005; Sewell *et al.*, 2006). A post-glacial sea level of approximately 2 m above present has been recorded in Hong Kong around 5,500 yr BP (Fyfe, 2000), corresponding to the peak of the period known as Holocene Climatic Optimum (HCO).

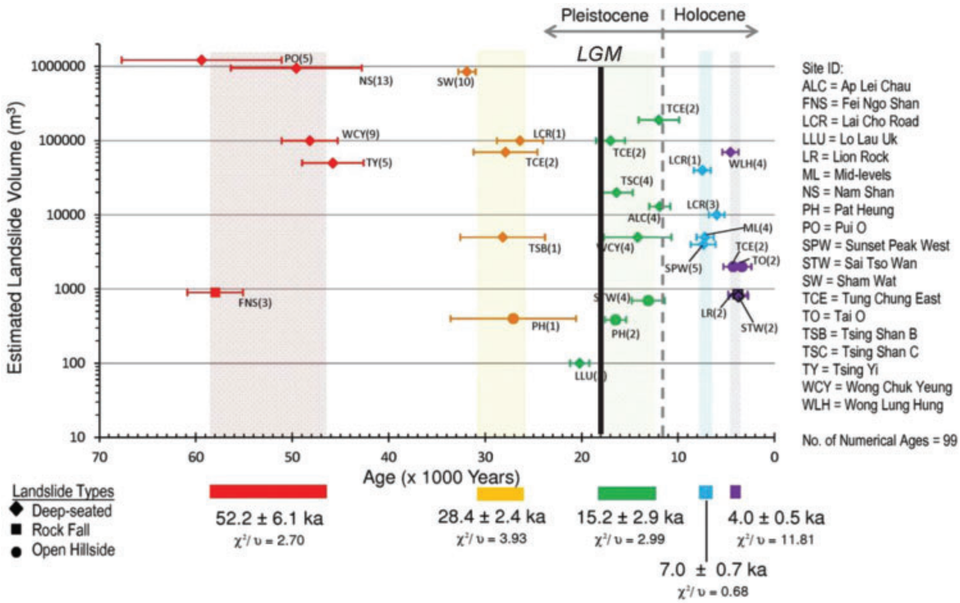


Figure 4.18 Ancient deep-seated landslide studies (Sewell *et al.*, 2013).

The mode and scale of landslide activity in Hong Kong appear to have changed over the past 50,000 years. Debris flow deposits seem to dominate during cool/dry periods whereas debris flood deposits seem to be more frequent during warm/moist periods.

The projected intensification of the East Asia Monsoon is likely to trigger more frequent sizeable landslide events and deep-seated landslides may be liable to become more common as the sea level rises significantly.

4.4.8 Landslide patterns corresponding to extreme rainfall

To obtain an estimate of the scale of the problem, the overall landslide patterns corresponding to extreme rainfall are extrapolated by projecting from the available information using the prevailing rainfall-landslide correlation. Hong Kong is data-rich in terms of high-quality information on rainfall and landslides, hence there is a reasonable basis for establishing the correlations between rainfall and different types of landslides by empirical means.

4.4.9 Rainfall-landslide correlations for man-made slopes

Rainfall-landslide correlations are practical tools to predict the response of man-made slopes and natural hillsides to rainfall. The GEO has been operating in conjunction with the HKO a territory-wide Landslip Warning System for over 35 years to alert the general public of possible landslide risk during periods of heavy rainfall. As part of the Landslip Warning System, the GEO operates an extensive network of automatic

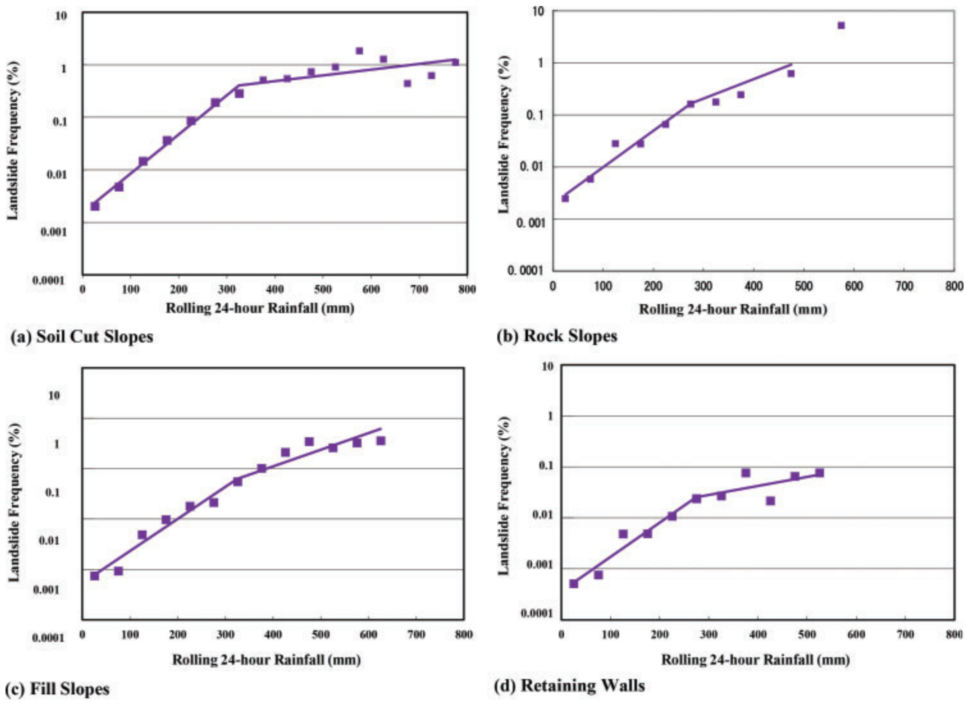


Figure 4.19 Correlations between landslide frequency and rolling 24-hour rainfall (Wong *et al.*, 2014).

raingauges which provide real-time data that can be combined with a short-term rainfall forecast undertaken by the HKO to predict, in a GIS platform, the number of landslides that may occur. This prediction is used for decision-making on whether a Landslip Warning would need to be issued or not.

The wealth of data on rainfall and landslides collected by the GEO over the past few decades has allowed the establishment of rainfall-landslide correlations for man-made slopes and natural hillsides respectively. Over the years, the GEO has been updating the rainfall-landslide correlations for man-made slope failures (Yu *et al.*, 2004). The correlations were based on the comprehensive data available on the spatial and temporal distribution of rainfall intensity and landslide occurrence.

The correlation between man-made slope failures and rainfall adopts a probability-based framework, which has been integrated with the spatial distribution of the registered man-made slopes together with the spatial and temporal variation of rainfall, for the prediction of the number and distribution of landslides. The model allows a realistic projection of the landslide pattern in real time as the rainfall pattern develops, which is essential for the effective operation of the Landslip Warning System. From past experience, different types of man-made slopes have different responses to the same rainfall intensities. Rainfall-landslide correlations have been developed for soil cut slopes, rock cut slopes, fill slopes and retaining walls respectively (Yu *et al.*, 2004). The latest correlations are based on rainfall and landslide data from 1996 to 2010 (see Figure 4.19).

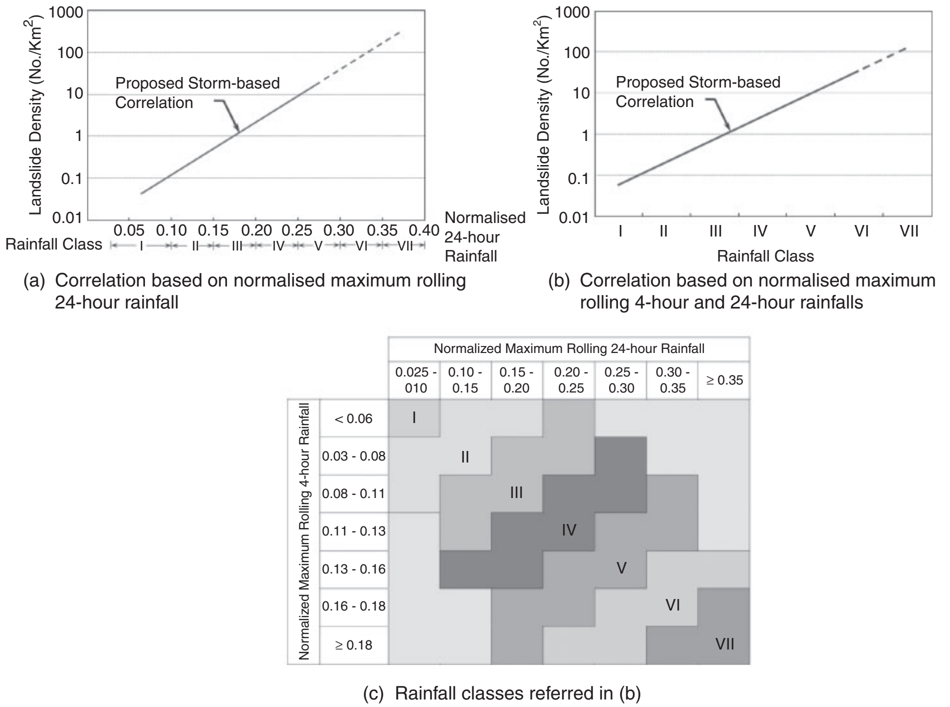


Figure 4.20 Rainfall-storm-based natural terrain landslide correlations for Hong Kong (Chan *et al.*, 2012).

4.4.10 Rainfall-landslide correlations for natural hillsides

As part of the R&D initiatives on the study and mitigation of natural terrain landslide hazards, the GEO has been developing relationship between rainfall and landslides on natural hillsides. Ko (2005) established a correlation between 24-hour rainfall and landslide density (viz. number of natural terrain landslides per km^2) on natural terrain based on normalised maximum rolling 24-hour rainfall intensities (i.e. dividing the maximum rolling 24-hour rainfall by the mean annual rainfall at the same location) and year-based natural terrain landslide data in the Natural Terrain Landslide Inventory (NTLI) from 1985 to 2000. The normalised maximum rolling 24-hour rainfall was found to be a better indicator of the severity of rainfall compared with maximum rolling 24-hour rainfall, because of the significant uneven rainfall distribution in Hong Kong. The year-based correlation was converted to a storm-based correlation based on rigorous spatial analysis of rainfall and natural terrain landslide data (Chan *et al.*, 2012). This approach is considered sufficiently reliable and useful for practical application, e.g. for formulating a natural terrain landslide warning system.

Following the severe rainfall in June 2008, the GEO updated the storm-based rainfall-landslide correlations for natural hillsides based on rainfall and landslide data from 1985 to 2008, see Figure 4.20(a) (Chan *et al.*, 2012). In addition to updating the

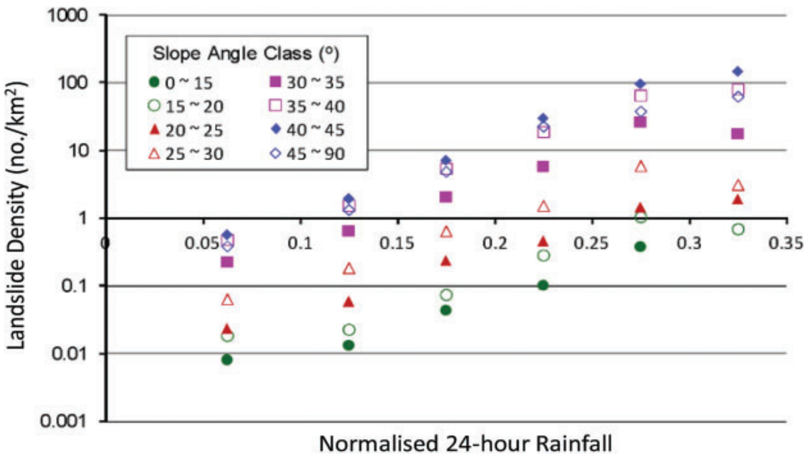


Figure 4.21 Year-based rainfall-landslide correlation.

correlation with normalised maximum rolling 24-hour rainfall, another correlation based on the combined consideration of both normalised maximum rolling 4-hour and 24-hour rainfalls respectively was also developed (Figure 4.20(b)).

The study indicates that the natural terrain landslide density tends to increase exponentially with increase in rainfall intensity. For an extreme rainfall event, significant implications on emergency preparedness and response planning are expected as widespread natural terrain landslides, probably with increased scale and mobility, will occur, which are expected to become the predominant landslide hazards. However, it should be noted that only limited data are available on landslides under extreme rainfall conditions for the establishment of the rainfall-landslide correlation. Hence, the forward prediction of extreme landslide scenarios would require considerable data extrapolation and should therefore be interpreted with caution.

The above rainfall-landslide correlations are being further refined by investigating the correlations for various slope angle classes in a territory-wide rainfall-based landslide susceptibility analysis for natural terrain in Hong Kong (Lo *et al.*, 2015 and Lo & Ko, 2015). Some of the results are shown in Figure 4.21.

4.4.11 Extreme rainfall scenarios

By nature, PMP is similar to the 'Maximum Credible Earthquake' concept in seismic hazard assessment and evaluation of extreme seismic event. In practice, realistic and credible extreme rainfall scenarios can be established by reference to the PMP estimates for a 'stress test' on the prevailing landslide emergency system (Wong, 2013).

For this purpose, the GEO opted to consider two extreme rainfall scenarios separately, namely (a) Level-1 extreme rainstorm involving an actual or near-miss event that has occurred in the past, which is unusual, severe and at the extremity of the local historical rainfall record. This is defined by transposing the actual June 2008

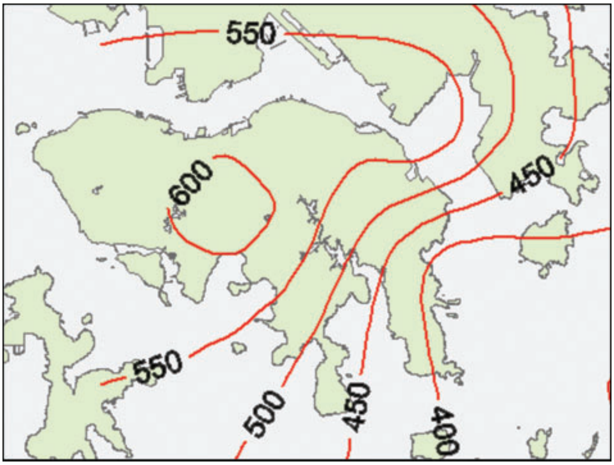


Figure 4.22 Level-1 extreme rainstorm: 24-hour rainfall distribution of June 2008 transposed from Lantau to Hong Kong Island.

rainstorm (which has a return period in the order of 1,000 years and corresponds to 60% PMP_{1999}) spatially from Lantau Island to Hong Kong Island (which is a densely urbanised area); and (b) Level-2 extreme rainstorm, which is a more severe, and rare but credible rainfall scenario as compared with the worst observed rainstorm. This is taken to correspond to 85% to 90% PMP_{1999} (with a projected return period in the order of 10,000 years) striking Hong Kong Island. This is similar to the range of notional return period mandated for earthquake emergency preparedness planning of major cities in Mainland China by the Chinese Authority.

The characteristics of the above two extreme rainfalls in terms of their spatial rainfall distributions are shown in Figures 4.22 and 4.23 respectively.

Based on the expert advice by HKO, GEO has also separately established a simulated rainstorm as an alternative approach to characterising the Level-2 extreme rainfall scenario for use in examining potential landslide impact, with due consideration of the effect of climate change. Rainfall isohyets of Typhoon Morakot that hit Taiwan in 2009 are transposed to Hong Kong taking into account the effect of local topography and the possible increase in tropical cyclone rainfall due to the effect of climate change projected to the end of the 21st century. It is estimated that the maximum 24-hour rainfall would be about 1,040 mm. In effect, this simulated rainstorm corresponds to about 70% PMP_{2014}. It should be noted that the corresponding notional return period (of about 10,000 years) would be reducing with time given the effect of climate change. This alternative approach allows a sensitivity check to be made on the extreme landslide scenario.

Recently, more refined assessments have been carried out making use of the newly developed rainfall-landslide correlation model developed in the territory-wide rainfall based landslide susceptibility analysis (Lo *et al.* 2015). The results of this latest study are generally in agreement with the findings of the assessments reported above.

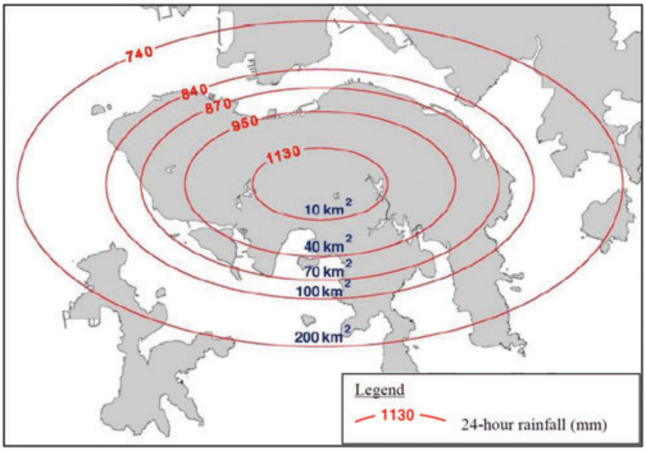


Figure 4.23 Level-2 extreme rainstorm: 24-hour rainfall distribution of a rainstorm corresponding to 85%/90% PMP_{1999} occurring over Hong Kong Island (after Leung & Lo, 2013).

4.4.12 Change in landslide portfolio with development of extreme rainfall

The June 2008 rainstorm was the most severe rainstorm hitting Hong Kong in the past few decades and resulted in widespread natural terrain landslides. Using the updated rainfall-landslide correlations for man-made slopes and natural hillsides, the landslide pattern under an extreme rainfall can be projected.

Figure 4.24 shows the curves that depict the estimated cumulative number of landslides for natural hillsides and man-made slopes respectively during the June 2008 rainstorm based on the rainfall-landslide correlations. It can be observed from Figure 4.24 that when the area was subjected to a 24-hour rolling rainfall greater than about 300 mm (at around 07:30 on 7 June 2008), the predicted number of landslides for natural terrain would start to increase rapidly resulting in a significant increase in the total landslide risk as well as the corresponding risk proportion. This is largely a result of the nature of the rainfall-landslide correlation for natural hillsides, whereby the landslide density increases exponentially with the normalised rainfall.

The projections therefore suggest that under extreme rainfall scenarios, natural terrain landslides would become the dominant landslide hazard.

4.4.13 Assessment of extreme landslide scenarios

Combining the probabilistic rainfall-landslide correlations for natural hillsides and man-made slopes, the rainfall characteristics corresponding to the above two extreme event scenarios for the stress test, together with the information in the Slope Catalogue and natural hillside inventory, the corresponding landslide scenarios can be projected. It should be reiterated that only limited data are available on landslides under extreme rainfall conditions. The forward prediction of extreme landslide scenarios therefore requires considerable data extrapolation and hence carries significant uncertainty.

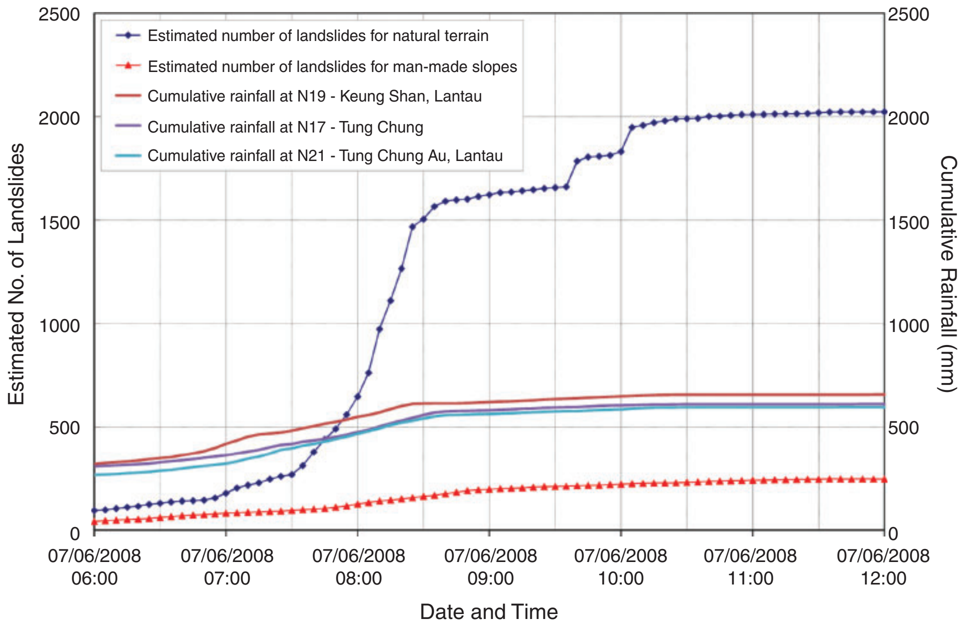


Figure 4.24 Comparison of estimated number of landslides from man-made slopes and natural terrain (based on the June 2008 rainstorm).

The historical data from the worst observed rainstorm in Hong Kong (i.e. the June 2008 rainstorm) since records began in 1885 provided a means to project the scale of natural terrain failure and debris mobility under extreme rainfall intensities in order to minimise data extrapolation as far as possible. Nonetheless, caution is needed when using historical data as a basis for assessing the scale of landslides and mobility of landslide debris under extreme rainfall events. Extreme rainfalls are liable to give rise to more watery debris, which tends to travel further and faster and is liable to overshoot from a drainage line. The increased surface runoff may overwhelm surface drainage provisions turning road pavement into drainage channels (or catchwater channels can become blocked and breached by landslides), overspilling a large volume of water onto the downhill slope at road bends and leading to washout type failures as well as flooding of the downhill areas. The possibility of major knock-on effects, such as the scenario of a service water reservoir being breached by major landslides releasing a colossal amount of water running violently downhill could also lead to major washout failures or debris floods, and grave consequences.

In essence, the possibility of large scale and mobile landslides being under-represented through data extrapolation needs to be borne in mind. Case histories of sizeable landslides triggered by world record or near world record rainfall intensities have indicated four main types of landslide hazards under extreme rainfall, namely mobile debris flows, mobile rockslides (or rock avalanches), large scale deep-seated landslides, and formation and subsequent collapse of landslide debris dams. The occurrence of the above hazards would depend on the site-specific setting (e.g. existence of

Table 4.2 Landslide consequences with Hong Kong Island struck by 60% PMP_{1999} and 85%/90% PMP_{1999} rainstorms respectively.

		Landslide scenarios					
		Level-1 extreme rainfall		*Level-2 extreme rainfall*			
				Approach A		*Approach B*	
		Hong Kong Island struck by 60% of PMP_{1999} (i.e. transposing the June 2008 rainstorm)		Hong Kong Island struck by *85%/90% PMP_{1999}*		*transposed to Hong Kong Island, with allowance for the projected effect of climate change (≈70% PMP_{2014})*	
Types of landslides and consequences		*No. of landslides*	*No. of landslides affecting buildings/ roads*	*No. of landslides*	*No. of landslides affecting buildings/ roads*	*No. of landslides*	*No. of landslides affecting buildings/ roads*
Man-made slope failures		105	65	745	465	1,000	620
Natural terrain landslides	All	1,900	150–250	50,000	3,000–10,000	49,000	3,800–8,000
	Volume > 1,000 m^3	20	2	500	30–100	490	38–80
	Volume > 10,000 m^3 (0.1%)	2	<1	50	3–10	49	4–8

fault zones or preferential sliding planes). The possibility of under-representing certain failure modes due to limited historical data under severe rainfall conditions cannot be overly emphasised.

4.4.14 Impact of Level-1 extreme rainfall

The Level-1 extreme rainfall scenario-based assessment for 60% PMP_{1999} rainfall, is based on transposition of the actual June 2008 rainstorm profile from Lantau Island (corresponds to 60% PMP_{1999}) to centre on the Mid-levels area of Hong Kong Island (see Figure 4.22).

The number of landslides is projected using the latest rainfall-landslide correlations. In assessing the landslide impact, reference was made to QRA models developed previously by the GEO for the quantification of landslide consequence (Ho *et al.*, 2000; Wong, 2005) through superimposing the landslide runout model onto the developed areas in a probabilistic framework. Details of the assessments are given by Lau *et al.* (2012). The results of the assessments are summarised in Table 4.2.

As explained above, natural terrain landslides would likely dominate under the extreme rainfall scenarios. The assessment indicated that about 1,900 natural terrain landslides could occur, some 150 to 250 of which would impact on buildings or roads. The assessment also showed that about 100 man-made slope failures (of which some 65 could affect buildings or roads) could occur. Using quantitative risk assessment, the corresponding Potential Loss of Life (PLL) given the occurrence of the events was also evaluated. For the 60% PMP_{1999} scenario, the calculated PLL for the event is about 10, which is about two orders of magnitude higher than the annual average PLL for the area.

The above assessment was also benchmarked against the outcome of the 1966 rainstorm, which was the most severe rainstorm that hit Hong Kong Island (corresponding to about 40% to 45% PMP_{1999} with the normalised maximum rolling 24-hour rainfall in the range of 0.1 to 0.25). The present assessment took into consideration that about 15% of the natural terrain landslides triggered by the June 1966 rainstorm reached the present-day development areas and allowed for the increased mobility of landslides under extreme rainfall, given that the June 2008 rainstorm at Lantau was about 40–50% more severe than the June 1966 rainstorm in terms of normalised maximum rolling 24-hour rainfall.

The 1966 rainstorm resulted in much damage and social disruption, including complete closure of many roads and 64 fatalities as a result of landslides and flooding. In comparison, the present assessment appears to be credible and the assessed consequences seem realistic and are broadly consistent with the past observations.

4.4.15 Impact of Level-2 extreme rainfall based on 85%/90% PMP1999

A similar analysis was conducted to assess the extreme landslide scenario on Hong Kong Island in the event of the Level-2 extreme rainfall based on 85%/90% PMP_{1999} (Leung & Lo, 2013).

The assessment indicated that about 50,000 natural terrain landslides could occur, some 3,000 to 10,000 of which could impact on buildings or roads. This corresponds to approximately one landslide per 1,000 m^2 of natural terrain area, which is about 20 times the estimate obtained in the assessment by Lau *et al.* (2012) for the scenario involving the June 2008 rainstorm hitting Hong Kong Island. The landslides would result in the detachment of about 10% of the natural terrain area.

The assessment also showed that about 750 man-made slope failures (of which some 450 cases could affect buildings or roads) could occur (see Table 4.2).

It is expected that PLL of this event would be much greater than that associated with the scenario of 60% PMP_{1999}(roughly by an order of magnitude). However, there is much uncertainty in the expected PLL values, given that the collapse of a number of high-rise buildings due to landslide debris impact cannot be ruled out in adverse combination of circumstances.

4.4.16 Impact of Level-2 extreme rainfall based on transposition of Typhoon Morakot to Hong Kong with climate change effect projected to the end of 21st century

Additional analyses were also carried out to assess the extreme landslide scenario on Hong Kong Island under the Level-2 extreme rainfall scenario of a transposed Typhoon Morakot rainstorm, with allowance made for the effect of climate change projected to the end of 21st century. This assessment indicated that about 49,000 natural terrain landslides could occur, some 4,000 to 8,000 of which could impact on

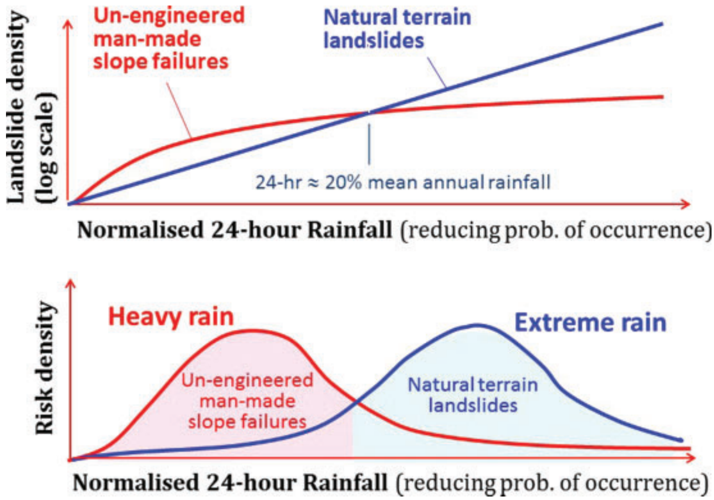


Figure 4.25 Distribution of landslide and risk density in response to extreme rainfall and climate change.

buildings or roads. The assessment also showed that about 1,000 man-made slope failures (of which some 620 cases affecting buildings or roads) could occur (see Table 4.2). It can be seen from Table 4.2 that the outcomes of the assessments using the above two different approaches in establishing the Level-2 extreme rainfall scenario were in the same ballpark.

4.4.17 Landslide risk due to extreme rainfall and climate change

Figure 4.25 illustrates diagrammatically the relationship between landslide density of man-made slopes and natural terrain respectively and increasing rainfall (with reducing chance of occurrence) based on the available data in Hong Kong.

When an area is subjected to severe rainfall that remains below the threshold (rolling 24-hour corresponding to about 20% of the mean annual rainfall), the dominant landslide problem is associated with man-made slopes, in particular non-engineered substandard man-made slopes. However, when the above rainfall threshold is exceeded, the number of natural terrain landslides would increase substantially based on the rainfall-landslide correlations and overtake that on man-made slopes, along with a notable increase in the volume of failure and the mobility of landslide debris. The corresponding shift in the risk density associated with the occurrence of extreme rainfall has major implications, as natural terrain landslides would then become the dominant problem.

The overall societal risk posed by natural terrain landslides was previously quantified by Cheng & Ko (2010) and the annual Potential Loss of Life (PLL) was assessed without the consideration of extreme rainfall events. With the latest projected extreme landslide scenarios, there are notable implications to the risk profile due to extreme rainfall events that are expected to become more frequent and more intense due to possible climate change. Making reference to the updated PMP_{2014} by AECOM and

Table 4.3 Summary of GEO's landslide emergency service from 1994 to 2013.

No. of Landslip Warning issued	*No. of reported landslide incidents*	*No. of building units evacuated**			*No. of road sections closed*
		Block	*House*	*Flat/Unit*	
62	5,274	21	119	1,003	2,434

Note: *A 'block' is a multi-storey building, which may comprise up to several dozens of flats/units. A 'house' is typically within 3 storeys, which comprises several flats/units.

Lin (2014), consideration of natural terrain landslide risk arising from extreme rainfall will bring about 50% increase in the overall risk in terms of annual PLL (Ko & Sun, 2016). However, one must not lose sight of the major uncertainties involved in assessing the risk of extreme landslide scenarios. The above risk quantification would at best give a very rough order of the possible risk level of extreme rainfall events and one must not be misled by the apparent precision of the estimate. Notwithstanding the above, the present assessment findings reinforce the notion that extreme rainfall would constitute an increasing concern and hence expanded efforts are warranted to enhance the resilience of Hong Kong's Slope Safety System in order to better manage the risk of extreme weather conditions.

4.4.18 Evaluating the capacity of landslide emergency management system

The findings from the above scenario-based assessments were used as a form of 'stress test' to review the adequacy of the GEO's prevailing landslide emergency preparedness.

Since 1978, the GEO has been operating a 24-hour year round landslide warning system and landslide emergency system to provide warning and emergency services and give professional advice to Government departments on actions to be taken in case of landslide danger. The aim is to minimise casualty and damage to property under heavy rainfall conditions, and facilitate recovery.

When it is predicted that numerous landslides will occur based on recorded and forecasted rainfall, the HKO in consultation with the GEO will issue the Landslip Warning to alert the general public of the potential landslide danger. As shown in Table 4.3 above, the landslide emergency service has played a significant role in minimising the exposure of the general public to landslide danger, thereby reducing landslide risk.

The landslide emergency system in Hong Kong has proved to be effective in dealing with emergency management under heavy rainfall conditions, such as those typically encountered when Landslide Warning is issued to the general public. However, the system has not been specifically designed to cope with, and tested for, extreme events, particularly in respect of preparedness, response and recovery.

An assessment has been made of the likely capacity of the landslide emergency management system, based on consideration of the available human resources for emergency inspection of landslide incidents that require GEO's input in emergency response (Wong, 2013).

The findings indicate that the current system is able to handle about 210 reported natural terrain landslides, or about 360 reported man-made slope failures.

It is noteworthy that the above is the existing capacity following the current practice of dealing with reported landslides and making recommendations on emergency actions to be taken, such as making recommendation on evacuation of buildings, closure of affected areas and urgent works needed to remove the immediate landslide danger.

All in all, it is projected that a Level-1 extreme rainstorm (viz. a 60% PMP$_{1999}$ hitting a densely populated area on Hong Kong Island) would stretch the existing system to the limit. In comparison, about one-third of the system capacity was mobilised in June 2008 when the rainfall event hit the relatively sparsely populated and less accessible western part of Lantau Island.

In case a Level-2 extreme rainstorm (viz. an extreme rainstorm corresponding to 85%/90% PMP$_{1999}$ or the transposed Morakot rainstorm allowing for the effect of climate change) were to hit a densely populated area on Hong Kong Island, the very large number of predicted natural terrain landslides would completely overwhelm the capacity of the current landslide emergency management system. Both the response and recovery phases would face acute challenges and the landslide consequences are likely to be very serious.

Other bottlenecks will almost certainly exist in emergency management for extreme events, such as transport arrangements, communication facilities, and provision for prompt and safe settlement of the affected community, which are constrained by the capacity of other Government agencies or non-government organisations involved in emergency management. All these issues need to be addressed in a holistic manner as part of the emergency preparedness for extreme landslide scenarios.

4.5 ADAPTATION STRATEGIES FOR MANAGING EXTREME LANDSLIDE EVENTS

In the context of risk management, emergency management is the discipline that deals with or mitigates the risk of weather-related extreme events or natural disasters. In the context of protecting the community from the adverse consequences of landslide disasters, the following adaptation strategies are pertinent:

(a) Prevention: This involves preventive activities to provide protection from disasters, e.g. setting up and enforcing the use of suitable slope investigation, design, construction, supervision and maintenance standards.
(b) Mitigation: This involves implementation of engineering measures to lessen the impact of landslides, e.g. retrofitting substandard slopes to reduce the chance of landslide, or providing mitigation measures (e.g. barriers or check dams) to reduce adverse landslide consequences.
(c) Preparedness: This focuses on formulating procedures, managing human resources, setting up emergency systems, preparing equipment, etc. for prompt mobilisation when a disaster occurs. It also involves preparing the vulnerable community to respond promptly and effectively to the landslide disaster, e.g. taking suitable personal precautionary actions during Landslip Warning.
(d) Response: The response phase of an emergency may involve search and rescue, as well as evacuation and fulfilling the basic humanitarian needs of the affected population. Emergency inspections for identification of any imminent danger

and advice on necessary response actions, safe settlement of those people who have been evacuated and provision of relief measures, are examples of response activities.

(e) Recovery: The recovery phase starts after the immediate threat to life has been dealt with. The goal is to bring the affected area back to normal, e.g. carrying out landslide repair or mitigation works.

Items (a) and (b) may be construed as broad risk reduction strategies whereas emergency management relates mainly to items (c) to (e). Resilience embraces items (a) to (e) and reflects the ability of a system to withstand shocks and stresses whilst maintaining its essential functions. Resilient systems are also more amenable to repair and recovery afterwards. Whilst slope safety systems commonly include provisions for emergency management, the existing systems are rarely designed for, nor tested against, extreme events.

Other options may include protection of the built environment by means of engineering works, allowing for 'safe' failure, embedding redundancy, better land-use planning, possible relocation of existing development, etc.

The various adaptation strategies and measures that are being implemented by the GEO to manage the risk of extreme rainfall events are outlined in the following.

4.5.1 Promulgate enhanced technical guidance and promote more robust mitigation measures

Following the June 2008 rainstorm, enhanced technical guidance was promulgated on the delineation of adverse site settings for the potential development of highly mobile channelised debris flows associated with major drainage lines fed by sizeable catchments. In addition, guidance was issued on the appropriate parameters for landslide debris runout modelling based on back analyses of actual mobile debris flows in 2008. Appropriate assessment of the mobility of natural terrain landslide debris is of the essence, as this will affect decision-making on whether or not mitigation measures are needed to protect a given facility and the detailed design of the corresponding mitigation measures. Furthermore, enhanced technical guidance on natural terrain hazard studies, together with empirical design of standard barriers for open hillside landslides, was promulgated in 2013 following consolidation of experience in the past few years and a probabilistic assessment of the scale and mobility of open hillside landslides triggered by the June 2008 rainstorm.

Designing slopes to a higher safety standard against possible extreme weather conditions (e.g. by adopting a higher factor of safety) may not be practicable or cost effective. Experience from disaster management of other natural hazards (e.g. earthquakes) indicates that it is generally more effective and appropriate to improve emergency management and enhance both system resilience and community resilience with a view to minimising landslide damage and protecting the community from the adverse consequences of landslide disasters.

Lessons learnt from systematic landslide studies in Hong Kong have emphasised the need to give due attention to improve the robustness of slope design and detailing by means of measures that will make the slopes less vulnerable to uncertainties (Ho & Lau, 2008). These include the use of more robust slope stabilisation schemes (e.g. soil nailing, retaining wall, etc.), improved design of slope surface drainage system (GEO, 2004; Tang & Cheung, 2010), application of prescriptive slope surface protection and drainage measures as contingency provisions (Wong *et al.*, 1999), as well as improved detailing of and enhanced redundancy in drainage provisions.

4.5.2 Low-frequency, large-magnitude landslides

In addition to the need to address extreme landslide scenarios involving widespread natural terrain landslides, the increase in the severity and frequency of rainfall also calls for attention to the challenges of low-frequency, large-magnitude landslides impacting on densely populated areas (viz. several tens of thousands m^3 or more, which can be highly damaging given Hong Kong's vulnerable setting).

Some low-frequency, large-magnitude landslides have occurred in Hong Kong within the last few decades. For example, the 1990 Tsing Shan landslide was triggered by a relatively moderate rainstorm, which involved a 400 m^3 failure at the source area and the adverse site setting resulted in a large and mobile debris flow due to significant entrainment along the runout path. The total active volume amounted to about 20,000 m^3 (King, 1996).

Another example is the 1995 Shum Wan Road failure, which involved a large-scale and mobile open hillside landslide. The drainage provisions along Shum Wan Road above the landslide source area were substandard and became blocked due to lack of maintenance, which resulted in the uncontrolled discharge of surface water flow onto the hillside below during severe rainfall. This led to concentrated water ingress in addition to rainwater infiltration arising from the severe rainstorm, triggering a fairly deep-seated and long runout open hillside landslide by exploiting the adverse geological features in the saprolite with weak clay infill. Two persons were killed in the incident. The additional source of concentrated water ingress arising from uncontrolled overflow of surface water that contributed to the large-scale failure illustrates the potential impact of extreme rainfall on the mode of landslide.

A further example is the 2008 Shek Pik reservoir landslide which comprised a sizeable and mobile channelised debris flow involving watery debris and a total debris deposition volume of about 46,000 m^3. The severe rainstorm in November 1993 only triggered a relatively small failure in the same catchment with limited mobility (travel distance of about 400 m), whereas the more severe June 2008 rainstorm triggered a very mobile failure (travel distance of about 1.3 km).

The identification of potential 'hot-spots' that are liable to give rise to low-frequency, large-magnitude landslide events is being examined along several fronts. These include (a) examination of large relict landslides and known distressed hillsides, (b) identification of vulnerable site settings based on an engineering geomorphological approach, and (c) delineation and mapping of major drainage lines fed by sizeable catchments.

Systematic assessment of digital elevation model (DEM) generated from territory-wide LiDAR data, together with field mapping, will assist with the identification of notable morphological features such as pre-historic deep-seated rockslides, relict scars of large landslides, sizeable colluvial lobes or fans, terrain with signs of disturbed drainage patterns, hillside with geomorphological signs of possible past large-scale slope instability, concentration of talluvium, etc.

To address the risk of potential debris flows or debris floods with significant entrainment and high mobility under extreme rainfall events, the need to give special attention to major drainage lines fed by sizeable catchments was highlighted by the June 2008 rainstorm, as these are potential locations of sizeable and mobile debris flows with watery debris. Catchment size, channelisation ratio, drainage line morphology, drainage order, length and straightness, together with presence of potentially entrainable material, are some of the important factors that govern the mobility of channelised debris flows. A GIS methodology has recently been developed by the GEO for the systematic delineation of major drainage lines and the corresponding catchment boundaries on a territory-wide basis (Lo & Ko, 2014). This was used to identify major drainage catchments (MDC), which are defined as hillside catchments with any drainage line of a length greater than 500 m that is originated from a watershed with a plan area of at least 10,000 m^2. The above definition has been benchmarked against the past large-magnitude channelised debris flows in Hong Kong.

4.5.3 Systematic implementation of mitigation measures on existing features posing highest risks to community

'Hardware' resilience may be enhanced through engineering measures in accordance with a risk-based approach to upgrade or retrofit the city infrastructure. The GEO has been systematically upgrading substandard man-made slopes since 1977 under the Landslip Preventive Measures (LPM) Programme. Over the last three decades, some 7,000 substandard man-made slopes were dealt with at a total expenditure of US$1.5B, resulting in about 75% reduction in overall landslide risk.

To dovetail the LPM Programme, the GEO launched in 2010 the Landslip Prevention and Mitigation (LPMit) Programme with an expanded scope to systematically mitigate natural terrain landslide hazards and retrofit the remaining substandard man-made slopes, in accordance with risk-based priority ranking systems. The pledged annual outputs approximately correspond to dealing with the worst 1% of the vulnerable hillside catchments and substandard man-made slopes every year on a rolling basis (Development Bureau, 2007).

The annual output in terms of number of catchments and slopes dealt with is not significant in comparison with the slope population and the extensive area of steep natural terrain in Hong Kong. Thus, the LPMitP cannot be the sole answer in addressing the impact of extreme rainfall events. However, as this systematic retrofitting programme systematically mitigates the risks of those hillside catchments and man-made slopes that are posing the highest risk to life, it will contribute to contain the overall landslide risk to an "as low as reasonably practicable" (ALARP) level and help to reduce the adverse consequences under extreme events, particularly in respect of the chances of multiple-fatality landslide events.

4.5.4 Improving crisis preparedness

The available resources of the existing landslide emergency system have a limited capacity in handling the reported landslide incidents under an extreme event. To further enhance the resilience of the Hong Kong Slope Safety System, crisis preparedness needs to be improved, albeit with different strategies and emphasis for the two extreme rainfall scenarios under consideration.

(a) Up to Level-1 extreme rainstorm scenario (viz. 60% PMP_{1999})
The main focus is to ensure effective and efficient emergency management when the system is stretched to the limit. This calls for streamlining the emergency response with due priority given to more critical cases, and enhancing preparedness by identifying and dealing with possible bottlenecks in the operation of the system.

(b) Exceeding Level-1 extreme rainstorm (viz. 60% PMP_{1999}) and up to Level-2 extreme rainstorm scenario (viz. 85%/90% PMP_{1999})
The capacity of the existing system will be completely overwhelmed. The current mode of emergency management operation including deploying professional geotechnical engineers to landslide sites to give advice on emergency actions will become impracticable. The development and implementation of a new strategy and mode of operation in managing the landslide emergency is therefore of the essence.

4.5.5 Enhancing and streamlining landslide emergency services

Based on the findings of the stress tests using the scenario-based assessments, the Hong Kong's landslide emergency system could in principle just about cope with the Level-1 extreme rainfall scenario (notional return period of 1,000 years) by stretching to its limits. There is scope, however, for further streamlining and continuous improvement and development of suitable contingency plans to enhance robustness. The constraints and bottlenecks associated with other relevant Government departments also require attention. The current landslide emergency system will break down under the Level-2 extreme rainfall scenario (notional return period of 10,000 years under the current climate condition).

The above scenario-based assessments and stress tests emphasise that the GEO needs to gear up its slope safety crisis preparedness under extreme rainfall conditions in respect of preparedness, response and recovery. As an illustration, the following measures have been undertaken recently by the GEO to strengthen and streamline the emergency service:

– Draw up a list of more experienced geologists/geotechnical engineers as a contingency provision for prompt deployment to the field to assist in assessing the residual risk of major natural terrain landslides.
– Put in place arrangements for GEO works contractors to be mobilised, if and when needed, to undertake emergency repair or risk mitigation works on large-scale natural terrain landslides. Flexible barrier components have been stockpiled for possible use in landslide emergency works.
– Use of modern information technology for sharing of key information and enhanced communication in order to facilitate prompt emergency response. A new, web-based landslide information management system was developed. This system is equipped with a mobile map and geo-location service that enables users to identify and record landslide locations conveniently. The timely reporting of

Table 4.4 Natural terrain alert criteria framework.

Equivalent Number of Predicted Natural Terrain Landslides	*Alert Level*	*Scenarios*
≥500 to <1000	1	Alert of possible widespread natural terrain landslides
≥1000 to <2000	2	Warning of widespread natural terrain landslides
≥2000	3	Warning of very widespread of natural terrain landslides

Note: The equivalent number of predicted natural terrain landslides is calculated based on the rainfall-landslide correlations and scaling factors (which reflect the relative hazard levels for different regions in Hong Kong).

key landslide information to aid identification and classification of landslides is particularly important under an extreme landslide scenario, as it will support the Emergency Manager in decision-making, action planning and setting priorities for the deployment of emergency teams.

– Put in place an Emergency Command System to handle situations that individual infrastructure departments might be unable to cope with the widespread damage in order to enhance the coordination of repair and recovery works.

4.5.6 Enhancing landslide warning system

The GEO has recently developed a separate set of landslip alert criteria for natural terrain (see Table 4.4) to supplement the current Landslip Warning system (Chan *et al.*, 2012). These have been in use since 2012 for internal reference by the GEO Emergency Manager so that a timely alert on possible widespread occurrence of natural terrain landslides can be provided in order to facilitate enhanced emergency preparedness and response.

4.5.7 Enhancing coordination of Government emergency services

The Hong Kong Government has put in place a Contingency Plan for Natural Disasters to ensure that all departments concerned will respond quickly and effectively in a coordinated manner to deal with emergency situations. The Government conducted an inter-departmental exercise in April 2012 to test its response and capabilities in the event of a serious nuclear incident at the Daya Bay Nuclear Power Station. The exercise included a drill on emergency evacuation of about 120 people caused by a landslide scenario that might occur during prolonged period of heavy rain incidental to the nuclear accident. The landslide drill provided an opportunity to test the Government's response at various critical stages of emergency evacuation, including evacuation of occupants, leading them out of the danger zone, taking stock of the evacuees and transporting them to temporary shelters.

The GEO has recently organised a pilot desktop exercise with 30 key departments/agencies to 'walk through' together several hypothetical extreme landslide scenarios and assess the likely major constraints in respect of emergency management. In addition, the GEO has met with the relevant stakeholders to brainstorm the possible cascading events with adverse knock-on effects that may be triggered by large-scale landslides.

4.6 FURTHER WORK

4.6.1 Strengthening and streamlining existing landslide emergency system

Potential areas for further improvement or streamlining of the prevailing landslide emergency system include the following:

- Sourcing additional and contingency resources to narrow the gap between the demand for emergency services and the existing emergency management capacity (e.g. develop plans for mobilisation of resources from the private sector and quasi-government organisations to assist in emergency management under extreme landslide events).
- Streamlining the emergency management procedures and practice for dealing with extreme landslide events, focusing on cases where priority attention is required in order to facilitate provision of the essential emergency response actions.
- Revamping the emergency management strategy to make it more pragmatic and effective to implement under the constraints of extreme landslide events. For example, geotechnical engineers may be deployed in district police/fire service command centres for more effective provision of geotechnical advice on emergency rescue actions.
- Improving public awareness of possible extreme landslide scenarios and equipping the general public with the knowledge and skills required for emergency management, e.g. launch appropriate publicity campaigns and public education programmes.
- Utilising the recently formulated natural terrain landslip alert criteria to enhance forewarning and landslide emergency mobilisation in the event that widespread natural terrain landslides are predicted under critical rainfall conditions.
- Conducting forums, workshops and drills to engage the vulnerable community and relevant stakeholders in emergency management and response (e.g. development of evacuation plans in advance).
- Revamping the emergency information system to facilitate sharing of information and communication among the different Government bureaux/departments/agencies responsible for different types of hazards via a common GIS operating platform.
- Improving communication with the public during a crisis, such as pre-written press releases and clear protocols in terms of the officers that will engage with the media.
- Providing enhanced advice and training to the Police and Fire Services Department on appropriate actions to be taken by their front-line staff on emergency duties for typical landslide incidents.
- Developing an emergency service continuity plan to react efficiently to unexpected situations, e.g. prolonged interruption of utility services (including power grids and communication networks).

Other potential bottlenecks and constraints still exist in the emergency management system, such as the provision and arrangements of emergency transport and communication facilities. All the potential bottlenecks need to be addressed in a holistic manner and contingency plans developed in order to further enhance system resilience.

4.6.2 Need to consider concurrent multiple hazard scenarios

In September 2013, when Super Typhoon Usagi was still travelling over the Pacific, it was recognised to have the potential to bring about significant storm surge to Hong Kong. In the event, the typhoon made landfall just to the east of Hong Kong at Shanwei, Guangdong Province, where at least 15,000 homes were destroyed and more than 30 fatalities were reported. Based on storm surge modelling, the HKO found that should the typhoon have travelled along a track to the west of Hong Kong, the highest sea level at Victoria Harbour would reach 5 m above Chart Datum, instead of 2.8 m as recorded during the typhoon (Ng et al., 2014). In this event, serious and widespread flooding would have occurred in the densely populated urban areas adjoining the harbour, with major impact to the infrastructure including both above-ground and below-ground facilities, and at the same time heavy downpour would probably have triggered extensive landslides.

By virtue of the vulnerable and densely urbanised settings, it is perceivable that an extreme weather event hitting Hong Kong could result in multiple hazards, such as landslides, flooding, storm surges, tree falls, damages to squatter huts and buildings by wind, breach of reservoirs and catchwaters, damage to port facilities by waves, etc., which call for different forms of emergency operations.

To effectively handle the impacts of such multiple hazards that could happen concurrently, the adoption of a holistic approach is of the essence in assessing the severity of the plausible combination of extreme events and development of suitable crisis preparedness plans. The GEO in conjunction with the relevant departments that manage other weather-related hazards is conducting scenario-based assessments of multiple hazard scenarios under extreme weather conditions, including the consideration of potential cascading events. In this regard, the extreme weather events to be adopted in emergency preparedness will be refined, and the projected landslide scenarios and consequences will be updated.

4.6.3 New strategy for landslide emergency management under extreme rainfall condition

Apart from the need to further strengthen and streamline the landslide emergency system to make it more robust and resilient, a new strategy and mode of operation are needed in enhancing the preparedness for extreme rainfall events. This new strategy would primarily involve key elements that include (a) enhancing the coordination and collaboration of emergency services provided by different Government departments, (b) enhancing community resilience by promoting the public to take personal precautionary measures, and (c) empowering and facilitating the public to take appropriate emergency response actions to protect themselves and minimise exposure to landslide hazards, by providing them with the necessary knowledge and information in a timely manner for their decision-making on emergency response.

Under the current system in dealing with normal emergency situations, the GEO will endeavour to attend to each significant or serious landslide incident in order to undertake an inspection and give advice on the immediate precautionary measures (e.g. evacuation or road closure) to safeguard public safety, and the necessary emergency works to remove the immediate or impending danger.

Such a mode of emergency service will become impractical during extreme rainfall and landslide conditions. Apart from the very large number of landslides that will be reported, many of them will likely become inaccessible as a large number of roads and footpaths are expected to be blocked by landslide debris, or flooding. A new strategy for managing the landslide emergency is therefore needed.

Enhancing the resilience of the vulnerable population and the relevant stakeholders in facing up to the extreme natural events is of the essence. Maintaining vigilance of the extreme landslide scenarios and awareness of emergency management constraints is critical to crisis preparedness. Hence, public education and communication would be as important as technical assessments, formulation of emergency plans and procedures, and preventive and mitigation works.

The key is to enhance the resilience of the community, without causing undue alarm or generating misunderstanding by the public on the Government's motives. Members of the public will need to be empowered and encouraged to take appropriate emergency response actions in order to protect themselves and their families, and to minimise their exposure to landslide hazards. This may be done by providing them with the necessary knowledge and information on the latest landslide and rainfall situations in a timely manner so as to assist them to make their own decisions on emergency response, before the arrival of GEO staff or other emergency staff. An analogy will be the general public taking appropriate emergency response actions in the event of a fire before the arrival of the firemen.

An account of GEO's expanded efforts on public education, information and communication under the Hong Kong Slope Safety System is given by Tam & Lui (2013). Focused and enhanced publicity and public education efforts are warranted to improve the community resilience against extreme landslide events.

4.7 OTHER INITIATIVES

In the 2008 Policy Address, the Chief Executive announced that the Hong Kong Government will make early preparations to meet the challenge of climate change, in particular in enhancing fuel efficiency, using clean fuels and relying less on fossil fuels to reduce carbon footprints of our city. It was proposed to adopt a voluntary carbon intensity reduction target of 50%–60% by 2020 as compared with 2005 level. (Environment Bureau, 2010).

The GEO has continued to promulgate environmental-friendly construction techniques in slope works. Soil nailing is now widely used by the local geotechnical profession to upgrade soil cut slopes, fill slopes and masonry walls. Apart from being robust, this technique is also more environmentally friendly and sustainable than other alternative solutions (such as trimming back a cut slope or re-compaction of loose fill) in terms of carbon emission. In comparison, carbon emission of soil nailing is some 40% lower than that of cutting back of a slope and 50% lower than that of fill re-compaction. Vegetation covers are also provided to slopes upgraded under the LPMP/LPMitP as far as practicable. This will not only enhance slope appearance but also contribute to negative carbon emission.

The GEO has recently completed a study on the carbon footprint of slope construction works under the LPMitP and concluded that the carbon emission intensity (i.e. carbon emission/project value) of LPMit works was lower than that of general civil and infrastructure works by about 15%. Also, the total carbon footprint of LPMit works is about 2% of the construction sector's total carbon emission in Hong Kong. Notwithstanding this, GEO will continue with the efforts to enhance green and sustainable construction practices in LPMit works.

4.8 DISCUSSION AND CONCLUSIONS

All the climate scenarios projected for Hong Kong so far, based on various approaches, are consistent in that they suggest increasing precipitation with greater extremes, as well as increasing spread (i.e. variability) with time. These are generally consistent with the projected regional climate change patterns in South China. In essence, both extreme changes and chronic changes need to be considered.

It is pertinent to note that there are major uncertainties associated with the various climate change projection models (Ho, 2014). The resolution of the predictions is not high, particularly for extreme rainfalls, because of the constraints of data availability and the current technical know-how. The approaches are mostly not amenable to verification or calibration. The physical processes involved (e.g. cloud microphysics, small-scale turbulence, etc.) are generally not well understood and often not modelled in detail. Thus, both model uncertainty and parameter uncertainty can be significant despite the use of state-of-the-art climate models, not to mention there may also be unknown unknowns in addition to the known unknowns. Given the many uncertainties involved, an adaptive management approach is promoted (e.g. Hall & O-Connell, 2013). Decision-making in public policy and risk management should be risk-based as far as possible.

A key observation is that the occurrence of extreme rainfall could be within the natural variability of the weather system, irrespective of whether or not there will be climate change. If climate change does lead to notable impacts, it is likely to lead to an increase in the frequency and severity of extreme rainfall, apart from other adverse consequences such as increase in sea water level, storm surge, droughts, etc. Hence, the risk of extreme rainfall would need to be managed. In view of the potential dire consequences to densely urbanised areas that are vulnerable to rain-induced landslide hazards, the impact of extreme rainfall should be duly considered from a strategy, policy and technical perspective, in order to assess the scale of the problem and the necessary risk management actions.

A 'stress test' of GEO's landslide emergency management system in a desktop exercise using scenario-based assessments, as described above, has provided considerable insights into the nature and scale of extreme landslide scenarios, as well as the gaps in emergency preparedness. Based on the study findings, the current landslide emergency system is currently not properly geared up to deal with extreme rainfall events in terms of preparedness, response and recovery. Both system resilience and community resilience to landslides under extreme rainfall conditions need to be enhanced. The general public generally expect or believe that the responsibility for slope safety lies with the Government. Most people tend to have a short memory of past landslide disasters. Landslide hazards are, by and large, not perceived to be of major concern in Hong Kong and that there is a general perception that the landslide problem is now under good control by the Government. At the same time, the public tend to have a very low tolerance level of fatal landslides (especially multiple-fatality landslides). Also, there appears to be an increasing 'blame culture' by the media in pinpointing which senior Government officials are to be accountable for major mishaps or incidents.

It is imperative that the community maintains highly vigilant about serious landslides and be better prepared to deal with extreme rainfall events. It is neither practical nor cost-effective to rely solely on engineering solutions to manage the risk of extreme rainfall. The engineering approach needs to be supplemented by non-works, 'software' measures involving enhanced emergency preparedness, response and recovery.

Consideration should be given to the possible concurrent occurrence of multiple hazards in a holistic manner and the development of integrated strategies using a systems approach. This would require concerted efforts by various Government bureaux and departments, and engaging the community through public education and communication, together with public awareness and publicity programmes, in order to enhance community resilience and response capabilities. The challenges of and difficulties in enhancing community resilience in a truly effective and sustained manner should, however, not be under-estimated, given the public (mis)perception or indifference to slope safety in Hong Kong.

A holistic and systems view is called for, including the consideration of the system of systems, possible interdependencies amongst different systems, and local distributed capacity. This is pertinent in the context of multi-hazards and the corresponding emergency responses. In addition, a more rigorous consideration of the resilience framework is warranted (e.g. Arup, 2014). Such a framework may include key elements such as robustness, redundancy, responsiveness, integration, inclusive, reflective and diversity. For example, a review is in progress by the Hong Kong Government with a view to establishing a 'Common Operation Picture' GIS platform for all emergency works agencies to share emergency information in real-time. This would bring about better integration and coordination, which would also enhance the responsiveness to emergency and is conducive to better planning of the emergency response. In addition, the adoption of suitable smart technologies (e.g. a city-wide Global Positioning System) and information technology and communication tools could promote better coordination and communication amongst the different emergency departments.

In terms of enhancing slope safety preparedness for extreme rainfall, further work is needed in respect of exploring the practicability of developing landslide evacuation plans for vulnerable communities, large-scale drills of emergency evacuations, consideration of the use of landslide detection and alert systems to supplement landslide risk mitigation works, or the possible use of such system as a risk management tool in lieu of mitigation works, etc.

A recent report by the Institution of Mechanical Engineers (2013) calls for a much greater focus on preparing people for the possibility of an extreme natural event occurring and building disaster resilience into communities. In particular, it estimates that every $1 spent on building preparedness and resilience can save as much as $4 in relief, recovery and reconstruction later.

For enhanced slope safety preparedness and resilience to extreme rainfall events to take root, it has to be embraced by the community. It is of the essence to engage the public for community support, education and preparedness. Soft skills such as capacity building need further development in Hong Kong so that the population could be better informed about how to avoid the dangers of extreme weather and the community can recover more quickly afterwards.

Well coordinated open dialogues and honest discussions with the general public and stakeholders regarding uncertainties and risks are likely to be needed in engaging the community and promoting buy-in by the public of the need to enhance community resilience.

The judicious use of suitable social science approaches and modern social media tools in public education and engagement merits further consideration. Creative ideas for suitable risk communication are needed in helping the community to build up a new culture of safety, i.e. one that acknowledges uncertainties, system limitations and the likely occurrence of failures with potentially very serious consequences, as well as securing community buy-in, and promoting self-protection and neighbourhood support. It is possible that different approaches may be needed for different sectors of the community.

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