Forty Years of Slope Engineering in Hong Kong

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ABSTRACT

Slope engineering practice in Hong Kong has been evolving for the past 40 years, both in terms of the geotechnology involved and its scope of application. Several key areas of change, together with the context under which these took place, are highlighted in this paper. Here, 'slope engineering' refers to not only the applied science of geotechnical engineering and engineering geology, but also slope safety management in general. With concerted effort from the profession, the changes have brought about advances in slope engineering and improvement in slope safety, rendering Hong Kong a positive example in urban landslide risk management. These also prepare the profession to meet the future challenge and undertake expanded responsibility, particularly in coping with extreme rainfall events which may become more frequent and severe in the wake of climate change.

1 PREMISE

The vast majority of our contemporary engineering structures, such as buildings and bridges, are designed to ensure that the chance of collapse throughout their service life is negligibly low. In contrast, slopes typically have a finite and much higher failure rate, which is reflected by the occurrence of landslides at times. Many of these slope failures are tolerated, either willingly or unwillingly. The former may involve consideration of cost-effectiveness, resource constraints, priority, etc. The latter applies to cases where slope failure is not commensurate with the design intent but occurs in connection with deficiency in design, human error, inadequate technical understanding, etc.

Under this overall setting, with escalating public's expectation of slope safety, improving knowledge of slope performance and better system of landslide risk management, slope engineering practice in Hong Kong has notably evolved over the past 40 years. Its positive outcome is reflected in the drastic change in the landslide risk trend, with significant reduction in annual landslide fatalities since the late 1970s (Figure 1). The changes that stand as milestones in the evolution of slope engineering practice over the period, together with the context of the changes, are described below.

2 STARTING POINT – ENGINEERING SLOPES WITH GEOTECHNOLOGY

The landslide risk trend in Hong Kong based on 15-year rolling average annual landslide fatalities is shown in Figure 1. In the 1960s and 1970s, landslide risk was increasing significantly. This was mainly attributed to the extensive formation of man-made slopes as part of the rapid urban development in the period. The slopes were mostly formed according to empirical rule of thumb with little geotechnical input. They failed frequently, particularly during heavy rain.

The disastrous consequence of the Po Shan (Figure 2) and Sau Mau Ping landslides in 1972, followed by the occurrence of a similar failure in Sau Mau Ping in 1976 (Figure 3), revealed to all the serious deficiency of this rule-of-thumb approach of slope engineering. With the awareness that the level of slope safety in Hong Kong should be improved to meet the community's expectation, the Geotechnical Control Office (renamed Geotechnical Engineering Office, GEO, in 1992) was set up in 1977 to regulate slope

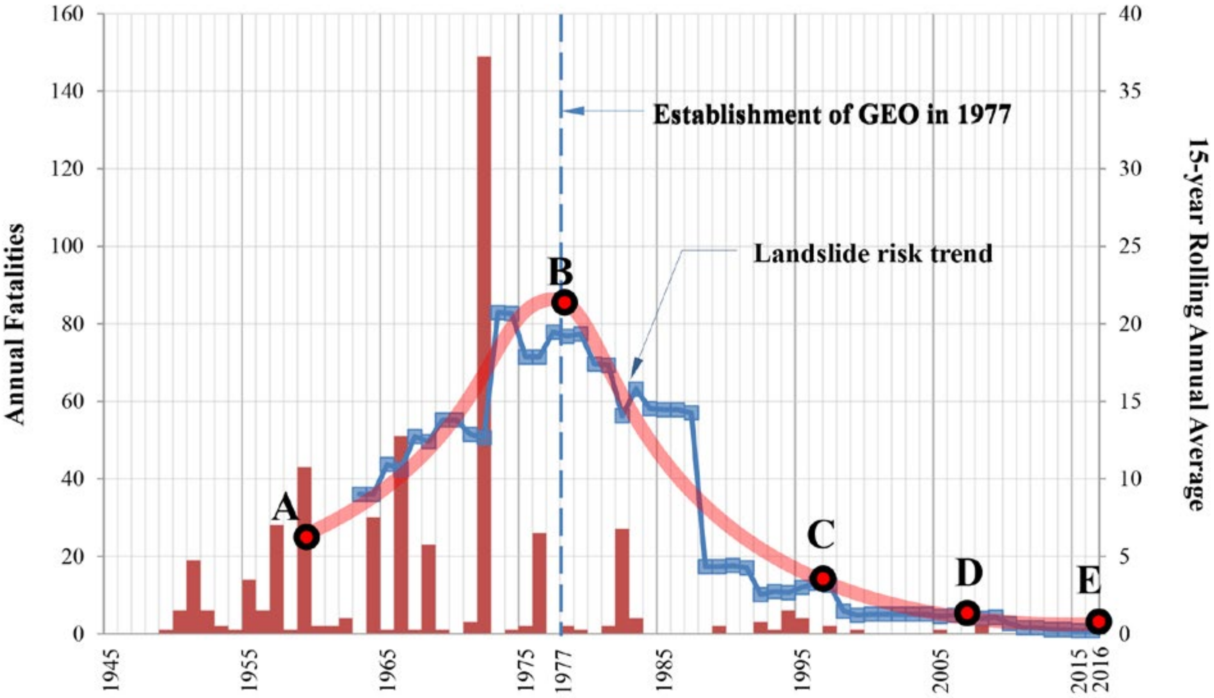


Figure 1: Landslide risk based on annual landslide fatalities in Hong Kong

Figure 2: Po Shan Landslide in 1972
(resulting in 67 fatalities)

engineering in Hong Kong. This marked the starting point of a complete revamp of the slope engineering practice in Hong Kong (Point B in Figure 1). It resulted in territory-wide application of state-of-the-art geotechnology to slope engineering and setting up of the Hong Kong Slope Safety System to regulate the application. Under the Slope Safety System, landslide risk is also being managed via other measures, e.g. retrofitting substandard slopes, landslide warning and emergency services, and public education on slope safety (Malone, 1998).

Figure 3: Sau Mau Ping Landslide in 1976
(resulting in 18 fatalities)

3 HIGHER LEVEL – ENHANCING ROBUSTNESS OF ENGINEERED SLOPES

Slope engineering with proper geotechnical input has enabled the practitioners to design new slopes according to geoscience principles, and to verify that the design meets the required geotechnical standards that are commensurate with international good practice. This, together with systematically retrofitting the existing, substandard slopes based on risk-based prioritization, has led to major reduction in the overall landslide risk (from Point B onward, Figure 1). It clearly demonstrates that slope stability is much improved by replacing the rule-of-thumb approach with application of geotechnology in slope engineering.

However, as time goes by when more engineered slopes have been formed and their actual performance in heavy rain tested, it becomes evident that even slopes engineered to the required design standards have a finite chance of failure (Wong & Ho, 2000). Many of these are small scale landslides, either washout failures caused by concentrated surface water flow (Figure 4) or slope instability controlled by localized geological weaknesses (Figure 5). Yet, sizeable failures of engineered slopes do also occur occasionally (e.g. see Figure 6), typically associated with adverse geological and hydrogeological setting that is not addressed in the design.

Through the landslip investigation programme launched as part of the follow-up actions of the 1994 Kwun Lung Lau landslide, the GEO has been systematically examining and studying all known

Figure 4: Concentrated flow of surface water commonly due to
lack of slope maintenance or deficient drainage provisions

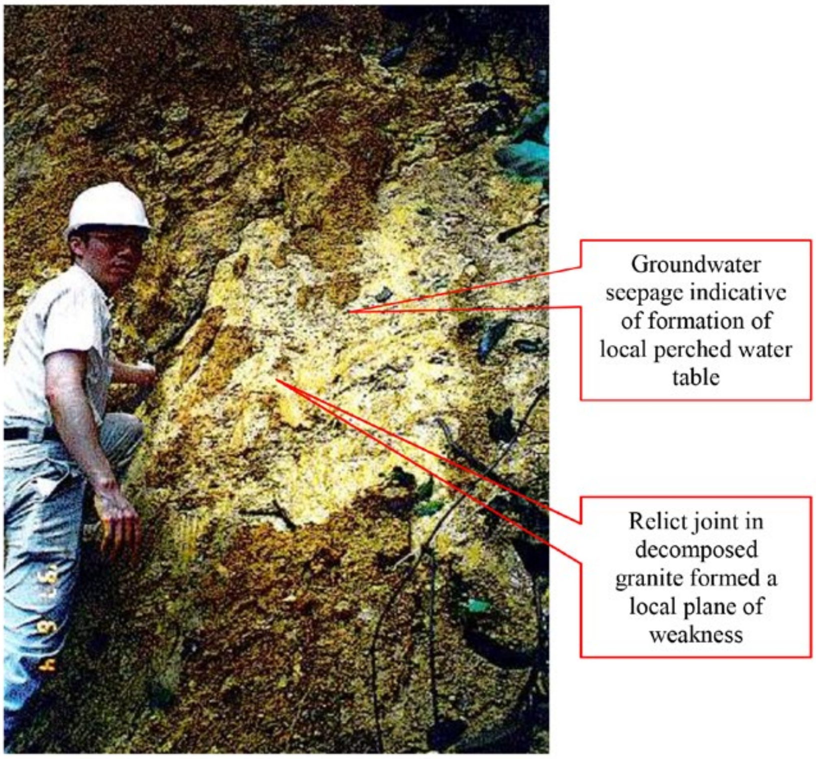


Figure 5: Small scale slope stability controlled by localized geological weakness

Figure 6: Ching Cheung Road Landslide in 1997 (~5,000m^3)

landslide incidents since 1997, including failure of engineered slopes. The investigation has provided comprehensive and rigorous data on the failure rates of different types of man-made slopes, together with useful findings on the causes of failure and areas for improvement.

The 5-year rolling average annual failure rates of engineered slopes and un-engineered slopes, based on the comprehensive data collated since 1997, are shown in Figure 7. The average annual failure rate of engineered slopes, which was 0.12% in the 5-year period from 1997 to 2001, was not negligible. Such a failure rate implies that over a notional design life of, say, 120 years, about 15% of the engineered slopes would fail at least once.

By the mid-1990s, although Hong Kong's slope engineering was on a par with international best practice and slope safety was greatly improved as compared with that in the 1970s, public's expectation of slope safety had further escalated as the quality of life continued to enhance. This is understandable

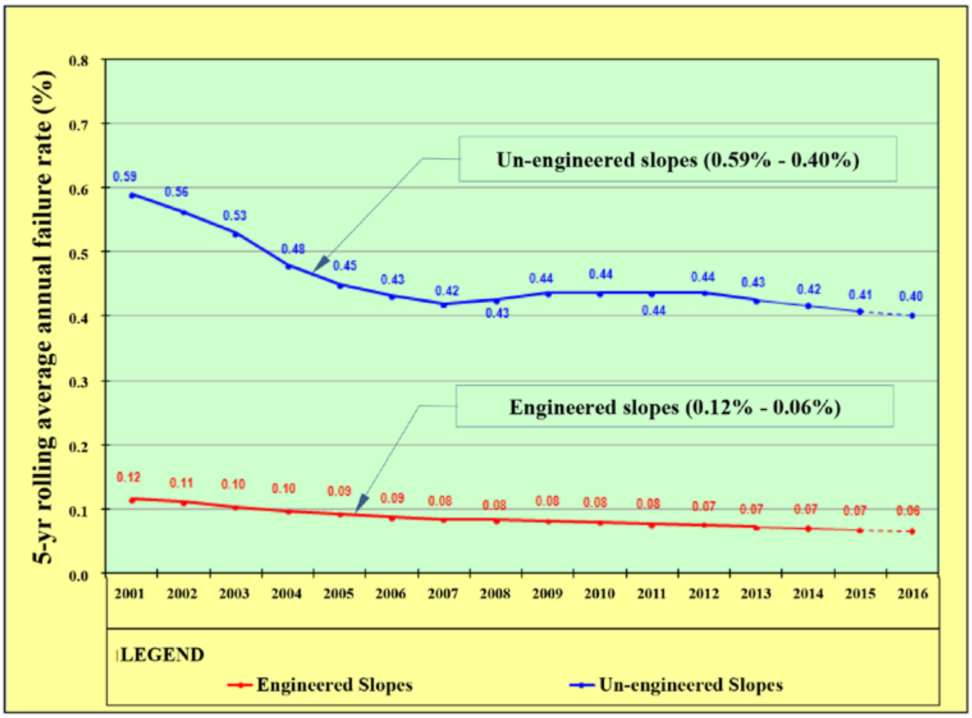


Figure 7: 5-year rolling average annual failure rates of engineered and un-engineered man-made slopes

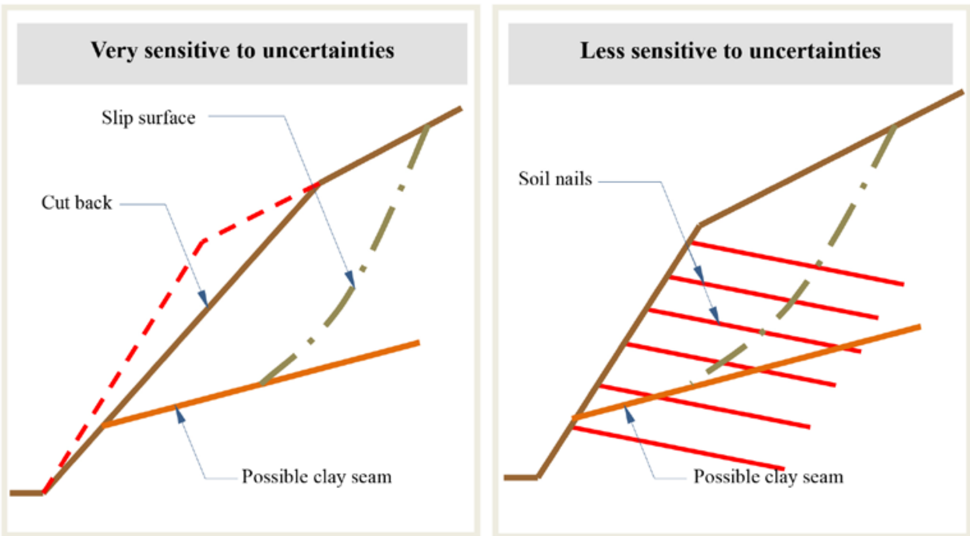


Figure 8: Enhancing the performance of engineered slopes with the use of robust design scheme (e.g. soil nailing)

given Hong Kong's setting as a major metropolitan with a high density of population and intense development on landslide-prone terrain. It was signified by the strong public reaction to a number of serious landslides occurred in the early to mid-1990s and the grave concern expressed in the failure of slopes subject to engineering input. In addition, the enhanced professional awareness of the actual performance and causes of failure of engineered slopes provided the essential technical insights and impetus for further improving the performance of engineered slopes. Consequently, Hong Kong's slope engineering underwent a new round of evolution in the late 1990s (Point C in Figure 1). The key changes included: (i) enhancing the robustness of engineered slopes through the use of design schemes that are less sensitive to uncertainties in geological and hydrogeological conditions (Figure 8), both in terms of the likelihood and consequence of failure, (ii) improving slope drainage and surface protection, and thereby making the slopes less vulnerable to adverse effects from concentrated surface water flow and subsurface seepages, and (iii) maintaining slopes to minimize deterioration and upkeep their stability condition (Wong, 2001). These took the engineering of man-made slopes to a higher level of reliability and safety. The improvement achieved is reflected in the progressive reduction in the 5-year rolling average annual failure rate of engineered slopes, up to about 50% by 2016 (Figure 7).

It is note-worthy that the failure rate of un-engineered slopes (i.e. slopes formed before 1977 without proper geotechnical input and verification that the required geotechnical standards are met), which was within about one order of magnitude higher than that of engineered slopes (Figure 7), was not exceedingly high. This probably reflects the contribution of the priority ranking system adopted in selecting the more vulnerable un-engineered slopes for priority retrofitting and the effectiveness of maintaining all slopes (including the bulk of the existing, un-engineered slopes which have not been given the priority for retrofitting) in minimizing their chance of failure. It should also be considered under the context that the rule-of-thumb approach adopted in forming the un-engineered slopes in the old days, being empirically based, nevertheless serves some useful engineering purposes.

4 NEW FRONT – DEALING WITH NATURAL TERRAIN LANDSLIDES

Up to about mid-2000s, slope engineering in Hong Kong was primarily concerned about dealing with man-made slopes. Before better knowledge about natural terrain landslides became available, there had been some early suppositions that the natural hillsides in Hong Kong are old and mature landforms and thereby should have evolved into a relatively 'stable' condition. These early suppositions included the views that natural hillsides showed no signs of creep, all failures are first-time slips, and the concept of 'ripening' being dismissed in view of the long time needed for the degree of weathering to become significantly altered by chemical weathering.

Whilst acknowledging that 'natural slopes are frequently close to limiting equilibrium over very large areas', it is stipulated in the Geotechnical Manual for Slopes (GCO 1984) that natural slopes need not meet the factor of safety requirements for slope design provided that two conditions are met: (i) the slope is undisturbed; and (ii) a careful examination is made to determine that there is no evidence of instability or severe surface erosion. There was apparently a time in the past that these two conditions were presumed to have been met in many parts of the natural terrain in Hong Kong.

With ample data available from the systematic study of natural terrain landslides in the rainstorms of November 1993 (Figure 9) and April 2000, review of the historical records of failures in 1966 and 1982, and the comprehensive review of the available aerial photographs for compilation of the Enhanced Natural Terrain Landslide Inventory (ENTLI), it is now known that natural hillsides in Hong Kong are

Wide-spread failures in South Lantau Island　　Debris flow in Tung Chung

Figure 9: Natural terrain landslides on Lantau Island in November 1993 rainstorm

indeed susceptible to rain-induced, shallow failures. Field investigations revealed that the failures typically occur within 1 to 2 m of the surface mantle, where erosion pipe holes, dilation and partial infilling of relict discontinuities, and localized tension cracks are often observed. The hillsides are subject to on-going degradation, and a large number of shallow landslides can be triggered under heavy rain (say, 24-hour rain exceeding 20% of the average annual rainfall) even though relatively few failures occur in less severe rainfall condition (Wong, 2009).

As Hong Kong is developing closer to the steep natural hillsides as a result of its continual urban growth, the overall risk of natural terrain landslides is increasing. In contrast, the risk of man-made slope failures has significantly reduced due to improved slope engineering practice and safety management. In the mid-2000s, the GEO estimated via Quantitative Risk Assessment (QRA) that the risk of landslides due to natural terrain failures would be comparable to that of man-made slope failures by the year 2010 (Wong et al, 2006). This sets the scene for an important change in the slope safety strategy (Point D in Figure 1) to: (i) step up the requirement of studying natural terrain landslide hazards and carrying out the necessary mitigation works as part of the new development in close proximity to natural hillsides, and (ii) commence systematic study and mitigation of natural terrain landslide hazards affecting existing development under Government's post-2010 Landslip Prevention and Mitigation Programme (LPMitP).

Consequently, the geotechnical profession is tasked to assess and mitigate natural terrain landslides, apart from engineering man-made slopes. This expanded responsibility calls for development of new areas of professional competence and further advances in our slope engineering practice. These include several important aspects, which are different from those conventionally involved in engineering man-made slopes: (i) natural terrain hazard study and related engineering geological assessment, (ii) modeling of the mobility of landslide debris (Figure 10), (iii) analysis of debris-barrier interaction and design of barriers, (iv) QRA for study and evaluation of natural terrain landslide risk.

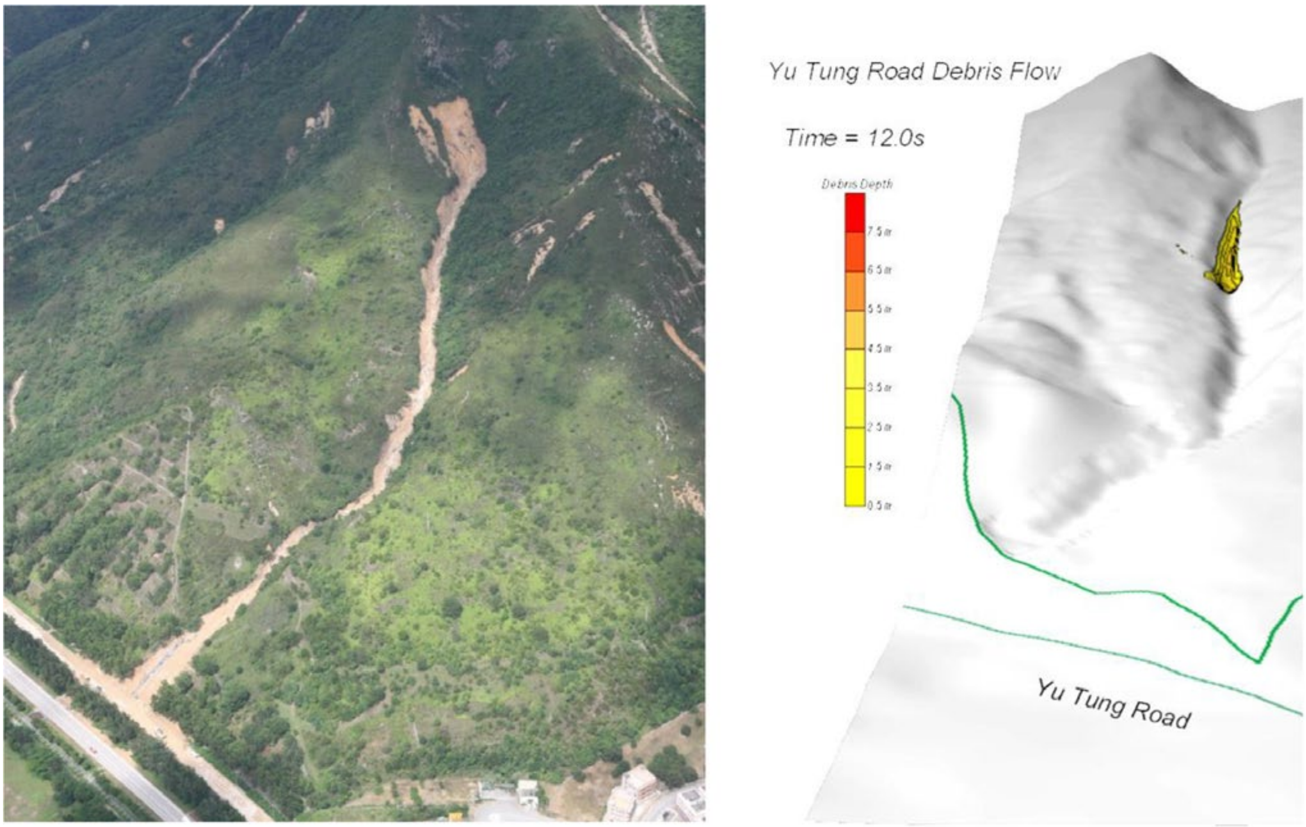


Figure 10: 3-D modeling of debris runout and mobility (The 2008 Yu Tung Road Debris Flow shown)

5 UNPRECEDENTED CHALLENGE – PREPARING FOR EXTREME WEATHER AND CLIMATE CHANGE

The concerted effort of the geotechnical profession has not only brought about continuous development in slope engineering practice, but also significant reduction of the landslide risk in Hong Kong. By 2016 (Point E, Figure 1), Hong Kong has experienced 8 consecutive years of zero landslide fatality, and 22 consecutive years with no multiple-fatality landslide. While the good slope safety performance provides an assurance of the effectiveness of our slope engineering practice in achieving the intended safety objectives, the profession is aware of the need to stay vigilant about the fact that our man-made slopes and natural hillsides still have a finite chance of failure, and that Hong Kong is still vulnerable to widespread and serious landslides particularly during extreme rainfall events. With the recognition that the global and local weather conditions are being affected by climate changes, meteorologists have assessed that this would not only increase the annual rainfall, but also escalate the frequency and severity of extreme rainfall events in Hong Kong (ENB, 2015). There are indications that the short-duration rainfall, e.g. 1-hr rainfall, in Hong Kong has already been significantly affected (Figure 11).

This poses an unprecedented challenge to slope safety in Hong Kong in the years to come, most notably in the following aspects: (i) the frequency and scale of failure of man-made slopes, including both un-engineered and engineered slopes, will increase as extreme rainfall events become more frequent and severe, (ii) washout failures will occur more frequently and seriously, due to increased short-duration rainfall intensity resulting in concentrated flow of surface water, which is difficult to control in an urbanized setting, (iii) widespread natural terrain landslides and debris flows will occur, with escalated frequency, scale and mobility, and (iv) concurrent occurrence of multiple hazards, such as landslides, flooding and storm surges, will lead to compounding effects and thereby aggravating the consequence and rendering landslide emergency more difficult to manage.

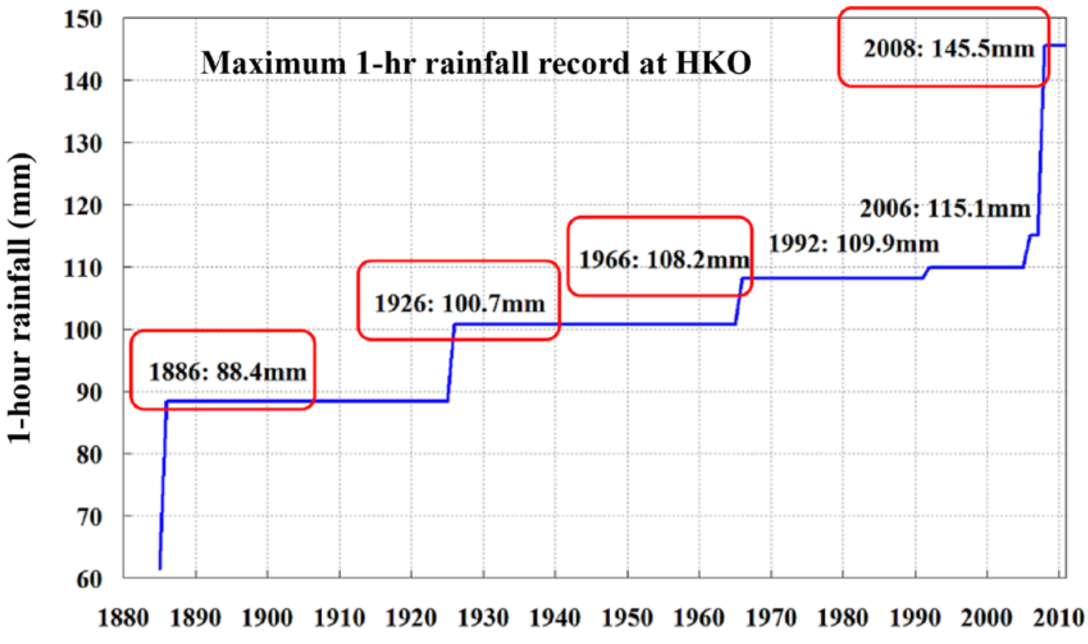


Figure 11: Record-breaking one-hour rainfall recorded by the Principal Raingauge in Hong Kong Observatory, Tsim Sha Tsui (Source: Hong Kong Observatory)

Since the 2010s, the GEO has been proactively undertaking studies on extreme rainfall events in collaboration with the Hong Kong Observatory and other research institutes. Scenario-based assessments of the territory-wide extent and consequence of landslides under extreme rainfall events have been conducted, together with evaluation of the capacity of the landslide emergency management system in coping with the events (Wong, 2013). It was found that natural terrain landslides and debris flows would overtake man-made slope failures as the principal slope safety concern in extreme rainfall events (Figure 12). This is evident in the record-breaking rainstorm of June 2008, which resulted in over 2,400 natural terrain landslides on Lantau Island (Figure 13). The work also provided useful information and insights about improving our preparedness for meeting the challenge. This includes formulation of adaptation strategy, which involves further enhancement of the prevailing slope engineering practice to minimize failure and damage under extreme rainfall events. It also calls for enhancing our emergency preparedness and strengthening the resilience of the community in coping with extreme events. These are important areas for the geotechnical profession to address in the years to come, and will lead to further evolution of our slope engineering practice to meet the unprecedented challenge ahead.

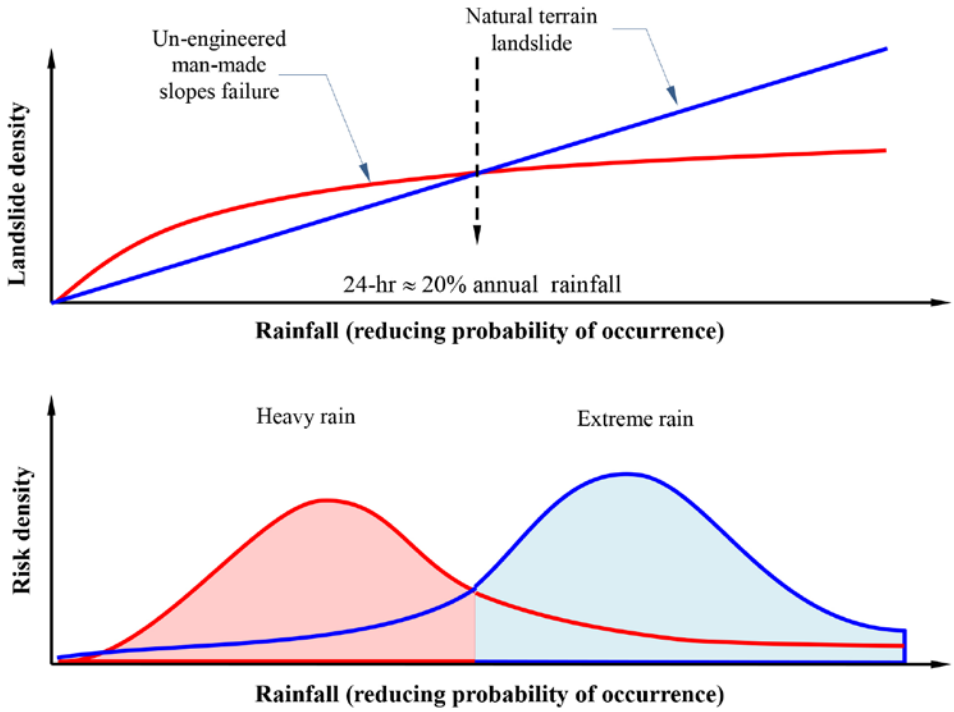
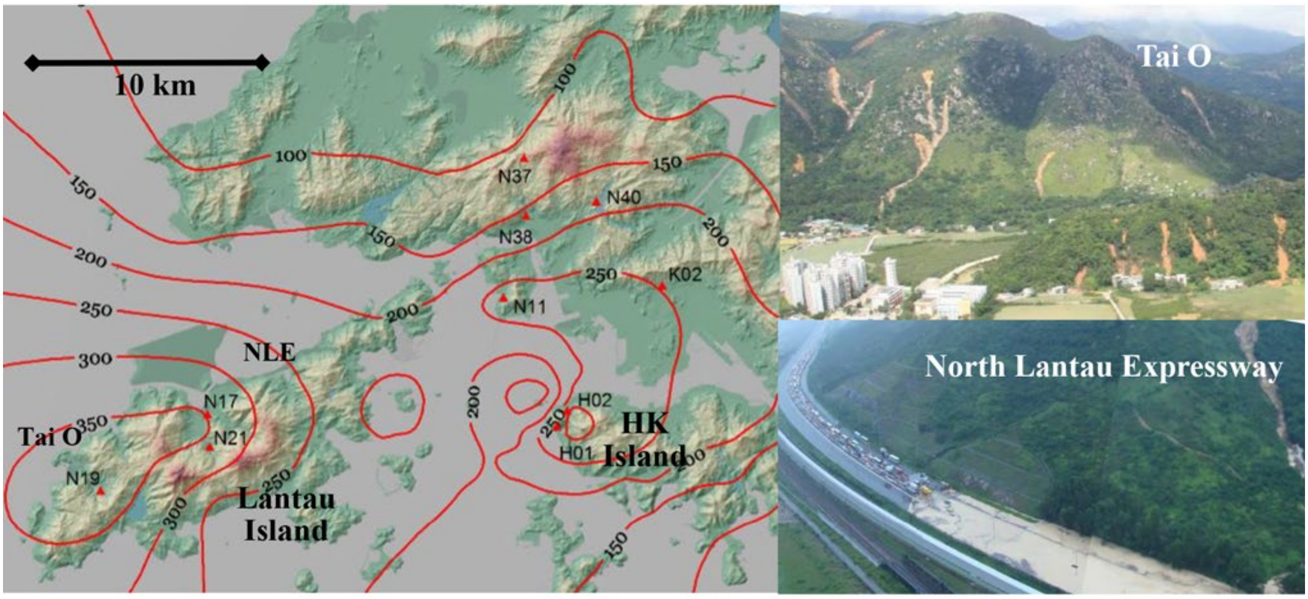


Figure 12: Diagrammatic illustration of change in principle landslide threat
From man-made slopes to natural terrain landslides in extreme rainfall events



4-hour rainfall distribution

Figure 13: June 2008 rainstorm resulting in over 2,400 natural terrain landslides on Lantau Island

6 CLOSING REMARKS

Slope engineering practice in Hong Kong has been evolving for the past 40 years, in parallel with increasing public expectation of slope safety and improving professional knowledge and capability. The evolution has led to advances in slope engineering, and provided Hong Kong with the positive reputation for landslide risk management. Consequentially, the landslide risk in Hong Kong has been substantially reduced. This, instead of suggesting that the mission of combating landslides is accomplished and the job is done, places the geotechnical profession in a pivotal position to prepare Hong Kong to face the forthcoming, unprecedented challenge of extreme rainfall events in the wake of climate change. It calls for sustained effort from the profession, and will further reinforce our role in enabling Kong Kong's sustainable development and chartering international best practice in urban slope engineering and landslide risk management.

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