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Keynote

ADVANCING DIGITAL-DRIVEN RESILIENCE-BASED HONG KONG SLOPE SAFETY SYSTEM: OPPORTUNITIES AND CHALLENGES

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Amidst repeated large-scale catastrophic landslides in the 1970s, the then Hong Kong Government established the Geotechnical Engineering Office (GEO) of the Civil Engineering and Development Department in 1977 to systematically deal with the imminent landslide risk in Hong Kong.Since then, the GEO has formulated and implemented the Hong Kong Slope Safety System (HKSSS) to manage the landslide problems to protect life and property in a holistic manner.The primary objective of the HKSSS is to control landslide risk by three key strategies namely (a) contain risk from new development, (b) reduce risk imposed on existing development, and (c) minimize landslide consequences.Recently, the GEO has leveraged the rapid advancement in innovation and technology to enhance the HKSSS with a view to withstanding the evident adverse impacts of climate change while maintaining essential functions and to navigating ahead future unexpected shocks and stresses with strength and resilience.

Over the past 45 years, the holistic HKSSS evolves as the society develops, technology improves, public expectation grows and climate changes. This paper presents the advancement of the HKSSS with highlights in the opportunities and challenges as it attempts to strengthen its resilience against climate change impacts through mastering cutting-edge innovation and technology. These include enhancing overall slope and landslide management, improving landslide prediction capability, strengthening emergency preparedness and response, and enhancing community resilience against extreme rainstorms using state-of-the-art technologies such as advanced remote sensing techniques, numerical modelling algorithms, Internet of Things, digital twins, spatial analyses and 3D visualization, machine learning and artificial intelligence algorithms and virtual reality concepts in landslide risk management.

Keywords: Landslide risk management; slope; climate change; resilience; innovation; technology; data-driven.

1. Landslide Risk and Associated Climate Impacts in Hong Kong

The unique combination of climate, steep terrain, deep weathering profile with complex geological and hydrogeological conditions and the rapid urban development since the post-Second World War period has shaped the acute and chronic landslide problems in Hong Kong, resulting in catastrophic loss of life and significant socio-economic consequences.

The climate of Hong Kong is subtropical. Short-duration high-intensity rainfall caused by summer monsoon tropical troughs and typhoons is common. The mean-average annual rainfall is around 2,400 mm and the storm-based 24-hour rainfall can be as high as 850 mm. Hong Kong has a mountainous terrain with a scarcity of flat land. Of the total land area of about 1,100 km^2, about 63% of the land is steeper than 15^o and 30% is steeper than 30^o. The predominant rock types in the urban areas are granite and volcanic rocks, which have deep and varied weathering fronts. The steep terrain is typically blanketed with a surface mantle of colluvium at foothills as a result of past mass movements, overlying thick weathered soils of potentially adverse geological and hydrogeological conditions. Hillsides of the above intrinsic characteristics are susceptible to landslides at times of heavy rainfall. Since the early 1950s, the population has increased gradually from less than one million to about 7.5 million in 2024. The rapid population growth and substantial economic expansion have resulted in a high concentration of urban developments on steep terrain in close proximity to man-made slopes and natural hillsides. Some 60,000 sizeable man-made slopes have been formed over the territory of Hong Kong.

In the aftermath of several disastrous landslides in the 1970s, two of which resulted in 156 fatalities in 1972, the Hong Kong Government established the then Geotechnical Control Office (later renamed as the Geotechnical Engineering Office (GEO)) in 1977 as the central authority to regulate geotechnical engineering and oversee slope safety in Hong Kong. On average, some 200 to 300 slope failures are reported to the GEO every year. Most of the reported landslides occur in man-made slopes and are of a relatively small scale (95% of the failures being less than 50 m^3 in volume as at 2024), but some can be sizeable (5,000 m^3 or more). In a densely urbanized area like Hong Kong, even a small landslide in close proximity to buildings or roads can cause devastating life and economic consequences.

The GEO has formulated a comprehensive framework known as the Hong Kong Slope Safety System (HKSSS) for managing landslide risk in Hong Kong.The system has undergone progressive improvement over the years. It has now evolved into a comprehensive regime, which embraces a range of initiatives that serve to

manage the landslide risk through an explicit risk-based strategy and approach, in a holistic manner.The key strategies of the HKSSS are (a) to contain risk from new development, (b) to reduce risk imposed on existing development, and (c) to minimize landslide consequences (Figure 1). The systematic and multi-pronged HKSSS entails the use of both engineering and non-engineering approaches, which include policing, safety standards and research, specialist works projects, regular slope maintenance, emergency service and public education and information. Over the past 45 years, the actual annual landslide fatalities in Hong Kong have been reduced to a significantly low level (Figure 1). In the absence of these sustained efforts, the landslide risk is deemed to re-bound. The HKSSS adds value to the sustainable development of Hong Kong through averting landslide fatalities (i.e. saving lives) and improving the built environment.

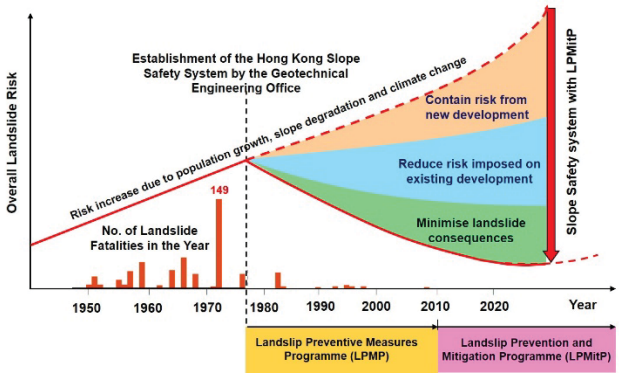

Fig. 1. Key strategies of the HKSSS and landslide fatalities in Hong Kong (1948-2024)

It is undoubtedly that climate change has altered the characteristics of rainfall across Hong Kong in recent years. A recent study conducted by the Hong Kong Observatory (HKO) observed significant intensification and an increasing frequency of extreme hourly rainfall, as well as a notable increase in both the maximum intensity of extreme rainfall events and the frequency of these events, despite an insignificant change in total rainfall, based on 131 years of local rainfall data up to 2022 (Lai et al. 2024). The trend of more frequent and increasingly severe extreme rainfall events poses an unprecedented challenge to slope safety in Hong Kong in the years to come, most notably in the aspects of more frequent and more severe failures of man-made slopes triggered by extreme rainfall events, more frequent and serious washout failures resulted from increased short-duration rainfall intensity, widespread natural terrain landslides and debris flows with escalated propensity, scale and mobility, and concurrent occurrence of multiple hazards. With a view to withstanding the evident adverse impacts of climate change while maintaining essential functions and to navigating ahead future unexpected shocks and stresses with strength and resilience, the GEO has leveraged the rapid advancement in innovation and technology as well as the enhanced capacity in big data analytics to elevate various components of the HKSSS.

2. Maximizing Opportunities

Following the rapid advance in computers, innovations and technology, the GEO has taken every possible opportunity to widen the adoption of technology coupled with innovations in every facet of the HKSSS to reducing landslide risk. Key achievements and new initiatives are highlighted below.

2.1.*Slope and Landslide Management*

In routine practice, advanced remote sensing technologies through the use of handheld laser scanning equipment and laser scanning equipment mounted on uncrewed aerial vehicles are applied for topography survey, rock joint mapping and mapping of natural terrain landslides. The remote sensing data collected through the state-of-the-art technology is of high-resolution that enables detailed mapping and evaluation of terrain, geological and hydrogeological features remotely, repeatedly and consistently. Building Information Modelling (BIM) isalso adopted to facilitate slope design and construction management, such as geological modelling, design optimization and automatic clash detection (Sun et al 2020).These digital technologies increase the accuracy and efficiency in data acquisition and processing in the planning and design of slope works.

The GEO has developed a digital twin network to regulate regional groundwater level at the drainage tunnels in the Po Shan area. The Po Shan Groundwater Regulation System captures continuous real-time data from the sub-vertical drains and piezometers in the region, enabling timely monitoring and control of groundwater release. Automatic releases and remote control capabilities via application-specific robotics are being explored. This innovative approach ensures rapid, informed responses to rainfall events, mitigating the landslide risk.

Recently, the GEO has also initiated pioneering digital twin models at selected sites to enhance understanding of groundwater levels, subsurface moisture, surface drainage performance and their impacts on slope stability. Leveraging data-driven analysisthrough extensive monitoring of field instrumentation managed on an Internetof Things (IoT) platform and advanced numerical modeling algorithms, including continuous fluid dynamics and transient seepage analyses, the GEO will analyze the interactions between rainfall and surface and

subsurface water flow, developingforward prediction capabilities for extreme rainfall events, thereby improving resilience against climate change impacts on slope stability.

The GEO is also in the process of developing a territory-wide 3D Geotechnical Information Infrastructure (3DGInfo) coupling a 3D Geotechnical Model (3DGM) that contains a suite of above-ground and sub-surface geotechnical information for use by the industry in geotechnical study and design. The 3DGInfo alone was put into operation in late 2023, which provides 3D visualization of natural and built environments, retrieval of 2D and 3D spatial geotechnical data and imagery on such as soil and rock, groundwater, slopes and buildings, landslides and land status, and key geospatial applications such as measurement of 3D slope boundary and geometry of adjacent buildings.

2.2. *Landslide Prediction*

The GEO and the HKO jointly operate the territory-wide Landslip Warning System (LWS) to forewarn the public of possible landslide risks during periods of heavy rainfall and trigger an emergency system within government departments, which mobilizes staff and other resources to deal with landslide incidents (Chung et al. 2023).The current generation of the LWS represents a significant breakthrough, integrating spatial distributions of man-made slopes with rainfall variations, enabling more accurate predictions of landslide occurrences and enhancing risk management in Hong Kong.In particular,the currentraingauge system, comprising 121 automatic raingauges that covers the whole territory of Hong Kong with an average density of one raingauge per 10 km^2,provides real-time five-minute rainfall data to support the LWS in a timely manner. In addition to data from raingauges, the HKO uses Doppler weather radars to continuously monitor the movement and development of rain-bearing clouds and high-resolution meteorological satellite images to keep informed of the cloud patterns around Hong Kong. By using a combination of real-time rainfall spatial and temporal distributions and rainfall forecasts in the coming 1 hour, 2 hours and 3 hours from the HKO, and based on the GEO's study on the rainfall-landslide relationship, the GEO is able to identify when it would be appropriate to issue the Landslip Warning.From the past 45 years of performance records, more than 90 percent of fatal landslide cases over the past 45 years occurred while the Landslip Warning was in force, demonstrating the effectiveness of the system.

Neither weather forecasting nor landslide prediction can be carried out without uncertainties, and the GEO strives to achieve greater advancement in data-driven analysis. Recently, the GEO has explored the potential application of machine learning (ML) and big data analytics for landslide predictions of man-made slopes in Hong Kong. A sister paper under the same proceedings, Cheung et al 2025,details the modeling workflow and presents the predictive performance of a ML algorithm. The study provides insights into landslide triggers and improves landslide prediction capability, achieving a realistic and reliable real-time prediction of the spatio-temporal distribution of reported landslides during a rainstorm event. In parallel, a pilot study detailed in Cheung et al. (2023) applied ML and big data analytics to enhance the natural terrain landslide susceptibility model, which predicts the spatial likelihood of landslide occurrences in the natural terrain across the territory. This study demonstrated the potential to refine the model's resolution, thereby improving the formulation of landslide risk management strategies, including spatial assessment of landslide risk, prioritization of mitigation works, and land use planning.

2.3. *Emergency Preparedness and Response Capacity*

Situational awareness and efficient communication are essential to emergency management and crisis preparedness. The GEO has developed, operated and maintainedtheCommon Operational Picture (COP)since2020which provides a new map-based common information technology platform with Geographic Information System functions for sharing real-time emergency and impact information,including landslides, flooding, and major road incidents, among various bureaus and departments in the government. It also incorporates relevant information such as weather conditions, locations of helicopter pads and hospitals and status of temporary shelters to provide a comprehensive platform for emergency responses. The COP could enhance the common situational awareness of emergency managers in relevant bureaus and departments and facilitate effective, consistent, and timely decisions and resource mobilization. It also strengthens coordination and enhances planning and responsiveness to emergency situations in a holistic manner.

The real-time landslide information in the COP is connected to the Landslide Information System (LIS), which is also operated and maintained by the GEO for conveniently recording landslide information on site by the inspecting geotechnical engineers and sharing the real-time information with the emergency control center. The use of the LISenhances the efficiency of the 24-hour, year-round landslide emergency service to provide geotechnical advice to government departments, including rescue teams and slope maintenance departments, on actions to be taken to deal with danger arising from landslides.

The GEO has developed the Smart Barrier System installed on landslide debris-resisting barriers, which are commonly designed to intercept landslide debris from natural terrain to reduce the chance of debris impacting downhill developments and facilities and causing casualties. Many barriers are located at natural

stream courses or hillsides, where the accumulation of landslide debris behind the barriers may easily go unnoticed. The Smart Barrier System aims to detect the occurrence of landslides by means of all-weather and non-stop monitoring of landslide debris-resisting barriers, facilitated by the use of state-of-the-art IoT technologies. The system will provide immediate alerts to relevant government officers via a mobile application when the barriers are hit by landslide debris, enabling timely arrangement for inspection and follow-up action to enhance public safety.

Simulations using virtual reality (VR) help to engage stakeholders by providing a unique environment and experience to the users. The GEO collaborated with the Hong Kong Jockey Club Disaster Preparedness and Response Institute in producing interactive VR training kits to simulate scenarios for inspecting professionals attending landslide inspections. These aim to enhance the preparedness of inspecting professionals in dealing with different situations during landslide inspections, further reinforcing the emergency preparedness of the team.

2.4. *Community Resilience Against Extreme Rainstorms*

As part of the public education efforts to promote slope safety awareness, the GEO has harnessed advanced 3D visualization technologies to enhance the general public's understanding of the triggers and socio-economic impacts of landslides under severe rainstorms, thereby preparing the community for future landslide incidents. The GEO has built a series of 3D digital models depicting recent significant landslide scenesthrough various mediums including 3D-printed models, 360-degree VR, and 3D stereo television.In particular, the GEO developed an interactive storyline detailing a significantly large landslide incidentthat happened in Hong Kong during the extreme rainfall event in September 2023 for display on a Spatial Reality Display, which allows viewing of 3D images without the need for special glasses or headsets. This storyline illustrates the changes at the landslide site, presenting the terrain conditions before the landslide, the immediate aftermath, the post-debris clearance phase, and the various stages of emergency works. The GEO also created several VR simulations that reproduce the experience of surviving past serious landslides such as the catastrophic incidents that resulted in 156 fatalities in 1972.These simulations were featured in a number of local exhibitions and events targeting the public from diverse backgrounds.These first-hand, realistic simulations have proven to be very popular in these exhibitions and events, effectively attracting the target audience, conveying the importance of slope safety, and reinforcing precautions against potential landslide incidents.

3. Navigating Challenges

As it evolves into a digital-driven, resilience-based system, the HKSSS needs unfailing momentum to keep its functionality and performance as well as reliability and flexibility in face of unexpected weather and landslide events. Highly devoted people, advanced equipment (both hardware and software), state-of-the-art knowledge and skills and aproactive and supportive environment (in both human and monetary terms) are imperative to the sustainability and continuous development of the HKSSS. With the experience in progressing the HKSSS in the past 45 years to meet changing needs, the GEO has committed in the long-term investment in attracting and grooming talents and building capacity of master computerized, digital technology. In particular, the GEO has established the Steering Committee on Strategies for Innovation and Technology (I&T) Development chaired by the Head of the GEO and increased human and monetary resources on managing and developing I&T related initiatives, synthesizing diverse, valuable efforts within the GEO with an aim to bringing high impact to the public.

4. Conclusions

The GEO is proactively advancing the HKSSS through innovation and technology and data-driven approaches to enhance resilience against landslide risk exacerbated by climate change. By enhancing overall slope and landslide management, improving landslide prediction capability, strengthening emergency preparedness and response,and enhancing community resilience through mastering cutting-edge innovation and technology, the GEO aims to mitigate the impacts of extreme rainfall events. Ongoing efforts, including the development of smart systems and enhanced emergency preparedness, underscore the commitment to safeguarding lives and infrastructure in Hong Kong's evolving climate landscape.

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