Mitigation Strategy for Low-frequency Large-magnitude Debris Flows in Hong Kong

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Abstract. Potential hazards arising from low-frequency large-magnitude debris flows have become apparent under the adverse impact of climate change and extreme weather. Hong Kong has systematically managed landslide risks arising from man-made slopes and natural hillsides since 1977, owing to its unique geographic location, steep terrain, deep weathering profile and post-war rapid urban development. In recent years, evaluation of potential hazards arising from low-frequency large-magnitude debris flows and their possible dire consequences has developed into a key part of the landslide mitigation effort in Hong Kong in light of the occurrence of more frequent and more severe extreme rainfall events. Valuable experience is gained in identifying potential low-frequency large-magnitude debris flow hazards, assessing their potential impacts to the public located at the densely populated foothills and developing a holistic strategy to mitigate against potentially catastrophic consequences. This paper sets out the mitigation strategy for mitigating low-frequency large-magnitude debris flows in Hong Kong and gives a case study to demonstrate the approach.

1 Introduction

The landslide problem in Hong Kong is chronic, owing to its unique geographic location, steep terrain, deep weathering profile and post-war rapid urban development. Since 1940s, landslides have caused over 470 fatalities in Hong Kong, majority of which have happened before the implementation of the comprehensive Slope Safety System by the Geotechnical Engineering Office (GEO) established in 1977 [1]. Recently, extreme rainfall events, which have become more frequent and severe in Hong Kong, have triggered sizeable landslides in terms of source volume and mobility that have resulted in unprecedented disruption and damage.

Hong Kong is located at the south-eastern tip of China and frequent with tropical cyclones and low pressure troughs between May and September, bringing heavy rain and thunderstorms. It has an average annual rainfall of 2,400 mm, which is highly seasonal, short-duration, high-intensity (24-hour intensity exceeding 300 mm and 1-hour intensity exceeding 70 mm are not uncommon) and unevenly distributed across Hong Kong. It has a land area of about 1,100 km^2, with some 75% steeper than 15° and over 30% steeper than 30°. The terrain is mantled by weak saprolitic or residual soils, or colluvial deposits derived from past landslides and erosion processes. Upon the impact of short-duration high-intensity rainfall, the steep hillsides are highly susceptible to rain-induced landslides as they are subject to continual degradation [2].

Hong Kong has a population of 7.3 million as in mid-2022. Intense urban development has taken place on flat ground and in foothill areas, and is progressively encroaching on the steep hillsides where landslides from man-made slopes and natural terrain could pose a significant hazard. With the highly populated developments along the foothill areas, even a small failure on natural terrain can cause devastating life and economic consequences.

In June 2008, a severe rainstorm hit Hong Kong and triggered over 3,000 landslides on the natural hillsides. Many of the landslides were sizeable debris flows with much greater runout distance than those that had previously occurred in Hong Kong and resulted in devastating disruption and damage (Fig. 1). The Hong Kong Observatory has indicated that extreme rainfall events have become more frequent and more severe. The hourly rainfall record at the Hong Kong Observatory Headquarters was broken several times in the last few decades, whereas in the past, one record was only broken in several decades (Fig. 2). In light of the looming impacts of extreme weather, the GEO has recognised the need to adopt a proactive approach to identify, study and mitigate against those sizeable debris flows, though relatively rare, with a view to reducing the landslide risk to the public to a level as low as reasonably practicable (ALARP). These sizeable but relatively rare events are termed low-frequency large-magnitude (LFLM) events in Hong Kong.

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Fig. 1. Landslide debris caused the closure of North Lantau Highway, the critical transport corridor to the Hong Kong International Airport, in June 2008.

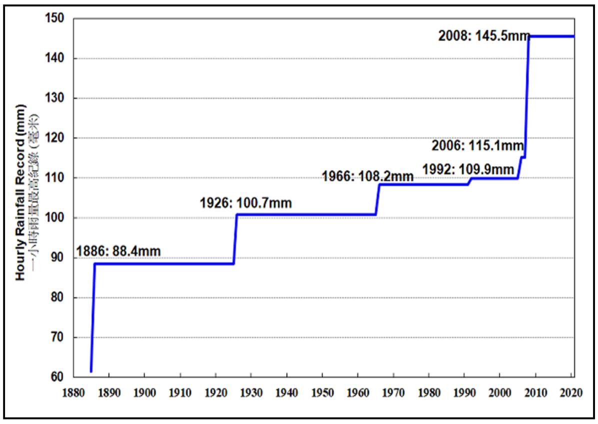

Fig. 2. Hourly rainfall record at the Hong Kong Observatory Headquarters.

2 LFLM debris flows

2.1 Characteristics

Numerous sizeable debris flows of notable volumes (e.g. an active debris volume in excess of 10,000 m^3) with long runout distances (>1 km on plan) occurred in the June 2008 severe rainstorm (Fig. 3). The normal range of volumes of natural terrain landslides in Hong Kong is in the order of a few tens to a few hundreds cubic metres. The large-magnitude events have previously not occurred in Hong Kong as far as the historical records have shown. The triggering June 2008 severe rainstorm was equally a rare event, with its maximum rolling 4-hour rainfall at the western Lantau Island of Hong Kong having a return period of about 1,000 years [2]. In addition, this rainstorm is ranked the fourth in terms of 4-hour maximum rainfall in the historical records kept by the Hong Kong Observatory (Table 1). The detailed mapping and back analyses of these LFLM debris flows have diagnosed their characteristics as:

(a) Hillside topography: The catchments are hilly with elevation differences more than 300 m [2]. The upper terrain is usually steeper than 30° and underlain by in-situ weathered volcanic or granitic rocks, while the foothill is generally gentle sloping (< 15°).

(b) Flow capability: The presence of a major drainage line in hillside catchments has been identified as an adverse site setting that are prone to the development of LFLM debris flows with watery debris of high mobility in Hong Kong [2]. These drainage lines are associated with large catchments and long debris flow paths where a large amount of storm water and entrainable materials may be available for mixing with the landslide debris under extreme rainfall scenarios.

(c) Landslide volume: Based on the characteristics of the landslides occurred in the June 2008 rainstorm, best-estimated, upper-credible and lower-credible models were proposed to establish the relationship between the magnitude and the notional return period (NRP) for catchments with adverse site settings pertaining to debris flows [3]. The results suggested that the probable orders of magnitude for LFLM debris flow events could be up to tens of thousands cubic metres.

(d) Landslide mobility: Based on the results of back analyses of selected LFLM debris flows occurred in the June 2008 rainstorm using 2d-DMM [4-5], the back calculated apparent friction angle (ϕ_a) and turbulence coefficient (ξ) of Voellmy model could be as low as 8° and 500 m/s^2 respectively [6].

Fig. 3. An example of a LFLM debris flow occurred during the June 2008 rainstorm.

Table 1. Top ranked 4-hour rainfall events at the Hong Kong Observatory Headquarters [7].

Rank	Date and Time (yy-mm-dd hh)	4-hour Maximum Rainfall (mm)
1	1889-05-30 02	302.3
2	1926-07-19 04	292.4
3	1966-06-12 06	273.4
4	2008-06-07 07	246.3

2.2 Need for mitigation

The GEO has recognised the need to adopt a proactive approach to identify, study and mitigate against those sizeable debris flows, though relatively rare, for the following considerations:

(a) As extreme weather is poised to increase, and from the lessons learnt in the mapping of the June 2008 landslides, LFLM debris flows may not be as rare as one might have perceived. At the same time, rapid urban development has resulted in denser population encroaching into steep hillsides, many of these with adverse site setting favourable to the occurrence of LFLM debris flows (Fig. 4). If a similar event as the June 2008 rainstorm hit these vulnerable areas again, dire consequences (e.g. building collapse or multiple fatalities) are probable. It is plausible to think and plan ahead how best the Government should and could protect public lives from landslide hazards arising from LFLM debris flows, knowing that actions take time to materialise.

(b) With continuous technical development in the understanding of debris flow initiation and motion in the past one to two decades, the methodology developed to identify and determine landslide source areas and volumes as well as entrainment potential has proved effective and practicable. Advanced numerical tools are also available to analyse and estimate debris mobility and debris-barrier interaction with higher degree of estimation and level of confidence [8]. The current state of knowledge and technical capability have enabled the development of some feasible solutions to mitigate LFLM events.

(c) In a very developed society as Hong Kong, the public has high expectation on the Government to protect them well and has low degree of tolerance to life loss, social disruption and property damage due to natural disasters. Despite there is a need to take a balance between what should be done and what could be done, and the need to strengthen public adaptation and resilience against adverse impacts of extreme weather, the Government always has a duty of care to protect public lives and property as far as practicable.

3 Mitigation strategy

The approach for Natural Terrain Hazard Study (NTHS) and design of mitigation measures for hazards up to a notional return period of 100 years (namely Design Event) are outlined in [9]. With a view to systematically dealing with the risk of LFLM events in Hong Kong, a three-tier approach is adopted:

(a) Design event - This event, which is expected to occur during the design life of the commonly adopted mitigation measures, such as rigid or flexible debris-resisting barriers, is assessed in an NTHS and the consequences mitigated on the basis of the current state of best knowledge of typical debris flows and design requirements [9]. A single debris-resisting barrier together with some deflection structures or energy dissipation structures at the lower portion of the terrain is usually effective.

Fig. 4. A view of natural terrain on Hong Kong Island overlooking the adjoining dense developments.

(b) LFLM event - The mitigation measures provided for the Design Event should endure for the LFLM event while debris volume beyond the Design Event is allowed to overflow downstream. This is to acknowledge the fact that it is impractical, costly and environmentally undesirable to construct a super-structure to fully contain a rare event, which is not credible.

(c) Overflow debris - Other prescriptive and sacrificial mitigation measures in the form of segregation, retention, deflection and/or energy dissipation of the overflow debris are adopted to further reduce the landslide risk to the public at the downstream as far as practicable.

Depending on the different topography of different terrain, there is considerable room for engineering innovation for improving the design, construction and maintenance of natural terrain landslide risk mitigation measures, bearing in mind the importance of communicating risk to the public, minimising disruption to the environment and facilitating future maintenance.

4 Case study

One of the vulnerable hillside catchments with adverse site setting is the Fei Ngo Shan study area. The study area comprises a channelised catchment with a major drainage line of approximately 700 m long, overlooking a residential development (Fig. 5). Methodology suggested in Section 2.1(c) was adopted for the estimation of the magnitude and frequency of potential landslides up to a NRP of 10,000 years in the study area. Debris mobility modelling using 2d-DMM [4-5] was carried out to determine (1) whether debris would reach the residential development concerned, and if affirmative, (2) the corresponding debris impact on the residential development. Vollemy parameters given in Section 2.1(d) were adopted in the modelling. Mitigation strategy including a rigid debris-resisting barrier for the Design Event and a series of prescriptive impediments (e.g. baffles) to reduce the mobility of the debris and damage beyond the Design Event was adopted.

In parallel, a quantitative risk assessment (QRA) was carried out to assess the risk level posed to the residential development concerned under extreme rainfall scenarios as compared to the risk tolerability criteria [10] and to verify the reasonableness of the mitigation strategy as proposed. The QRA generally followed the framework by [11] and the key modules of work suggested in [12] for the Ling Pei site.

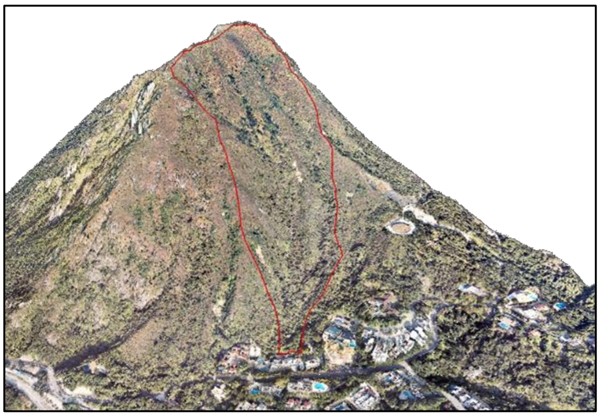

Fig. 5. General view of the Fei Ngo Shan study area.

The results of this site-specific QRA revealed that both the calculated Personal Individual Risk (PIR) and Societal Risk (SR) arising from the Design Event with a NRP of 100 years are unacceptable (Fig. 6). However, the calculated PIR and SR arising from the LFLM event are acceptable and within the ALARP region respectively. A rigid debris-resisting barrier for the Design Event and prescriptive measures should be proposed to deal with both the calculated and residual risks arising from the Design Event and LFLM event respectively (Fig. 7). The QRA results confirmed that the mitigation strategy as proposed is appropriate and reasonable.

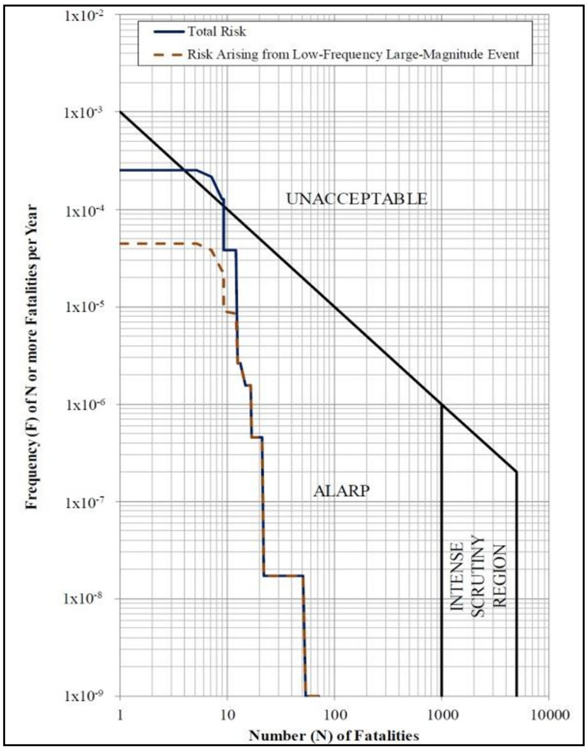

Fig. 6. Calculated F-N curve for the Fei Ngo Shan study area.

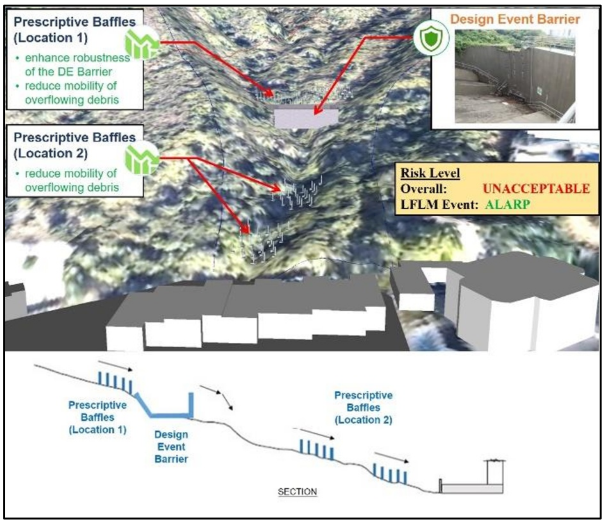

Fig. 7. Schematic model of the mitigation strategy for the Fei Ngo Shan study area.

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