Enhancing the Resilience of Slope Safety System against Extreme Events
提升斜坡安全系統應對極端事故的能力

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Abstract
Severe earthquakes could bring about widespread and disastrous landslides resulting in major damage and casualties, as in the 2008 Wenchuan earthquake. While this poses an acute challenge to slope safety management, it also provides invaluable insights into possible problems and mitigation strategy for extreme landslide scenarios. The slope safety systems currently in place for managing landslide hazards are rarely designed for, nor tested against, extreme events. The Hong Kong Slope Safety System, which is administered by the Geotechnical Engineering Office (GEO) and is regarded as a role model in landslide risk management, has been evolving with time to incorporate enhancements arising from improved knowledge and practice. In recognition of the likelihood of more frequent occurrence of extreme rainfall conditions due to the effects of climate change, the GEO has made an expanded effort to assess and improve the resilience of the Hong Kong Slope Safety System in combating extreme rainfall events. Many of the key issues involved are akin to those encountered in extreme landslide scenarios under severe earthquakes. Selected aspects, including identifying the nature and scale of the extreme landslide events, assessing the severity of the landslide consequences, evaluating the capacity of emergency management and improving crisis preparedness, are highlighted in this paper.

Keywords
Earthquake, Emergency Management, Extreme Event, Landslide, Probable Maximum Precipitation, Risk Management, Slope Safety System

1. INTRODUCTION

The 2008 Wenchuan earthquake resulted in about 20,000 reported landslide fatalities (Yin et al, 2009). This is one of the most serious extreme events with disastrous landslide consequences in the last decade. It emphasizes the acute challenges posed by extreme landslide scenarios to crisis preparedness and emergency management, which is an area requiring due attention in landslide risk management. This paper highlights the role of emergency management as a key component of a slope safety system and the issues involved in dealing with extreme landslide events. The available world landslide and earthquake data are reviewed to facilitate interpretation of the characteristics and severity of extreme landslide events in a global context. Reference is made to the Hong Kong Slope Safety System, which is administrated by the Geotechnical Engineering Office (GEO) of Civil Engineering and Development Department for management of landslide risk in Hong Kong. Salient aspects of the initiatives being pursued in assessing and enhancing the resilience of the Hong Kong Slope Safety System in tackling extreme landslide events are described. Some preliminary findings are presented to illustrate the work involved and the possible outcome.

2. SLOPE SAFEY SYSTEM

With increasing awareness of the need for applying risk management methodology to deal with landslide hazards, there has been notable development worldwide not only in enhancing the technical approach for slope engineering and landslide hazard mitigation but also in developing and implementing slope safety systems for managing landslide risk in a holistic manner. A slope safety system entails the policy, strategic, legislative, administrative, technical and procedural framework for management of landslide risk. It may operate at a city, country or regional level.

An informative series of papers that describe the slope safety systems and landslide risk management practices in sixteen places, including cities and countries, are contained in the Proceedings of the International Forum on Landslide Disaster Management held in Hong Kong (Ho and Lee, 2007). Reports on the landslide risk management systems adopted at, or recommended for, individual places have also been published elsewhere. For example: Hong Kong (Works Branch 1995, Malone 1998, Chan 2000, Wong & Ho 2005, Chan & Lau 2008), Taiwan (Lin et al. 2007), United Kingdom (Hutchinson & Bromhead 2002, Winter et al. 2007), and United States (National Research Council 2004, Laprade & Paston 2005). The salient features of three of the systems, viz. those of Seattle, Malaysia and Hong Kong, were reviewed by Wong (2009). It was noted that while the systems differ in their scope and emphases given the diverse range of landslide problems and socio-economic, administrative and political setting in different places, they tend to share some common threads:

- The systems are evolving, typically with changes triggered by serious landslide events.

- Engineering and non-engineering measures are adopted for managing landslide risk. A multi-pronged approach, typically involving hazard avoidance and prevention, study and mitigation of risk, public education and emergency management, is adopted.

- The systems call for partnership with the community and other key stakeholders, such as administrators, politicians and multi-disciplinary specialists (e.g. social scientists), apart from input from landslide professionals.

- The systems are managed by government or quasi-government authorities that are entrusted with comprehensive responsibilities for slope safety.

Components of Slope Safety System	Primary contribution of each component to: Reduce landslide risk – Reduce likelihood	Primary contribution of each component to: Reduce landslide risk – Reduce consequence	Primary contribution of each component to: Address public attitude and tolerability
Policing			
– Checking new slope works	✓		
– Slope maintenance audits	✓		
– Recommending safety clearance of vulnerable squatters and unauthorised structures threatened by hillsides		✓	
– Exercising geotechnical control through input in land use planning		✓	
– Safety screening studies and recommending statutory repair orders for private slopes	✓		
Works projects			
– Retrofitting substandard Government man-made slopes	✓		
– Natural terrain landslide mitigation and boulder stabilisation works	✓		
Research and setting standards	✓	✓	✓
Education and information			
– Slope maintenance campaigns	✓		✓
– Risk awareness programmes and personal precaution campaigns	✓	✓	✓
– Information services	✓	✓	✓
– Landslip warning and emergency services		✓	✓

Table 1 The Slope Safety System in Hong Kong (based on Malone 1998)

The Hong Kong Slope Safety System, which is regarded as a role model in urban landslide risk management, is one of the most established and effective systems in place. Following a number of disastrous landslides with multiple fatalities in the 1970s, the GEO was established in 1977 as a central body to regulate geotechnical engineering and slope safety in Hong Kong (Hong Kong Government, 1977). A comprehensive slope safety system, commonly known as the Hong Kong Slope Safety System, has been developed and implemented by the GEO to manage slope safety. The key components and functions of the Hong Kong Slope Safety System are summarized in Table 1. A range of initiatives are included in the System to manage landslide risk in a holistic manner, via: (i) improving slope safety standards, technology and administrative and regulatory frameworks, (ii) ensuring safety standards of new slopes, (iii) rectifying sub-standard Government slopes and maintaining them, (iv) ensuring that private owners take responsibility for slope safety, and (v) promoting public awareness in and response to slope safety.

The System serves to minimize landslide risk to the community through a policy of priority and partnership for reducing landslide frequency and consequence, and addressing public attitude and tolerability of landslide risk to avoid unrealistic expectations. The System adds value to the society through averting potential fatalities and improving the built environment. It has proven to be successful in containing Hong Kong's landslide risk to within an As Low as Reasonably Practicable (ALARP) level. This is evident from the significant reduction in landslide fatalities in Hong Kong (Figure 1) and from analysis of the landslide risk trend (Wong, 2009a) based on application of Quantitative Risk Assessment (QRA).

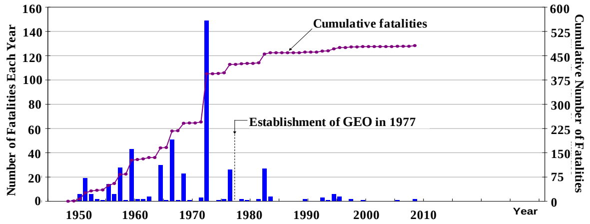

Fig. 1 Historical annual landslide fatalities in Hong Kong

The Hong Kong Slope Safety System is subject to continuous improvement with time to incorporate enhanced knowledge and professional practice, as well as lessons learnt from landslides and audits of the system performance. Development and application of the system since 1977 has resulted in significant improvements in many aspects of landslide risk management. For instance, the comprehensive Government's Slope Catalogue has been compiled to maintain comprehensive records of about 60,000 sizeable man-made slopes and retaining walls. This database provides the necessary information for regular maintenance and the systematic selection of substandard slopes to be retrofitted. In order to ensure that the most deserving slopes are selected, risk-based priority ranking systems utilizing QRA results have been developed. Regulatory and administrative frameworks have been formulated to ensure that new slopes are designed and constructed to the required safety standards. An emergency system is operated by the GEO to issue Landslip Warning during heavy rainfall conditions and provide round-the-clock landslip emergency services. Landslides are systematically studied to enhance knowledge of slope performance and audit the slope safety system. Concerted effort is made in collaboration with researchers and practitioners in developing state-of-the-art geotechnical standards and professional practice that best suit the local application. As the risk of man-made slopes is progressively under control, increased attention is now given to studying and mitigating the risk of natural terrain landslides. Promoting public awareness and response in slope safety is included as a key component of the system. The system is reviewed regularly and benchmarked against international best practice through a Slope Safety Technical Review Board.

3. EMERGENCY MANAGEMENT AND EXTREME EVENTS

3.1 Landslide Emergency Management in Slope Safety System

Given its densely urbanized setting in a hilly terrain with vulnerable geological and weather conditions, Hong Kong and many other places alike are prone to landslides. Even with the implementation of a robust slope safety system, landslide risk cannot be entirely eliminated. This is illustrated by the fact that an average of about 300 landslides occurring within or close to developed areas in Hong Kong are reported to the GEO each year; the exact number varies significantly depending on the actual weather conditions (Figure 2). In addition, many more landslides, especially natural terrain landslides, occurring further away from the developed areas are not reported to the GEO. Landslide emergency management is an essential component of a slope safety system, to deal with landslides in adverse circumstances, such as heavy rain, snowmelt or earthquake. Hong Kong faces such adverse circumstances normally three to four times each year, when hit by severe monsoon rainfall typically exceeding about 250 mm (i.e. about 10% of the average annual rainfall) in 24 hours. In such an event, the GEO issues Landslip Warning through the Hong Kong Observatory (HKO). Rainfall at this level of intensity, which occurs from time to time, is not an extreme event in Hong Kong.

Emergency management is the discipline of dealing with and avoiding or mitigating natural and man-made disasters. It serves to protect the community from the adverse consequences of disasters, via developing and implementing processes to manage a range of related phases and activities, including:

- 'Prevention': Preventative activities to provide protection from disasters, e.g. in the case of landslide emergency management, setting up and enforcing the use of suitable slope design, construction, supervision and maintenance standards.

- 'Mitigation': Mitigation involves structural engineering and non-structural engineering measures to limit the impact of disasters, e.g. retrofitting sub-standard slopes to reduce the chance of landslide.

- 'Preparedness': Preparedness focuses on preparing equipment, procedures, etc. for use when a disaster occurs. It also involves preparing the vulnerable community to respond to the landslide disaster, e.g. taking suitable personal precautionary actions during Landslip Warning.

- 'Response': The response phase of an emergency may commence with search and rescue, and it also involves evacuating and fulfilling the basic humanitarian needs of the affected population. Emergency inspections for identification of any imminent danger and necessary response actions, and safe settlement of the people evacuated are examples of response activities.

- 'Recovery': The recovery phase starts after the immediate threat to human life has subsided. The immediate goal of the recovery phase is to bring the affected area back to some degree of normalcy, e.g. carrying out landslide repair works.

While slope safety systems commonly include provision for emergency management, the existing systems are rarely designed for, nor tested against, extreme events. The Hong Kong Slope Safety System is of no exception. The system has proved to be effective in managing landslide risk and in dealing with emergency management under severe rainfall conditions, such as those typically encountered in Hong Kong when Landslip Warning is issued. Having a sound system in place and thereby maintaining a healthy state of 'Prevention' and 'Mitigation' would help reduce the adverse consequences under extreme events. However, the system has not been specifically designed to cope with extreme events, particularly in respect of 'Preparedness', 'Response' and 'Recovery'.

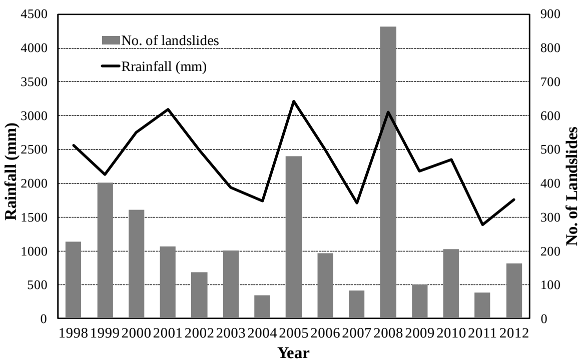

Fig. 2 Annual rainfall and reported landslides for the past 15 years

3.2 Landslides under Extreme Earthquake Events

In this paper, 'extreme event' generally refers to rare, fierce and adverse physical conditions at the extremes of the relevant historical or statistical distribution. As far as landslide risk management is concerned, the extreme events under consideration are those which would bring about many sizeable and/or mobile landslides. Extreme landslide scenarios are landslide scenarios under such extreme events. They are characterized by widespread and disastrous landsliding which could lead to serious loss of life and damage, as was observed in severe earthquakes, such as the 2008 Wenchuan earthquake.

Source	Data Period	Total Death Toll Due to Landslides (A)	Death Toll Due to Earthquake-induced Landslides (B)	Percentage due to Earthquake-induced Landslides (%)
Petley (2011)	2004 - 2010	80,058 (11,437 per year)	47,736 (6,819 per year)	~ 60%
USGS (2010)	1911 - 2010	267,833 (2,678 per year)	176,655 (1,767 per year)	~ 65%
Source	Data Period	Total Death Toll Due to Earthquake (A)	Death Toll Due to Earthquake-induced Landslides (B)	Percentage due to Earthquake-induced Landslides (%)
Marano et al (2010)	1968 - 2008	1,217,342 (29,691 per year)	70,525 (1,720 per year)	~ 6%
Daniell & Vervaeck (2012)	1900 - 2012	1,875,839 (16,600 per year)	270,253 (2,392 per year)	~ 14%

Table 2 World Landslide and Earthquake Fatalities

Table 2 shows the available data on world landslide and earthquake fatalities. The data compiled by Petley (2011) indicated that about 60% of the 80,058 known landslide fatalities from 2004 to 2010 were caused by landslides directly triggered by earthquakes. The 32,322 non-seismic landslide fatalities occurred in 2,620 landslides, i.e. on average 12 fatalities in a non-seismic landslide. However, the vast majority (approximately 95%) of seismic landslide fatalities came from two extreme events, viz. the 2005 Kashmir earthquake in Pakistan (7.6 Mw) and the 2008 Wenchuan earthquake in China (7.9 Mw). As illustrated in Figure 3, the world non-seismic landslide fatalities have a relatively linear occurrence. In contrast, seismic landslide fatalities predominantly take place in individual extreme earthquake events. This shows, from the perspective of landslide risk management in a global context, the need to give due attention to seismic-induced landslides under extreme earthquake events. These extreme earthquake events also provide invaluable information and insights for evaluating and preparing for extreme landslide scenarios arising from other extreme physical events.

In earthquakes, the proportion of death toll due to seismic-induced landslides varies significantly, depending largely on whether or not the earthquakes hit landslide-prone areas that are populated. It has been reported that about 6% to 14 % of the world earthquake fatalities are due to landslides directly caused by earthquakes (Table 2). However, in the 2008 Wenchuan earthquake, about 20,000 of the 69,000 total fatalities, i.e. 29%, were reported to have been directly caused by landslides (Yin et al, 2009; USGS, 2013). Also, in the 2005 Kashmir earthquake, about 25,500 of the 86,000 total fatalities, i.e. 30%, were reported to have been directly caused by landslides (USGS, 2010; USGS, 2013). The severity of seismic-induced landsides in extreme earthquake events is also evident from the widespread slope failures and the scale and mobility of the landslides (Figure 4), which not only result in serious direct damage but also pose major difficulties to the 'Response' and "Recovery' work.

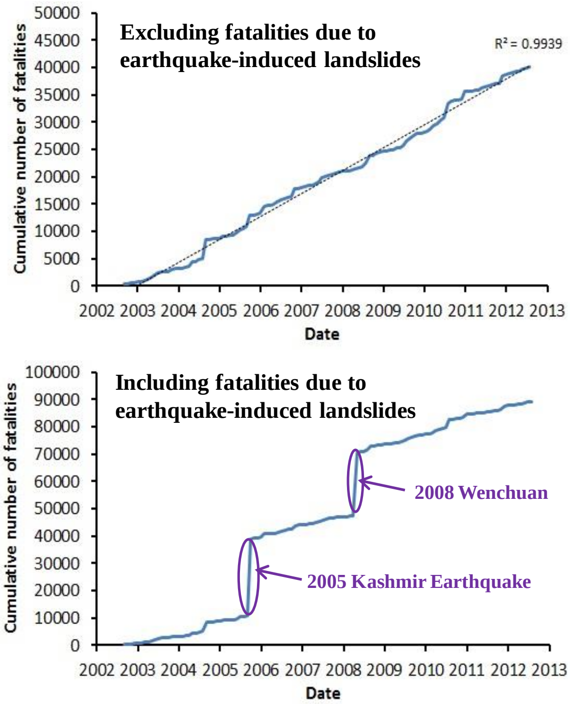

Fig. 3 World landslide fatalities from 2002 to 2012 (Petley, 2012)

Apart from landslides directly triggered by seismic actions, rain-induced landslide and debris flow activities are known to increase significantly after landslide-prone areas are hit by strong earthquakes. The effect could last for decades. It could seriously hinder the rescue work and recovery phase, and become a new challenge to the slope safety system in managing landslide risk after the earthquake. For instance, the total landslide area in Taiwan was reported to have increased drastically, both in terms of the frequency of occurrence and scale of failure, after the 1999 7.7 Mw Chi-chi earthquake (Lin et al, 2003). About 160 fatalities were reported to have been caused by landslides in the earthquake. However, six debris flows in the earthquake-hit area in the two years after the earthquake resulted in more than 240 fatalities, while the average annual number of landslide fatalities in Taiwan before the earthquake was about 15 from 1941 to 1986 (Chang, 1996). Likewise, increased landslide activity and damage are observed in Sichuan after the 2008 Wenchuan earthquake (e.g. Yin et al, 2009). Figure 5 shows the cumulative number of non-seismic landslide fatalities in Sichuan Province, China from 2003 to 2011 (Petley, 2011). It is noted that the annual number of non-seismic landslide fatalities after the Wenchuan earthquake (i.e. about 150 nos.) is approximately twice as much as that before the earthquake (i.e. about 70 nos.).

Fig. 4 Widespread slope failures in 2008 Wenchuan Earthquake

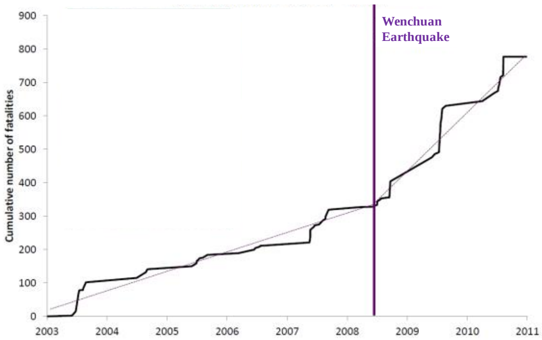

Fig. 5 Cumulative fatalities from non-seismic landslides in Sichuan Province, China (Petley, 2011)

3.3 Landslides under Extreme Rainfall Events

It is well recognized that landslide activity would increase with rainfall, and many cases of widespread landslides and disastrous slope failures triggered by severe rain have been reported by researchers and practitioners. However, little work on comprehensive assessment of extreme rainfall events and the consequential extreme landslide scenarios has been conducted. It is an established practice that strong earthquakes are systematically studied by international teams. However, similar arrangements are rarely made on landslides in extreme rainfall events.

Hong Kong has maintained comprehensive landslide records in the past 30 years since the setting up of the GEO. Recent and relict natural terrain landslides and debris flows in Hong Kong have been systematically mapped by the GEO using the available stock of territory-wide, high resolution aerial photographs dating back to the 1920s, together with application of the latest air-borne Light Detection and Ranging (LiDAR) technology. These data provide essential information for evaluating slope/hillside responses to rainfall, and form a basis for operation of GEO's Landslip Warning system, landslide QRA, and the on-going work on assessment of extreme landslide scenarios.

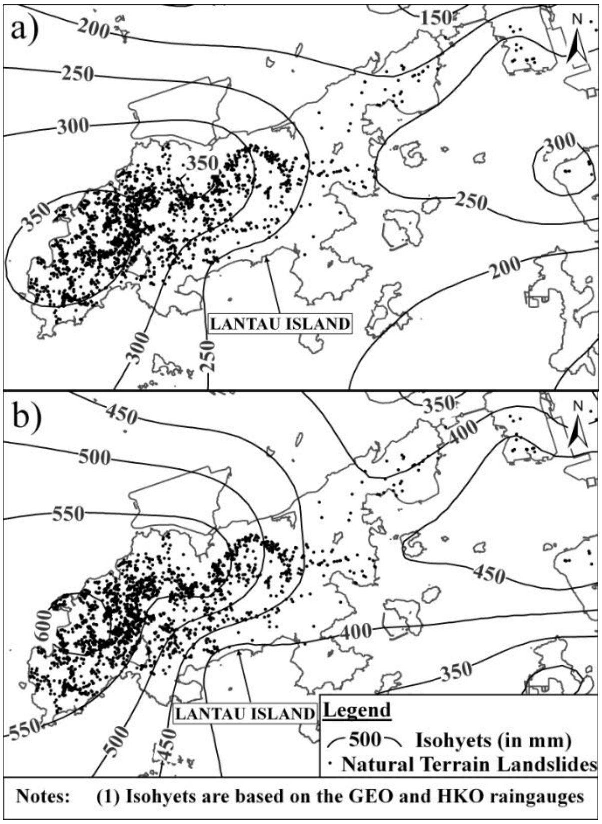

Fig. 6 Maximum rolling a). 4-hr and b). 24-hr rainfall distribution for the 7 June 2008 rainstorm.

Fig. 7 Landslides in the June 2008 rainstorm

Among the available Hong Kong data, the June 2008 rainstorm which hit Lantau Island (Figures 6 and 7) is most illustrative of the acute landslide conditions that may resemble that occurring in an extreme rainfall event. The maximum 4-hour rainfall of 384 mm recorded in the rainstorm corresponds to a projected statistical return period of over 1,100 years, while the maximum 24-hour rainfall of 623 mm (i.e. about 27% of the average annual rainfall) has a return period of 200 years. The rainstorm resulted in about 2,400 natural terrain landslides on Lantau Island. Apart from occurrence of widespread landslides, the mobility of landslide debris (Figure 8) and the scale (i.e. volume) of landslides were also observed to have significantly increased as compared with that in the landslide inventory (Wong, 2009b). The landslides have resulted in serious disruptions to the local community and difficulties in the response and recovery operations. The June 2008 rainstorm illustrates that occurrence of extreme rainfall events with serious landslide consequences in Hong Kong is possible and cannot be disregarded in slope safety management.

Fig. 8 Mobile debris flows on Lantau in the June 2008 rainstorm

3.4 Addressing Extreme Landslide Scenarios

Extreme landslide scenarios, whether earthquake- or rain-induced, share some similarities which are of primary concern in risk and emergency management:

- Widespread landslides with increased propensity, scale and mobility of failure, and resulting in serious damage and casualties.

- The large number of landslides and affected population, together with breakdown of infrastructure and the ongoing nature of landslide hazards, pose a grave challenge to the response and recovery work.

- There is generally a lack of understanding of the nature and severity of extreme landslide scenarios, partly due to the scarcity of their occurrence and partly due to insufficient attention given to studying extreme landslide events in the past. Preparedness for their emergency management is generally inadequate, which could perceivably aggravate the consequence of the disaster.

- The available data indicate that landslides caused by individual extreme earthquakes have brought about a major proportion of the total landslide fatalities worldwide. This should be considered in the light that strong earthquakes could affect a very large region, e.g. landslides in the 2008 Wenchuan earthquake led to strong ground shaking and widespread landslides in about 300 km by 100 km of hilly terrain (Fan et al, 2012). Extreme rainfall events tend to affect a much smaller region. Hence, while the total landslide damage and death toll in extreme rainfall events would not be as drastic as those in extreme earthquake events, the landslide impact of an extreme rainfall event in a more local area, e.g. a city like Hong Kong, could be as serious as the landslide impact from an extreme earthquake event. Furthermore, given the possible effects of climate change, there is a concern of both increased frequency of occurrence and severity of extreme rainfall events.

- It is known that landslide activity would increase and thereby result in a prolonged landslide risk management challenge after a strong earthquake. As the natural hillside in Hong Kong is subject to an ongoing degrading process, the author believes that increased nature terrain landslide activity may also occur in Hong Kong after an extreme rainfall event, albeit perhaps not as severe as in the case after an extreme earthquake event.

- From a global perspective, the available data indicate that the overwhelming majority (about 90% in the period from 2001 to 2010) of the worldwide geophysical and hydrological victims (Table 3), including those caused by earthquake, landslide, volcanic and flood disasters, occur in Asia (Guha-Sapir et al, 2012). Hence, the Asia region is most in need of expanded attention to tackle the potential disasters.

Average number of victims (million) / Continent	Geophysical (Earthquake, Volcano, Mass Movement (dry))	Hydrological (Flood, Mass Movement (wet))
Africa	0.08 (0.9%)	2.18 (2.0%)
Americas	1.02 (11.4%)	3.31 (3.1%)
Asia	7.77 (87.1%)	100.82 (94.5%)
Europe	0.01 (0.1%)	0.35 (0.3%)
Oceania	0.04 (0.5%)	0.04 (0.1%)
Global	8.92 (100%)	106.70 (100%)

Table 3 Natural disaster victims in different continents from 2001 to 2010 (based on Guha-Sapir et al, 2012)

- Given the nature of extreme events and the limitations of the available technology and resources, it is not pragmatic to aim to prevent failures in extreme landslide scenarios. Taking cognizance of the infrequent occurrence of extreme landslide scenarios, emergency management would constitute the principal strategy for tackling extreme landslide scenarios. This has also been the approach taken in dealing with non-landslide-related damages (e.g. structural failures) in extreme earthquake events.

As part of continuous improvement to the Hong Kong Slope Safety System, the GEO has been making an expanded effort to assess and enhance the resilience of the system in combating extreme landslide events. This is a prudent and timely endeavor given the vulnerability of the population at risk and infrastructure to landslides and the likelihood of more frequent occurrence of extreme rainfall conditions due to effects of climate change. Salient aspects and preliminary findings are briefly described below.

4. PREPAREDNESS FOR EXTREME LANDSLIDE EVENTS IN HONG KONG

4.1 Identifying the Nature and Magnitude of Extreme Events

As presented by Cheung & Koo (2013) to this Conference, studies conducted by the GEO have concluded that the probability of slope failure triggered directly by seismic activity is about one order of magnitude lower than that of rain-induced landslides in Hong Kong. Hence, extreme rainfall events, rather than earthquake events, are of primary concern in slope safety management in Hong Kong.

In order to determine the theoretical upper limit of the depth of precipitation that may bring about extreme landslide scenarios in Hong Kong, the GEO conducted a study in collaboration with the HKO on the Probable Maximum Precipitation (PMP) in the late 1990s. PMP is defined as the greatest depth of precipitation for a given duration meteorologically possible for a design watershed or a given storm area at a particular location at a particular time of year (WMO, 2009). By nature, this is similar to 'Maximum Credible Earthquake' in seismic hazard assessment and in evaluation of extreme seismic events. The PMP relevant to landslide assessment in Hong Kong was found to be a maximum of 1300 mm in 24 hours, with a characteristic spatial distribution of rainfall with different intensities, see Figure 9 (HKO, 1999). In terms of the maximum 24-hour rainfall, the June 2008 rainstorm corresponds to about 60% of the PMP. This has been adopted by the GEO as an extreme event scenario for evaluation of emergency preparedness. Consideration is also given to the scenario of about 85% to 90% of PMP, which corresponds to a notional return period in the order of 10,000 years, for evaluating extreme landslide events to be addressed in the worst circumstance.

The PMP assessment is being updated in an on-going study by the GEO, with support from Nanjing University of Information Science & Technology and a working group comprising HKO, University of Hong Kong, Hong Kong University of Science & Technology, Hong Kong Institution of Engineers, Drainage Services Department and Water Supplies Department. In this update, consideration is given to modeling a hypothetical rainstorm based on the rainfall data of the Typhoon Morakot that hit Taiwan in 2009 using the storm transposition technique. The typhoon resulted in the maximum 24-hour rainfall of about 1600 mm in Taiwan (Central Weather Bureau, 2013). It is likely that the update will result in an assessed PMP with a higher 24-hour rainfall. At this stage, no account has been taken of the potential effects of long-term climate trends, which may impact on both the frequency and severity of the assessed PMP scenarios.

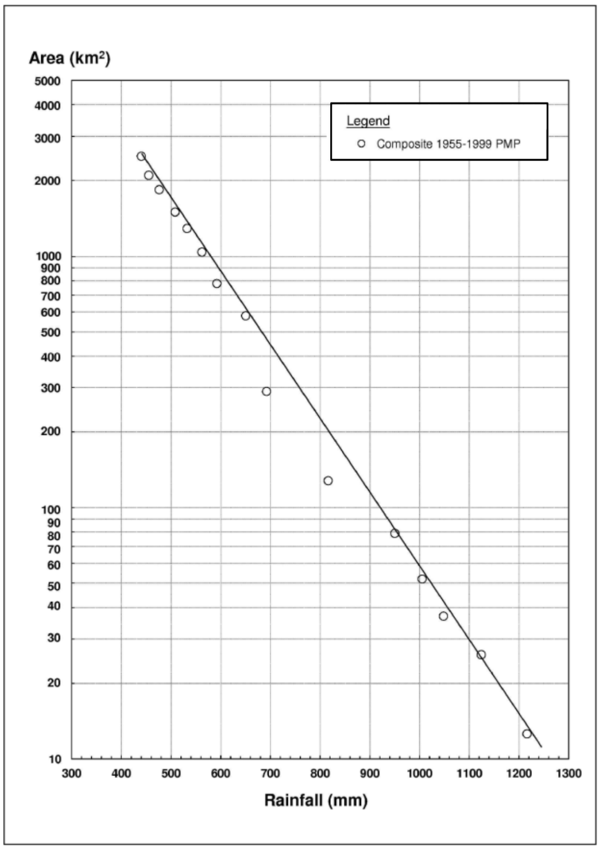

Fig. 9 Current 24-hour PMP Estimate for Hong Kong (HKO, 1999)

4.2 Assessing the Severity of Landslide Scenarios

Two important areas of work are involved in assessing the severity of landslide scenarios: (i) assessing the landslide responses, i.e. extreme landslide scenarios, under rainfall scenarios corresponding to the 60% and 85% to 90% of the PMP, and (ii) assessing the consequences of the extreme landslide scenarios.

For (i), the GEO has established probabilistic landslide-rainfall correlations for both man-made slope failures (Yu et al, 2003) and natural terrain landslides (Ko, 2005). The correlations were based on the comprehensive data available on the spatial and temporal distribution of rainfall intensity and landslide occurrence. Figure 10 shows the rainfall-natural terrain landslide correlation based on normalized maximum rolling 24-hour rainfall (obtained by dividing the maximum rolling 24-hour rainfall by the mean annual rainfall (1952 to 2000) at the same location). The landslide density is the number of natural terrain landslide per km^2. The landslide density increases exponentially with the normalized maximum rolling 24-hour rainfall. In extreme rainfall conditions, widespread natural terrain landslides would occur and become the predominant landslide hazards. It should be noted that only limited data are available on landslides under extreme rainfall intensities. The forward prediction of the landslide scenarios under extreme rainfall intensities therefore requires considerable data extrapolation and hence involves significant uncertainty. The historical data available from individual severe rainstorms, e.g. the June 2008 rainstorm, provide a means for projecting the scale of natural terrain failure and debris mobility under extreme rainfall intensities. However, caution is also needed when using the historical data as a basis for assessing the scale of landslide and mobility of landslide debris in extreme events by data extrapolation. Large scale and mobile landslides may potentially be under-represented.

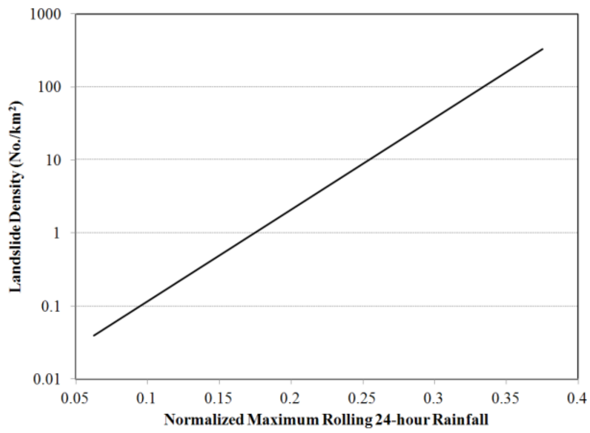

Fig. 10 Rainfall-Natural Terrain Landslide Correlation Based on Normalized Maximum Rolling 24-hour Rainfall

For (ii), the GEO has developed QRA models to assess and quantify the consequence of landslides (Wong et al, 1997; ERM-Hong Kong, Ltd, 1999; Wong, 2005). The models have been applied in a preliminary assessment of the landslide consequence for a hypothetical scenario in which the Mid-levels area on Hong Kong Island is hit by the 2008 rainstorm which actually affected the western part of Lantau Island, i.e. 60% PMP scenario. The assessment indicated that about 1,900 natural terrain landslides could occur, about 150 to 250 of which could affect roads and buildings (Lau et al, 2012). The Potential Loss of Life (PLL) predicted by the models is about 10, which is about two orders of magnitude higher than the annual average PLL in the area.

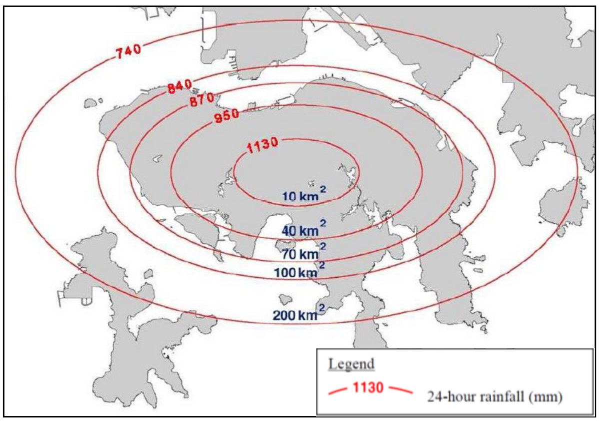

Fig. 11 24-hour Rainfall Distribution of a Hypothetical Rainstorm Corresponding to 0.9 times the Current PMP Estimate Occurring over Hong Kong Island

A similar analysis was also conducted to assess the landslide scenario of Hong Kong Island being struck by an extreme rainstorm that corresponds to 90% of the PMP (Figure 11). The assessment indicated that about 50,000 natural terrain landslides could occur on Hong Kong Island (Leung & Lo, 2013), where the landslides may result in detachment of about 10% of the natural terrain area. About 3,000 to 10,000 of the landslides could affect roads and buildings. This large predicted number of natural terrain landslides resulting from the extreme rainstorm would overwhelm the capacity of the current landslide emergency management system, as discussed below. Both the 'response' and 'recovery' phases would face acute challenges and the landslide consequences could be very serious.

4.3 Evaluating the Capacity of Emergency Management

The GEO has been operating a landslide emergency system since 1978 to provide emergency services to minimize casualty and damage to property and to facilitate recovery under adverse rainfall conditions. An assessment has been made on the possible capacity of the system in handling landslip emergency, based on consideration of the available human resources for emergency inspection of landslide incidents that require GEO's input in the emergency response. The preliminary findings indicate that the existing system is able to handle up to about 160 to 190 nos. of natural terrain failures, or about 340 to 390 nos. of man-made slope failures, For natural terrain failures, based on the assumptions that 15% of the landslides run into developed areas and 40% of these require GEO's emergency input, this corresponds to a total of about 2,700 landslides. In practice, the proportion of natural terrain landslides running into developed areas and requiring GEO's emergency input varies in different parts of Hong Kong. For man-made slopes failures, this corresponds to a total of about 1,100 to 1,300 landslides, based on past experience about the overall proportion of reported landslides that involve significant consequences and require GEO's emergency input. It should be noted that this is the existing capacity following the current practice of dealing with reported landslides and making recommendations on emergency actions to be taken, such as evacuation of buildings, closure of affected areas and assessment of the urgent works required to ensure public safety. This implies that, under the current set-up, a 60% PMP hitting a densely populated area on Hong Kong Island would stretch the existing system to the limit. In comparison, within about one-third of the capacity of the system was mobilized in June 2008 when the event hit the relatively sparsely populated and yet less accessible western part of Lantau Island.

Other bottlenecks would almost certainly exist in emergency management, such as transport arrangement, communication facilities and provision for safe settlement of the affected community, which are constrained by the capacity of the other government agencies or non-government organizations 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.

4.4 Improving Crisis Preparedness

The available resources of the existing system have a limited capacity in handling landslide emergency under an extreme event, particularly when 60% PMP is exceeded under which widespread natural terrain landslides would occur. To further enhance the resilience of the Hong Kong Slope Safety System in combating extreme landslide events, attention should be given to improving crisis preparedness, with different strategies and emphases for the following two extreme rainfall scenarios:

(a) Up to about 60% PMP which corresponds to a notional return period in the order of 1,000 years:

The main focus is to ensure effective and efficient emergency management when the system is stretched to the limit, which calls for streamlining the emergency response with due priority given to critical cases and enhancing preparedness by identifying and dealing with possible bottlenecks.

(b) Exceeding 60% PMP and up to about 85% PMP which corresponds to a notional return period in the order of 10,000 years:

The capacity of the existing system will be exceedingly overwhelmed, and the current mode of operation will become ineffective and inefficient in emergency management. This calls for development and implementation of a new strategy and measures for managing the emergency.

While the approach for enhancing the resilience differs in the two scenarios, potential areas for improvement include:

- 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 mobilization of resources from the private sector and quasi-government organizations to assist in emergency management under extreme landslide events.
- Streamlining the emergency management procedures and practice for dealing with extreme landslide events focusing on where priority attention are required in order to facilitate provision of the essential emergency response actions, e.g. ensure timely acquisition of the key information required for identification and classification of landslides to facilitate deployment of emergency teams to sites most in need of support.
- Revamping the emergency management strategy to make it more pragmatic and effective to implement within the constraints under extreme landslide events, e.g. empower the affected members of the public to take the appropriate emergency response actions to protect themselves and minimize exposure to landslide hazards by providing them with the necessary knowledge and information to make their own decisions on emergency response.
- Improving 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.
- Utilizing the new set of natural terrain landslide alert criteria recently formulated (Chan et al. 2012) to enhance fore-warning and landslide emergency mobilization in the event that widespread natural terrain landslides are predicted under critical rainfall conditions.
- Conducting forums, workshops and drills to ensure preparedness of the emergency teams and engage the vulnerable community and relevant stakeholders in emergency management and response.

The resilience of the slope safety system in combating extreme landslide events is critically affected by the resilience of the vulnerable population and the relevant stakeholders in facing the events. Maintaining vigilance of the extreme landslide scenarios and awareness of emergency management is essential to crisis preparedness. Hence, public education and communication are as important as technical assessments, formulation of emergency plans and procedures, and preventive and mitigation works. An account of the role of public education and communication in the Hong Kong Slope Safety System is presented to this Conference by Tam & Lui (2013).

5. CONCLUSION

Extreme landslide scenarios induced by strong earthquakes or acute rainfall conditions are characterized by widespread landslides with escalated propensity, scale and mobility of failure. These could lead to disastrous consequences, and pose a grave challenge to crisis preparedness and slope safety management. Increased attention is called for to enhance the resilience of the existing slope safety systems in dealing with extreme landslide events. The work that is being pursued in Hong Kong illustrates the possible scope and outcome of the initiatives on assessing and improving emergency management under extreme landslide scenarios.

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