Learning from Slope Failures in Hong Kong

H. N. Wong & K. K. S. Ho
Geotechnical Engineering Office, Civil Engineering Department, Hong Kong

Synopsis: This paper presents the salient findings on slope failures in Hong Kong from systematic landslide studies carried out over the last several years. The studies have brought about an improved understanding of the causes and mechanisms of landslides and significant advancement in slope engineering practice in Hong Kong. The work has provided information which challenges concepts previously established locally and given rise to insights into means of enhancing the slope stability assessment process and slope improvement works in tropically weathered rocks and improving the slope safety management system for dense urban hillside developments.

INTRODUCTION

The acute slope safety problems faced by Hong Kong are the result of dense development of a hilly terrain, high seasonal rainfall and a large number of potentially substandard man-made slopes mostly formed before the 1970's without proper geotechnical input and control.

This paper presents the salient observations made during systematic landslide studies in the last decade in Hong Kong. The studies have provided information which challenges previously established concepts and gives rise to new insights into enhancing the slope stability assessment process in tropically weathered rocks and improving the slope safety management system for dense urban hillside developments.

GEOLOGY AND LANDSLIDES IN HONG KONG

The geology of Hong Kong is described in detail by Fletcher (1997), Fletcher et al (1997), Davis et al (1997), and Sewell & Campbell (1997).

A simplified geological map showing the principal rock types in Hong Kong is given in Figure 1. The two dominant rock types in the urbanized areas are granites and volcanic rocks. These rocks have been deeply weathered in situ, with a highly variable weathering depth (locally can be in excess of 60 m). The ground profiles are typically highly heterogeneous. Corestones may be left behind in a matrix of soil derived from insitu rock weathering which retains evidence of the original rock texture, fabric and structure (termed saprolite). Granitic and volcanic saprolites tend to be fairly well-graded, typically being a sandy silt to silty sand with some gravels and a small amount of clay. Relic joints are preserved in the saprolitic zone and intrusions in the form of dykes (e.g. dolerite, porphyry, etc.) are not uncommon. Kaolin veins or seams as a product of weathering or hydrothermal alteration can also be present. A detailed account of the effects of mineralogy and microfabric in saprolites is given by Irfan (1996). Near the ground surface, colluvium resulting from past mass movement may exist.

The significant increase in the population of Hong Kong since the early 1900's resulted in major urban development on marginally stable hillsides involving extensive civil engineering and building works. The hillsides were cut and filled on to make room for developments and infrastructure. There are also squatters on steep hillsides, many of which comprise flimsy huts with unscrupulous slope cuttings and inadequate drainage.

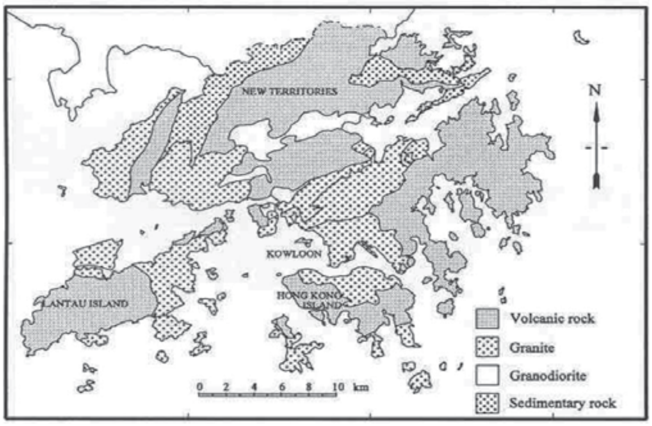


Figure 1. Simplified geological map of Hong Kong

Almost all of the landslides in Hong Kong are triggered by heavy rainfall. On average, some two to three hundred slope failures are reported every year. This equates approximately to an average density of one landslide per year for every square kilometre of the developed area. Most of the landslides occur on man-made slope features (i.e. slopes and retaining walls) and are of a relatively small scale (within 50 m^3), but some can be large (5,000 m^3 or more). In a dense urban area like Hong Kong, even a small landslide

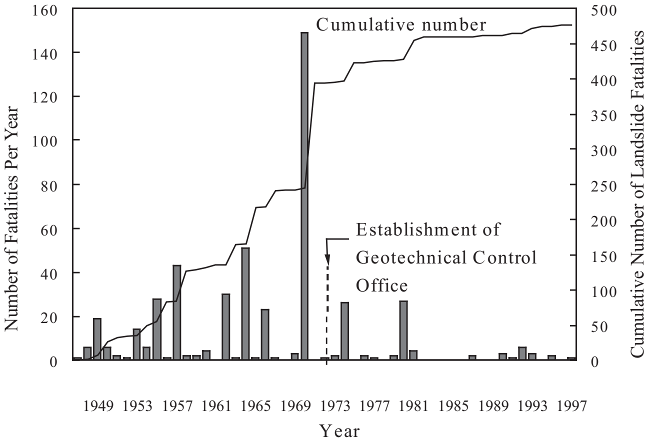
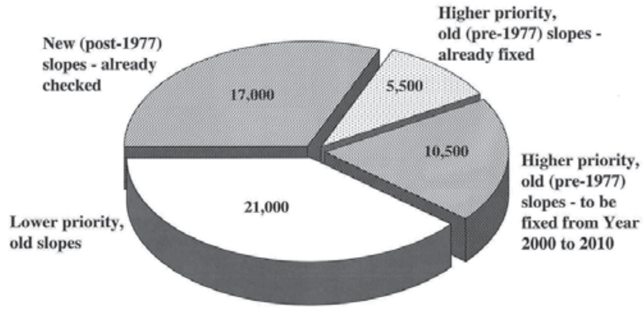


Figure 2. Annual landslide fatalities in Hong Kong



Notes : (1) A total of about 54,000 sizable man-made slopes (generally > 3 m high) have been registered in the New Catalogue of Slopes.
(2) About 30% of the registered slopes are owned by private parties and 70% owned by Government.

Figure 3. Breakdown of man-made slopes in Hong Kong's New Catalogue of Slopes

in close proximity to buildings or roads can result in casualties. In addition, the consequential economic losses and social impact because of landslides can be significant. The scale of the landslide problem in Hong Kong is reflected by a death toll of over 470 people since the late 1940's, mainly as a result of collapses of substandard man-made slopes (Figure 2). Given that even small failures can result in serious consequences, a high level of slope safety is called for.

In the aftermath of several major landslides with multiple fatalities in 1972 and 1976, Hong Kong Government created a central policing body, the Geotechnical Control Office (GCO, renamed Geotechnical Engineering Office in 1991) in 1977 to regulate planning, investigation, design, construction, monitoring and maintenance of slopes in Hong Kong. The comprehensive slope safety system, which has evolved in response to experience and through reform initiatives, is described in detail by Malone (1998) and Chan (2000).

The legacy of a large number of old man-made slopes and retaining walls has to be dealt with by the Geotechnical Engineering Office. Nearly all of these pre-1977 slopes had not been subjected to any rigorous geotechnical investigation and design checking and they do not meet the required geotechnical standards. Of the 54,000 sizeable man-made slopes registered in the Catalogue of Slopes, about 37,000 slope features were formed before the introduction of proper geotechnical control in 1977 in Hong Kong (Figure 3).

With the setting up of the comprehensive slope safety system since 1977, new slopes have to meet the required geotechnical standard and old slopes are investigated and upgraded under a systematic retrofitting programme (referred to as the Landslip Preventive Measures Programme).

After a number of uneventful years since the mid-1980's, a number of fatal landslides in the early 1990's have highlighted the public expectation that the slope retrofitting programme should be accelerated. The need to reduce risk in a more expeditious manner calls for enhancement of the landslide risk management strategy and innovative ideas on risk-reduction measures. A review of the slope safety system was carried out in 1995 (Works Bureau, 1995). Subsequently, additional resources were made available and new initiatives were put in place. A systematic landslide investigation programme was introduced, together with other initiatives, in the mid-1990's to enhance the slope safety system. The landslide investigation work has led to an improved understanding of the causes and mechanisms of landslides. The work has also facilitated further enhancement of slope engineering practice and improvement of the slope safety system in Hong Kong.

SLOPE ENGINEERING PRACTICE IN THE 1980'S

Slope Design Methodology

Slope formation in Hong Kong before the 1970's was largely done in an empirical manner with no proper geotechnical control on both the design and construction process. Since the establishment of the Geotechnical Control Office in 1977, significant advances have been made throughout the 1980's on basic aspects related to slope stability in tropically weathered rocks, including the introduction of classification systems for weathered rocks based on material and mass properties, improved ground investigation techniques, research and development work on the shear strength of saprolite materials (including contribution of suction and large inclusions, effects of relic joints, bonding, etc.), assessment of groundwater response, etc.

Guidance on slope assessment and design is given in the Geotechnical Manual of Slopes (GCO, 1984), which have been widely adopted in local professional practice. The perception at that time was that there was nothing about slope stability problems in Hong Kong which was especially different from that in non-tropical areas (Brand, 1985). The preferred soil mechanics approach to tackling slope problems involved the use of theoretical stability analysis based on the conventional limit equilibrium approach. Minimum Factors of Safety are prescribed for different categories of facilities affected (defined in terms of the degree of usage) for both new and existing slopes (i.e. those satisfying certain qualifying criteria). An appropriate geological model is to be formulated based on site-specific ground investigations. Designers are expected to account for the variability in material strengths (determined by triaxial tests or sometimes shear box tests) through judicious choice of design parameters. General guidelines are given in the Geotechnical Manual for Slopes for assessing the design groundwater conditions for prescribed rainfall return periods. In practice, the most popular approach has been to resort to site-specific groundwater monitoring over a period of time, typically one wet season preferably with significant rainstorms, with the design groundwater level assessed by means of extrapolation of the available data. In many cases, the wetting band theory (Lumb, 1962) is invoked to assist in assessing the design groundwater conditions.

Brand (1985) reviewed the state-of-the-art of limit equilibrium stability analysis for slopes in tropically weathered rocks by reference to the key components of slope stability prediction, namely, mode of failure, method of analysis, shear strength and pore pressure distribution at failure. He concluded that the application of rigorous soil mechanics methods of slope stability analysis alone to weathered profiles is fraught with extreme difficulties. He advocated adopting such an approach in conjunction with a thorough engineering geological assessment, together with the application of elements of geomorphology and hydrology as well as sound judgement. It was recognized that the main difficulty related to possible over-simplification of the geological profile and that construction reviews to verify the validity of design assumptions is critical. The application of the back analysis approach was sometimes favoured but it was recognized that the results needed to be tempered with caution (Hencher et al, 1984).

Perception of the Nature of Landslide Problem in the 1980's

Based on the statistics that the majority of the landslides reported to the GEO affected man-made slopes and retaining walls, the general perception during the 1980's was that the landslide problem in Hong Kong was dominated by failures of old man-made slopes built before 1977. There was also the perception that slopes built after 1977 to current standards were of little instability concern.

As reported by Premchitt et al (1985), short-term rainfall intensity was considered the dominant parameter causing rain-induced landslides, with the antecedent rainfall not being a significant factor in landslide occurrence in Hong Kong. This empirical observation based on rainfall and landslide data available at that time was attributed to the relatively high permeability of the soils in Hong Kong.

Many of the failures were considered to be related to the action of concentrated surface runoff or concentrated water ingress. The runoff is generally concentrated in the form of flooding or channelised flow because of man-made features in a built-up environment and can cause significant hydraulic scouring (Au & Suen, 1996). Lumb (1975) noted that in many of the landslides in Hong Kong, no significant seepage was observed and that the exposed soil was usually not completely saturated. Thus, there was a perception in the 1980's that rise in the groundwater table was rarely a cause of landslides in Hong Kong.

The proposition put forward by Lumb (1975) that slope failures in Hong Kong are abrupt and rapid, with little or no prior warning, has remained unchallenged throughout the 1980's. Ground movement monitoring was generally considered to be of limited use. A number of slow-moving failures have been observed and studied in the 1980's (Irfan et al, 1987; Irfan, 1989). However, such incidents were essentially regarded as the exceptions.

Investigations into selected landslides were carried out on an ad-hoc basis throughout the 1980's. These studies covered some of the more significant slope failures in Hong Kong but it appears that the general perceptions as noted above were not challenged or significantly altered by the study findings.

The efforts of the Landslip Preventive Measures Programme in Hong Kong focused on upgrading old slopes posing a significant threat, such as sizeable cut slopes and fill slopes. Old loose fill slopes were upgraded to the required geotechnical standard by recompaction to prevent rain-induced liquefaction failures. Cut slopes were commonly upgraded by cutting back, with retaining structures incorporated at the slope toe in case of space constraints, on the basis of conventional stability analysis.

THE NEW LANDSLIDE INVESTIGATION INITIATIVE IN THE 1990'S

Following the 1994 Kwun Lung Lau landslide (GEO, 1994; Morgenstern, 1994), a systematic landslide investigation initiative was introduced. Under this initiative, the following types of landslide investigations are carried out by the GEO:

(a) Landslide Review – All landslide incidents are reviewed shortly after they are reported to the GEO, to collate data for analysis and to identify cases which deserve further studies. An overall diagnostic review of all the landslides occurring in a year is carried out to identify trends and patterns.

(b) Detailed Landslide Study – An in-depth study is carried out on selected landslides to examine the history of the failed slope and identify the causes and mechanisms of failure.

(c) Forensic Investigation – An investigation is conducted on each fatal or serious landslide to the highest possible rigour of proof in order to prepare a report which can be presented as evidence in legal proceedings.

The main objectives of the systematic landslide studies were to:

(a) identify slopes in need of early attention before the situation deteriorates to result in a more serious problem (i.e. it serves as a safety net),
(b) provide forensic assessment and evidence,
(c) audit the performance of the slope safety system and identify areas for improvement, and
(d) advance the understanding of the causes and mechanisms of landslides to support technical development work and improve the reliability of preventive and remedial works to slopes.

Any necessary site-specific follow-up actions will be recommended following the study. In addition, more general recommendations on means to improve the relevant technical aspects of engineering practice or related procedural (or policy) matters associated with the risk management system are also made.

Some important documentations relating to landslides in the 1990's are as follows:

Document	Scope
The 1990 Tsing Shan debris flow by Chan et al (1991) and King (1996)	These document the largest recorded (20,000 m^3) channelised debris flow in Hong Kong from a natural hillside which affected a platform that was previously designated for housing estate development.
The 1991 Shau Kei Wan landslide by Evans & Irfan (1991).	This report documents the investigation of a blast-induced rock cut slope failure during construction.
The 1992 Siu Sai Wan failure by Ho & Evans (1993) and Franks (1999)	These document the investigation of a slow-moving failure (5,000 m^3) that occurred at a newly constructed soil cut slope.
The 1993 man-made slope failures in Lantau Island by Wong & Ho (1995)	This report documents the systematic study of more than 250 old cut slope failures along roads and catchwaters during a very severe rainstorm (>700 mm in 24 hours) in November 1993.
The 1993 natural terrain failures in Lantau Island by Wong et al (1997b) and Wong & Lam (1998)	These document the study of 56 selected natural terrain landslides following a review of over 800 hillside failures that occurred during the very severe rainstorm in November 1993.
The 1993 natural terrain failures at Tung Chung by Franks (1998) and Franks (1999)	These document the study of 52 landslides that occurred during the rainstorms of 17 July 1992 and 5 November 1993 on the natural hillside overlooking a new town development area. The landslides included a channelised debris flow with a total trail of 450 m.
Report on six fatal or significant landslides between 1992 and 1995 by Chan et al (1996)	This report documents the investigation of six significant landslides, including four fatal incidents undertaken between 1992 and 1995.
The 1994 Kwun Lung Lau landslide by GEO (1994) and Wong & Ho (1997)	These document the investigation of a serious landslide involving the collapse of a more than 100-year old masonry facing that resulted in five fatalities and three serious injuries.
The 1994 Fei Tsui Road landslide by GEO (1996a)	This report documents the investigation of a fatal landslide involving the failure of a large soil/rock cut slope.
The 1994 Shum Wan Road landslide by GEO (1996b)	This report documents the investigation of a fatal landslide involving the collapse of an old fill embankment and the hillside below.
The 1997 Ching Cheung Road landslide by Halcrow (1998a)	This report documents the investigation of a significant landslide involving the failure of a large soil and rock cut slope which was previously upgraded under the Government's slope retrofitting programme.
The 1997 Kau Wa Keng landslide by Halcrow (1998b)	This report documents the investigation of a fatal landslide involving the failure of an old cut slope and the ground above adjoining a squatter structure.
The 1997 Ten Thousand Buddhas' Monastery landslide by Halcrow (1998c)	This report documents the investigation of a fatal landslide involving the failure of an old cut slope.
Reports on studies of 1997 landslides (GEO Reports Nos. 79 and 88 to 92)	These reports document the investigation of selected significant landslides that occurred in 1997 by GEO's term landslide investigation consultants.

Review report by the 1997 Landslide Investigation Consultancy (GEO, 1999)	This report documents the landslide investigation methodology and experience gained from its application to the 1997 landslides.
Report on the Review of 1997 and 1998 landslides (Wong & Ho, 1999)	This report documents a comprehensive review of the 1997 and 1998 landslide data and evaluates failure rates of different classes of slopes and examines the key technical findings. A total of 21 landslides in 1998 were studied and the findings were documented in a series of landslide study reports.
The 1997 Lai Ping Road failure by Sun & Campbell (1999) and Sun et al (2000)	This report documents the investigation of the failure of a large cut slope and the hillside above (detached volume of 4,000 m^3) which had suffered significant slope deformation (by several metres) over the previous years reflecting the instability of a very large volume of material (100,000 m^3)
The 1997 Sau Mau Ping Road rock slope failure by Leung et al (1999)	This report documents the investigation of a blast-induced failure of a rock cut slope during construction.
The 1999 Shek Kip Mei landslide by Fugro Maunsell Scott Wilson (2000a)	This report documents the investigation of a serious landslide at an old cut slope that had been reviewed and improved in the late 1970's. The landslide resulted in the permanent evacuation of about 700 people from three housing blocks.
The 1999 Sham Tseng debris flow by Fugro Maunsell Scott Wilson (2000b)	This report documents the investigation of a debris flow from natural hillside that affected a squatter village and resulted in one fatality.

OVERVIEW OF SLOPE FAILURES IN HONG KONG

The common types of slope hazards in Hong Kong have been summarised by Wong et al (1998) with respect to the different slope types, nature of slope-forming material and mechanisms of fast-moving failures (Table 1). Common contributory factors in landslides in Hong Kong are shown in Table 2.

Table 1. Common mechanisms of fast-moving failures of man-made slopes in Hong Kong

<table>
<tr><th>Slope Type</th><th>Failure Mechanism</th><th>Description</th></tr>
<tr><td rowspan="3">Fill Slope [(1)]</td><td>Sliding</td><td>Detachment of part of the soil mass by way of sliding along a shearing surface or within a relatively thin shear zone, which may be straight or curvilinear.</td></tr>
<tr><td>Liquefaction</td><td>Sudden collapse of the metastable soil structure within a loose soil mass in the slope when it is subjected to a high degree of saturation under sustained shear stresses, resulting in a significant reduction in soil shear strength and leading to a flowslide type failure. This is a special case of 'Sliding' failure.</td></tr>
<tr><td rowspan="2">Washout</td><td rowspan="2">Detachment of part of the soil mass induced by the scouring action of running surface water.</td></tr>
<tr><td rowspan="2">Soil Cut Slope</td></tr>
<tr><td>Sliding</td><td>Detachment of part of the soil mass by way of sliding along a shearing surface or within a relatively narrow shear zone. For saprolitic soil, the failure mechanisms operating in rock cut slopes are also possible.</td></tr>
<tr><td rowspan="4">Rock Cut Slope</td><td>Sliding</td><td>Detachment of part of the rock mass by way of sliding along a planar or near-planar discontinuity in the rock mass in combination with a release surface.</td></tr>
<tr><td>Toppling</td><td>Detachment of blocks of rock by way of rotation about the base of rock blocks delineated by sub-vertical and sub-horizontal discontinuities.</td></tr>
<tr><td>Wedge Failure</td><td>Detachment of wedges of rock by way of sliding along the intersection of sets of discontinuities.</td></tr>
<tr><td>Ravelling</td><td>Detachment of small individual rock fragments from the slope face.</td></tr>
<tr><td colspan="3">Note: (1) This commonly comprises soil fill derived from decomposed granites, decomposed volcanics, residual soil or colluvium. Rock fill is not considered here.</td></tr>
</table>

Table 2. Notable generic factors contributing to fast-moving landslides

Generic Factors		Relative Degree of Occurrence	Examples
Inherent adverse geological weaknesses and unfavourable hydrogeological regime	Adverse geological materials, e.g. intensively kaolinised granites and volcanics, weathered dykes, sedimentary layers within volcanic formations, etc.	NC	Hudson & Hencher (1982); Hencher & Martin (1984); Au (1986); Chan et al (1996)
	Adverse geological discontinuities, e.g. adversely-orientated, extensive and persistent, clay- or silt-infilled discontinuities, pre-existing shear surfaces or zones, well-developed discontinuities that are slickensided or heavily coated with minerals or kaolinite.	NC	Cowland & Carbray (1988); Siu & Premchitt (1990); Hencher & McNicholl (1995); GEO (1996a)
	Hydrogeological setting favourable to development of perched water level, e.g. a surface layer of loose colluvium or fill overlying weathered rock	C	Pun & Li (1993); Hencher & McNicholl (1995); Wong & Ho (1995)
	Hydrogeological setting favourable to development of a high base groundwater table	NC	Wong & Ho (1995)
Inadequate design and construction practice	Oversteep slopes, e.g. oversteep pre-GCO man-made slopes constructed without rigorous geotechnical investigation and design	VC	Lumb (1975); Brand & Hudson (1982); Brand (1985); Wong & Ho (1995)
	Embankments comprising loose fill	VC	Lumb (1975); Hong Kong Government (1977); Wong (1992)
	Inadequate slope surface drainage provisions and poor detailing, e.g. inadequately designed surface drainage channels that are vulnerable to overspill during heavy rain	VC	Au & Suen (1996)
	Inadequate slope surface protection provisions and poor detailing, e.g. wetting of the slope and build-up of water pressures behind impermeable slope surface covers due to inadequate drainage	C	Wong & Ho (1995)
Adverse topography	Topographical setting susceptible to concentrated discharge or ingress of surface water, e.g. slopes situated below a low point of a crest platform or below a road bend from which surface water may overflow	C	GCO (1983); Au & Suen (1996)
Inadequate slope maintenance	Inadequate slope maintenance, e.g. de-vegetation, cracked surface cover, blocked surface drainage channels and weepholes, etc.	VC	Malone & Chan (1996); Wong & Ho (1995)
Inadequate maintenance of water-carrying services	Leakage from poorly-sited, defective water-carrying services and reservoirs	C	So (1976); GEO (1994)
Adverse combination of circumstances	Knock-on effects	NC	Chan & Pun (1992); GEO (1996b); Wong & Ho (1995)
Legend : VC Very common C Common NC Not common			
Note: The examples given are those when the individual factors have played a part in the failure case histories. It should be noted that many failures are due to a combination of factors.			

The majority of the landslides in Hong Kong are shallow (<3 m deep) and of a small scale. On average, about 90% of the failures are less than 50 m^3 in volume and about 50% are less than 10 m^3 in volume. Most of the failures occur on old cut slopes (with an average failure rate of about 1 in 100) but old fill slopes and retaining walls are also involved (with average failure rates of about 1 in 350 and 1 in 500 respectively). The corresponding failure rates of major failures (defined as having a volume of $\geqq 50\ m^3$) are lower by about one order of magnitude, and some 3% of the landslides are greater than 500 m^3 in volume. Of the major failures in old fill slopes, about 10% of these cases involve liquefaction failures.

The systematic review of the status and history of slopes involved in failures has provided insight into the nature of the landslide problems in Hong Kong. The different classes of man-made slope failures with respect to the age of slopes, whether the slope has been subjected to geotechnical engineering input since 1977 as required by the slope safety system (referred to as engineered slopes in this paper) and the adequacy of the geotechnical input are illustrated in Figure 4. It is important to distinguish between the year of slope formation with respect to the year 1977 because this was the time when proper geotechnical control was introduced. Failures do often occur at pre-1977 slopes which have not been engineered and are substandard. However, failures are also found on post-1977 slopes that should have been, but were not, engineered as required by the slope safety system (i.e. system compliance problem), and post-1977 slopes that were not covered by the then slope safety system (i.e. gaps in the system). Failures have also occurred at engineered slopes that do not meet the current geotechnical standards. This may reflect problems associated with implementation of the slope safety system or non-conformance with good engineering practice. Failures have also occurred on slopes engineered to current geotechnical standards, which raise questions concerning the adequacy of the prevailing standards.

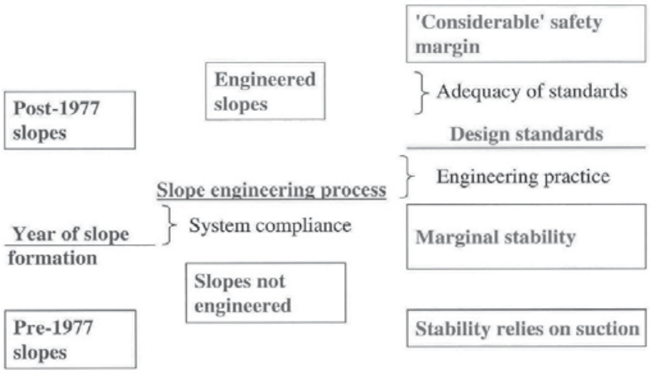


Figure 4. Different classes of man-made slopes

The detailed examination of the slope history and slope status has led to a more insightful classification of the landslides and diagnosis of the problems involved. It has also revealed a much more diverse landslide problem in Hong Kong in that failures do also occur in post-1977 slopes, including those designed to the required geotechnical standards.

Apart from the above important observation on the nature and range of landslide problems, specific technical observations made from systematic landslide studies are described below.

SLOPE MAINTENANCE AND IMPROVED SLOPE DETAILING

Surface water undoubtedly plays an important role in triggering many landslides in Hong Kong, particularly the shallow, small-scale failures. The main failure mechanism involves surface runoff leading to erosion or concentrated water ingress during intense rain. This notable type of failure on man-made slopes in an urban setting has been described in detail by Au & Suen (1996). Systematic landslide studies carried out in recent years have, apart from providing further data on such landslide triggers, also revealed the importance of two related root causes: lack of slope maintenance, and poor detailing in particular inadequate drainage provisions.

Inadequate maintenance generally takes the form of blocked or disrupted drainage channels, damaged hard surface cover (e.g. shotcrete), or poorly maintained vegetation. Many of the landslides involved washout failure due to overspill from blocked or damaged crest drains (Figure 5), infiltration into oversteep slopes through bare or poorly maintained vegetated ground or cracked surface protective cover, build-up of water pressure behind hard surface cover with blocked weepholes, or leakage from poorly maintained

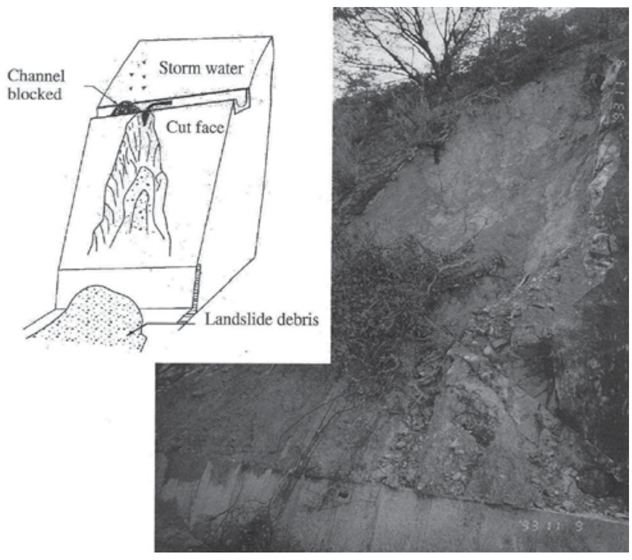


Figure 5. Washout failure due to overspilling from blocked crest drain

buried water-carrying services. A review of the global landslide data suggests that inadequate maintenance was a contributory cause of failure in more than 30% of the landslides in Hong Kong (Lo et al, 1998). The study of more than 250 man-made slope failures in Lantau Island during a severe rainstorm in November 1993 also suggests that about 40% of the failures involved inadequate maintenance (Wong & Ho, 1995).

Lack of slope maintenance can sometimes contribute to large-scale failures, particularly where the site setting is unfavourable (e.g. slopes with pre-existing tension cracks which are sensitive to loss of suction arising from infiltration through local defects in the slope surface cover). An initial small failure caused by inadequate maintenance of the slope surface protective and/or drainage provisions is also liable to create an unfavourable setting and trigger a sequence of events that could lead to a large-scale failure.

Inadequate attention to proper detailing may involve drainage channels that are undersized or with inadequate fall for self-flushing and hence are vulnerable to blockage, drainage detailing which is prone to over-spilling, etc. (Figure 6). Sometimes, surface water flow or ponding due to the adverse site setting or topography (e.g. slopes below the low point of a crest platform or a road bend can be subjected to concentration of surface water flow during intense rain) are not properly addressed in the design (Figure 7). The identification of surface water flow paths requires tracking all the possible pathways outside the immediate site environs since the sources of surface water concentration may be at a considerable distance away from the site. However, studies of landslides have revealed that the assessment may not have been done properly in practice.

Figure 6. Over-spilling due to inadequate surface drainage detailing

Figure 7. Ponding due to poor surface drainage provision

Where such root causes are prevalent, surface water can trigger landslides in old slopes as well as slopes that are up to current geotechnical standards. It was also noted from landslide studies that some landslides had occurred where the slopes had previously remained stable for a substantial period of time, having apparently survived a number of more severe rainstorms in the past. These failures are of a surprise from a rainfall 'loading' point of view and they may reflect inadequate maintenance or changes in the overall site setting (e.g. surface water catchment characteristics altered by upslope developments).

In recognition of the need to tackle the problem of slope maintenance and detailing, two major technical advances have been made in Hong Kong over the past few years. Firstly, a technical guide on good practice on slope maintenance was published by the Geotechnical Engineering Office in 1995 and further revised in 1998 (GEO, 1998). Secondly, guidance on improved detailing of a preventive nature in the form of prescriptive measures was published in 1996 (Wong & Pang, 1996) and further revised in 1999 (Wong et al, 1999) to enhance surface protection and drainage provisions.

On the administrative side, a comprehensive slope maintenance system has been set up in Hong Kong. All sizeable man-made slopes are now registered in the Catalogue of Slopes and the corresponding maintenance responsibility determined. Every Government-owned slope has been assigned to a responsible department or party for maintenance. In accordance with GEO (1998), routine maintenance inspections and works are done at least once a year, and each of the slopes will be inspected by a qualified geotechnical professional at an interval of not more than 5 years. For private slopes, public education is used to impress on owners the importance of slope maintenance in order to induce voluntary action (Yim et al, 1999).

GROUNDWATER

Although many landslides in Hong Kong are triggered by surface water, systematic landslide studies in recent years have pointed to the important role played by subsurface water in causing many of the landslides, particularly for sizeable failures. This finding is derived from timely field observations made shortly after landslide occurrence (which was mostly not possible before the introduction of the landslide investigation initiative) and consideration of landslide data which have been appropriately classified to avoid clouding the data by lumping different data together. Field inspections indicate that seepage from landslide scars can dissipate rapidly and is liable to be missed if prompt field inspections are not made. These observations also illustrate the transient nature of build-up in groundwater pressure in slopes in Hong Kong.

Figure 8. Erosion pipe with heavy seepage

One common cause of failure involves a shallow perching phenomenon. This can occur where there is a surface layer of thin colluvium overlying less permeable saprolite. Perching is also possible at the interface of loose (younger) colluvium and dense (older) colluvium. Loose colluvium can be prone to the formation of erosion pipes which act as conduits resulting in rapid rise in groundwater pressure during heavy rainfall (Figure 8). The geometry of the failure

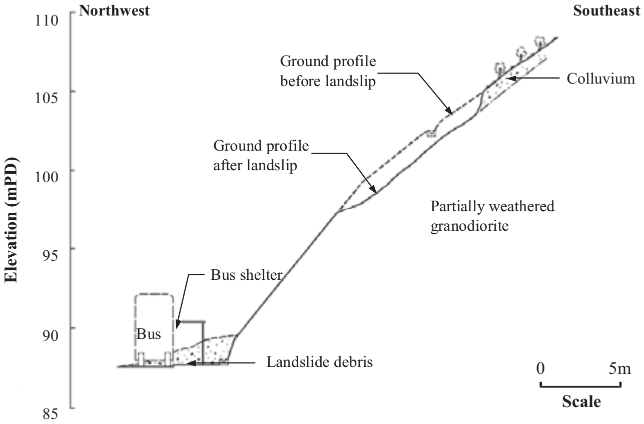


Figure 9. Cross-section of the 1993 Cheung Shan landslide

scar associated with the above adverse hydrogeological setting is typically confined to the shallow depths within the upper portion of a cut face and can extend uphill for some distance. Because of this, such failure mode can result in serious consequences in the case of a high cut slope, even though the scale of failure may be small. To illustrate such failure mode, a cross section through the 1993 Cheung Shan landslide is shown in Figure 9. In the study of more than 250 failures of cut slopes along roads and catchwater caused by a severe rainstorm in November 1993, Wong & Ho (1995) reported that up to about 25% of the failures involved a perched water table in the surface mantle of colluvium (Figure 10).

Landslides involving such a failure mode are also found in engineered slopes. The unfavourable hydrogeological setting giving rise to shallow perching can be difficult to detect and is often not identified in routine design practice in Hong Kong. Even if the thin colluvial mantle is identified, it would not be easy to confidently design against the above failure mode given the uncertainties in the rapid and large increase in the pore water pressure ratio (r_u) in the surface mantle. In practice, this calls for an alternative approach involving prescriptive drainage measures

Figure 10. Failure involving surface mantle of colluvium

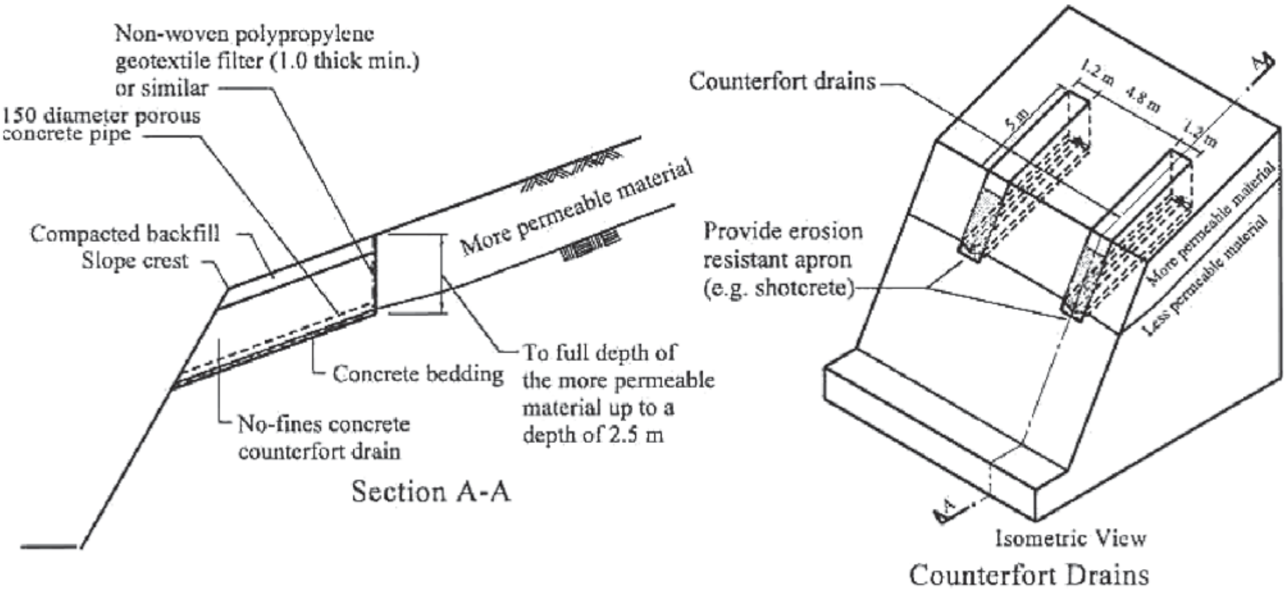


Figure 11. Prescriptive drainage provisions for possible shallow perching

(Wong et al, 1999), as contingency design provisions (Figure 11).

The build-up of perched water table above clay seams or infilled relict discontinuities has also led to deep landslides (GEO, 1996a).

A notable number of large-scale failures involved a significant rise in the deeper groundwater table within saprolite following prolonged severe rainfall. This may be partly related to the regional groundwater flow and affected by concentration of subsurface groundwater flow along old drainage lines (Figure 12), major depression in rockhead, significant erosion pipes (which may be associated with relict failure), damming behind less permeable dyke intrusions, etc. Some of these significant failures occurred some time after cessation of intense rainfall, e.g. by one to two days. Such a delayed response may in part be a function of antecedent wetness of the ground and subsurface seepage from a large catchment. Given the complexity of the weathering profile which can greatly affect the

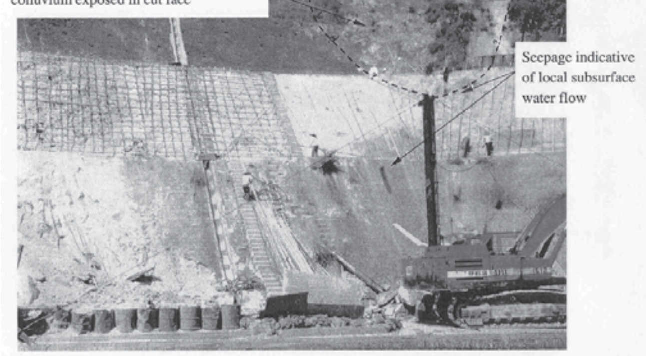


Figure 12. Old drainage course with subsurface water concentration (This processed slope failed in 1997)

hydrogeological regime, it is important to note that the subsurface catchment does not necessarily correspond to the surface catchment.

The practical engineering solution to combat the above problem is to pay special attention to potentially difficult sites with complex geology and/or groundwater conditions, and further improve the understanding of groundwater responses to facilitate more reliable assessment. A pragmatic approach is to incorporate contingency drainage provisions in the design (e.g. prescriptive horizontal drains) to avoid possible adverse build-up of groundwater pressure and use of more robust design solutions. This will be discussed further in the following.

ENHANCING THE RELIABILITY AND ROBUSTNESS OF SLOPE IMPROVEMENT WORKS

The audit of the performance of the slope safety system based on landslide studies has enabled the failure rates of the different classes of slopes to be assessed. The failure rates of engineered slopes are not small. This emphasizes the fact that even engineered slopes have a finite chance of failure despite having an adequate calculated Factor of Safety. The uncertainties and complexity associated with local geological weaknesses and groundwater regimes have led to failures, both of small and large scale, at engineered slopes.

Based on the comprehensive review of the 1997 and 1998 landslide data, a total of 42 incidents involved engineered slopes. This corresponds to an average annual failure rate of 0.12% for engineered man-made slopes. The corresponding average annual failure rate for major failures (i.e. ≧50 m^3) at

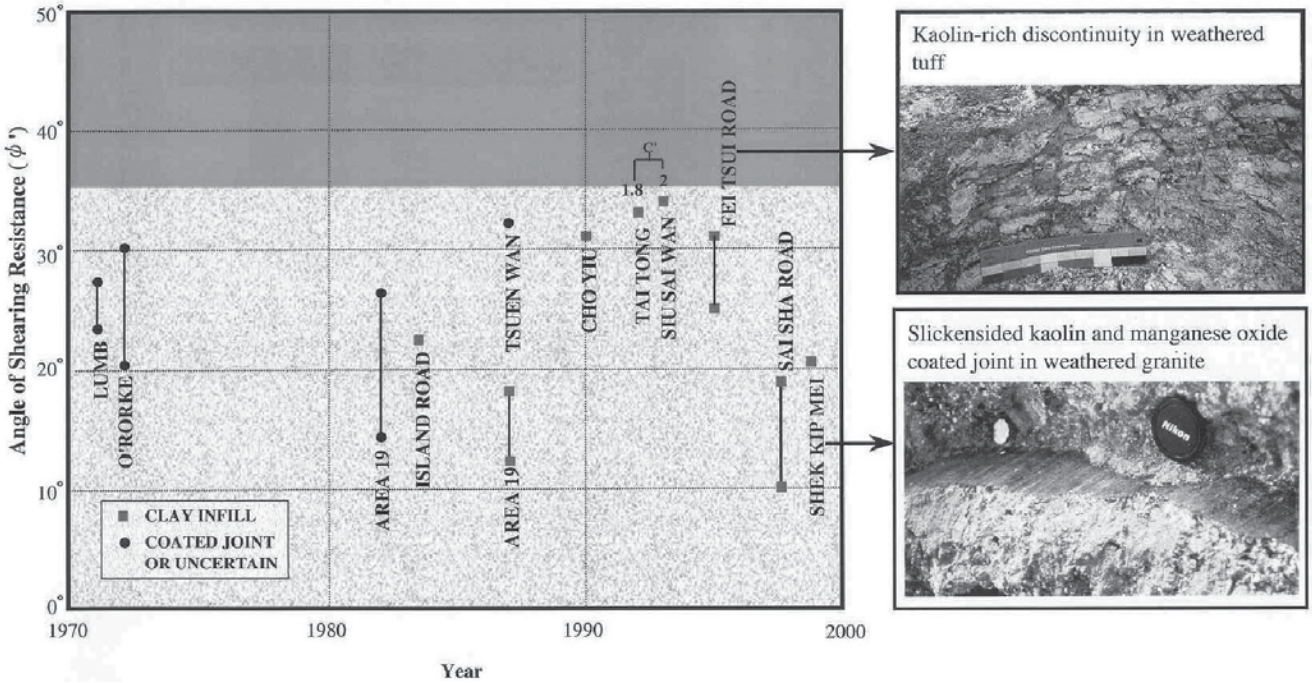


Figure 13. Selected lanslides involving relict-jointed saprolite

engineered slopes is 0.032%.

It should be cautioned that the above deduced failure rates are not necessarily the long-term average values given the uncertainties associated with the relatively short period of observation and that in Hong Kong the years 1997 and 1998 were wetter than normal. Notwithstanding this qualification, the available information suggests that the likelihood of failure of engineered slopes is, on average, about five times less than that of slopes that had not been engineered to current standards.

The nature of the problem of failure of engineered slopes has been diagnosed through systematic landslide studies. The breakdown of the 42 slope failures at engineered slopes in terms of slope type consisted of 25 affecting soil cut slopes, 12 affecting rock cut slopes and 5 affecting fill slopes.

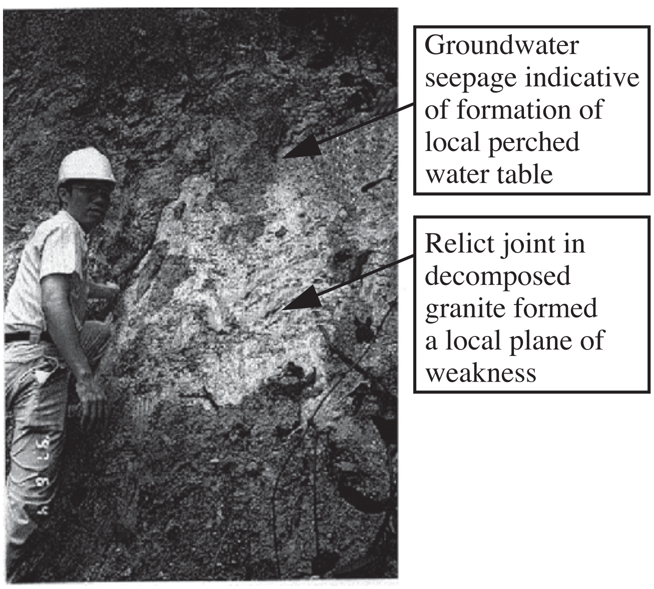


Figure 14. Landslide controlled by local adverse geological and hydrogeological conditions

Of the failures at engineered soil cut slopes, 72% involved more adverse groundwater conditions than those allowed for in the design, 28% involved more adverse geological material than that allowed for in the design and 39% involved inadequate slope maintenance. Many of these failures involve weak materials not accounted for in the geological model and the design. Figure 13 depicts the range of shear strength of adverse geological materials which shows that the conventional safety margin (i.e. typically 1.2 to 1.4 in Hong Kong) will not be adequate to cover for such adverse geological materials if the geological model is deficient.

About 70% of the landslides at engineered soil cut slopes were small scale failures controlled mainly by the local geological and/or groundwater conditions (Figure 14). This gives an indication of the annual defect rate (about 0.15%) associated with such localised failures given the current state-of-practice in Hong Kong.

All of the 12 rock cut slope failures (out of the 42 failures at engineered slopes) involved small-scale failures but the consequence could have been serious because of a dense urban setting. The instabilities were generally caused by local groundwater or local adverse (or open) jointing in the rock mass which might not have been adequately considered in the design. Also, it appears that rock slopes can be vulnerable to localised deterioration, bearing in mind that most rock slopes in Hong Kong are not provided with a surface protective cover.

Of the 5 failures at engineered fill slopes, two involved poor detailing, two involved non-compliance with the stipulated standards (i.e. slopes not constructed in accordance with the design requirements) and one involved leaky water services. There are generally less uncertainties with respect to groundwater and materials in engineered fill slopes than in engineered cut slopes of the same status formed in natural material, provided the fill slopes have been properly detailed and constructed. The main issues with this class of slope problem appear to be improved construction control, detailing and non-conformances with current requirements.

The above diagnosis highlights the need to improve current slope engineering practice in order to further reduce the failure rates of engineered slopes in the following four aspects, and these have already been implemented in Hong Kong:

(a) The occurrence of minor failures arising from local adverse groundwater regimes and local weak materials in the soil or rock mass, which is possibly exacerbated by deterioration, is very difficult to confidently guard against in design assessments. This emphasizes the need for improved detailing and protective measures as an integral element of design, such as debris traps, meshing, toe barriers, buffer zones, etc. to cater for such local detachments (i.e. adopting a design philosophy which directly caters for such failure modes).

(b) It is important that due attention be paid to identifying difficult sites at an early stage that require more geotechnical and geological input. The landslide data point to a number of indicators of potentially difficult sites. These include:

- sites with relic massive or major failures (there is a significant proportion of the massive landslides at slopes with relic massive failures),
- evidence of high groundwater, or high level seepages, associated with drainage valleys, subsurface drainage concentration (e.g. depression in rockhead profile), dyke or persistent infilled subvertical discontinuities,
- planar geological features (such as joints, faults, seams, bedding, foliation, planar soil rock interface), especially where they are dipping out of the slope, laterally persistent, showing evidence of previous movement, associated with zones of weak materials such as kaolin, and affecting groundwater flow,
- evidence of progressive deterioration and movement,
- slopes with a history of failure after being assessed or built to current geotechnical standards,
- complex groundwater conditions with a significant storm response or delayed response, and
- large cuttings in a deep weathering profile.

(c) The robustness of design options, i.e. their sensitivity to uncertainties in geological and hydrogeological conditions, should be considered. Many of the soil cut slopes in Hong Kong treated in the 1980's involved trimming back to an 'adequately safe' gradient based on stability analyses. The gradual shift in the trend in the 1990's has been towards the use of soil nails, which was an attractive solution from a logistics, programming and cost point of view. To date, there have been no recorded failures of slopes that have been treated with soil nails in Hong Kong. It is now recognized that a major advantage of the soil nail scheme lies in its robust nature, i.e. the ability to deal with unforeseen geological defects and groundwater conditions.

(d) To enhance the reliability of slope assessment and slope improvement works, due attention must be given to the following:

- A comprehensive aerial photograph interpretation report should be prepared to establish the history and nature of any past failures that may affect the slope.
- In assessing the design option to be adopted, the reliability and the robust nature of the design scheme should be considered, taking into account the sensitivity of the option to the uncertainties involved. Such an assessment should be included as part of the design documentation.
- The findings of verification of the design geological model during slope works should be incorporated as part of the as-built records. These, together with a schedule of key geotechnical design assumptions, should be included in the Maintenance Manual for future reference.
- A post-construction review of the adequacy of design assumptions and slope performance should be carried out by the designer during the Contract Maintenance Period in addition to the design reviews during the critical stages of construction.

PROGRESSIVE SLOPE DETERIORATION AND MOVEMENT

There is now ample evidence from detailed landslide studies to show that many failures, especially large-scale failures of sizeable cut and fill slopes in Hong Kong, exhibit prolonged movement before failure for a considerable period of time (several years or more), as reflected by open tension cracks infilled with foreign materials or displacement across infilled discontinuities (Figures 15 and 16). This evidence refutes the school of thought that slope failures in Hong Kong occur with little or no prior warning. Also, slope deterioration plays an important role in landslides, which is partly associated with lack of maintenance and partly related to progressive movement (e.g. extensive tension cracks, ground opening up resulting in changes in hydrogeological conditions and increased water ingress).

Figure 15. Infilled tension crack

Figure 16. Prolonged slope deformation before full detachment

Based on a review of the 1997 and 1998 landslide data, at least 17 cases were confirmed to have involved significant progressive slope deformation, five of which had major detachments from part of the unstable mass. Seven of these 17 cases were previously engineered to current standards. This amounts to 17% of the total number of failures involving engineered slopes.

The above observations had led to a fundamental change in the perception of the mode of rain-induced failures of saprolitic slopes in Hong Kong. These have a number of major implications to our approach to slope assessment and landslide prevention.

Firstly, slopes with progressive movement and pre-existing tension cracks are liable to deteriorate as the unstable ground mass continues to open up without full detachment (e.g. during a severe rainstorm) which could fail in subsequent less severe rainstorms. These landslides are effectively a surprise in that the slopes apparently survived more severe rainstorms in the past. Slope distress may be caused by previous severe rainstorms, with subsequent failures occurring in less severe rainstorms given different hydrogeological conditions. Based on the 1997 and 1998 landslide data, 18 incidents involving engineered slopes had detailed information both on the severity of the rainstorm that triggered the landslide and the causes of failure. Seven out of the 18 incidents failed during rainstorms which were notably less severe than those experienced in the past according to automatic raingauges installed since about the mid-1980's. The notion that the continued stability of a pre-existing slope may be proven by past rainstorms must be treated with extreme caution. Before one could confidently count on past slope performance regarding the margin of safety for long-term stability, there is a need to consider factors such as slope deterioration, deformation and possible changes in the site setting.

Secondly, as slopes may not necessarily fail without prior warning, care is needed to confirm the absence or otherwise of signs of distress or slope deformation during landslide inspections by examining a sufficiently large extent of the affected slope. Apart from the slope face, the ground above the slope should also be inspected to establish the extent of distress. The signs of distress may not necessarily be obvious on the slope face if the distressed zone is deep and extends for some distance beyond the crest of the slope face, e.g. the 1999 Lai Ping Road landslide (Sun et al, 2000) and the 1999 Shek Kip Mei landslide (Fugro Maunsell Scott Wilson, 2000). Such distressed ground can pose a significant hazard of further instabilities during subsequent rainstorms. Also, the periodic inspections by geotechnical engineers as part of the slope maintenance programme will provide a safety net by reviewing the adequacy of past slope assessment in the light of the actual slope performance. One of the important functions is to identify the need for enhanced maintenance works to reduce the rate of deterioration, or the need for further stabilisation measures for slopes approaching the limits of their service life.

Thirdly, the fact that slopes may exhibit signs of movements before detachment also opens up the possible avenue for slope movement detection and monitoring, particularly given further advances made in monitoring and remote-sensing techniques.

MOBILITY OF LANDSLIDE DEBRIS

The travel distance of landslide debris forms an important element in the assessment of the failure consequence of a slope and the quantification of risk. The approach adopted was to collect field data and consider the landslide mechanism. Based on these, analysis and modelling can be carried out, the results of which can be used to predict debris mobility (Wong & Ho, 1996).

In terms of travel angle (Cruden & Varnes, 1996), the data in Hong Kong indicate that for typical rain-induced landslides involving small to medium scale failures (viz. landslide volume of <2,000 m^3) generally ranges from 30° to 40°, which is similar to the angle of shearing resistance of saprolite (Figure 17). The field data indicate that the travel angle tends to reduce with

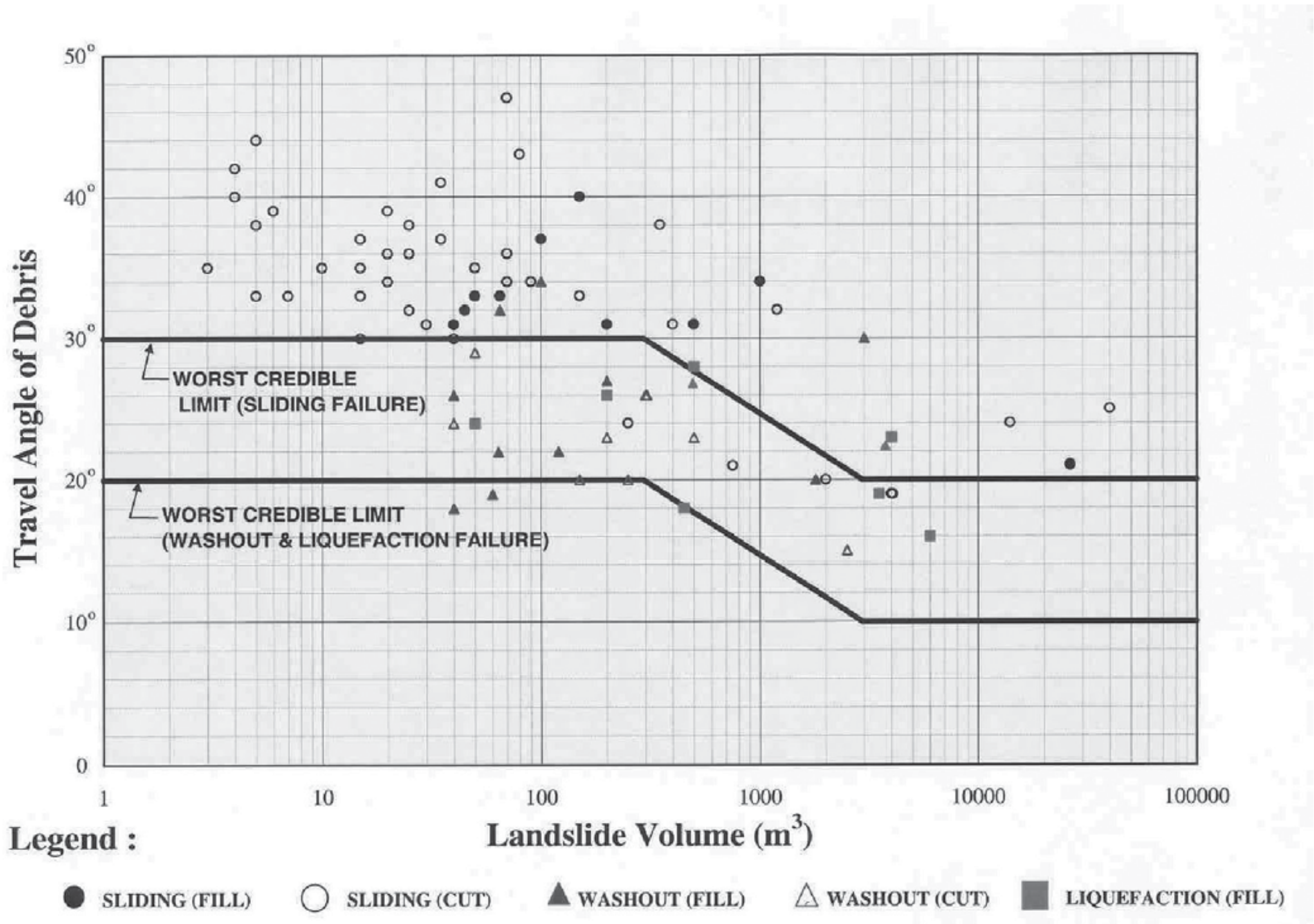


Figure 17. Data on debris mobility for different mechanisms and scale of landslides in Hong Kong

increase in landslide volume (i.e. the runout tends to increase), which is consistent with the trends reported elsewhere (e.g. Hutchinson, 1988).

Highly mobile failures can result in disastrous consequences because of the high velocity and reach of the debris. Scenarios that have been shown to be liable to result in mobile debris in Hong Kong situation include the following:

(a) liquefaction of loose fill bodies which have a metastable structure,
(b) major 'washout' or debris flow type failures due to the action of concentrated surface water,
(c) large-scale failures (say >2,000 m^3 in volume),
(d) undrained loading on wet and loose material (e.g. water-logged or saturated debris such as that from a previous phase of failure deposited along the subsequent debris path), and
(e) failures involving a high groundwater level (e.g. significant groundwater seepage over a large area) or controlled by weak material (e.g. clay seam).

A scenario that is of particular concern and great practical significance is where an apparently ductile failure with limited mobility turns into a brittle, mobile failure with fast-moving debris. There are reported landslides in Hong Kong which exhibit an apparent change in failure mechanism, e.g. the 1997 Lai Ping Road landslide as shown in Figure 18 (Sun & Campbell, 1999). This is usually related to the progressive deterioration of the distressed ground which promotes increased water ingress and brings about detachment of material, possibly via a different mechanism (e.g. cleft water pressure) than that operating in the slow-moving ground mass.

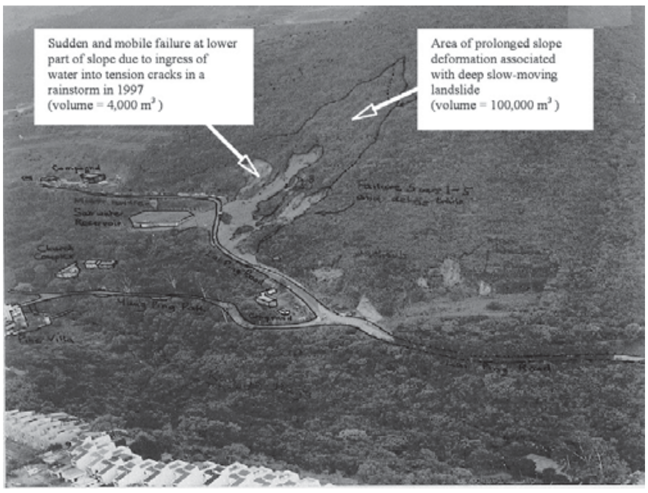


Figure 18. The 1997 Lai Ping Road landslide

A practical implication of the above observation is that a small detachment from a slope with a history of failure could be the surface expression of a large-scale instability that is developing progressively. The systematic landslide investigation initiative provides an important mechanism for picking up such sites for timely attention before the situation deteriorates to result in a serious problem. Progressive slope movement has been observed in both soil cut slopes and fill slopes. Target candidates that deserve attention during landslide inspections are failures in large soil cut or fill slopes, particularly if they have previously been assessed or built to current standards.

QUANTITATIVE RISK ASSESSMENT

There has been a move in Hong Kong towards the development of a risk-based approach to supplement the conventional deterministic approach based on the use of factor of safety. This may be attributed to the following considerations:

(a) There is considerable uncertainty associated with the ground and groundwater conditions in the weathered profile and the rainfall characteristics; even slopes which have been designed to current standards may fail, as reflected by the landslide statistics,

(b) a risk-based approach can assist in the prioritization of the retrofitting of slopes with less serious failure consequences/probability and the development of a strategy to deal with this category of slopes, and

(c) a risk-based approach facilitates the communication of landslide risk to the general public.

Landslide studies have contributed significantly to the development and application of QRA by providing good quality data on failures as a source of information to quantify landslide risk. In addition, these studies have also led to an improved understanding of failure mechanisms which assist greatly in hazard identification and systematic analysis of failure data. For example, good quality data on travel distance of debris have been obtained for different failure mechanisms and site settings (Wong & Ho, 1996). Such systematic diagnosis of data is important for the development of failure frequency and consequence models for risk quantification.

QRA may be applied in a number of areas. These include:

(a) Global risk assessment to examine the scale of a problem to facilitate formulation of risk management policies and optimal resource allocation.

(b) Site-specific assessment to evaluate the level of risk in terms of fatality (or economic loss) at a given site. This facilitates the assessment of whether the risk levels at a specific site are acceptable and the evaluation of risk mitigation measures on the basis of cost-benefit analysis.

(c) Relative risk assessment involving the determination of the priority for action, e.g. ranking of old man-made slopes under the systematic retrofitting programme.

A full review of the development and use of the quantitative risk assessment (QRA) technique in Hong Kong is beyond the scope of this paper. As examples to illustrate the application of QRA in our landslide prevention and risk management work, three case studies are summarized below.

A global landslide QRA has been carried out to assess the overall risk posed by the approximately 37,000 old man-made slopes to the community. The hazard model adopted reflects the different types of slopes of differing heights, mechanisms and scale of failure. For example, in the case of fill slopes, different mechanisms of failure, (namely liquefaction, washout and sliding) have been distinguished. The failure rates associated with the different hazards can be assessed by reference to failure statistics. A generalized consequence model was formulated which considers all the key factors affecting the mobility of landslide debris and the vulnerability of affected facilities, including type of facilities, temporal presence of population, mobility of landslide debris, scale of failure and the degree of protection by the facility (Wong et al, 1997a).

The risk profile shown in Figure 19 shows that about half of the overall risk is derived from approximately 10% of the slope population that has a higher potential risk (Wong & Ho, 1998). This means that the upgrading of a relatively small proportion of the old slopes posing the highest potential risk would result in a major risk reduction. It also emphasizes the importance of an appropriate risk-based ranking system for prioritizing landslide preventive actions.

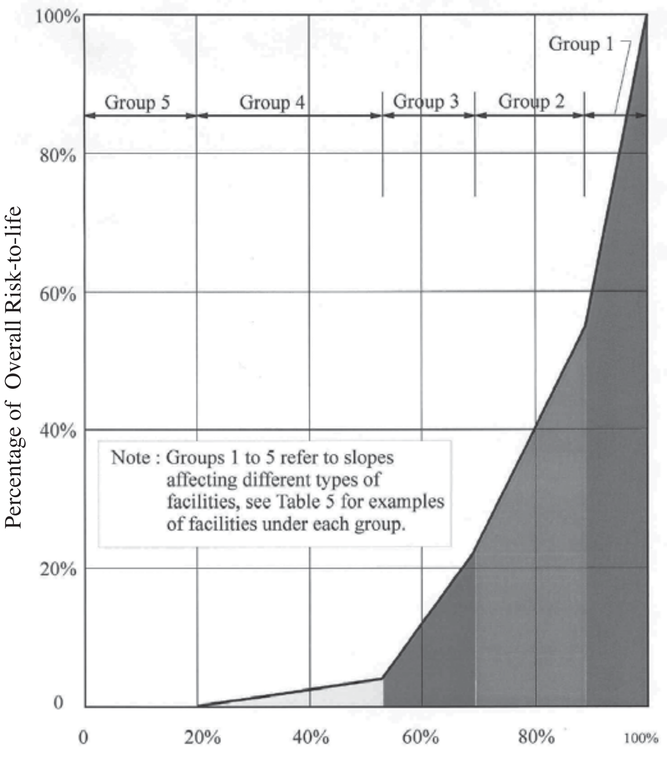


Figure 19. Risk profile of pre-1977 slopes

The average annual potential loss of life can be calculated, using QRA techniques, sufficiently accurately to determine longer-term trends and predict future performance. QRA calculations show that by the year 2010, the overall landslide risk from sizeable old man-made slopes will have been reduced to about 25% of that existed in 1977.

The second example concerns a site-specific QRA. The generalized consequence model was used to back-analyse the Fei Tsui Road landslide, which occurred in the early hours of 13 August 1995 with a failure volume of some 14,000 m^3. The road in front of the slope was totally engulfed by landslide debris of up to about 6 m thick (Figure 20). The incident resulted in one fatality and one other person narrowly escaped injury. The theoretical consequence model predicts an average number of four fatalities arising from the given landslide. This illustrates the near-miss nature of the incident with only one fatality. The f-N curve derived from QRA calculations (Figure 21) shows the level of societal risk posed to the community by the Fei Tsui Road landslide.

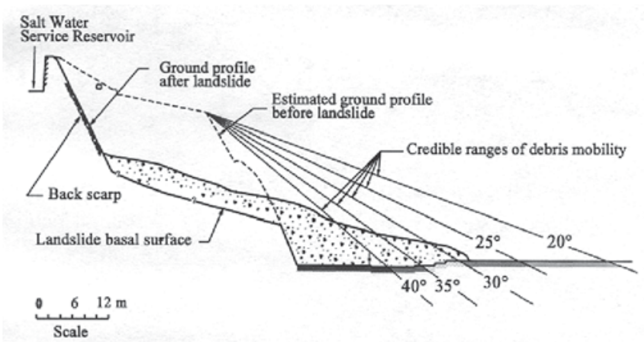


Figure 20. Cross-section through the 1995 Fei Tsui Road landslide

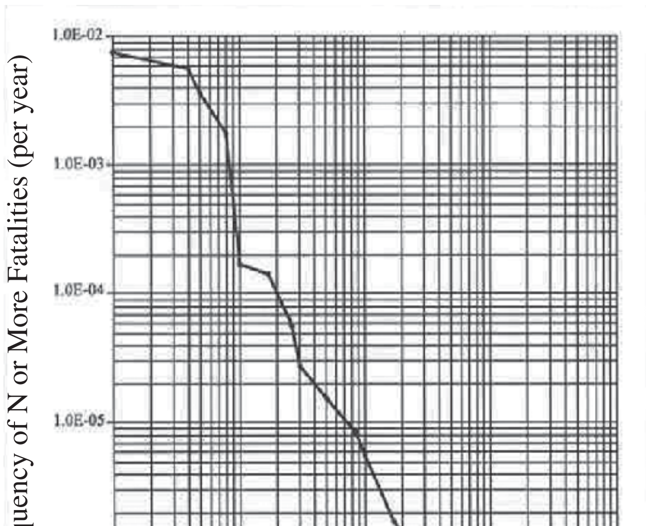


Figure 21. f-N curve for the 1995 Fei Tsui Road landslide

The third example concerns the use of QRA concept for risk-based priority ranking purposes. The priority classification system for fill slopes developed by the Geotechnical Engineering Office is in the form of a scoring system (Figure 22) which reflects the relative risk posed by old fill slopes (Wong, 1998). The system is based on a detailed review of the available failure records with particular reference to the mechanisms of fill slope failure and factors affecting the likelihood and consequence of failure respectively. Three failure mechanisms are recognized, viz. sliding (including minor washout), liquefaction and major washout (i.e. mobile failure involving concentrated discharge of surface water resulting in scouring and erosion). For each mechanism of failure, an Instability Score and a Consequence Score are derived for each slope. The Instability Score reflects the likelihood of occurrence of the mechanisms of failure, based on correlation with historical slope failure data. The Consequence Score is the potential loss of life (i.e. the estimated number of fatalities for a given failure) assessed by applying the consequence model described in Wong et al (1997a) for the corresponding mechanism of failure.

The ranking order for further action is governed by the Total Score which is derived from the sum of the products of Instability and Consequence Scores for different failure mechanisms. The system is couched in such a way that the Total Score reflects directly the landslide risk posed by the slope to the community. The system has been benchmarked directly with case histories to examine if the priority assessment is sensible. The results of the calibration exercise (summarised in Table 3) show that there is a good correlation between the predicted (i.e. Consequence Score) and the actual number of fatalities. The actual mechanism of failure is also consistent with that assessed by the Instability Scores. This risk-based ranking system has now been adopted in prioritising old fill slopes for stability study and upgrading works under the Landslip Preventive Measures Programme.

PRESCRIPTIVE SLOPE UPGRADING

Given a large number of smaller size, old substandard man-made slopes that require improvement, there is a need to bring about risk reduction in a cost-effective manner. Failures from these slopes of less serious consequences can be costly to repair and cause disruption to the community (e.g. road blockages). In view of this, the prescriptive approach has been developed based on past design experience and observed slope behaviour. Elements of prescriptive measures which can be prescribed under this approach are illustrated in Figure 23. This approach entails the use of prescriptive measures, which are pre-determined, experience-based, and suitably conservative modules of works prescribed to improve slope stability or reduce the rate of failure, without

Slope Data

Slope No. :	SIFT No. :	SIFT Class :
Slope Height, H = ______ m Slope Angle, θ = ______ °	Crest Wall Height, H_{wc} = ______ m Toe Wall Height, H_{wt} = ______ m	
SIFT Section Profile No.	Part of Larger Fill Body : Yes / No	

Instability Score (IS)

Sliding (IS_1 = a.b.c.d.e.f.g =)

(a) Geometry (From Figure C1)
S1 = 32
S2 = 16
S3 = 8
S4 = 4
S5 = 2
S6 = 1

(b) Type of Surface Cover
Bare = 4
Vegetated = 3
Chunam = 1.5
Shotcrete = 1

(c) Surface Drainage Provision
No = 2
Yes = 1

(d) Signs of Seepage
Yes = 2
No = 1

(e) Potential Leaking Services
Leaking = 2
Presence = 1.5
None = 1

(f) Past Instability
Major = 8
Minor = 2
No = 1

(g) Signs of Distress
Yes = 4
No = 1

Liquefaction (IS_2 = ¼.IS_1.h.i =)

(h) Slope Height
≥30 m = 4
≥20 - <30 = 3
≥10 - <20 = 1
<10 m = 0.5

(i) Type of Surface Cover
Bare = 1.1
Vegetated = 1.1
Chunam = 0.5
Shotcrete = 0.25

Major Washout (IS_3 = $(IS_1)^{1/3}$ .j.k.l.m.n.o.p.q =)

(j) Catchment Characteristics : Topographic Setting and Size of Catchment

Topographic Setting	Size of Catchment (m^2)				
	≤100	100 - 500	500 - 1000	1000 - 10000	>10000
Traverse Drainage Line	2	4	8	16	32
Adjacent Drainage Line	2	3	6	12	24
Traverse Topographic Depression	1	2	4	8	16
Adjacent Topographic Depression	1	2	3	6	12
Planar Slope	0.5	1	3	5	10
Spur	0.5	1	2	4	8

(k) Type of Crest Facility

Road	Platform & Urban development	Catch-water	Minor Development eg. Rural Footpath	Natural
1.0	0.5	0.25	0.10	0.05

(l) Volume of Fill Body (m^3)

≤100	100 - 500	500 - 1000	1000 - 10000	>10000
0.10	0.25	0.5	1	2

(m) Channelisation of Debris — Yes = 2.0, No = 0.5

(n) Erosion and Entrainment along Debris Trail — Yes = 2.0, No = 1.0

(o) Spread of Debris — Yes = 0.5, No = 1.0

(p) Unstable Terrain — Yes = 2.0, No = 1.0

(q) Masonry Wall at Crest

Wall Height ≥ 3 m	2.0
Wall Height < 3 m	1.5
No Masonry Wall	1.0

Consequence Score (CS)

Facility	Type	Group No.	Proximity			K	L	V			C = H * K * L * V / 10		
								V_1	V_2	V_3	C_1	C_2	C_3
Toe (1)			α =										
Toe (2)			α =										
Crest (1)			<3 m	3 - 6 m	6 - 10 m								
Crest (2)			<3 m	3 - 6 m	6 - 10 m								
										CS = ΣC			

Figure 22. Priority classification system for fill slopes

Table 3. Bench-marking with past fill slope failures

Cases (year of failure)	Sliding		Liquefaction		Wash-out		Total Score	Description of failure
	IS1	CS1	IS2	CS2	IS3	CS3		
Sau Mau Ping - A (1976)	2304	0.85	2534	10.27	106	3.19	4.45	4000 m^3 liquefaction failure; 18 fatalities. IS includes consideration of 1972 failure.
Sau Mau Ping - B (1972)	576	1.16	634	18.08	133	6.60	4.11	6000 m^3 liquefaction failure; 71 fatalities (high fatalities due to flimsy structures completely damaged by landslide debris).
Kennedy Road – A (1992)	3072	1.71	845	3.91	5	3.49	3.93	500 m^3 liquefaction failure; 1 fatality. Slope exhibited signs of distress before failure.
Kennedy Road – B (1989)	96	1.63	36	3.90	1	4.18	2.48	500 m^3 sliding failure; no fatality: a near-miss event.
Baguio Villas (1992)	192	0.32	53	1.32	277	0.60	2.47	3000 m^3 wash-out failure; 2 fatalities (a child and an engineer on inspection duty).
Waterloo Road (1989)	96	0.43	26	0.67	11	0.43	1.80	50 m^3 liquefaction failure; blockage of 3 lanes of road but no fatality.
Broadcast Drive (1988)	72	0.05	10	0.16	4	0.05	0.73	120 m^3 wash-out failure due to burst of water main; insignificant consequence.
Kung Lok Rd. Park (1988)	24	0.01	3	0.02	46	0.01	-0.02	200 m^3 wash-out failure; insignificant consequence

Notes :
(1) IS = Instability Score, which reflects the likelihood of the respective mechanism of failure
(2) CS = Consequence Score, which is the potential loss of life (PLL) for the respective mechanism of failure
(3) Total Score = log (∑ IS * CS)

detailed ground investigations, laboratory testing and design analyses. This provides for an efficient and practical means of slope improvement and repair. A major advantage of using prescriptive measures over conventional analytical design methods is the significant saving in both time and human resources (Figure 24).

The analytical design experience in conventional detailed engineering approach has been assimilated to produce a simple prescriptive design approach involving soil nails for upgrading old soil cut slopes (Pang & Wong, 1998). This prescriptive approach has incorporated qualification criteria to define their scope of application. These criteria cover geological formation, slope geometry, severity of consequence in the event of failure, together with adverse geological structures and groundwater conditions (Table 4). In addition, the requirements on qualifications and experience of personnel specifying the prescriptive design measures are stipulated. An important element of the prescriptive measures package is the requirement for the designer to inspect the slope during the critical stages of construction and review the adequacy of the prescribed measures against the actual ground conditions.

The prescriptive design methodology is given in Wong et al (1999). Standardized prescriptive soil nail patterns and lengths for achieving different degrees of improvement in the safety margin for slopes of different heights are shown in Table 5 and Figure 25.

A similar prescriptive design approach has also been formulated for the upgrading of old masonry walls involving the provision of a reinforced concrete skin wall. Details of this approach are given in Wong et al (1999).

CONCLUSIONS

Much has been learnt from studies of landslides in advancing the understanding of slope failures and enhancing slope engineering practice in Hong Kong. Confucius, the ancient Chinese philosopher, is reported to have said: "Man has three ways of learning: firstly, by meditation, this is the noblest; secondly, by imitation, this is the easiest; and thirdly, by experience, this is the most bitter". Whilst the occurrence of landslides will inevitably be bitter experience, it has proved to be of great value for us to learnt about its prevention.

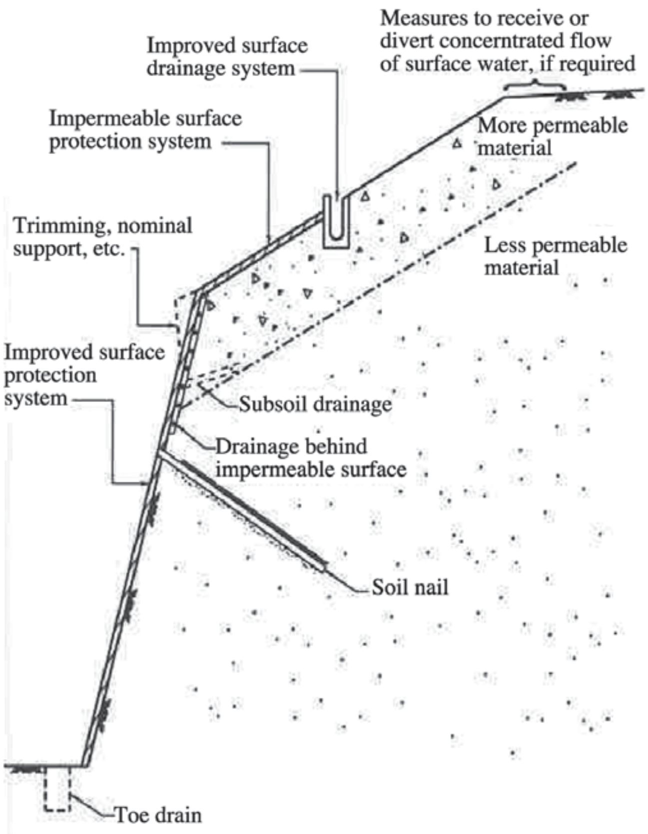


Figure 23. Typical prescriptive measures for soil cut slope

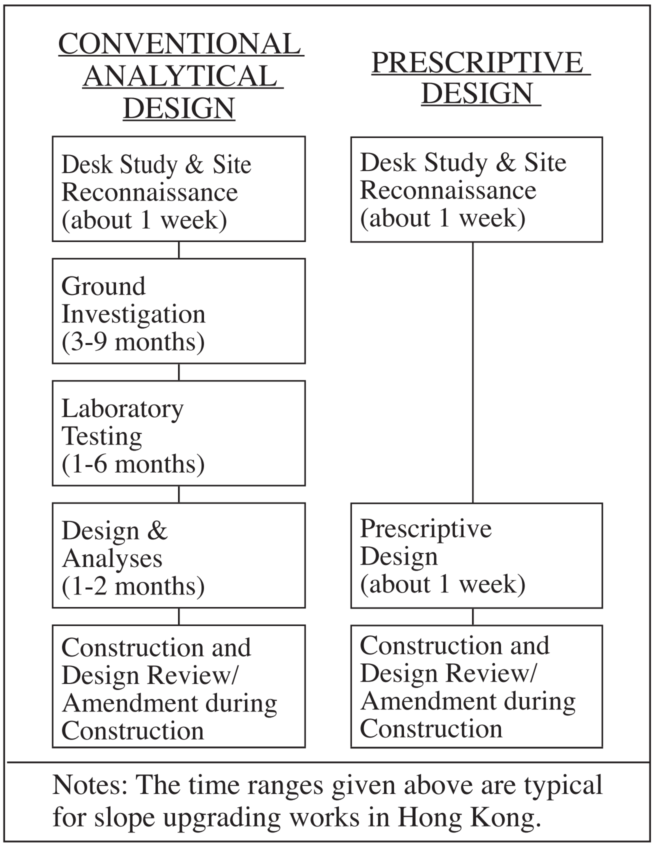


Figure 24. Comparison of the procedures for conventional analytical design and prescriptive design

Table 4. Standard soil nail layout

Effective Slope Height(m)	Bar Diameter (mm)	N	Horizontal Spacing of Nails, s_h (m)		
			A	B	C
3.0	25	2	1.5	1.5	1.5
4.0	25	2	1.5	1.5	1.5
5.0	25	3	1.5	1.5	2.0
7.5	25	3	1.5	1.5	1.5
10.0	25	4	1.5	1.5	1.5
12.5	32	5	1.5	1.5	2.0
15.0	32	6	1.5	1.5	2.0
17.5	32	8	1.5	2.0	2.0
20.0	32	9	2.0	2.0	2.0
22.5	32	9	2.0	2.0	2.0
25.0	32	10	2.0	2.0	2.0

Notes: (1) 'A' for $0.3 \leq \Delta FOS \leq 0.5$, 'B' for $0.1 \leq \Delta FOS < 0.3$ and 'C' for $\Delta FOS < 0.1$. ΔFOS is the required increase in the factor of safety of the slope.
(2) N refers to number of rows of soil nails. Hole diameter is 100 mm.

Table 5. Qualifying criteria for prescriptive measures

Geometry and Consequence Criteria :		
Facility Group & Examples	Soil Cut Slope Height (m)	
	Upgrading Works	Urgent Repair Works
1. Densely-used buildings, roads with very heavy traffic.	≤10	≤10
2. Lightly-used buildings, roads with heavy traffic.	≤10	≤10
3. Densely-used open space, roads with moderate traffic.	≤13	≤15
4. Lightly-used open space, road with low traffic.	≤18	≤20
5. Remote areas, roads with very low traffic.	≤18	*

Geological and Engineering Criteria :
(a) Old (i.e. pre-1977) Government soil cut slope
(b) Within selected geological formations in published geological maps, i.e. areas that compose a solid geology of Granite or selected formations of volcanics
(c) No observable or recorded adverse geological structures
(d) No observable or recorded adverse groundwater conditions
* For Group 5 facilities, soil nails are not normally required for urgent repair works

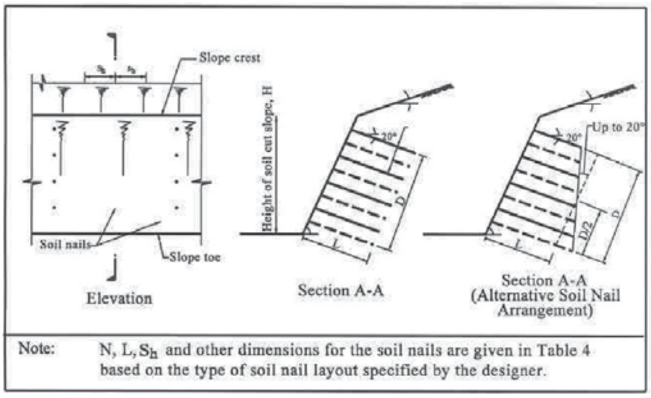


Figure 25. Soil nailing to cut slope

ACKNOWLEDGEMENTS

This paper is published with the permission of the Head of the Geotechnical Engineering Office and the Director of Civil Engineering, Government of the Hong Kong Special Administrative Region.

The authors would like to gratefully acknowledge the contributions made by colleagues in the Geotechnical Engineering Office and consultants involved in landslide investigation work in Hong Kong.

REFERENCES

Au, S.W.C. (1986). Decomposed dolerite dykes as a cause of slope failure. Hong Kong Engineer, vol. 14, no. 2, pp 33-36.

Au, S.W.C. & Suen, Y.C. (1996). Environmental factors in triggering slope failures. Proceedings of the Seventh International Symposium on Landslides, Trondheim, Norway, vol. 2, pp 611-616.

Brand, E.W. (1985). Predicting the performance of residual soil slopes. (Theme Lecture). Proceedings of the 11th International Conference on Soil Mechanics and Foundation Engineering, San Francisco, vol. 5, pp 2541-2578.

Brand, E.W. & Hudson, R.R. (1982). CHASE – An empirical approach to the design of cut slopes in Hong Kong soils. Proceedings of the Seventh Southeast Asian Geotechnical Conference, Hong Kong, vol. 1, pp 1-16. (Discussion, vol. 2, pp 61-72 and 77-79).

Burland, J.B. (2000). Report on the Shek Kip Mei Landslide of 25 August 1999. Vol. 2 – Lessons Learnt and Recommendations. Government of the Hong Kong Special Administrative Region, 9 p.

Chan, R.K.S. (2000). Hong Kong Slope Safety Management System. Proceedings of the Symposium on Slope Hazards and Their Prevention, The Jockey Club Research and Information Centre for Landslip Prevention and Land Development, The University of Hong Kong (In press).

Chan, Y.C. & Pun, W.K. (1992). Report on the Investigation of the 8 May 1992 Baguio Landslide. Advisory Report No. ADR 26/92, Geotechnical Engineering Office, Hong Kong, 26 p. (Also published as GEO Report No. 52, pp 5-30, by Chan et al (1996)).

Chan, Y.C., Lam, C.H. & Shum, W.L. (1991). The September 1990 Tsing Shan Landslide : A Factual Report. Technical Note No. TN 4/91, Geotechnical Engineering Office, Hong Kong, 91 p.

Chan, Y.C., Pun, W.K., Wong, H.N., Li, A.C.O. & Yeo, K.C. (1996). Investigation of Some Major Slope Failures between 1992 and 1995. GEO Report 52, Geotechnical Engineering Office, Hong Kong, 97 p.

Cowland, J.W. & Carbray, A.M. (1988). Three cut slope failures on relict discontinuities in saprolitic soils. Proceedings of the Second International Conference on Geomechanics in Tropical Soils, Singapore, vol. 1, pp 253-258.

Cruden, D.M. & Varnes, D.J. (1996). Landslide Type and Processes. Chapter 3, Landslides Investigation and Mitigation, Transportation Research Board, Special Report 247, National Research Council, pp 36-75.

Davis, D.W., Sewell, R.J. & Campbell, S.D.G. (1997). U-Pb dating of Mesozoic igneous rocks from Hong Kong. Journal of the Geological Society, London, vol. 154, pp 1067-1076.

Evans, N. & Irfan, T.Y. (1991). Blast-induced Rock Slide at Shau Kei Wan. Special Project Report No. 6/91, Geotechnical Engineering Office, Hong Kong, 27 p.

Fletcher, C.J.N. (1997). The geology of Hong Kong. Journal of the Geological Society, London, vol. 154, pp 999-1000.

Fletcher, C.J.N., Campbell, S.D.G., Carruthers, R.M., Busby, J.P. & Lai, K.W. (1997). Regional setting of Hong Kong: implications of new gravity models. Journal of the Geological Society, London, vol. 154, pp 1021-1030.

Franks, C.A.M. (1998). Study of Rainfall Induced Landslides on Natural Slopes in the Vicinity of Tung Chung New Town, Lantau Island. GEO Report No. 57, Geotechnical Engineering Office, Hong Kong, 102 p.

Franks, C.A.M. (1999). Characteristics of some rainfall-induced landslides on natural slopes, Lantau Island, Hong Kong. Quarterly Journal of Engineering Geology, vol. 32, pp 247-259.

Fugro Maunsell Scott Wilson Joint Venture (2000a). Report on the Shek Kip Mei Landslide of 25 August 1999. Vol. 1 – Findings of the Landslide Investigation. Geotechnical Engineering Office, Hong Kong, 156 p.

Fugro Maunsell Scott Wilson Joint Venture (2000b) Report on the Sham Tseng San Tsuen Debris Flow - Findings of the Landslide Investigation.

Geotechnical Engineering Office, Hong Kong, 92 p.
Geotechnical Control Office (1983). Landslip at Peak Road Opposite House No. 40, GCO Report 5/83, Geotechnical Control Office, Hong Kong, 3 volumes, 241 p.
Geotechnical Control Office (1984). Geotechnical Manual for Slopes. (Second edition). Geotechnical Control Office, Hong Kong, 295 p.
Geotechnical Engineering Office (1994). Report on the Kwun Lung Lau landslide of 23 July 1994. Vol 2 – Findings of the Landslide Investigation. Geotechnical Engineering Office, Hong Kong, 379 p.
Geotechnical Engineering Office (1996a). Report on the Fei Tsui Road Landslide of 13 August 1995. Vol. 2 - Findings of the Landslide Investigation. Geotechnical Engineering Office, Hong Kong, 68 p.
Geotechnical Engineering Office (1996b). Report on the Shum Wan Road Landslide of 13 August 1995. Vol. 2 - Findings of the Landslide Investigation. Geotechnical Engineering Office, Hong Kong, 51 p.
Geotechnical Engineering Office (1998). Guide to Slope Maintenance (Geoguide 5). (Second edition). Geotechnical Engineering Office, Hong Kong, 91 p.
Halcrow Asia Partnership Ltd. (1998a). Report on the Ching Cheung Road Landslide of 3 August 1997. Geotechnical Engineering Office, Hong Kong, 142 p.
Halcrow Asia Partnership Ltd. (1998b). Report on the Landslides at Hut No. 26 Kau Wa Keng Upper Village of 4 June 1997. Geotechnical Engineering Office, Hong Kong, 100 p.
Halcrow Asia Partnership Ltd. (1998c). Report on the Landslide at the Ten Thousand Buddhas' Monastery of 2 July 1997. Geotechnical Engineering Office, Hong Kong, 96 p.
Hencher, S.R. & Martin, R.P. (1984). The failure of a cut slope on the Tuen Mun Road in Hong Kong. Proceedings of the International Conference on Case Histories in Geotechnical Engineering, St Louis, Missouri, vol.2, pp 683-688.
Hencher, S.R., Massey, J.B. & Brand, E.W. (1984). Application of back analysis to some Hong Kong landslides. Proceedings of the Fourth International Symposium on Landslides, Toronto, vol. 1, pp 631-638.
Hencher, S.R. & McNicholl, D.P. (1995). Engineering in weathered rock. Quarterly Journal of Engineering Geology, vol. 28, pp 253-266.
Hong Kong Government (1972). Final Report on the Commission of Inquiry into the Rainstorm Disasters. Hong Kong Government Printers, 94 p.
Hong Kong Government (1977). Report on the Slope Failures at Sau Mau Ping, August 1976. Hong Kong Government Printer, 105 p. plus 8 drgs. (Also published as GEO Report No. 86).
Hudson, R.R. & Hencher, S.R. (1984). The delayed failure of a large cutting in Hong Kong Proceedings of the international Conference on case Histories in Geotechnical Engineering, St Louis, Missouri, vol. 2, pp 679-682.
Hutchinson, J.N. (1988). General Report: Morphology and geotechnical parameters of landslides in relation to geology and hydrogeology. Proceedings of the Fifth International Symposium on Landslides, Lusanne, Switzerland, vol. 1, pp 3-35.
Irfan, T.Y. (1989). Landslide Studies: Island Road Government School Landslip, Aberdeen. Special Project Report No. 4/89, Geotechnical Engineering Office, 2 volumes, 323 p.
Irfan, T.Y. (1996). Mineralogy, fabric properties and classification of weathered granites in Hong Kong. Quarterly Journal of Engineering Geology, vol. 29, pp 5-35.
Irfan, T.Y., Koirala, N.P. & Tang, K.Y. (1987). A complex slope failure in a highly weathered rock mass. Proceedings of the Sixth International Congress on Rock Mechanics, Montreal, vol. 1, pp 397-402.
King, J.P. (1996). The Tsing Shan Debris Flow. Special Project Project No. SPR 6/96, Geotechnical Engineering Office, Hong Kong, 3 vols.
Leung, B.N., Leung, S.C. & Franks, C.A.M. (1999). Report on the Rock Slope Failure at Cut Slope 11NE-D/C7 along Sau Mau Ping Road on 4 December 1997. GEO Report No. 94, Geotechnical Engineering Office, Hong Kong, 69 p.
Lo, D.O.K., Ho, K.K.S. & Wong, H.N. (1998). Effectiveness of slope maintenance in reducing the likelihood of landslide. Proceedings of Seminar on Slope Engineering in Hong Kong, Hong Kong, A.A. Balkema Publisher, pp 251-258.
Lumb, P. (1962). Effects of rain storms on slope stability. Proceedings of the Symposium on Hong Kong soils, Hong Kong, pp 73-87.
Lumb, P. (1975). Slope failures in Hong Kong. Quarterly Journal of Engineering Geology, vol. 8, pp 31-65.
Malone, A.W. (1998). Risk management and slope safety in Hong Kong. Proceedings of Seminar on Slope Engineering in Hong Kong, Hong Kong, A.A. Balkema Publisher, pp 3-17.
Malone, A.W. & Chan, T.C.F. (1996). A public education campaign on slope maintenance in Hong Kong. Asia Engineer, vol. 24, no. 2, pp 16-18.
Morgenstern, N.R. (1994). Report on the Kwun Lung Lau Landslide. Vol. 1 - Causes of the Landslide and Adequacy of Slope Safety Practice in Hong Kong, Hong Kong Government, 21 p.
Pang, L.S. & Wong, H.N. (1998). Prescriptive design of soil nails to upgrade soil cut slopes. Proceedings of Seminar on Slope Engineering in Hong Kong, Hong Kong, A.A. Balkema Publisher, pp 259-266.
Premchitt, J., Brand, E.W. & Phillipson, H.B. (1985). Landslides caused by rapid groundwater changes. Proceedings of the 21st Annual Conference of the Engineering Group of the Geological Society,

Sheffield, pp 87-94.
Pun, W.K. & Li, A.C.O. (1993). Report on the Investigation of the 16 June 1993 Landslip at Cheung Shan Estate. Advisory Report No. ADR 10/93, Geotechnical Engineering Office, Hong Kong, 14 p. (Also published as GEO Report No. 52, pp 44-57, by Chan et al (1996)).
Sewell, R.J. & Campbell, S.D.G. (1997). Geochemistry of coeval Mesozoic plutonic and volcanic suites in Hong Kong. Journal of the Geological Society, London, vol. 154, pp 1053-1066.
Siu, K.L. & Premchitt, J. (1990). Slope failure in weathered granite in Tsuen Wan, Hong Kong. Proceedings of Seminar on Failures in Geotechnical Engineering, Hong Kong, pp 95-105.
So, C.L. (1976). Some problems of slopes in Hong Kong. Geografiska Annaler, vol. 58a, no. 3, pp 149-154.
Sun, H.W. & Campbell, S.D.G. (1999). The Lai Ping Road Landslide of 2 July 1997. GEO Report No. 95, Geotechnical Engineering Office, Hong Kong, 140 p.
Sun, H.W., Ho, K.K.S., Campbell, S.D.C. & Koor, N.P. (2000). The 2 July 1997 Lai Ping Road landslide, Hong Kong – Assessment of landslide mechanism. Proceedings of the 8th International Symposium on Landslides, Cardiff, 2000 (in print).
Wong, C.K.L. (1998). The New Priority Classification Systems for Slopes and Retaining Walls. GEO Report No. 68, Geotechnical Engineering Office, Hong Kong, 117 p.
Wong, H.N. (1992). Report on the Investigation of the 8 May 1992 Kennedy Road Landslide. Advisory report No. ADR 27/92, Geotechnical Engineering Office, Hong Kong, 13 p. (Also published as GEO Report No. 52, pp 31-43, by Chan et al (1996)).
Wong, H.N. & Ho, K.K.S. (1995). General Report on Landslips on 5 November 1993 at Man-made Slopes in Lantau. GEO Report No. 44, Geotechnical Engineering Office, Hong Kong, 78 p.
Wong, H.N. & Ho, K.K.S. (1996). Travel distance of landslide debris. Proceedings of the Seventh International Symposium on Landslides, Trondheim, Norway, vol. 1, pp 417-422.
Wong, H.N. & Ho, K.K.S. (1997). The 23 July 1994 landslide at Kwun Lung Lau, Hong Kong. Canadian Geotechnical Journal, vol. 34, pp 825-840.
Wong, H.N. & Lam, K.C. (1998). The November 1993 natural terrain landslides on Lantau Island, Hong Kong. Proceedings of Seminar on Slope Engineering in Hong Kong, Hong Kong, A.A. Balkema Publisher, pp 51-57.
Wong, H.N. & Pang, L.S. (1996). Application of Prescriptive Measures to Soil Cut Slopes. GEO Report No. 56, Geotechnical Engineering Office, Hong Kong, 52 p.
Wong, H.N., Ho, K.K.S. & Chan, Y.C. (1997a). Assessment of consequence of landslides. Proceedings of the International Workshop on Landslide Risk Assessment, Honolulu, pp 111-149.
Wong, H.N., Lam, K.C. & Ho, K.K.S. (1997b). Diagnostic Report on the November 1993 Natural Terrain Landslides on Lantau Island. GEO Report No. 69, Geotechnical Engineering Office, Hong Kong, 98 p.
Wong, H.N. & Ho, K.K.S. (1998). Overview of risk of old man-made slopes and retaining walls in Hong Kong. Proceedings of Seminar on Slope Engineering in Hong Kong, Hong Kong, A.A. Balkema Publisher, pp 193-200.
Wong, H.N. & Ho, K.K.S. (1999). Review of 1997 and 1998 Landslides. Landslide Study Report LSR No. 15/99, Geotechnical Engineering Office, Hong Kong, 49 p.
Wong, H.N., Ho, K.K.S., Pun, W.K. & Pang, P.L.R. (1998). Observations from some landslide studies in Hong Kong. Proceedings of Seminar on Slope Engineering in Hong Kong, Hong Kong, A.A. Balkema Publisher, pp 277-286.
Wong, H.N., Pang, L.S., Wong, A.C.W., Pun, W.K. & Yu, Y.F. (1999). Application of Prescriptive Measures to Slopes and Retaining Walls. GEO Report No. 56 (Second Edition), Geotechnical Engineering Office, Hong Kong, 73 p.
Works Bureau (1985). Report on the Slope Safety Review. Works Bureau, Hong Kong, 20 p.
Yim, K.P., Lau, S.T. & Massey, J.B. (1999). Community preparedness and response in landslide risk reduction. Proceedings of Seminar on Geotechnical Risk Management, Hong Kong Institution of Engineers, pp 145-155.