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Successful interception of natural terrain landslides by reinforced concrete debris-resisting barriers at two sites in Hong Kong

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ABSTRACT: A record-breaking severe rainstorm from 7 to 9 September 2023 triggered over 800 natural terrain landslides in Hong Kong, China. Reinforced concrete debris-resisting barriers built on the hillsides above Lei Pui Street and Hong Chi Pinehill Village effectively arrested the landslide debris, avoiding negative consequences for residents and facilities downstream. Post-landslide inspections found that the barriers remained intact without apparent damage. Investigations into these two rainfall-induced landslide incidents revealed that the landslides above Lei Pui Street were primarily caused by rainwater infiltrating the hillside through household refuse and fill. This infiltration was exacerbated by soil pipes and the concentrated discharge of surface water from squatter structures uphill, leading to a transient rise of the perched water table in the groundmass. In contrast, the landslides above Hong Chi Pinehill Village were attributed to water ingress into colluvium, developing a transient perched water table at the interface with the underlying saprolitic soil and locally shallow rockhead. Both incidents involved a transition from open hillslope failures to channelised debris flows. Separately, to understand the trajectory of the failed material and back-analyse the key rheological parameters, three-dimensional simulations were conducted to model the mobility of the debris flow and the debris impact on the barriers. The software used was LS-DYNA, which includes coupled Finite Element Method and Arbitrary Lagrangian-Eulerian solvers. For the numerical back-analyses, the apparent basal friction angles and turbulence coefficients were back-analysed to understand the evolution of the rheology as the flows entered channels. These incidents provide valuable insights into the performance of barriers in mitigating landslide risk on natural hillsides in Hong Kong. They also emphasise the importance of conducting comprehensive natural terrain hazard studies that consider site geology, geomorphology, and debris mobility in the design of mitigation works.

KEYWORDS: Landslides, natural terrain hazard studies, reinforced concrete debris-resisting barriers, debris mobility.

1 INTRODUCTION

Hong Kong, a metropolitan city located on the southeastern coast of China, is renowned for its unique integration of dense urban development and natural landscapes. With a population exceeding seven million and limited flat land, much of the city's infrastructure has been built on steep terrain near man-made slopes and natural hillsides. Hong Kong's sub-tropical climate brings a rainy season from April to October each year, leading to short-duration high-intensity rainfall caused by tropical troughs and typhoons. Over the past century, rain-induced landslides have frequently occurred in Hong Kong, causing significant socio-economic damage and loss of life, with 470 fatalities recorded since 1948. On average, approximately 300 landslides are reported to the government annually.

From 7 to 9 September 2023, Hong Kong experienced a record-breaking severe rainstorm associated with the remnants of Tropical Cyclone HaiKui (Tam et al., 2025). During this period, extreme rainfall overwhelmed the city, with the Hong Kong Observatory Headquarters recording an hourly rainfall of 158.1 mm between 11:00 p.m. and midnight on 7 September. This marked the highest hourly rainfall ever recorded since records began in 1884. From 7 to 8 September, the 24-hour total rainfall at the Hong Kong Observatory Headquarters reached 638.5 mm, which is approximately a quarter of the annual normal of 2,431.2 mm recorded between 1991 and 2020. This deluge caused widespread impacts across the territory, with many areas experiencing over 400 mm of rainfall within 24 hours. The Eastern District and Southern District of Hong Kong Island were particularly hard-hit, with rainfall exceeding 800 mm during this time.

This unprecedented rainstorm led to widespread devastation, triggering about 170 landslides on man-made slopes and over 800 landslides on natural hillsides. The torrential downpour swamped drainage systems and destabilised slopes across the territory. Among the significant incidents were two major landslides on the hillsides above Lei Pui Street and Hong Chi Pinehill Village. Both events were successfully intercepted by reinforced concrete debris-resisting barriers (referred to as 'rigid barriers'), preventing any adverse consequences for nearby residents and infrastructure. Notably, the rigid barriers remained undamaged.

Following these landslides, the Geotechnical Engineering Office (GEO) of the Civil Engineering and Development Department conducted detailed investigations to determine the probable causes and mechanisms of the failures. The landslides were likely triggered by the build-up of transient perched water tables at the interface between fill/colluvium and saprolite/bedrock, leading to a rapid loss of effective stress. Both landslides began as open hillslope failures and subsequently developed into channelised debris flows. Previous anthropogenic activities, including over-steepening and concentrated surface water discharge, had loosened near-surface materials, increasing the probability of landslides.

The investigation included topographic surveys, aerial photograph interpretation, and detailed geological mapping. To back-analyse key rheological parameters and assess the performance of the rigid barriers, a three-dimensional (3D) program, LS-DYNA, was used. These analyses enabled the modelling of the debris flow trajectory and the behaviour of the flows upon impacting the barriers. The rheological parameters describing the flows were hence evaluated, allowing for comparison with the design rheological parameters.

This paper describes the numerical modelling procedures and presents the findings from the landslide investigations and numerical analyses. The results provide valuable insights into natural terrain hazard mitigation strategies applicable to geologically vulnerable regions worldwide.

2 NUMERICAL MODELLING METHODOLOGY

LS-DYNA is a 3D physics-based program, which incorporates coupled Finite Element Method (FEM) and Arbitrary Lagrangian-Eulerian (ALE) formulations. The ALE can be used to model fluids, with flow dynamics ultimately governed by the Navier-Stokes (N-S) equations (the details of which can be modified to model specific equivalent fluids). A mesh must be defined for the ALE to specify where fluids can flow; the mesh can be set to move with the flow or be static, which are the Lagrangian and Eulerian usages, respectively. In this study, for modelling landslide events across highly uneven terrain, a Eulerian mesh is adopted, which practically is equivalent to the Finite Volume Method; no remeshing is involved. Solving the N-S equations in the ALE framework allows the flow to arbitrarily bifurcate or recombine, depending on its trajectory along the terrain, with no special handling necessary.

LS-DYNA has been calibrated against notable landslides in Hong Kong and benchmarked against other numerical programs (Koo, 2017). It has also been applied in various studies to simulate debris mobility, the behaviour of flexible steel debris-resisting barriers under impact, and the interactions between debris and barriers (e.g., Huang et al., 2014; Cheung et al., 2018).

2.1 *Topography and meshing*

In LS-DYNA, the topography is described by rigid, immobile two-dimensional planes defined through a sheet of linked nodes. The topographies for both sites were prepared by programmatically combining: (*i*) terrain profile data from a territory-wide Light Detection and Ranging (LiDAR) survey conducted prior to the landslides; and (*ii*) a post-landslide unmanned aerial vehicle (UAV) survey. Some manual adjustments were made to the terrain models to minimise noise from the UAV survey. For both cases, the digital terrain model had a resolution of 0.5 m, which was determined through a preliminary sensitivity study that identified this value as an optimal balance between numerical accuracy and runtime.

Generally, the 3D mesh for the ALE material was extruded vertically from the underlying topography, with a vertical mesh resolution of 0.5 m. This extrusion technique produces mesh elements that are deformed cuboids and provides an acceptable balance of physical accuracy and computational efficiency. In most regions of the domain, the 3D mesh extended approximately 4 m above the topography and about 1 m below it, which was sufficient to prevent boundary effects given the typical flow depth of 2 m. After an initial trial process, the 3D mesh was trimmed to cover only areas where the debris flow was likely to occur, optimising computational time.

2.2 *Modelling of reinforced concrete debris-resisting barriers*

The rigid barriers included structural walls, a deflector and gabion blocks. All these structural elements remained undamaged during the landslides. Consequently, they were modelled as 3D rigid elements in LS-DYNA. These elements belong to the FEM solver, but since they are rigid and fixed in space, no deformation occurs, so there is no need for attention to aspects such as hourglassing. Indeed, they simply behave as a fixed boundary condition for the equivalent fluids, with penalty-based coupling mediating contacts. For the penalty-coupling, nine coupling points were used per face of the solid elements within the barriers to facilitate proper interaction with debris.

The barriers were represented in LS-DYNA by drawing the footprint of each barrier component and then extruding it vertically. The elements were meshed in 3D, ensuring that the size of the solid elements comprising the barrier was comparable to the ALE mesh.

2.3 *Modelling of debris and its rheology*

In LS-DYNA, the landslide debris was modelled as a continuum using a static ALE formulation (i.e. Eulerian), allowing for large-scale deformation characteristic of flowing landslides to be captured. The continuum was described as an undrained, elasto-plastic material based on the Drucker-Prager constitutive model. The initial mass of the debris material was generated within enclosed spaces defined by shells at each source, with the remaining space filled with air. The debris rheology constituted an equivalent fluid. It employed a 3D formulation of the friction model for open hillslope failures and the very well-known Voellmy model for channelised debris flows, with the primary variable inputs for calibration being the apparent basal friction angle and the internal friction angle for the open hillside failure and channelised debris flow zones, respectively. Another variable was the turbulence coefficient. Vegetation is modelled implicitly as being part of the equivalent fluid, per typical design practice. Other parameters, including bulk density and Poisson's ratio, were calibrated with typical natural terrain landslides in Hong Kong.

2.4 *Modelling procedures*

At the initial time (t = 0 s), LS-DYNA generates the debris based on the specific source locations. Gravity is then gradually increased from zero to full strength over a period of 2 seconds to allow the debris to flow downstream. The commonly used 'dam break' technique is employed to release the debris in a manner consistent with the identified failure mechanism, which involves a widespread loss of effective stress across the failure surface. In the 'dam break' method, the mass of debris is released all at once by deactivating the top enclosure of the debris source in LS-DYNA, enabling the debris to flow downstream under the influence of gravity.

For the multi-source event at Hong Chi Pinehill Village, the materials in the source areas were assumed to fail simultaneously for simplicity. During both landslide events, the rheological parameters within the friction and Voellmy models were adjusted mid-simulation to account for reduced effective friction parameters once the debris material entered the drainage lines and became channelised. Previous back-analyses of debris flows in Hong Kong suggested that channelised debris flows experience significantly higher sustained pore pressures at the flow-ground interface than open hillslope failures, justifying changing the apparent basal friction angle.

The simulations continued until the global flow rate dropped below approximately 1 % of the maximum. After each simulation, data on the extent of debris deposition, the velocity and depth of the flow, and the forces exerted on the terminal barriers were extracted for analysis.

An iterative process was implemented to systematically study the flow rheology (including the interface friction angle and internal friction angles for the open hillside failure and channelised debris flow zones). The specific times during the simulation when the rheologies were modified for each source were also treated as a variable in this study. The primary criteria for calibration were the volume and spatial distribution of the deposited debris.

3 THE LEI PUI STREET LANDSLIDE

3.1 *Site setting*

The natural hillside above Lei Pui Street consists of a steep, southwest-facing terrain with elevations ranging from +109 mPD to +360 mPD. Several ephemeral drainage lines converge at the toe of the hillside, channelling water into a 2 m-wide concrete open channel that descends into the rigid barrier via a cascade. Since the 1960s, the development of Shek Lei Hill Village has significantly altered the area's landscape through the creation of agricultural terraces, footpaths, and squatter structures. There was a notable increase in the number of squatter structures and agricultural terraces up until 1974, after which the number stopped changing.

In response to a debris flow incident in 2001 on the natural hillside above Lei Pui Street (Maunsell, 2004), a rigid barrier was built at the toe of the hillside under the Landslip Preventive Measures Programme (LPMP) in 2002, as illustrated in Figure 1 (described in Section 3.3).

3.2 *Previous natural terrain hazard study*

In 2005, following the construction of the rigid barrier above Lei Pui Street, the GEO conducted a natural terrain hazard study. The purpose of the study was to identify potential natural terrain hazards that could affect existing residential development near Lei Pui Street and to assess the adequacy of the rigid barrier in mitigating potential landslide risks. The study employed both the design event approach and Quantitative Risk Assessment (QRA) (Ko et al., 2023).

The study identified potential channelised debris flows on the hillside, estimating a design event volume of 1,100 m^3, which included 600 m^3 at the source and 500 m^3 of entrainment along the flow path. The QRA confirmed that the rigid barrier was adequately designed to mitigate landslide risks to the facilities at the toe.

3.3 *Reinforced concrete debris-resisting barrier*

The rigid barrier has an L-shaped design in plan view, with a 19 m long main wall and a 10 m long wing wall. The main wall stands 4.5 m high, with a thickness varying from 1.5 m at the top to 1.8 m at the base. The wing wall has a constant thickness of 1.5 m. Additionally, two more wing walls were constructed further southeast to strengthen the system. Wing wall A is 4.5 m high and 10.5 m long, while wing wall B is 1.5 m high and 9.5 m long. Both wing walls have a thickness of 0.7 m.

The site also includes a 250 mm-wide U-channel, two open channels that are 1.5 m and 2 m wide, and the cascade (Figures 1 and 2a). These components are designed to intercept water flow from the natural stream course and redirect it away from the rigid barrier. Additionally, handrails are provided along the open channels to prevent falls from height (Figure 2a). Furthermore, two drainage pits with grilles and steel gratings were installed at the retention basin and cascade outlet to enhance water flow control and reduce the risk of blockage.

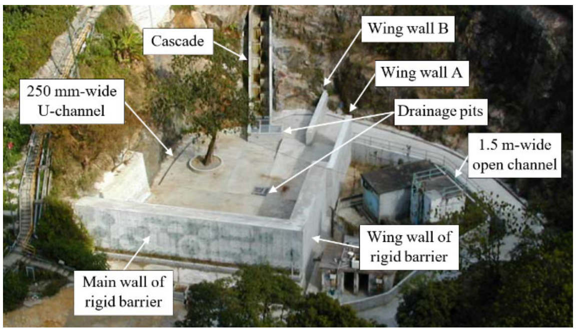

Figure 1. Rigid barrier prior to the landslide in 2023 (Lei Pui Street)

3.4 *Post-landslide investigation*

The landslide occurred beneath squatter structures on a concave, open hillslope terrain (Figure 2a). Before the landslide, the slope profile included terraced and vegetated areas, with a dip of approximately 35°. The source area measured 26 m in length and 19 m in width, with a maximum depth of 1.6 m. The landslide scar exposed a veneer of fill and household refuse up to 1 m thick, underlain by a 0.5 m-thick layer of residual soil (RS), and then strata of completely to highly decomposed granite (C/HDG). Soil pipes were occasionally observed at the base of the RS or C/HDG layers on the main scarp. The sources of rill erosion were traced back to surface runoff on a platform outside the squatter structures.

A significant debris lobe accumulated along a footpath adjacent to the 2 m-wide open channel at the base of the landslide scar. Although no debris was found inside the open channel, scattered debris was observed on the opposite side. It is likely that the debris initially entered the open channel, mixed with a large volume of water from the stream course, and was subsequently transported to the retention basin of the rigid barrier. The debris along the open channel and cascade resembled a channelised debris flow.

Inside the rigid barrier, the debris comprised unsorted silty sand with gravel, cobble, and occasionally boulder-sized rock fragments within a fine matrix. At the cascade outlet, the debris was intercepted by the debris grille at the drainage pit, allowing water to flow freely into the 1.5 m-wide open channel below.

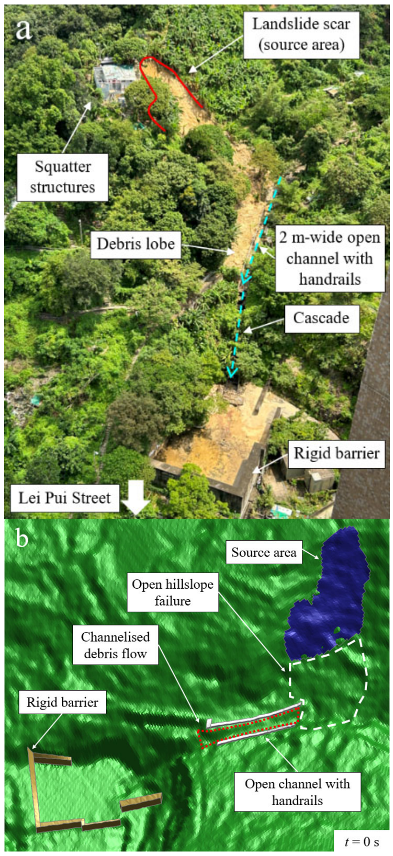

Figure 2. General view of the landslide (Lei Pui Street). (a) Aerial photo; (b) top-down view of the topography modelled in LS-DYNA ($t = 0$ s).

A change detection analysis was conducted to compare the point cloud model generated from the post-landslide handheld laser scanning and UAV survey data with the LiDAR survey data collected in 2020. Based on this analysis, the estimated source volume was about 260 m^3. Approximately 150 m^3 of the landslide debris was deposited on the footpath below the scar, while the remaining 100 m^3 travelled further downslope and was mostly contained by the rigid barrier. An outwash of debris of about 10 m^3 was observed outside the barrier.

The rigid barrier effectively intercepted and retained most of the debris from the landslide. No visible damage or deformation was observed on the barrier since the debris settled before impacting the main wall.

3.5 *Numerical back-analyses*

The landslide initially occurred as an open hillslope failure on the hillside (Figure 2b). A portion of the landslide debris entered the 2 m-wide open channel, where it became confined and channelised before coming to rest in the retention basin of the rigid barrier (Figure 3a). Most of this debris was contained within the area bordered by the handrails along the footpath. A small amount of debris that flowed beyond the handrails remained on the hillside, which was consistent with field observations.

By t = 45 seconds, the simulation was considered complete, as most of the debris had settled, with some entering the rigid barrier (Figure 3b). The numerical analyses effectively captured the progression and containment of the debris flow, aligning reasonably with the observed field conditions. Both in the simulations and in reality, the barrier did not use all its volumetric capacity, suggesting that the design was on the safe side.

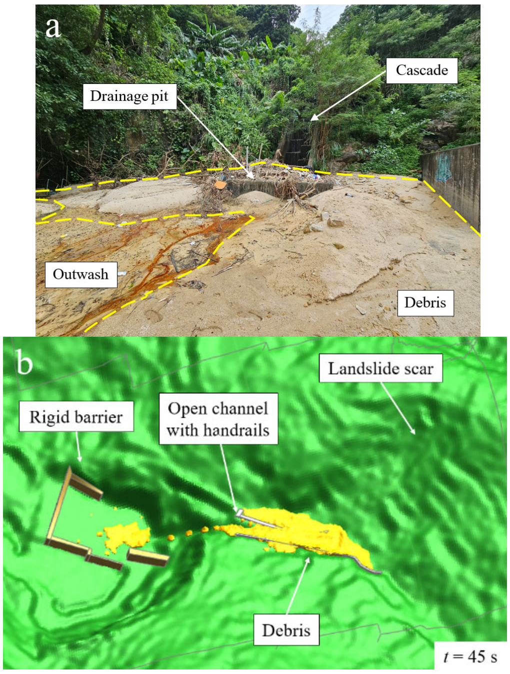

Figure 3. Debris contained within the rigid barrier (Lei Pui Street). (a) Photography, looking upstream in the rigid barrier; (b) top-down view of the debris deposited in LS-DYNA (t = 45 s).

4 THE HONG CHI PINEHILL VILLAGE LANDSLIDES

4.1 *Site setting*

Hong Chi Pinehill Village, including the Hong Chi Children's Home and Hong Chi Pinehill Schools, serves as a rehabilitation facility for individuals with intellectual disabilities located in Hong Kong. The village is situated at the toe of a natural hillside. The hillside features a southeast-facing terrain with elevations ranging from +46 mPD to +198 mPD. There are two drainage lines that direct water downhill toward a rigid barrier. Anthropogenic activities, such as vegetation clearance and horticultural planting, have taken place between the drainage lines in the middle and lower portions of the hillside, where the slope gradient ranges from 30° to 40°.

4.2 *Previous natural terrain hazard studies*

In 2011 and 2018, the GEO conducted natural terrain hazard studies for the hillside above Hong Chi Pinehill Village, an area with a known history of landsliding, under the Landslip Prevention and Mitigation Programme (LPMitP). The study identified channelised debris flows as a potential landslide hazard for the area. Using the design event approach (Wong, 2009), the estimated source volume for the largest channelised debris flow was about 460 m^3 at a spur. This estimate was based on a relict landslide, which had a high degree of certainty, along with aerial photograph interpretation and detailed field mapping. An additional entrainment volume of about 233 m^3 was included to account for material likely to be transported in the drainage lines due to colluvium along the flanks of the flow path. Consequently, the total design event volume was estimated at 693 m^3.

Debris mobility analyses for this design event were modelled using the two-dimensional numerical program DAN-W (HGR, 2010). Simulation results indicated a debris velocity of 9.6 m/s and a thickness of 0.6 m at the location of the rigid barrier under free-field conditions. In a multi-surge scenario, where the debris fills the barrier sequentially up to the design retention height in sequence (Kwan, 2012; Kwan et al., 2023), the analyses predicted a dynamic soil debris impact force of 101 kN/m during the first surge. Once the retention basin was completelyfilled with debris, accompanied by overtopping flow, the static soil debris force was estimated to be 585 kN/m.

4.3 *Reinforced concrete debris-resisting barrier*

The rigid barrier is a reinforced concrete structure built at the toe of the hillside between 2019 and 2022. It has a retention capacity of 1,050 m^3, which exceeds the design volume of 693 m^3 due to specific site constraints. These constraints included factors such as the bulking effect of the debris, the run-up height, and the channel width necessary to prevent excessive spillage or overflow.

The rigid barrier has a trapezoidal shape in plan view, featuring a front wall facing downslope, two wing walls on the flanks, and a stem wall located within the retention basin (Figure 4). The front wall measures about 15 m in length and 0.8 m in thickness, while each wing wall is 18 m long and 1 m thick. All walls are 6 m in height. The stem wall, which is 1.5 m thick and 12 m long, is positioned about 2 m behind the front wall within the retention basin. It extends up to 7.3 m, including a deflector at its top. In front of the stem wall, five layers of 1 m-thick gabion blocks are placed, facing the hillside, to aid in energy dissipation.

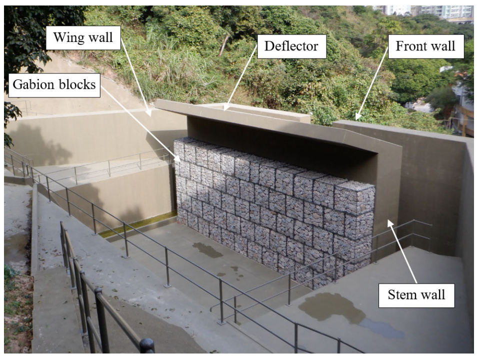

Figure 4. Rigid barrier before the landslides in 2023 (Hong Chi Pinehill Village)

Additionally, the rigid barrier is equipped with surface drainage provisions to manage water flow. Features such as catchpits, stepped channels, and U-channels direct surface water from the barrier to a drainage opening. This opening diverts water to a 450 mm-wide U-channel located downstream.

4.4 *Post-landslide investigation*

A total of nine landslides were reported on the natural hillside above Hong Chi Pinehill Village. Among these, debris from four landslides (landslide scars L1 to L4) in the middle and lower portions of the hillside reached the rigid barrier (Figure 5a). These four landslides began as open hillslope failures, with source volumes ranging from 5 m^3 to 180 m^3, resulting in a total volume of approximately 405 m^3.

The landslide scars L1 to L4 were mostly shallow, with depths of less than 3 m. The widths and lengths of the source areas ranged from 3.5 m to 7.5 m and from 3.0 m to 18.0 m, respectively. The materials exposed in the landslide scars included 1 m-thick topsoil and colluvium overlying completely and highly decomposed granodiorite.

Upon entering drainage lines DL1 and DL2, the debris became channelised and entrained an additional 20 m^3 of soil debris. This debris then impacted the gabion blocks and was subsequently deposited within the retention basin of the rigid barrier (Figure 6a). The debris reached an approximate depth of 2 m, with minor splashes reaching up to 4.8 m high, leaving marks on the gabion blocks. The debris composition was primarily a mixture of sandy silt, gravel, and cobbles, with no sizeable rock fragments or boulders observed.

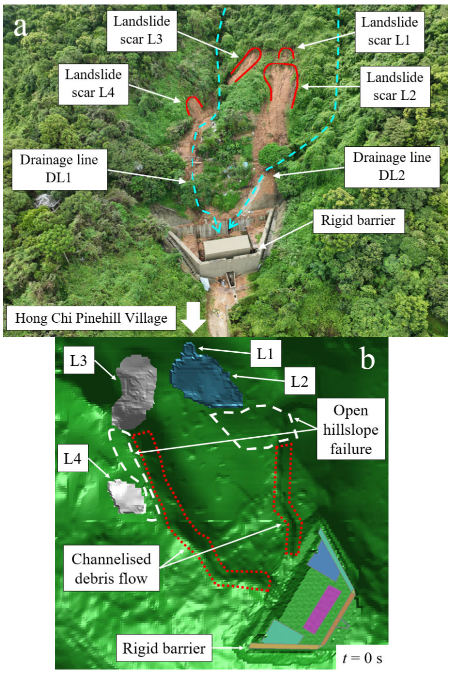

Figure 5. General view of the landslide (Hong Chi Pinehill Village) (a) Aerial photo; (b) top-down view of the topography modelled in LS-DYNA ($t = 0$ s).

Based on the change detection analysis, about 300 m^3 of debris was fully contained by the rigid barrier, while approximately 10 m^3 of soil debris formed an outwash outside the partially blocked drainage opening. The remaining 115 m^3 was deposited along the debris trails on the hillside.

Site inspections showed no noticeable damage or deformation to the walls or gabion blocks, aside from the damaged handrails at the rear edge. These observations indicate that the gabion blocks effectively withstood the impact of the landslide debris, and the overall stability of the rigid barrier was adequate during the landslide event. The rigid barrier successfully intercepted and contained the landslide debris from the uphill area, avoiding damage to downstream facilities.

4.5 *Numerical back-analyses*

The landslides initially occurred as open hillslope failures on the planar hillside (Figure 5b). The landslide debris entered the drainage lines below the landslide scars, where it became channelised towards the rigid barrier. The debris impacted the gabion blocks and stem wall and was deposited within the retention basin of the rigid barrier.

At $t = 50$ s, the quantity of debris trapped inside the rigid barrier was similar to the deposition observed physically (Figure 6b). Some debris was deposited in drainage line DL2, aligning with field observations.

The maximum debris velocity from the simulation was about 4.9 m/s, which was smaller than 9.6 m/s predicted for the design event. The debris thickness gradually increased to a final height of about 2.7 m, reflecting the progressive deposition of the debris within the retention basin. The maximum static soil debris force reached approximately 60 kN/m when most of the debris came to rest. This force was less than both dynamic and static forces in the design event.

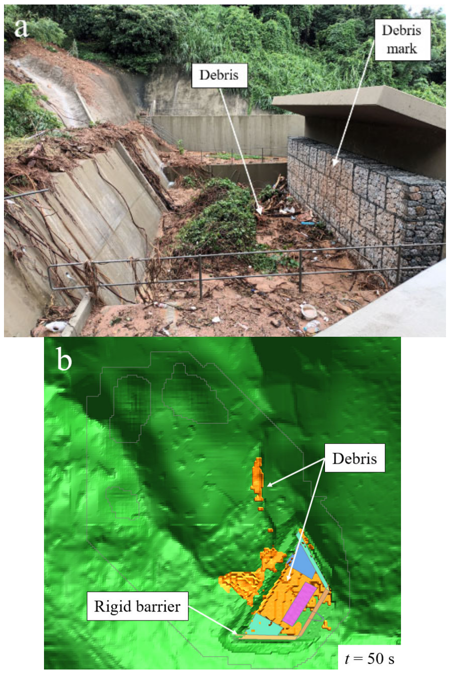

Figure 6. Debris deposition in the rigid barrier (Hong Chi Pinehill Village). (a) Photography, looking at the rigid barrier ; (b) top-down view of the debris deposited in LS-DYNA ($t = 50$ s).

Compared to the design event, the travel distances of the channelised debris flows were shorter, approximately 80 m, with gentle channel profiles and no drainage confluence point from tributaries. These factors limited the momentum of the debris and reduced the development of faster and larger watery debris flows, restraining the debris impact.

5 DISCUSSION

5.1 *Back-analyses of rheological parameters*

The landslides were modelled in two phases: open hillslope failures at the source areas and the nearby planar hillsides, followed by channelised debris flows once the debris entered the open channel and drainage lines. An apparent basal friction angle of 30° to 32° characterised the open hillslope failures, while the channelised debris flows were characterised by an apparent basal friction angle of about 12° to 14° and a turbulence coefficient of 500 m/s^2. There is some uncertainty associated with the back-analysed parameters due to the assumption of a homogenous equivalent fluid, and the lack of consideration of topographic features such as trees, but the general range is consistent with other back-analyses.

Back-analyses demonstrated that the landslides on 8 September 2023 could be reliably replicated, with results closely matching field observations. This included the extent to which the barriers were filled, with only one-third of the actual barrier capacity used. The validated rheological parameters were higher than the recommended design values in Hong Kong (GEO, 2023a; 2023b) and those obtained from back-analyses of debris flows in Hong Kong (Koo, 2017). This suggests that the 8 September 2023 landslides were less mobile than previous events, implying that the initial analyses of debris flows for the design event were on the safe side.

5.2 *Essence of natural terrain landslide studies*

Prior to the landslides on 8 September 2023, the hillsides above Lei Pui Street and Hong Chi Pinehill Village were thoroughly studied in detail. These natural terrain landslide studies comprehensively reviewed site characteristics using techniques such as remote sensing and on-site assessments to evaluate terrain stability. This meticulous examination identified potential risk factors contributing to landslides, such as over-steep slopes and drainage patterns.

By understanding these factors, the studies enhanced preparedness and response strategies for potential landslide events. The pivotal role of natural terrain landslide studies in Hong Kong lies in their ability to inform proactive measures, which not only mitigate the risk of future landslides but also enhance community resilience and safety.

5.3 *Performance of the rigid barriers*

Previous studies at the Lei Pui Street and Hong Chi Pinehill Village sites identified potential landslide hazards and proposed mitigation measures, including rigid debris-resisting barriers, designed under the LPMP and LPMitP. These barriers were robustly designed to withstand the impacts of the landslides, successfully protecting downslope facilities during the events.

Looking ahead, future landslide events involving impacted barriers present an opportunity to further refine and optimise the recommended design rheological parameters as more data becomes available. This continual improvement will enhance the effectiveness of mitigation measures and contribute to the advancement of best practices in landslide risk management.

Furthermore, there is potential to develop an innovative and balanced approach to conservativeness, ensuring that mitigation measures remain adaptable and resilient in the face of the evolving challenges posed by climate change. By embracing these opportunities, stakeholders can continue to strengthen the ability to safeguard communities and infrastructure, ultimately fostering greater resilience against landslide hazards and reducing potential risks.

6 CONCLUSIONS

The findings from this study are pertinent for mountainous and densely populated regions like Hong Kong, which are characterised by small debris volumes, short runout distances, and a high potential for loss of life. As urbanisation continues to encroach onto mountainous regions globally, these conditions are likely to become more prevalent.

The landslides on 8 September 2023 highlighted the importance of conducting comprehensive natural terrain hazard studies to assess landslide risks and implement effective mitigation strategies, and gave confidence to the procedures used for estimating the debris volume. This ensured that the rigid barrier was strategically positioned and designed to accommodate the anticipated volumes of debris and flow dynamics, thereby protecting the residential areas near Lei Pui Street and Hong Chi Pinehill Village from landslide hazards. Such studies are particularly important for hillsides located near urban fringes or densely populated areas with a known history of landslides, where large-scale earth movements could be consequential.

The data obtained from the back-analyses is invaluable for refining the design of future mitigation measures. Using LS-DYNA, this landslide study evaluated barrier performance under debris impact, highlighting that the barrier design at Hong Chi Pinehill Village was on the conservative design for the actual events, such that more sustainable designs may be considered in the future.

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