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Debris flow mitigation – research and practice in Hong Kong

Ken K.S. Ho[a,*], Raymond C.H. Koo[a], Julian S.H. Kwan[a]

[a] *Geotechnical Engineering Office, Civil Engineering and Development Department, Hong Kong SAR Government, China*

Abstract

Dense urban development on a hilly terrain, coupled with intense seasonal rainfall and heterogeneous weathered profiles, gives rise to acute debris flow problems in Hong Kong. The Geotechnical Engineering Office (GEO) of the Hong Kong SAR Government has launched a holistic R&D programme and collaborated with various tertiary institutes and professional bodies to support the development of a comprehensive technical framework for managing landslide risk and designing debris flow mitigation measures. The scope of the technical development work includes compilation of landslide inventories, field studies of debris flows, development and calibration of tools for landslide runout modelling, back analysis of notable debris flows, physical and numerical modelling of the interaction of debris flow and mitigation measures, formulation of a technical framework for evaluating debris flow hazards, and development of pragmatic mitigation strategies and design methodologies for debris flow countermeasures. The work has advanced the technical understanding of debris flow hazards and transformed the natural terrain landslide risk management practice in Hong Kong. New analytical tools and improved design methodologies are being applied in routine geotechnical engineering practice.

Keywords: Debris flow mitigation; landslide risk management

1. Introduction

Starting in 2010, systematic study and mitigation of natural terrain landslide risk has become a core component of the Hong Kong Government′s Landslip Prevention and Mitigation (LPMit) Programme, which is managed by the Geotechnical Engineering Office (GEO). In order to tackle natural terrain landslide hazards, technical development work has been in progress by GEO since the late-1990s. Through systematic mapping and studies of notable landslides, advances have been made in the understanding of the mechanisms and classification of natural terrain landslides and debris movement, together with the formulation of risk management and hazard mitigation strategies.

Based on the state-of-the-art knowledge, GEO developed a technical framework for evaluating landslide hazards (Ho et al., 2015), and implemented R&D studies to advance the strategy and design of mitigation measures in order to reduce landslide risk to an as low as reasonably practicable (ALARP) level.

This paper presents the progressive development of the natural terrain risk mitigation practice in Hong Kong, and the advances made by the R&D work. The practical challenges in relation to the design, construction and maintenance of landslide mitigation measures are discussed.

2. Nature of Natural Terrain Landslides

Hong Kong has a population of over 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 being steeper than 15° and 30% steeper than 30°. Rainfall intensities exceeding 70 mm/hour and 300 mm/day are not uncommon. The dense urban development on a hilly terrain, together with intense seasonal rainfall and variable weathered profiles, gives rises to acute slope safety problems in Hong Kong. This is reflected by a death toll of over 470 fatalities due to landslides since the 1940s.

* Corresponding author e-mail address*: kenho@cedd.gov.hk*

Hong Kong comprises a hilly terrain with dense urban development close to steep hillsides. The natural terrain is typically mantled by weak and heterogeneous saprolite or colluvium, which is susceptible to shallow, small to medium-scale landslides (see Figure 1), usually several hundreds cubic metres, or occasionally more sizeable, due to loss of suction or build up of local perched water pressure as a result of intense rainstorms. This can be further complicated by ongoing progressive deterioration of the condition of the natural hillside due to successive heavy rainstorms. These landslides can develop into debris flows where debris reaches drainage lines with surface water flow resulting in increased mobility (i.e. larger velocity and greater runout distance). Based on the landslide inventory, on average about one landslide occurs each year for every 2 km^2 of natural hillside in Hong Kong. Occasionally, larger scale debris flows (see Figure 2) can occur given adverse site setting and intense rainfall. The inventory, compiled using aerial photographs, contains records of more than 100,000 past failures on the natural hillsides in Hong Kong.

Apart from structural, geological and hydrogeological factors, unfavourable topographical factors can also contribute to increased susceptibility to landslide initiation, such as breaks in slope, topographic depression, head of drainage line, and presence of regolith downslope of a rock outcrop.

Channelised debris flows along incised drainage lines or pronounced topographic depressions with concentrated surface water flow tend to be more mobile (as compared to landslides on a planar hillslope) with notable velocities (in the order of 10 m/s or more). Due cognizance needs to be taken of the nature of channelised debris flows in the design of mitigation measures. Debris flows can occur in pulses and may entrain loose materials due to erosion along the flowpath. They can also engulf large boulders, which can be isolated or in clusters occurring as a bouldery front, typically with an inverse grading due to reverse segregation (see Figure 3). The complex and transient nature of such surge two-phase flows can be further complicated by the presence of large broken tree trunks. Additionally, there is the possibility of dam break pulses occurring along the drainage line due to build-up of a temporary debris dam.

Fig. 1. Landslide-prone natural terrain of Hong Kong

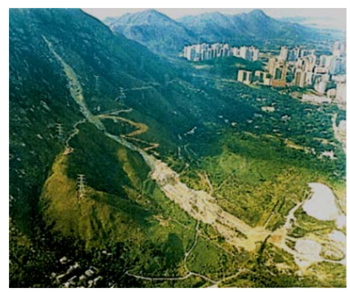


Fig. 2. The 1990 channelised debris flow at Tsing Shan

Fig. 3. Bouldery front of channelised debris flows observed in June 2008 in Hong Kong

3. Natural Terrain Landslide Risk Management

The Geotechnical Engineering Office (GEO) has launched a holistic R&D programme and collaborated with various tertiary institutes and professional bodies to support the development of a comprehensive technical framework for managing landslide risk and designing debris flow mitigation measures with more scientific rigour. The scope of the technical development work includes compilation of landslide inventories, field studies of debris flows, development and calibration of tools for landslide mobility modelling, back analysis of notable debris flows, physical and numerical modelling of the interaction of debris flow and mitigation measures, formulation of a technical framework for evaluating debris flow hazards, and development of pragmatic mitigation strategies and design methodologies for debris flow countermeasures. The work, which spans the last two decades, has advanced the technical understanding of debris flow hazards and transformed the natural terrain landslide risk management practice in Hong Kong. New analytical tools and improved design methodologies are being applied in routine geotechnical engineering practice by local practitioners including geotechnical engineers and engineering geologists.

One of these new tools is an emphasis on risk-based management. Landslide risk can be quantified as follows:

$$\text{Risk} = P_{\text{i}} \times C_{\text{i}} \tag{1}$$

where P_{i} is probability of occurrence of landslide hazard and C_{i} is landslide consequence.

The risk posed to a given facility can be managed by reducing P_{i} by means of stabilisation works or by reducing C_{i} through mitigation measures, or by doing both. For existing facilities such as buildings or roads subjected to natural terrain hazards, slope stabilisation on the steep hillside is often neither practically nor economically and environmentally justifiable. Instead, an active mitigation strategy involving the implementation of mitigation measures (such as debris-resisting rigid barriers, steel flexible barriers, or boulder fences) is more practicable (Ho, et al., 2015). In view of the complexities and uncertainties associated with debris flows, emphasis has been given by GEO in developing and adopting pragmatic and suitably simplified barrier design methods. An overview of the advances in geotechnology for slope stabilisation and landslide mitigation was given by Ho (2005).

4. Evolution of Barrier Design Practice

4.1. Phase 1 – Development of Barrier Design Guidelines

Traditionally, the assessment of natural terrain landslide hazards was undertaken by engineering geologists through an engineering geological approach, with a qualitative risk assessment and the necessary risk mitigation measures determined largely by experience and judgement. The process was typically not particularly transparent.

Starting in the late 1990s, significant advances have been made by GEO in developing practical numerical tools for debris mobility assessment and calibrating the rheological models and input parameters through systematic back analysis of local case histories of the more mobile landslides (Kwan & Sun, 2007). GEO also promulgated guidance on the assessment of debris discharge, flow velocity and thickness, debris run-up, retention capacity of barriers, and surface drainage provisions (GEO, 2014).

The technical guidance on mitigation measures promulgated by GEO at that time covers primarily the design of rigid barriers against debris and boulder impact. In developing the guidance, a holistic approach was adopted including benchmarking against international practice and reviewing relevant laboratory and field studies, back analysis of instrumented field data, performance review of barriers upon impact by landslides, etc. In essence, the basis of the guidance promulgated at this early stage was largely empirical, supported by literature review and limited field studies.

4.2. Phase 2 – Rationalisation and Enhancement of Barrier Design Guidelines

From about 2010 onwards, GEO initiated further R&D work focusing on the use of flexible and rigid barriers to arrest natural terrain landslides.

The advances have led to an improved understanding which enables the guidance on barrier design to be rationalised and expanded. The basis of the enhanced design approaches is multi-pronged, including back analysis of field observations, use of physical models (laboratory flume), numerical techniques, analytical solutions, etc. A key consideration is to build in sufficient robustness to cater for the uncertainties in the field associated with the complex characteristics and variable composition of debris flows. The work culminated in the promulgation of new or improved design guidance covering the following areas:

(a) a design methodology for the impact of debris and boulders on rigid and flexible barriers using a force approach (Kwan & Cheung, 2012);

(b) a design methodology for debris impact on flexible barriers using the energy approach based on insight from Discrete Element Model (DEM) analysis and a simplified analytical framework (Sun & Law, 2012);

(c) a design methodology for debris impact on rigid or flexible barriers using the force approach, including a multiple-phase debris impact model which accounts for dynamic impact pressure and static earth pressure of the deposited debris , with due allowance made for the variation in debris velocities at different phases of debris impact as computed from debris mobility analysis (GEO, 2015), together with allowance for the additional drag force in the event the debris overtops the barrier;

(d) an analytical framework for the design of multiple barriers (with the upstream barriers acting as check dams) based on a newly developed staged mobility analysis (Kwan et al., 2015); and

(e) a design framework for the use of prescribed flexible barriers in mitigating open hillslope landslides in order to streamline the design process (GEO, 2014).

The current design approaches adopted in Hong Kong are summarised in Figures 4 and 5.

Step 1

(i) Calculate energy loading for pile-up mechanism (E_p)

$$E_p = \frac{\alpha \rho Q_0 (U_0)^3}{4(\mu \cos\theta - \sin\theta) g}$$

(ii) Calculate energy loading for run-up mechanism (E_r)

$$E_r = \frac{\rho Q_0 (U_0)^5 \cos(\theta+\gamma)\sin(\theta+\gamma)}{48 h_0 g^2 (\mu\cos\theta - \sin\theta)^2}$$

where α is dynamic coefficient (taken to be 2.0 for flexible barrier); ρ is debris density; Q_0 is discharge rate; U_0 is debris impact velocity; μ is basal friction coefficient (i.e. tan ϕ); ϕ is debris friction angle; θ is inclination of channel base; γ is inclination of ramp formed by debris behind the barrier; and g is gravity

Step 2

(i) Calculate kinetic energy of landslide debris when the debris front reaches the design location of flexible barrier (E_{k1})

(ii) Calculate kinetic energy of landslide debris that pass through the design location of flexible barrier (E_{k2})

Step 3

Design energy loading $E = \min\{\max(E_p, E_r), \max(E_{k1}, E_{k2})\}$

Step 4

Check if design energy loading $\leq 0.75 \times$ energy rating of flexible barrier certified by ETA full-scale rockfall test.

Notes: (1) For other design checks, see (ii), (iii) & (iv) of Figure 5.
(2) If Step 4 cannot be satisfied, then use force approach for design.

Fig. 4. Summary of the energy approach for design of flexible barriers

(i) Calculate dynamic load of debris and boulder impact

Debris impact pressure $p = \alpha \rho v^2$ where α is dynamic coefficient, ρ is debris density & v is impact velocity

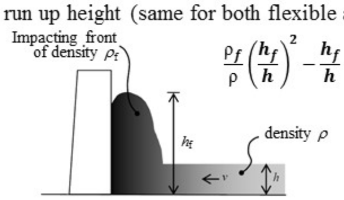
Rigid barriers - assume $\alpha = 2.5$ for debris with boulders up to 0.5 m in size

Flexible barriers - assume $\alpha = 2.0$ for debris with boulders up to 2.0 m in size

Boulder impact force $F = 4000\, K_c\, v_b^{1.2}\, r_b^2$ (for rigid barriers)

where K_c is reduction coefficient (taken = 0.1), v_b is impact velocity and r_b is boulder diameter

(ii) Check run up height (same for both flexible and rigid barriers)



$$\frac{\rho_f}{\rho}\left(\frac{h_f}{h}\right)^2 - \frac{h_f}{h} - 1 + \left(\frac{\rho_f h_f}{\rho h}\right)^{-1} - 2\frac{v^2}{gh} = 0$$

(Kwan & Cheung, 2012)

where ρ is debris density, v is impact velocity, g is gravity and h is debris thickness

(iii) Check static load from debris deposited behind the barrier (same for both flexible and rigid barriers)

Debris static pressure $p_s = K \rho g h$ where K is lateral pressure coefficient (taken = 1), g is gravity & h is deposited debris height

(iv) Check retention capacity based on gradient of the deposition area (i.e. tan γ) and gradient of the slope channel (i.e. tan θ)

tan γ = 1/2 to 3/4 × tan θ (for rigid barriers)

tan γ = 0 (for flexible barriers)

For flexible barriers, the residual barrier height should be considered after final barrier deformation upon debris impact.

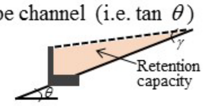


Fig. 5. Summary of the force approach and key design checks for flexible and rigid barriers

The concepts of a composite structure comprising a rigid barrier with baffles to dissipate the energy of landslide debris and arrest some of the boulders, together with a cushioning layer on the rigid barrier front face to help reduce boulder impact load, are promoted to enhance robustness.

Apart from the promulgation of technical design guidelines, GEO has also published guidance on other related design and construction issues as follows:

(a) suitable detailing of rigid and flexible barriers (e.g. avoiding damage of posts in flexible barrier due to boulder impact, improving drainage provisions, and enhancing resilience against scouring of the substrate of the barrier foundation, detailing of a deflector at the crest of a rigid barrier to avoid spillage of debris due to debris run-up upon impact, etc.);

(b) improvement of contract specification for new flexible barriers to enhance durability based on a performance review of about 100 local barriers, together with retrofitting of deteriorated steel components of existing barriers; and

(c) guidance on slope landscaping and use of bioengineering techniques to improve the aesthetics and biodiversity of the plants on or close to the barriers (GEO, 2011).

GEO is currently also using Building Information Modelling (BIM) model to examine buildability issues and construction sequencing in order to optimise the design layout of barriers and minimise cut and fill operations.

4.3. Phase 3 – Optimisation of Barrier Design

To validate or calibrate the various design approaches and improve the understanding of barrier behaviour with a view to optimising barrier design, GEO has continued to undertake in-house development work and collaborate with practitioners and with local tertiary institutes and overseas experts in pursuing various R&D initiatives. These include the use of state-of-the-art physical modelling (centrifuge as well as laboratory and field flume tests) to study mechanisms, application of advanced numerical modelling, and development of new analytical approaches.

i. Displacement-based approach for assessing geotechnical stability and flexural response of rigid barriers

Conventional force-based design approaches often result in over-design of rigid barriers subject to debris impact which is transient in nature. The newly proposed displacement-based approach could provide a more realistic evaluation of the performance of rigid barriers subject to boulder impact. Based on fundamental principles of dynamic analysis, Lam & Kwan (2016) developed closed-form formulae for estimating the translational and rotational movements, as well as the flexural deflection and tensile reinforcement strain of rigid barriers, due to boulder impact. A series of small scale impact tests were carried out to verify the predictions using this displacement-based approach (Lam et al., 2017) and good agreement was obtained. A comparison was made between the displacement-based approach and the conventional limit equilibrium analysis. Based on the impact scenarios that are typically encountered in routine design (i.e. a 1 m diameter boulder with a velocity of 10 m/s impacting onto a typical 6 m high, 10 m long rigid barrier), the predicted translational and rotational movements of the barrier were found to be insignificant based on the displacement-based approach. Large-scale tests were also carried out to investigate the structural response of a rigid barrier subject to impact by a solid steel impactor, which successfully validated the enhanced flexural stiffness method. The above have demonstrated that substantial cost savings could potentially be achieved in barrier designs by accounting for the inertia effect of a rigid barrier.

ii. Field testing of cushioning materials for reducing boulder impact load on rigid barriers

Field monitoring and observations together with recent centrifuge tests indicate that impacts due to hard inclusions (i.e. boulder front) of a debris flow can result in high magnitude and transient loads on a rigid barrier. With a view to damping out these force spikes, a systematic study on the use of different cushioning materials to shield the barrier was initiated by the GEO. In general, the cushioning materials are deformable and thus capable of prolonging the impact process and attenuating the impulsive forces due to the hard inclusions. A large-scale instrumented pendulum impact test facility involving a 1.16 m diameter concrete ball (2,000 kg in weight) with a maximum impact velocity of 8.4 m/s and a kinetic energy of up to 70 kJ was set up. Four types of cushioning materials, namely rock-filled gabions, recycled glass cullet, ethylene-vinyl acetate (EVA) foam, and cellular glass, were tested. The results show that the cushion layer could effectively reduce the maximum impact forces although it would become less effective after successive impacts (Ng et al., 2018). The test data were also used to calibrate numerical models for further parametric studies.

Recent large-scale impact tests have also shown the effectiveness of a gabion cushioning layer in preventing localized structural damage (such as cracking, penetration, perforation and scabbing) in a reinforced concrete barrier, and in substantially reducing the flexural deflection at barrier crest (by 67% to 90%).

iii. Study on use of baffles to dissipate energy of debris flow

Baffles are flow-impeding structures installed along the flow path to dissipate the energy of debris flows and screen out large boulders. A series of instrumented flume tests and back analyses were carried out to investigate dry sand flow impact on an array of baffles (Choi et al., 2014). The influence of baffle height, number of rows, and transverse and longitudinal spacing of baffles was systematically examined. These small-scale tests with dry sand indicate that increasing the baffle height from 0.75 to 1.5 times the approaching flow depth would lead to a more effective development of subcritical flow condition which promotes energy dissipation of the debris. Increasing the number of rows from a single row to a staggered three-row array results in about 70% additional energy loss. Energy loss is attributed to the deflection of granular jets and backwater effects.

iv. Advanced coupled analysis of debris-barrier interaction

Advanced numerical modelling has been adopted to simulate debris-barrier interaction using the computer program LS-DYNA. Various researchers (e.g. Kwan et al., 2015, Koo et al., 2018) have demonstrated that the use of Arbitrary Lagrangian-Eulerian method in LS-DYNA appears to be a promising tool for modelling debris flow and debris-barrier interaction. Such modelling has been benchmarked against laboratory flume tests and actual landslide cases in terms of debris runout characteristics. In the conventional approach, landslide mobility analyses and structural analyses of the barrier are carried out separately. The landslide mobility is first simulated under a free-field condition to obtain design parameters such as flow velocity and depth (e.g. 3d-DMM by Kwan & Sun, 2007), which are then converted into a pseudo-static impact force as input to a separate structural model (e.g. computer program NIDA-MNN by Sze et al., 2018). This latter approach however neglects the dynamics of debris-barrier interaction.

Coupled analyses can be carried out using LS-DYNA, with the landslide mass modelled as a continuum in a finite element formulation (see Figure 6). The results successfully reproduced the deformation and forces in various structural components as observed in instrumented case studies (Cheung et al., 2018). The coupled analyses also provided insight on the energy dissipation of landslide debris in the debris-barrier interaction process. The preliminary findings are that the overall strain energy absorbed by the flexible barrier upon debris impact only amounted to a fairly small portion (generally less than 35% based on parametric studies) of the total debris impact energy, as due to internal distortion of the debris and changes in momentum flux direction under a debris run-up mechanism upon impact. It is noteworthy that the continuum model adopted in LS-DYNA has certain limitations as it may not fully simulate particle-fluid interaction and the presence of hard inclusions at the debris front. Other research tools such as coupled analysis using discrete element models and computational fluid dynamics models are being used to examine the potential effects of particle-fluid interaction (Li & Zhao, 2018).

v. Parametric study of varied debris composition and different barrier configurations using physical tests

Centrifuge and/or flume tests were conducted for various types of mitigation structures (e.g. flexible barrier, curved rigid barrier, slit barrier, etc.) to examine the effects of impact mechanisms and influence of different debris composition under controlled conditions (Choi et al., 2016; Ng et al., 2016; Song et al., 2017). During the frontal impact of a two-phase debris flow without hard inclusions, the measured dynamic pressure coefficient in the hydrodynamic approach is close to unity (which confirms the principle of conservation of momentum), for both rigid and flexible barriers that are upright (note that the coefficient is less than unity for a curved rigid barrier subject to impact by coarse granular flow). Increasing the solid fraction of a debris flow was found to promote transition from run-up to pile-up mechanisms. Furthermore, test results indicate that the presence of large hard inclusions (boulders) in the debris flow are liable to induce transient force spikes reflecting significant impulse loading on a rigid barrier.

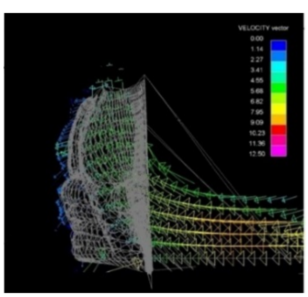


Fig. 6. LS-DYNA simulation of debris impact on flexible barrier

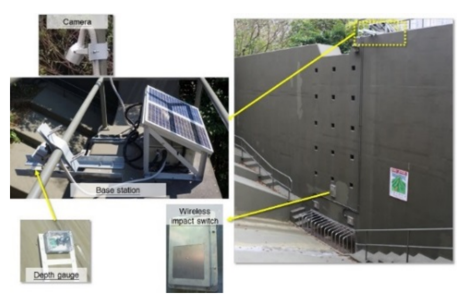


Fig. 7. Smart rigid barrier system

5. Way Forward

The above studies have provided useful yardsticks for calibrating or bracketing existing design approaches. They further highlight that there is potential scope for further rationalising and optimising the design, e.g. the numerical coupled analyses suggest that the impact energy transmitted to a flexible barrier could be much lower than that assessed by the current design approach because of internal distortion of the debris and change in momentum flux direction. Similarly, the displacement approach, corroborated by laboratory model tests, suggests that the dynamic force exerted on a rigid barrier would be much lower than conventional elastic theory taking due account of the inertia effect. Notwithstanding the above, it should be borne in mind that the physical models are constrained by the use of idealised materials as compared to real life debris flows, and potentially by uncertainties involved in scaling up the observed behaviour. As a basis for validation of the observed insights from the latest R&D work with a view to optimising the design methods, large-scale field tests are planned with a failure volume up to about 500 m^3. Class A predictions could be made, which would be calibrated by large-scale field tests using a material composition that resembles real debris flows as much as possible.

6. Ongoing Challenges

Some ongoing challenges and pertinent issues faced by the practitioners are highlighted below:

(a) Behaviour of energy dissipation (or brake) elements – brake elements are an essential component of a flexible barrier in dissipating the impact energy. However, there is as yet no internationally recognised testing standard to check their stress strain characteristics at an appropriate strain rate and assess their degree of variability. Based on limited site observations following debris impact (e.g. Kwan et al., 2014), there is an element of uncertainty regarding the actual behaviour of different types of brake elements, particularly when they become buried by landslide debris (as some of them apparently were not activated following debris impact and barrier deformation).

(b) Potential for under-estimation of landslide hazards due to climate change – recent local experience with extreme rainfall events has shown that the response of natural hillsides in Hong Kong is highly sensitive to more severe rainfall in that the number, scale and mobility of landslides are much elevated. The assessment of the landslide hazard to be designed for during the design life of the mitigation measure is fraught with considerable uncertainty and difficulty, given that the relatively short time window available for compiling the landslide inventory may not have captured the extreme rainfall events. This is exacerbated by the increased likelihood of occurrence of more frequent and intense weather events associated with potential climate change. The possibility of barriers being under-designed and overwhelmed by more sizeable and/or more mobile landslide hazards than those anticipated by designers based on prior knowledge and experience calls for a paradigm shift in the strategy for managing the associated landslide risk. A recent initiative by the GEO is the development of smart barriers incorporating the use of real time wireless sensors and Internet of Things (IoT) and cloud computing technology to provide early warning of landslide impact and facilitate timely emergency response (see Figure 7). Other recent advances in the management of landslide risk associated with extreme weather events in Hong Kong entailed refinement of the landslide warning system (Ho et al., 2017), development of rainfall-based landslide susceptibility zoning (Ko & Lo, 2018), and innovative approaches in enhanced public education. The above are some of the non-structural measures of landslide risk management under a systems approach in addressing landslide risk in a holistic manner.

(c) Durability and long-term maintenance of flexible barriers – a cost effective long term strategy for maintenance of flexible barriers is needed, given that the steel components are subject to progressive deterioration in hot and humid climates like Hong Kong. It is also necessary to have improved knowledge on the rate of corrosion of steel components and various forms of treatment in corrosive environments.

7. Concluding Remarks

The design of landslide risk mitigation measures for debris flows and other flow-like landslides is highly challenging in light of the many uncertainties involved. A holistic and progressive approach has been adopted in Hong Kong to improve our fundamental knowledge of debris flows and to provide scientific insight into the behaviour of debris-resisting landslide barriers as a result of debris-structure interaction (e.g. effect of Froude number of debris flows on impact behaviour, influence of debris impact mechanisms, presence of a dead zone associated with debris deposition upon initial impact, effect of varied debris composition including solid fraction, postulated effect of suction on debris mobility and impact behaviour, influence of compressibility of debris flow on impact behaviour, etc.). The systematic technical development work carried out on landslide mitigation measures has led to an improved understanding of the related mechanisms and the controlling parameters. Nevertheless, it is important to remain pragmatic and to strike a suitable balance in translating research findings into practice with due account taken of the simplifications made in the model testing and computational analyses as opposed to the complex and random nature of real debris flows in the field. Due allowance should also be made in the design for enhanced robustness and redundancy in managing the uncertainties.

Apart from the consideration of appropriate technical standards and improved design methodologies, it should be borne in mind that there are other pertinent issues that are of relevance to practitioners, including guidance on proper detailing of the works, consideration of buildability, the structural form to be adopted (e.g. post-supported flexible barrier versus side-anchored flexible barriers), an appropriate acceptance system for flexible barrier products for quality assurance and quality control, landscaping works, etc.

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