Hong Kong landslides

2 authors:

Steve Hencher
University of Leeds

Andrew W. Malone
The University of Hong Kong

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STEPHEN R. HENCHER AND ANDREW W. MALONE

ABSTRACT

Most landslides in Hong Kong are associated with rainstorms, and the greater the rainfall intensity the greater the number of landslides. Schematic, graphical hydrogeological models are presented to help explain the nature and cause of landslides that have been investigated in the past 30 years. The notional landslide types are associated with idealized geologic features and linked to times of landslide relative to transient rainfall.

30.1 INTRODUCTION

This chapter briefly summarizes the history of the study of landslides in Hong Kong and discusses the geologic features, weathering characteristics, and hydrogeologic circumstances that bear on landslide occurrence. A wide variety of landslides occur in the weathered terrain of Hong Kong because of the relatively complex geology and diverse geomorphological environments, which range from steep rock cliffs to deeply weathered foothills. Failures in man-made cuts, retaining walls, and embankments have had the greatest impact historically, but failures from natural slopes are also a significant hazard. The terrain is largely mountainous and is subject to severe rainstorms lasting several days, with total rainfall of the order of 500–1000 mm and short-term rainfall intensities that may exceed 100 mm h^{-1}. Most failures are less than 5 m^3 in volume, and 90 percent are less than 50 m^3. They typically detach and move rapidly upon failure; a few, mainly large, landslides stay relatively intact. Because of the dense population and steep terrain, damage and injuries have been common; even a small debris slide or rockfall can cause a fatality in a crowded area or on a busy highway. Records of severe landsliding impacting the population date back to 1889, and since the middle of the last century more than 480 people have been killed by landslides. A concerted effort has been made to reduce landslide risk to the population since the establishment of a Geotechnical Control Office (GCO) in 1977 (now the Geotechnical Engineering Office, GEO). Since that date, the designs of all new slopes in Hong Kong have been subject to geotechnical checking and approval. Furthermore all pre-existing man-made slopes are being investigated and upgraded as necessary following a risk-based priority system. There has been a marked reduction in fatalities since the establishment of the GCO, although much of this reduction can be attributed to a policy to rehouse people who had built their “squatter huts” in locations that were inherently hazardous (Fig. 30.1). The strategy for dealing with the risk of landslides in Hong Kong is discussed by Brand (1984) and has been updated by Malone (1997) and Wong (2005).

30.2 LANDSLIDE INVESTIGATIONS

Lumb (1975) identified the importance of rainfall intensity in triggering landslides in cuttings and embankments in Hong Kong. Three major landslides caused large numbers of deaths in 1972 and 1976 and were investigated, respectively, by a judge-led commission of inquiry and an independent panel of experts; the latter made recommendations that led to the establishment of the GCO in 1977. Near the end of the 1970s, there was considerable debate on the need for research specific to Hong Kong and its weathered rocks; the focus was on slope stability analysis rather than landslides as phenomena (Beattie and Chau, 1976; Sweeney and Robertson, 1979). It was recognized that many steep-cut slopes with low calculated factors of safety had survived severe rainstorms without collapsing. In 1981 the “Cut Slopes in Hong Kong – Assessment of Stability by Empiricism” (CHASE) study was undertaken by the GCO

Landslides: Types, Mechanisms and Modeling, ed. John J. Clague and Douglas Stead. Published by Cambridge University Press.

Fig. 30.1. Failure involving squatter huts at Yuen Mo Village, Lam Tin, 1982.

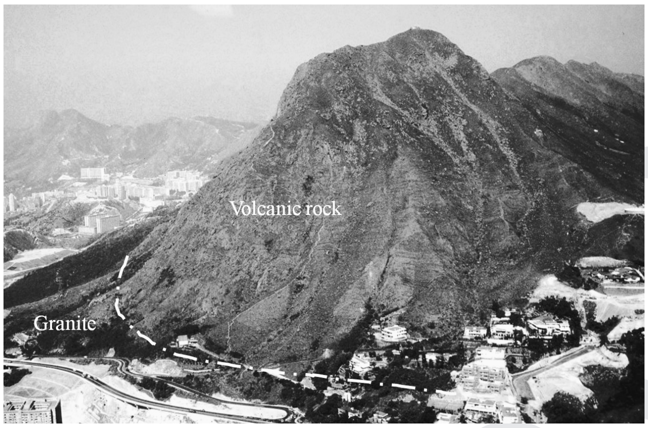

Fig. 30.2. Kowloon Peak (Fei Ngo Shan) is developed in volcanic rock, with weathered granite underlying the foothills. Note the large colluvial lobes on the side slopes. Lion Rock (resistant granite) is visible in distance.

Fig. 30.3. Mafic dike cutting granite.

(Brand and Hudson, 1982). About 200 failed and apparently stable slopes were investigated to try to differentiate them on the basis of mass-strength estimates derived from detailed logging, index testing, and other characteristics. The approach was similar to what might be attempted these days using a rock mass classification scheme such as the geological strength index (GSI; Hoek, 1999). The study, however, failed to achieve a clear differentiation; in the light of later landslide investigations, it is likely that the one-dimensional logging approach (where a narrow strip of surface cover was removed to allow inspection) failed to adequately characterize slope-specific geologic structures that probably controlled many of the failures. Other important studies carried out in the early 1980s included the Mid Levels Study (Geotechnical Control Office, 1982), which led to a much better appreciation of hydrogeologic processes, including soil suction and soil properties, and better methods of ground investigation, soil testing, and instrumentation. The North Point Study (Golder Associates UK Ltd., 1981) similarly led to improved methods for investigating and understanding rock-slope stability, and techniques for measuring shear strength along rock joints.

From 1978, records were kept of some reported landslide incidents (Malone and Shelton, 1982), and summary reports were compiled from 1982. In 1982, two major rainstorms caused hundreds of landslides, and a team of geotechnical engineers investigated some of these in detail. Six major landslides had occurred in spite of engineering design or assessment (Hencher, 1983). Based on these incidents, it was concluded that ground models used in design were often inadequate for identifying landslide mechanisms, and that piezometric pressures were underestimated in stability assessments, partly because piezometers were not installed at the depths where perched water tables developed. The major problem appeared to be in ground investigation and interpretation rather than in calculations of stability, and it was noted that adopting higher factors of safety could not compensate for incorrect geological models.

Landslides have been studied systematically in Hong Kong since the creation of a Landslide Investigation Division in the GEO in 1996. Between 1997 and 2009, about 3000 landslide records have been examined and 200 landslide studies carried out. Most reports are freely available to the profession and public for download from the Hong Kong Government website. Ho and Lau (2010) have reviewed the findings. Key factors contributing to relatively small failures include uncontrolled surface water flow, inadequate slope maintenance or drainage, and poor detailing of surface protection. The importance of adequate geological and hydrogeological models for understanding major failures (>50 m^3) has been confirmed. An additional factor that has become better appreciated is progressive slope deterioration in large slopes prior to failure (Malone, 1998, 2000; Hencher, 2006).

30.3 GROUND CONDITIONS

30.3.1 GEOLOGY

Current understanding of the geology of Hong Kong is summarized in two publications of the Hong Kong Geological Survey (Fyfe *et al*., 2000; Sewell *et al*., 2000). The major urban areas are underlain by Jurassic and Early Cretaceous volcanic rocks – mostly tuffs – and by granitic rocks of similar age but intrusive into the volcanic suite. Volcanic rocks make up the higher mountainous areas surrounding Hong Kong Harbor, as illustrated in Figure 30.2, although some of the rugged hills, such as Lion Rock, are granitic. The central harbor basin and many other low-lying areas are granitic and are commonly deeply weathered. Some of the contacts between the many igneous intrusions and volcanic rocks are faulted and may be associated with poor-quality rock, although these have rarely been cited as important factors for Hong Kong landslides, perhaps due to lack of recognition.

Mafic and intermediate dikes cut the major volcanic and granitic bodies (Fig. 30.3). Where fresh, the contacts tend to be sharp and fused, but where weathered, grain-size contrasts between the intrusion and host rock result in abrupt changes in permeability.

Much of the natural terrain is blanketed with colluvium, which is generally a few meters thick and comprises transported soil with rock fragments. The colluvium overlies in-situ weathered rock. Thicker deposits derived from landslides are commonly boulder-rich and can have high permeability, with many natural pipes and channels. Some colluvial deposits are ancient, as evidenced by the weathered state of boulders, induration, and cementation and, in some instances, the presence of geologic discontinuities (Fig. 30.4).

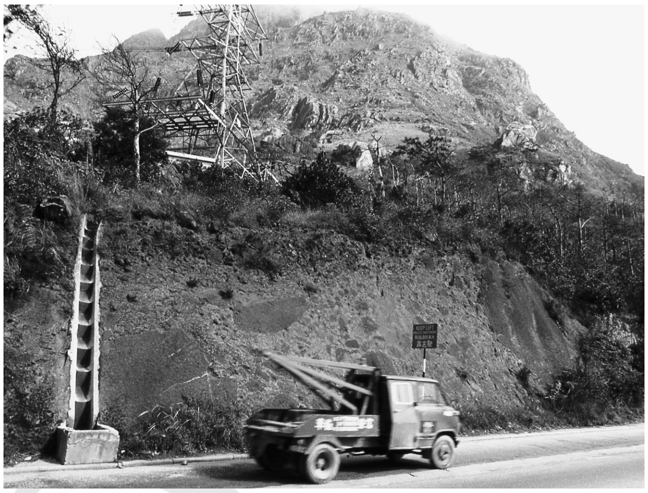

Fig. 30.4. Ancient colluvium with very large weathered boulders along Clearwater Bay Road.

30.3.2 DISCONTINUITIES AND GEOLOGIC STRUCTURES

Studies over the past 30 years in Hong Kong have confirmed the importance of relict geologic discontinuities as contributing factors to many landslides in weathered rock profiles (Deere and Patton, 1971). Typical features include sheeting joints, tectonic and cooling joints, shear zones, primary volcanic fabrics, and dikes. Discontinuities are loci of weathering and may be partially infilled with transported clay and other sediments, commonly in association with dilation of the rock mass (Kirk *et al*. 1997). Toward the center of the granitic plutons, where encountered at depth in tunnels, visible joints may be extremely widely spaced (tens of meters), but nearer the ground surface the rock tends to be more extensively jointed (Fig. 30.5). It is evident that many of these visible fractures have opened up through weathering and exhumation, as discussed by Hencher and Knipe (2007). The process is illustrated by the comprehensive disintegration into small fragments of a rock wedge defined by master joints in moderately weathered rock in Figure 30.6a, b. Within the granitic rocks, especially, joints tend to be steeply dipping and occur in orthogonal sets. Shallowly dipping joints also occur, and some of these are probably formed by shrinkage during cooling (Table 30.1). Sheeting joints are common in Hong Kong and occur as extensive features running roughly parallel to the steep terrain in rock that was unfractured at the time of slope formation (Hencher *et al*., 2011). They are characteristic of many exposed, weakly weathered, granitic bodies, but are less common in volcanic terrain, probably because these rocks contain relatively close incipient jointing that allows stresses to be dissipated without the formation of new fractures. Sheeting joints are commonly associated with rockfalls and deeper-seated failures, especially where the joint walls are severely weathered or where the joints persist as relict discontinuities within a thick weathering profile. Such joints are commonly associated with channelized water flow, development of cleft and perched water pressures, and the influx and deposition of transported soil.

30.3.3 WEATHERING

DISTRIBUTION OF WEATHERED ROCK

Rocks in Hong Kong are locally deeply weathered, at some locations to depths of more than 100 m. Ruxton and Berry (1957) suggested that, over a long period, the weathering front descends to an equilibrium position controlled by the water table. They presented a suite of weathering profiles depicting

Fig. 30.5. Closely jointed granite, Anderson Road Quarry.

Fig. 30.6. (a) Well-defined wedge failure along master joints in volcanic rock, Kwai Shing Estate, Tsuen Wan. b) A wedge that has broken up along closely spaced incipient joints.

the development of weathering profiles with time. The idealized "mature" stage includes remnant corestones of less-weathered rock surrounded by rock decomposed to a soil-like state that has weathered inward, away from major joints and other discontinuities that carry groundwater (Figs. 30.7 and 30.8). In the "old age" profile, nearly corestone-free saprolite overlies rock with little transition, and such profiles are common. Weathered rocks are described in this chapter according to the tried-and-tested material classification used in Hong Kong and published by the Geotechnical Control Office (1988). Residual soils (grade VI) in Hong Kong are typically red-brown, dense, and clay-rich, lack the parent rock fabric, and are 1–2 m thick. Beneath the residual soil, completely weathered rock (grade V) retains the parent rock texture and fabric, but the dry density can be as low as 1.2 Mg m^{-3}; that is, less than half that of fresh rock. The material is open-textured, susceptible to disturbance, and prone to disaggregation (slaking) if placed in water. Highly decomposed material (grade IV) can be broken down by hand but, by definition, does not slake.

At the mass scale, the distribution of soil and rock fractions can be very complex, reflecting the parent rock structure and history of weathering. Thus, mass weathering classifications based on idealized corestone profiles are often difficult to apply. The depth and extent of weathering are difficult to estimate from landscape features alone. Some, but not all, valleys are associated with deep weathering. Depth of weathering differs considerably and abruptly laterally, especially across faults, which makes the extrapolation of ground investigation data difficult, not only for slopes but also for foundations. As a consequence, it is normal practice in Hong Kong to put down at least one borehole at every bored pile location to determine the location and nature of the weathering profile.

ENGINEERING PROPERTIES

Sampling and testing of soil-like weathered rock (saprolite) without significant disturbance is difficult (Vaughan, 1990); thus properties at a particular site may need to be estimated from experience elsewhere. This issue is one of the main reasons for employing a material weathering classification linked to index tests; in doing so, empirical rules and relationships can be applied (Irfan, 1996, 1999; Hencher, 2006). In granitic saprolite, peak angles of internal friction are typically greater than 30° (Martin, 1986). El-Ramly *et al.* (2005) report little difference between friction angle values for grade IV and V granite soils, with an average friction angle of 38°; the same value is typical for the basic dilation-corrected friction angle of natural rock joints in granite (Hencher and Richards, 1989). Some volcanic rock joints have lower basic friction angles, approaching 30° for fine-grained varieties. Coatings on joints can have an angle of friction as low as 17° at low stresses for chlorite (Brand *et al.* 1983), and even lower values have been measured across joints filled with clay. The patchy disposition of clay in depressions on joint surfaces, however, may mean that rock asperities still control shear strength of laterally persistent joints.

True cohesion of intact saprolite ranges widely, from zero for very weak grade V soils to a few MPa at the boundary between highly and moderately (grade III) weathered rock (Hencher, 2006). Reported values for true cohesion of saprolite are,

Table 30.1. *Typical discontinuities in Hong Kong rocks (at all stages of weathering (after Hencher, 2000).*

Discontinuity type	Occurrence	Geotechnical aspects
Tectonic joints	Fractures resulting from tectonic stresses	Parallel orthogonal, or conjugate sets, or occur in spectra; can be planar; they commonly only develop fully as mechanical fractures during exhumation.
Cooling joints	Perpendicular to cooling surface in igneous rocks, especially rhyolite and granite Doming joints occur in granites	Steep orthogonal sets are common in granites and may act as release surfaces and conduits that create cleft water pressures. Doming joints have characteristics similar to sheeting joints (see below); however, they are found at greater depths.
Sheeting joints	Parallel to natural slope; more closely spaced nearer to the ground surface (generally upper 10 m) Most common in granitic rocks and tend to be locally developed where pre-existing mechanical fractures were absent at time of formation Stress-relief fractures are also associated with natural terrain failures	Rough and wavy tensile fractures; can persist for many meters but terminate against younger cross-joints. Short sections, away from the point of exposure and measurement, may dip more steeply on an "up-wave" within the rock mass, leading to local rock block failure. Weathering is focused along sheeting joints; clay commonly develops in joints; sheeting joints may act as conduits for water flow.
Petrological boundaries	Boundaries between different rock types, especially minor intrusions such as dolerite, basalt, or rhyolite dikes	May mark change in engineering properties, although boundaries are strong in fresh rock; boundaries are strong, welded, and not a plane of weakness. Where adjacent rocks have different grain-size properties, weathered products may have different permeability; boundaries may be barriers to water flow and result in localized water accumulation.
Faults	Fractures along which displacement has occurred; may be associated with poor-quality rock and intense weathering	Can extend for tens or hundreds of meters and be associated with weakened zones many meters wide, with associated weathering and the presence of groundwater; can dip steeply and therefore not favor sliding; shallower thrust faults can contribute to failures.

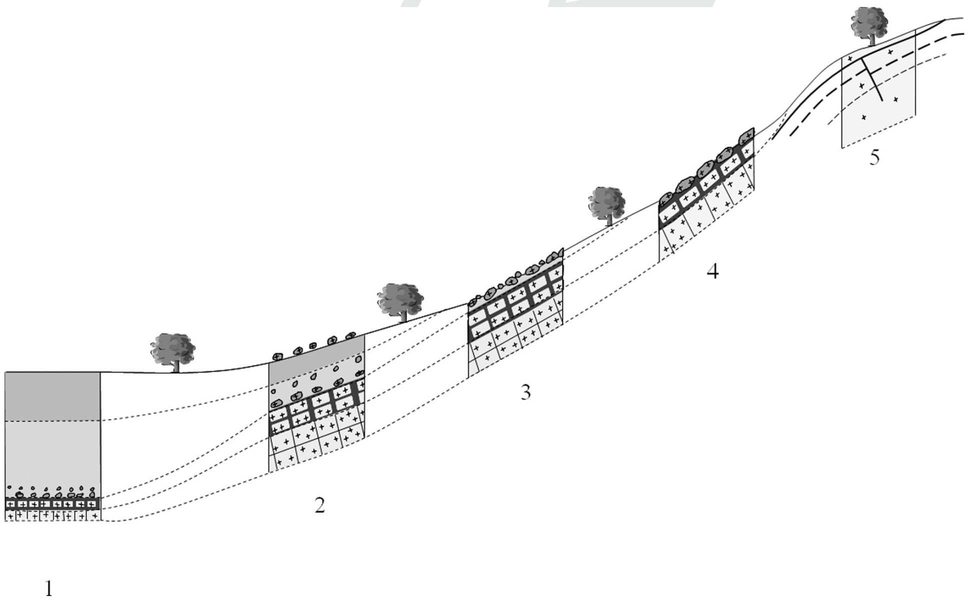

Fig. 30.7. Weathering profiles anticipated on different parts of a slope in Hong Kong. Sections 1–4 have been redrawn from the "mature" weathering profile of Ruxton and Berry (1957). At section 5, with sheeting joints, erosion exceeds weathering.

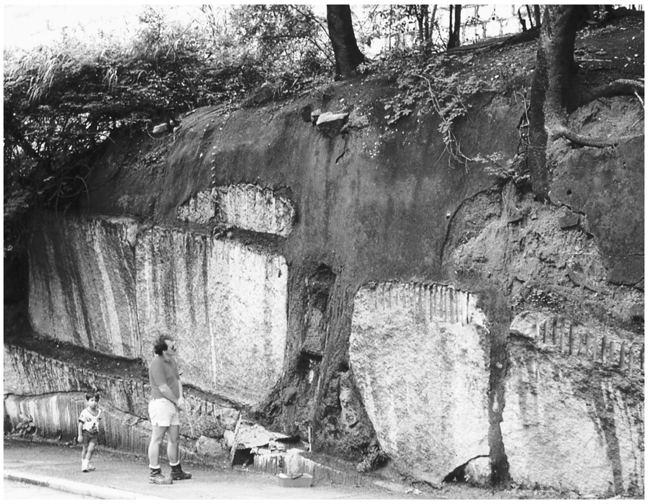

Fig. 30.8. Corestone-rich weathering profile in granite, Tai Tam Reservoir. Height of exposure is approximately 4 m.

however, remarkably low. El-Ramly *et al*. (2005) report a range of up to 25 kPa for the boundary between grades IV and V, while Ebuk (1991) measured higher values, up to 300 kPa for grade IV granite. The absence in the literature of even higher values probably reflects a lack of reported laboratory data on relatively strong saprolite.

Suction (water pressure lower than atmospheric pressure) in partially saturated soil is an ephemeral component of effective stress, and therefore strength (Fredlund, 1981; Shen, 1998). It cannot be used in design, however, because it is lost rapidly with wetting (Geotechnical Control Office, 1982; Rodin *et al.* 1982).

30.4 LINKS BETWEEN LANDSLIDES AND RAINFALL

Most landslides in Hong Kong are associated with periods of intense rainfall from April to September; severe storms sometimes occur outside that period and cause many failures (Wong and Ho, 1995). Rainfall intensity across Hong Kong during a storm can be highly variable, and hilly regions with the highest rainfall intensity experience the greatest density of landslides. Hencher *et al.* (2006) analyzed available data on reported landslides, with no differentiation on size or severity, and plotted them as function of number per square kilometer vs. maximum rolling 24-hour rainfall. In the case of the 1982 rainstorms, where the 24-hour rainfall exceeded about 500 mm in some areas, the density of reported landslides was about 5–10 km^{-2}. Extrapolating to the heaviest rainfall that Hong Kong is likely to experience (Geotechnical Engineering Office, 2004), the density of landslides in areas of extreme rainfall could be 20–50 km^{-2}.

30.5 HYDROGEOLOGICAL CONSIDERATIONS

Theoretical calculations of pore pressure rise due to infiltration through uniform materials generally predict a slow response to rainfall (Lumb, 1962; Iverson, 2000). However, instruments show that rainfall-related rises in water pressure can be quick and dramatic. Richards and Cowland (1986) report rapid, sharp, but localized, rises in head of several meters of water pressure in sheeting joints in granite during rainstorms. Pope *et al*. (1982) present data from piezometers installed at different depths and report significant rises in water pressure at depths up to 12 m in bouldery colluvium within a few hours of the first rainfall. In comparison, piezometers installed in decomposed granite at depths between 20 and 40 m did not begin to respond until about 2 days after the first rainfall; water pressure then rose gradually, peaking about 5 days after the first rainfall and 2 days after the last rainfall.

The heterogeneity of weathered rock profiles mantled by colluvium is illustrated schematically in Figure 30.9. In general, hydraulic gradients run parallel to hillsides, and subsurface runoff may be dominated by pipe systems (Nash and Dale, 1984). Channel flow is also very important in less-weathered rock. These preferential flow paths can lead to relatively rapid infiltration and through-flow. Water is often observed issuing along these paths from the scarps of medium-sized and deep-seated landslides (Hencher, 2010). Water pressure in fractured bedrock at depth can cause upward flow into the overlying weathered mantle (Geotechnical Control Office, 1982; Leach and Herbert, 1982; Jiao *et al.*, 2005, 2006).

30.6 TIMES OF LANDSLIDES

Table 30.2 is a proposed classification of landslides in Hong Kong, based on time of occurrence relative to rainfall in a severe storm and failure mechanism (Fig. 30.10).

30.6.1 DURING AN INTENSE STORM

Shallow washouts, erosion, and rockfall (Types Ia and Ib)Shallow landslides typically happen during, or very soon after, severe rainstorms. A concentrated flow of surface water toward topographic depressions is probably an important factor (Anderson *et al.*, 1983), and blocked or inadequately sized drains can also contribute to these failures (Au and Suen, 1991).

LOSS OF SUCTION (TYPE IC)

Loss of suction due to rainfall may play a significant role in many landslides, but has rarely been identified as a primary contributing factor. An example is described by Hencher *et al.* (1984).

SHALLOW PERCHED WATER TABLE (TYPE ID)

Landslides involving less than a few meters of colluvium or other soil above saprolite or rock are common and can occur relatively early during a storm. Failure is due to the development of perched water and cleft water pressure, as described by Devonald *et al*. (2009).

Table 30.2. *Classification of landslides based on timing and hydrologic processes.*

Timing	Size	Hydrogeologic process		Example	Comments
I During intense storm	Small to medium	Ia	Surface flow causing erosion and undermining	Gullying, shallow washouts, rockfall	Convergence of flow toward topographic hollows
		Ib	Water pressure build-up in rock joint	Rockfall, rock-slab failure above adversely oriented joint	May be indicative of progressive, intermittent failure before final detachment
		Ic	Loss of suction or softening	Shallow failure in steep cut slope	Stability relies on apparent cohesion
		Id	Shallow perched water	Shallow slip in colluvium or saprolite overlying more competent rock or another aquitard such as a clay-rich seam	Very common in natural terrain, typically less than 3 m deep
II Late in storm or hours or days afterward	Medium to large	IIa	Deeper perched water table	Water perching above aquiclude within saprolite	Aquiclude may be filled with clay; discontinuity or geological unit of lower permeability, such as a weathered sill or clay-filled fault
		IIb	Rapid infiltration and through-flow by piping or along other high-permeability channels at depth	Natural pipes at base of thick colluvial deposits Permeable fault or shear zone	Higher catchment or source of recharge can result in large failures, with pore pressures maintained until final detachment in spite of displacement and dilation of mass
III Delayed by days or weeks	Large	IIIa	Deep rise in water table, possibly by recharge from underlying bedrock	Fractured rock may channel water from remote catchment to location of landslide	Relatively rare
		IIIb	Can be triggered by only minor rainfall	Progressive failure leads to increased vulnerability	Delay can result from rise in water table or a complex landslide mechanism that takes time to develop

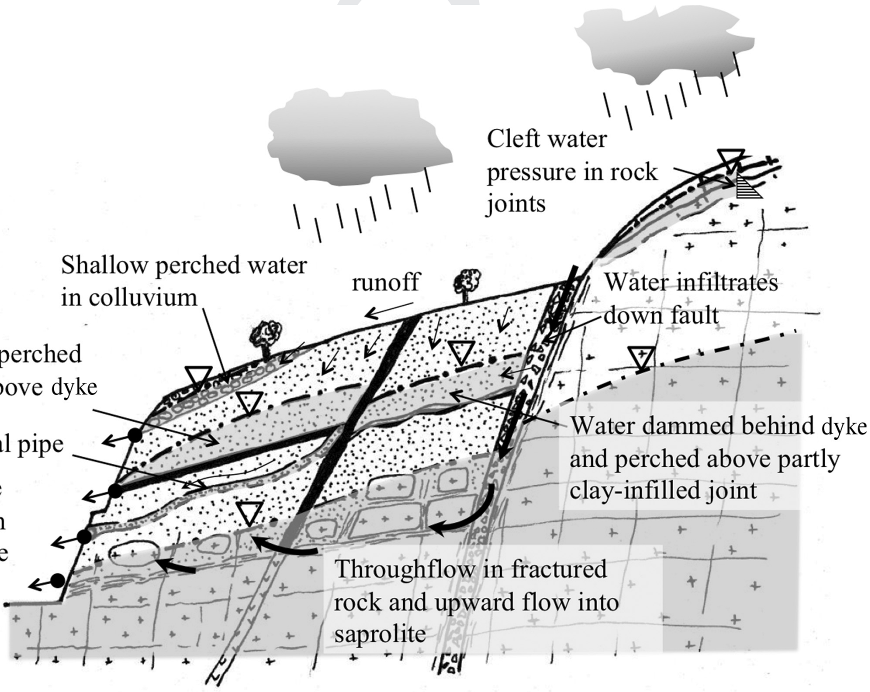

Fig. 30.9. Hydrogeologic processes that operate in saprolite and weathered rock in Hong Kong (modified from Hencher, 2010).

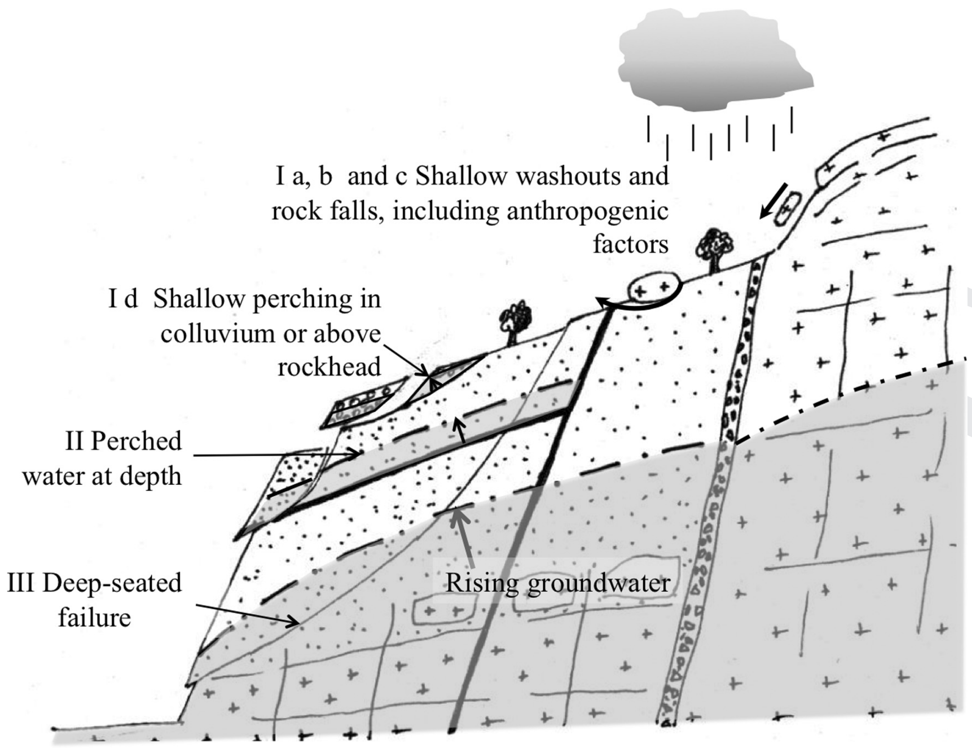

Fig. 30.10. Types of slope failure in Hong Kong (modified from Hencher and Lee, 2010).

30.6.2 LATE IN STORM OR HOURS OR DAYS AFTERWARD

Perching of water at greater depth in weathered rock or above aquitards (Type IIa)Type IIa landslides are distinguished from Type Id events mainly by their greater volume, by the involvement of relatively deep geologic structures, and by their timing. Through-flow in the rock mass is restricted by aquitards, such as weathered dikes or clay-filled joints, above which high water pressure can build up. Failure can be delayed by a few hours – or even days – because of the time it takes for the perched water pressure to develop; in some cases, however, pre-existing tension cracks and other channels facilitate a relatively fast response to storms.

Figure 30.11 shows a series of Type IIa landslides on the Tuen Mun Highway in Hong Kong. Martin and Hencher (1984) attributed the largest failure to temporary perching of water above a weathered dike, which is seen as a depression in the slope below. The weathered dike is less permeable than the granite. Several other examples are presented in Hencher *et al.* (1984) and in Hencher and Lee (2010).

HIGH THROUGH-FLOW IN PERMEABLE ZONES OR CHANNELS (TYPE IIB)

In other situations, shear zones and zones of highly fractured rock can allow rapid through-flow. Examples of failures associated with such highly transmissive zones are described by Hencher *et al*. (1984), Sun and Campbell (1999), Koor and Campbell (2005), and Hencher and Lee (2010). In many such cases, channels or zones of high permeability are observed in landslide scarps. These features continue to issue water after the landslide has occurred and the rainstorm has passed, which illustrates a distinctive feature of this landslide mechanism. Whereas in a shallow failure (e.g., Type I), initial dilation of the sliding mass might cause a reduction in water pressure, and hence cessation of the movement, deeper failures involve a larger supply of water, fed by underground stream systems, that can drive the failure to full collapse.

30.6.3 DELAYED BY DAYS OR WEEKS

GENERAL RISE IN WATER TABLE (TYPE IIIA)

Perhaps the simplest hydrogeologic control on landslides in Hong Kong is the descent of a wetting band, created by infiltration, that reaches and raises the groundwater table. Lumb (1962) calculated that even continuous heavy rainfall for more than 12 hours would only saturate the upper few meters of typical Hong Kong saprolite; therefore it would take a long time for a wetting band from a storm to reach a groundwater table at a depth of 10 or more meters in such materials. In such situations, deep-seated failures may occur several days after the causative storm. In fact, deep groundwater may not be responsive to individual storms, but rather may show a seasonal response, as exemplified by a case described by Insley and McNicholl (1982). However, where there is hydraulic connection from an uphill recharge area, it is possible for the deep water table to respond more rapidly to storms, as discussed by Jiao *et al.* (2005, 2006).

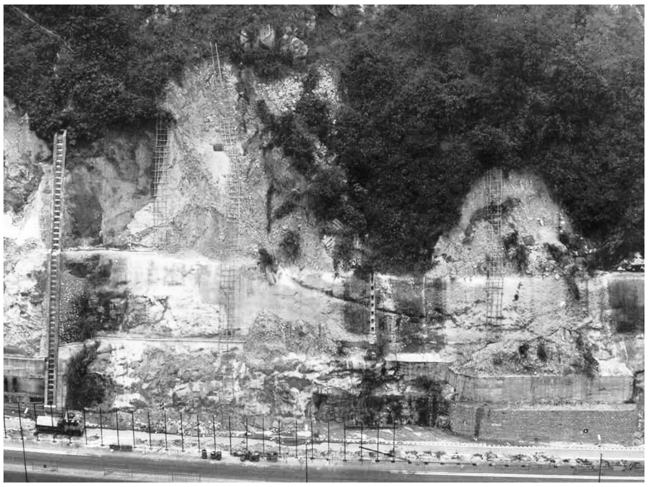

Fig. 30.11. Slope failures on Tuen Mun Highway; a shallow-dipping dike runs up through main landslide.

PROGRESSIVE DETERIORATION (TYPE IIIB)

Large and disastrous failures can occur unexpectedly in Hong Kong, even during a minor storm. The slope may have deteriorated progressively over a long period, making it susceptible to a final triggering storm. The Po Shan landslide of 1972 occurred after 3 days of heavy rainfall, but cracking in the road and local slips had been occurring for at least 11 months before the failure (Cooper, 1992). Careful mapping and investigation of the Lai Ping landslide of 1997 demonstrated that it had probably been moving intermittently for 20 years (Sun and Campbell, 1999; Koor and Campbell, 2005).

30.7 CONCLUSIONS

There is a long history of study and engineering of slopes to reduce risk from landslides in Hong Kong. Investigations carried out 30 years ago showed that geologic structures commonly control hydrogeologic conditions and landslides. However, despite all the slope remediation work that has been completed, landslides still occur every year in Hong Kong, almost always during intense rainstorms. Shallow failures, including minor rockfalls, are the most common type of failure; they generally occur during storms. These failures are typically associated with surface erosion or saturation of surface layers of colluvium or residual soil, with perching of water above the underlying saprolite or bedrock. Deeper-seated landslides may be delayed, even by many days after the rainstorm. Studies in the 1990s in Hong Kong have identified the importance of precursory movements and ongoing deterioration prior to the final failure.

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