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Notes

Landslide mechanisms in Hong Kong

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Abstract: This paper reviews the nature and mechanics of landslides in the weathered terrain of Hong Kong. The vast majority of landslides are very shallow (a few metres depth) and occur during intense rainstorms. Deeper-seated landslides, in contrast, may occur days or weeks after intense rainstorms. The time of occurrence of landslides can be linked to hydrological and hydrogeological factors, and a hydrogeological grouping of landslide mechanisms is introduced related to timing in a storm. A relationship is presented that links intensity of landsliding to 24 h rainfall. The gradual deterioration and internal erosion of slopes prior to detachment is discussed and allows some realistic opportunity for identifying progressive major landslides. In particular, the growth of natural piping systems and infilling of dilated fracture networks are recommended as important indicators of landslide development. The conclusions are supported by case examples of slope failures, the study of some of which has been taken to a forensic level.

Landslides are a common hazard in Hong Kong and this hazard has been addressed over many years by the concerted efforts of the Hong Kong Government, its consultants and contractors through a specialized office, previously known as the Geotechnical Control Office (GCO), and now as the Geotechnical Engineering Office (GEO). This office vets the designs of all new slopes and is going through a process of upgrading old slopes through the implementation of extensive landslide preventive works, wherever necessary. Over the last few years, it has also begun to tackle, in a managed way, the risks from landslides issuing from the steep and rugged natural terrain that is typical of most of the territory. The early history of the Hong Kong Government on dealing with the risk of landslides has been discussed by Brand (1984), and the situation has been updated by Malone (1997) and Wong (2005).

Ground conditions

Geology

Current understanding of the geology of Hong Kong is summarized in two government publications (Fyfe *et al.* 2000; Sewell *et al.* 2000). The major urban areas are underlain by Jurassic and Early Cretaceous volcanic rocks and by granitic rocks of similar age but intrusive into the volcanic rocks. The volcanic rocks, which in their fresh state can have unconfined compressive strength well in excess of 200 MPa, largely make up the higher mountainous areas

surrounding Hong Kong harbour and peaks on Lantau Island, as illustrated in Figures 1 and 2. The central harbour basin and other low-lying areas and more flat-lying islands comprise granitic rocks that include granite, granodiorite and quartz monzonite (Figs 3–5). Differences in petrology can be reflected to a degree in engineering behaviour. For example, quartz monzonite has been linked to particular ground problems such as preferentially weathered zones encountered in construction of the Aberdeen tunnel, which necessitated extensive dewatering and grouting (Cochrane 1984) and low shear strength rock joints in the Yip Kan Street landslide (Hencher 1981, 2000).

Weathering

Distribution of weathered rock

Hong Kong rocks are locally deeply weathered to depths as great as 60 m and sometimes more. Typical profiles are illustrated schematically in Figure 6. Active weathering processes and the implications for geotechnical engineering have been discussed by Hencher (2006). The weathered rocks range from completely restructured and fairly dense residual soil to soil-like weathered rocks that retain the original rock texture and fabric but have dry densities as low as 1.2 Mg m^{-3} , which is less than half the density of rock in its unweathered state and indicative of a very porous, open and sensitive condition. At a mass scale the weathering front is sometimes very sharp, with a zone of uniform soil-like weathered rock overlying almost fresh rock (Fig. 7). Elsewhere, the change is more gradual, with mixtures of rock

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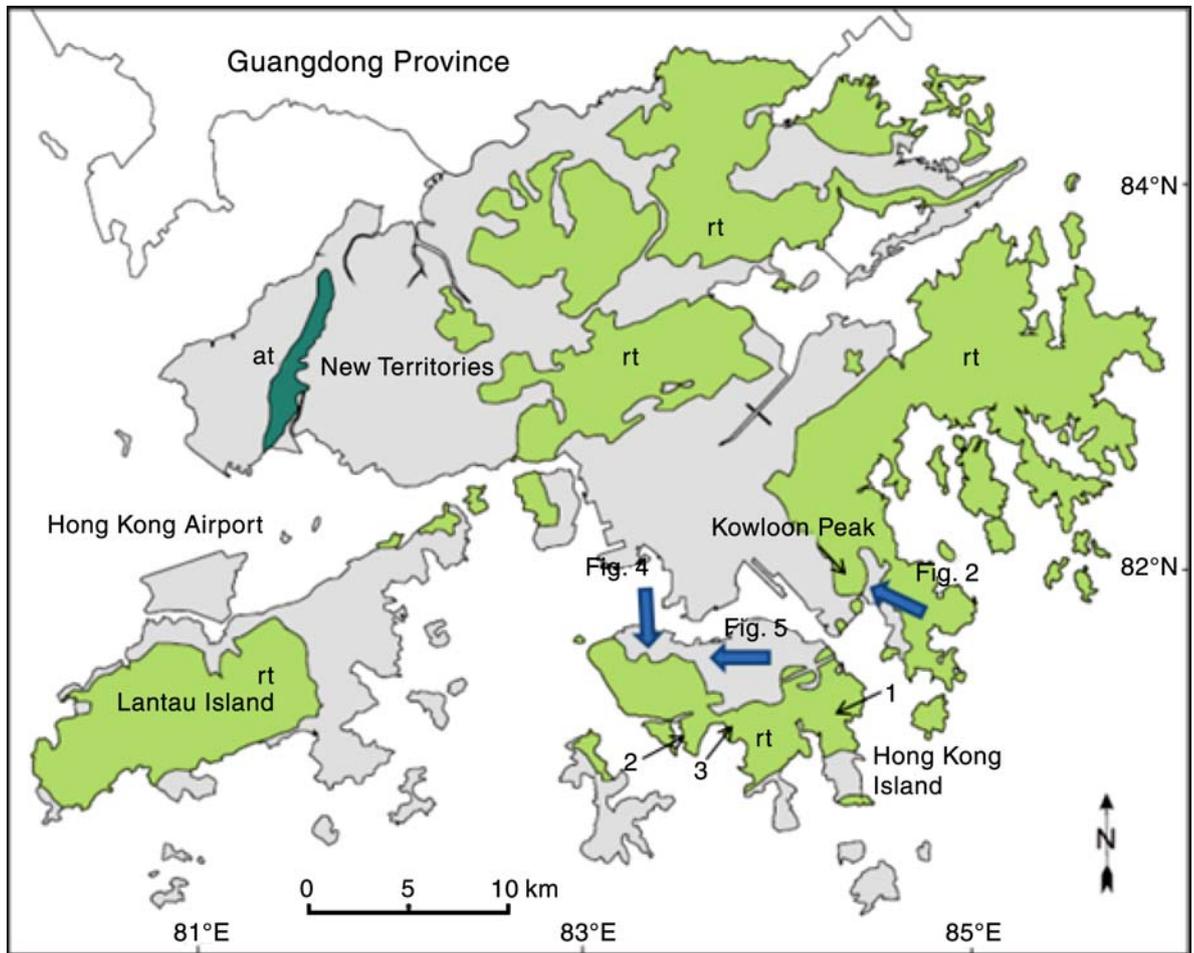


Fig. 1. Distribution of major volcanic outcrop in Hong Kong (adapted from Fletcher 2004). rt, predominantly rhyolite tuff with some lava and sedimentary rock; at, predominantly andesitic lava with some tuff and sedimentary rock; 1, Chai Wan Road; 2, Shum Wan Road, Aberdeen; 3, South Bay Close, Repulse Bay (numbers refer to locations mentioned in the text).

and soil occurring between zones that are fully soil or fully rock (Figs 8 & 9), or the weathering profile can be completely haphazard (see Fig. 10).

The distribution of weathering can be difficult to predict from current topography. Sometimes hills are underlain by thick weathered profiles but at other locations the hills comprise 100% rock from the ground surface. Valleys may be the location of deep weathering but elsewhere rivers run directly on exposed rock even where the valley reflects the presence of a fault. The difficulties for investigation and characterization are obvious. Surface mapping ('regolith mapping') is advocated by some researchers as a first stage in identifying susceptibility to natural terrain landslides (e.g. Fletcher *et al.* 2002) but there remain great uncertainties in interpreting the underlying ground conditions from surface expression alone and surprises are common.

Weathering terminology

The terminology for weathering used in this paper is that advocated in *Geoguide 3* (GCO 1988) and essentially the same as that recommended by Anonymous (1995) and adopted in BS5930 (BSI 1999). The scheme is illustrated in Figure 11. It is generally found useful in Hong Kong to classify hand-size (material) samples at the scale of core logging and laboratory testing according to the left-hand table in the figure. The classification does not cater readily for all the varieties of weathered rock that are encountered; for example, it is difficult to apply to rocks that are highly disintegrated. It does, however, often allow relatively uniform weathered rock of similar strength to be grouped using simple index tests (Henchler & Martin 1982; Martin 1986). At the larger scale, for engineering works and landslide analysis, units or zones need to be differentiated

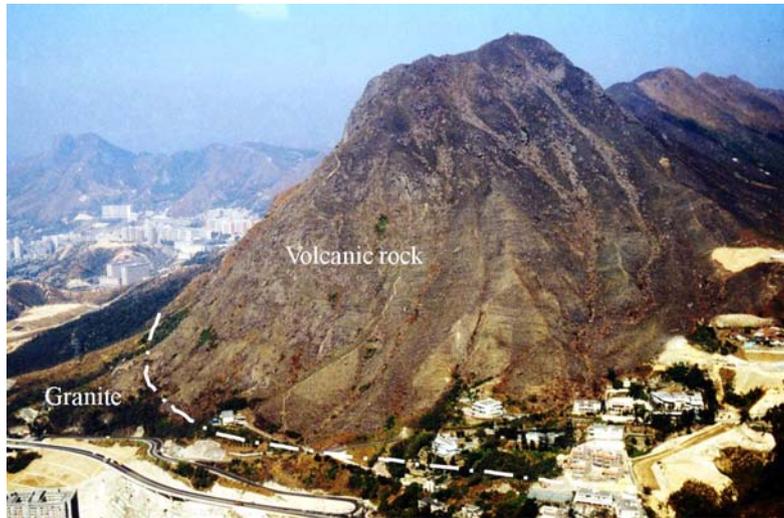


Fig. 2. Kowloon Peak (Fei Ngo Shan) in volcanic rock with weathered granite making up the foothills. (Note large colluvial lobes on the side slopes.) Lion Rock (resistant granite) in distant background.

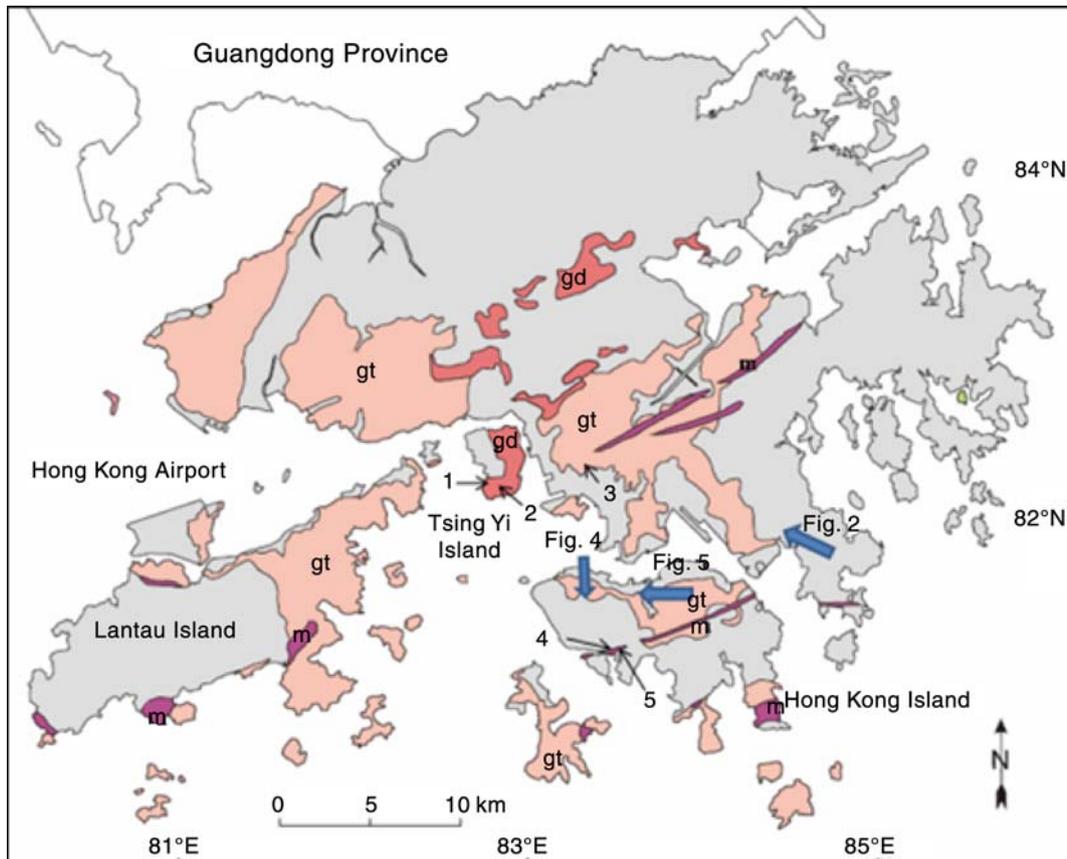


Fig. 3. Distribution of main granitic rock bodies in Hong Kong (adapted from Fletcher 2004). gt, granite; gd, granodiorite; m, quartz monzonite; 1, Tsing Yi 1; 2, Tsing Yi 2; 3, Ching Cheung Road; 4, Yip Kan Street; 5, Aberdeen Tunnel Portal (numbers refer to locations mentioned in the text).



Fig. 4. Aerial view (IR photograph) of part of Mid Levels District above Hong Kong Harbour.



Fig. 5. View westwards across northern part of Hong Kong Island showing change in gradient from steep volcanic rhyolite tuffs to underlying more weathered granite.

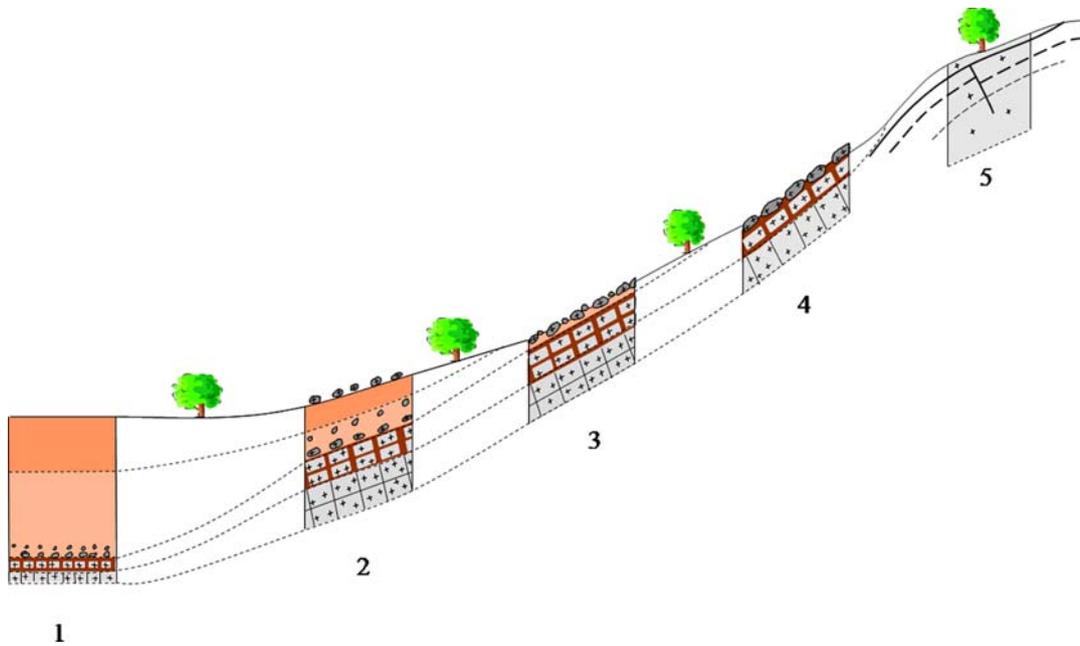


Fig. 6. Variety of weathering profiles to be anticipated in different parts of slope profile (schematic and not to be relied upon). Sections 1–4 redrawn from the Ruxton & Berry (1957) representation of an old age weathering profile. Sheeting joint section (5) is area where erosion rate exceeds weathering.



Fig. 7. Sharp weathering front in weathered granite, Tai Tam Reservoir, Hong Kong.



Fig. 8. Corestone development in granite. Tai Tam Reservoir, Hong Kong. Height of exposure is approximately 4 m.

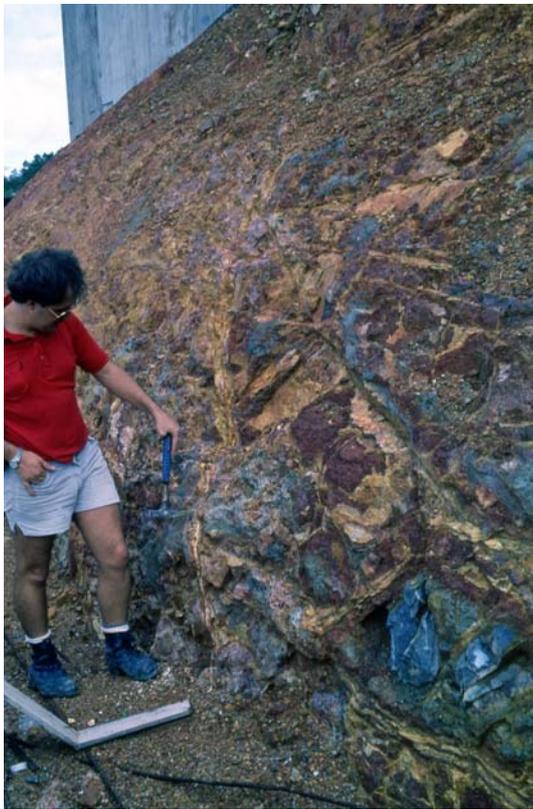


Fig. 9. Corestone development in volcanic rocks, Victoria Peak, Hong Kong.

according to variations in mass properties. Prescriptive zonal classifications are sometimes used in Hong Kong following the principles discussed by Martin & Hencher (1986). The schemes of *Geoguide 3* (GCO 1988) and Anonymous (1995) for heterogeneous weathered profiles are illustrated on the right-hand side of Figure 11. In the author's experience such zonal schemes for weathered rock masses are actually of little use other than for the broad communication of rock mass conditions, because they are inflexible and fail to account for important factors such as geological structure and fracture spacing, which are often of overriding importance to stability and properties at the mass scale. No one, to the author's knowledge, has ever attempted to link ranges of geotechnical parameters such as E or ϕ values to particular prescriptive weathering zones, which is very wise because it would be very difficult to generalize meaningfully, given the often extremely heterogeneous nature of zones of weathered rock. In the author's opinion, classification is no substitute for description at the mass scale. Incidentally, it is to be noted that the weathering classification schemes illustrated in Figure 11 are not used world-wide and, confusingly, many of the terms defined in that figure are used elsewhere in different ways. This problem was addressed in detail by Anonymous (1995) and Martin & Hencher (1986), but despite the inevitable confusion, committees continue to invent new schemes, redefining the same terms, often apparently without any research or reasoning. Hencher (2008) has provided a critique of the new scheme adopted for Eurocode 7, where a new mass classification has been prescribed that conflicts with all other such classifications world-wide yet fails to provide any guidance on material-scale weathering classification, which experience shows is the most useful.

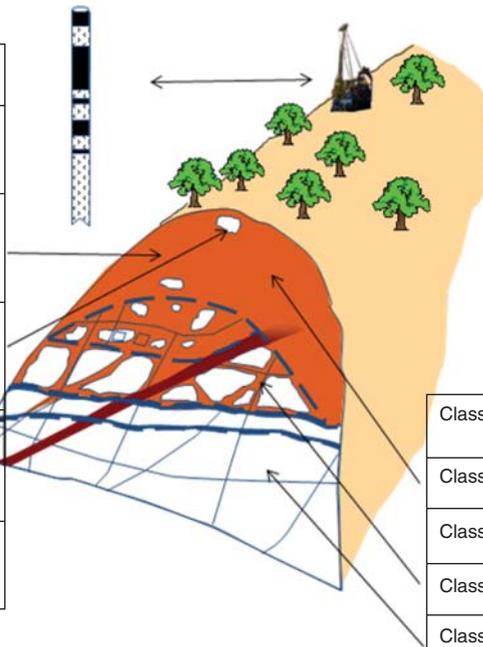


Fig. 10. Highly heterogeneous profile with single very large corestone. Right-hand photograph shows detail with very rapid transition from Grade V, completely decomposed rock, to almost fresh rock within the corestone. Tai Po, Hong Kong. Width of right-hand photograph approximately 1 m.

Material Grade Classification

Applies to intact samples and core description

Grade VI Residual Soil	<i>In situ</i> but lost rock texture
Grade V Completely Weathered	Disaggregates in water
Grade IV Highly Weathered	Large pieces broken and crumbled by hand
Grade III Moderately Weathered	Large pieces cannot be broken by hand
Grade II Slightly Weathered	Weakened (generally mass has some discoloration)
Grade I Fresh	Rarely encountered at Earth's surface



Zone Classifications

Apply to large units

GEO (1988)

Residual Soil (100% Soil)
Partially Weathered PW 0/30 (0–30% Rock)
PW 30/50
PW 50/90
PW 90/100
PW 100

ANON (1995)

Class 6	100% Soil (Material Grades VI to IV)
Class 5	0–30% Rock
Class 4	30–50% Rock
Class 3	50–90% Rock
Class 2	90–100% Rock
Class 1	100% Rock

Fig. 11. Weathering classification.



Fig. 12. Relict joint through Grade IV, highly weathered granite. Near Shek O, Hong Kong.

Engineering properties

Properties of weathered rocks can be difficult to ascertain because sampling and testing of very weak and sensitive weathered materials without disturbance can be impossible, and because of the heterogeneous nature of weathered rock masses. The difficulty of conducting high-quality laboratory tests that provide realistic properties is one of the main reasons for employing a material weathering classification linked to simple index tests. Parameters can be transferred from one location to another. At the mass scale one may wish to account for contributions from corestones within the profile. These problems have been addressed partly by Hencher & McNicoll (1995) and Hencher (2006).

Geological structure, fabric and texture survive at least in part right through to the final stage of weathering, residual soil, where the soil collapses and becomes reworked, so relict joints (Fig. 12) and joints that develop during weathering and unloading (Hencher 2006; Hencher & Knipe 2007) dominate stability in many slopes. Larger structures such as dykes, sills and faults often result in differential weathering within the rock mass. Variation in soil particle grading, texture and clay content results in permeability contrasts that control groundwater flow and partitioning, as discussed below with respect to landsliding. Groundwater flow through the rock mass can cause erosion pipes to form, typically at discontinuity intersections but also commonly as part of the overall degradation and progressive failure of slopes (Nash & Dale 1984; Hencher 2006). These erosion pipes can lead to relatively rapid infiltration and throughflow, and are a common feature associated

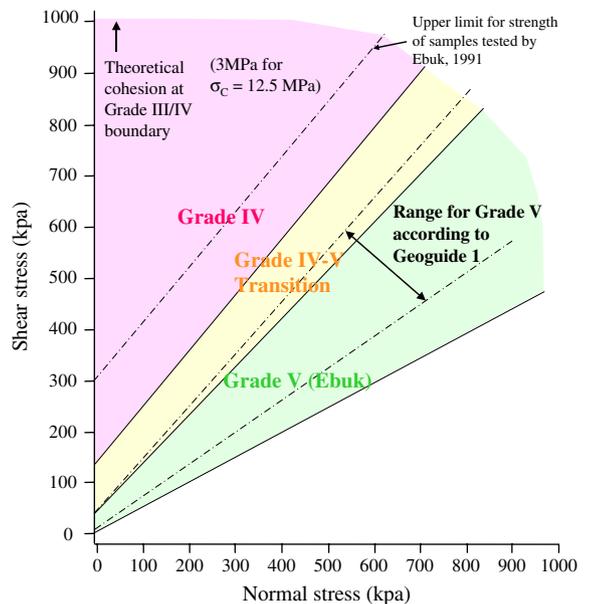


Fig. 13. Range of shear strength envelopes measured by Ebuk (1991) as reported by Ebuk *et al.* (1993) and presented by Hencher (2006). Geoguide 1 is GEO (1993).

with large, deep-seated landslides, as discussed in more detail below.

Properties of typical weathered rock materials in Hong Kong have been discussed by Irfan (1996, 1999) and Hencher (2006). In granite saprolite (predominantly Grades IV and V materials), friction angles are typically $\geq 30^\circ$ (Martin 1986). El-Ramly *et al.* (2005) reported little difference between friction values for Grades IV and V granite from Hong Kong, with an average ϕ value of

37.7° . Hencher (1983a, 2006) reported tests on samples of Grade IV granite of various dry densities, corrected for dilation angle at peak strength, which gave non-dilatant, basic ϕ values in the range of $38\text{--}40^\circ$, which is the same as the corrected non-dilatational friction angle for rough granite joints (Hencher & Richards 1982) and actually the same as for many other silicate rocks (Papaliangas *et al.* 1996). Volcanic rock joints, however, sometimes give lower dilation-corrected shear strengths, down to 32° for

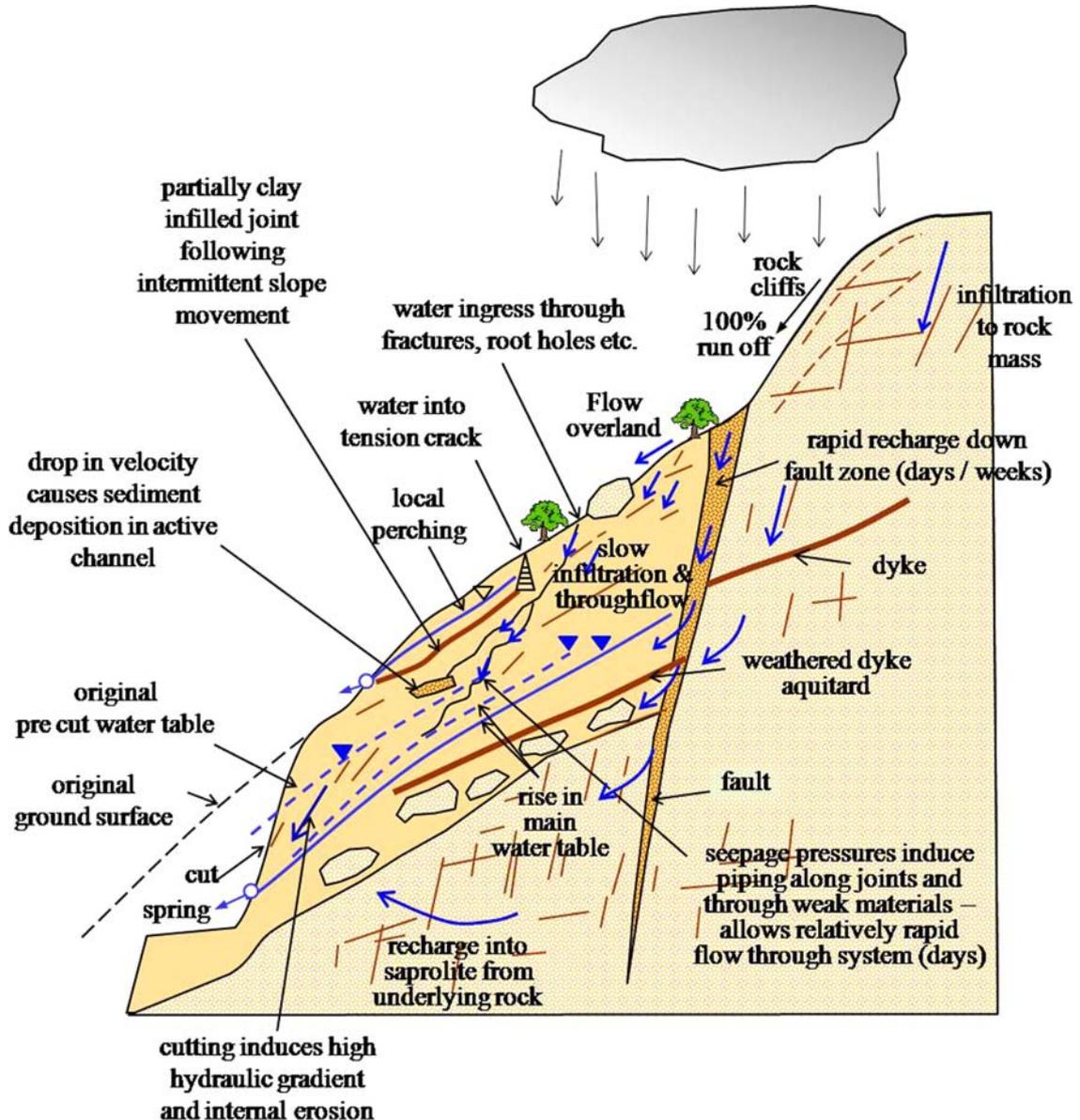


Fig. 14. Hydrogeological processes in weathered rock profiles in Hong Kong.

fine-grained varieties. Coatings on joints can lead to considerably reduced shear strength of 17° at low stresses for chlorite (Hencher 1981; Brand *et al.* 1983), and values for joints infilled with clay can be even lower, of the order of $20\text{--}10^\circ$ (Koor *et al.* 2000). In the case of clay-infilled discontinuities, much depends upon the continuity of the clay infill and its thickness relative to the wall rock roughness. If it occurs only as accumulations in hollows along an intermittently dilating rock joint, as in examples discussed below, then the shear strength characteristics of the infill may be irrelevant although its contribution to reduced permeability may be significant. Proper geological characterization of such structures is necessary. One slightly undulating and very persistent (>60 m laterally) clay-infilled discontinuity of unknown geological origin contributed to the Shek Kip Mei landslide of 1999 (FMSWJV 2000) but such features are fortunately rare.

True cohesion in the sense of adhesional bonding between grains is present in soil-like, weathered rock material (Grades VI–IV) as a result of relict bonding from the parent rock and sometimes because of secondary cementation but reported values from Hong Kong are usually very low. El-Ramly *et al.* (2005), in a review of selected data, gave a range of 0–25 kPa. Ebuk (1991) measured cohesion up to 300 kPa for Grade IV granite from Hong Kong (Fig. 13), but it is considered that even higher values probably exist *in situ* for intact material, given that the upper bound unconfined compressive strength of Grade IV is about 10–15 MPa (break by hand), as discussed by Hencher (2006). It is suspected that the lack of higher reported values is due to a lack of systematic study.

Suction (negative water pressure in partially saturated soil) clearly provides some temporary increase in effective stress and therefore strength in many slopes (Fredlund

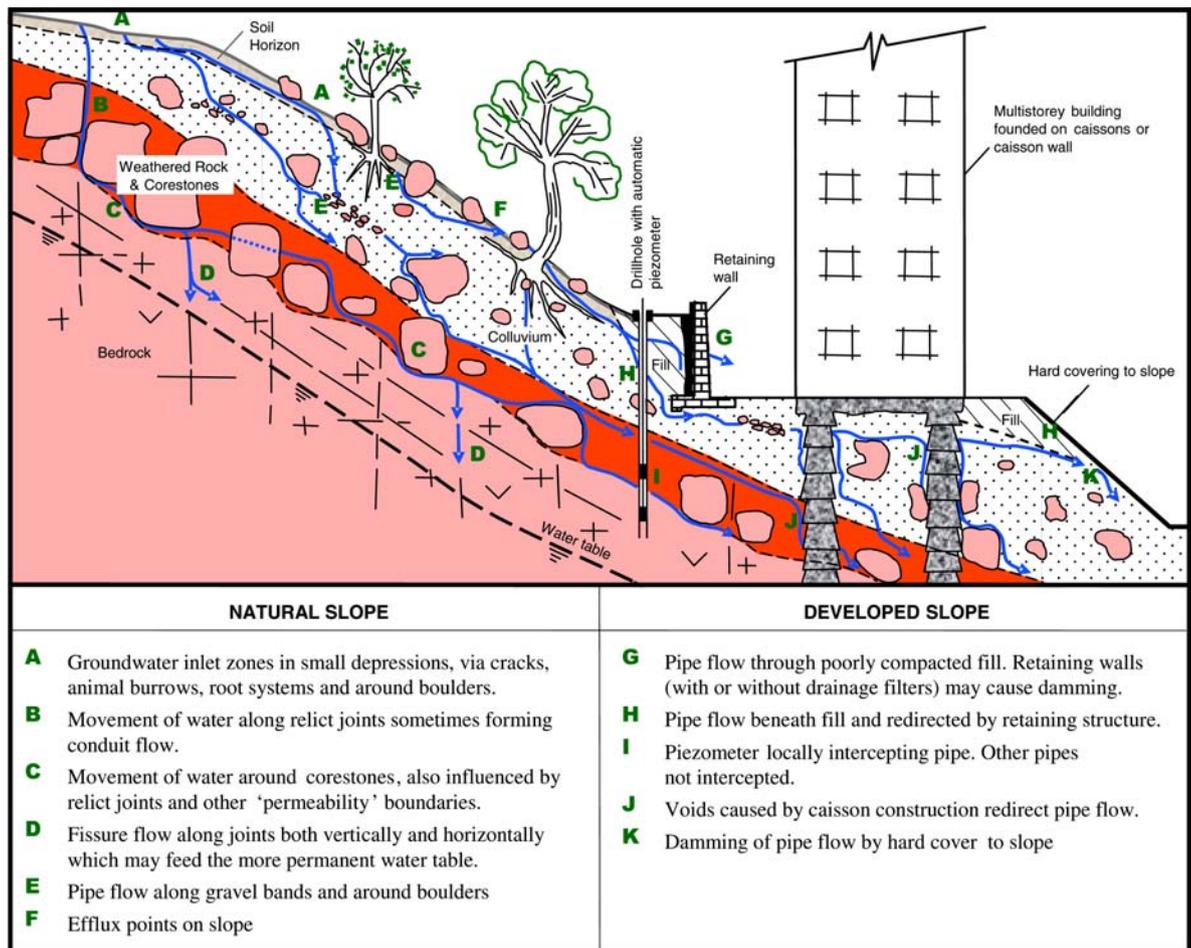


Fig. 15. Schematic representation of hydrogeological conditions close to developments (after Nash & Dale 1984).

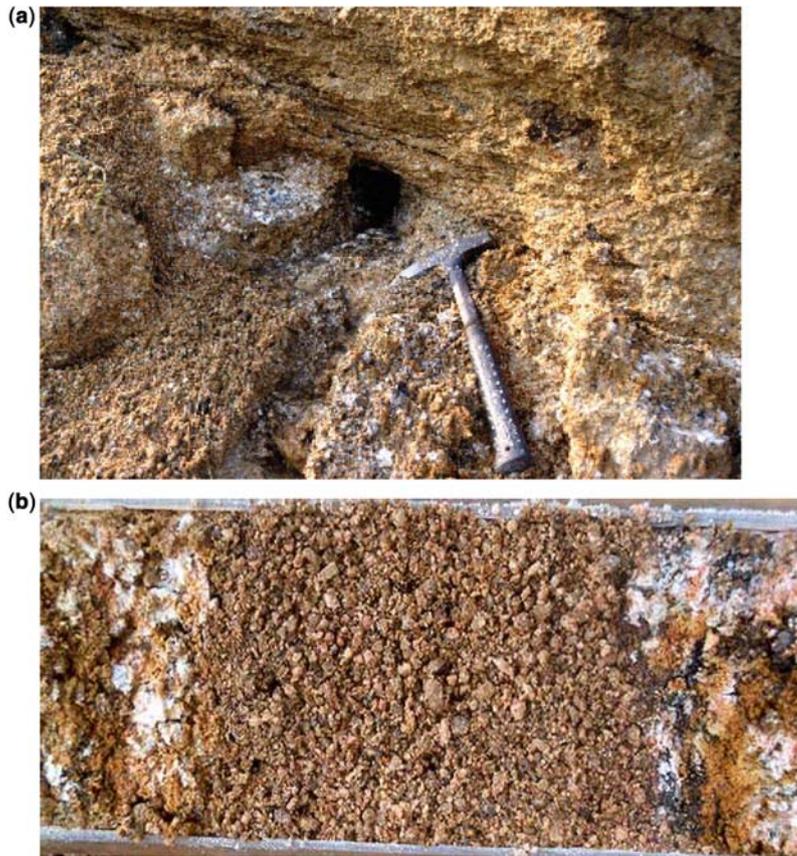


Fig. 16. (a) Natural pipe through decomposed granite exposed in landslide at Tsing Yi (2); (b) alluvial sand sandwiched between decomposed granite within continuous Mazier sample from depth at location of Ching Cheung Road landslide, 1997.

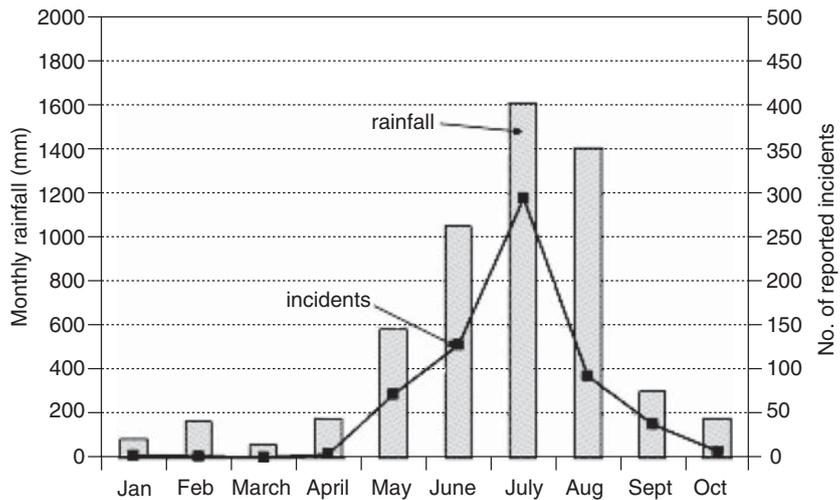


Fig. 17. Landslide incidents reported to GEO v. monthly rainfall, 1997.

1981) but cannot be relied on for design purposes because it can be lost rapidly during a rainstorm (GCO 1982; Rodin *et al.* 1982). Nevertheless, its loss on wetting is probably a factor in many landslides.

Hydrogeology

As illustrated below, almost all landslides in Hong Kong are triggered by rainfall in some way and hydrogeological controls are all-important. The heterogeneity and activity of the weathered rock profiles, often mantled by thick colluvial deposits, lead to a wide variety of hydrogeological conditions, as illustrated schematically in Figure 14. Many of these conditions were identified previously in the insightful paper by Deere & Patton (1971). In Hong Kong these conditions are strongly influenced by anthropogenic activities such as deep bored pile foundations and site formations including very deep cuttings and retaining walls (Pope &

Ho 1982; Nash & Dale 1984; Blake *et al.* 2003), as illustrated in Figure 15.

Hydraulic gradients are often very steep, running parallel to natural hillsides, and throughflow is enhanced by the development of natural pipe systems, particularly in colluvium and saprolite (Fig. 16). At some locations large-diameter underground stream systems develop, leading to karstic-like collapse, even in weathered granite terrain (Halcrow China Ltd. 2003; Hencher *et al.* 2008). Channel flow and piping is also very important in less weathered rock, as evidenced by direct observation and preferential discoloration.

Generally infiltration is slow but locally will be faster down tension cracks or exploiting root and pipe systems. Rises in the deeper, permanent water table in the saprolite can be dramatic, with perhaps 10 m rise in head, and there is evidence that some of the water is fed by channel flow through the underlying rock and then upwards, linked back hydraulically to much higher terrain and consequent artesian conditions (GCO 1982; Leach & Herbert 1982; Jiao *et al.*

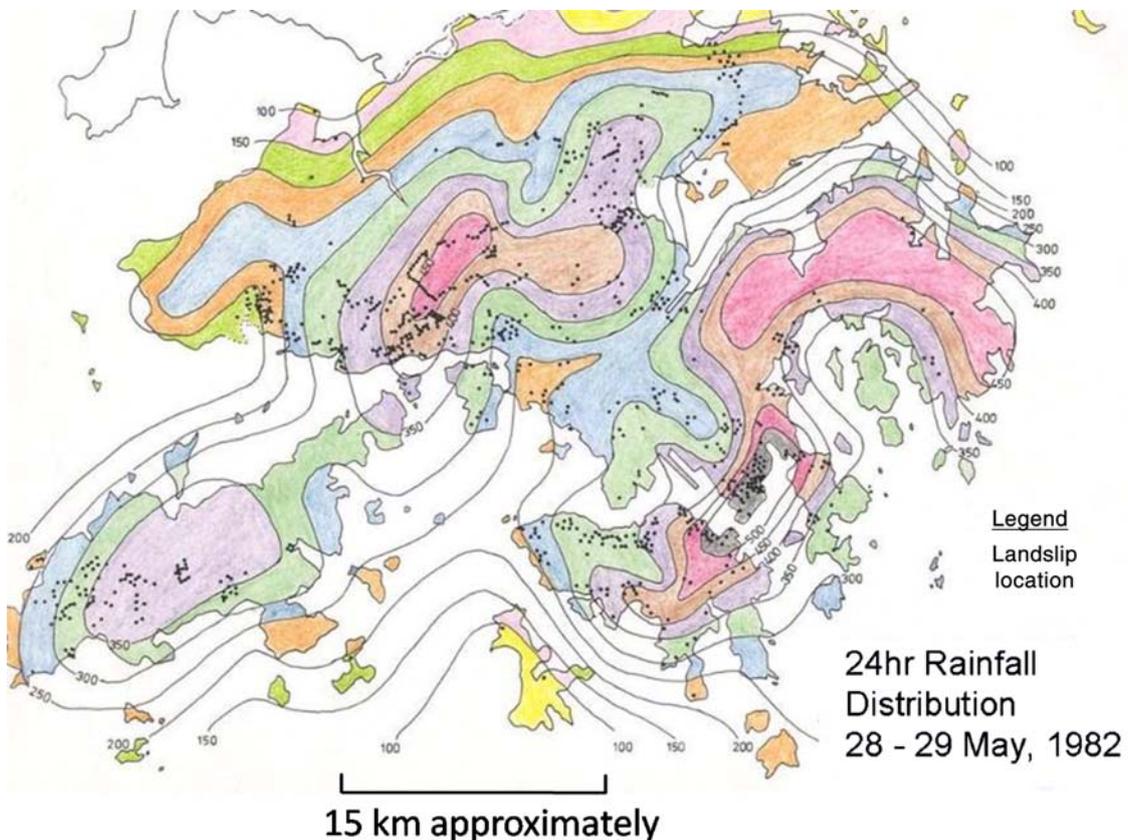


Fig. 18. Rainfall isohyets for 24 h period, 28–29 May 1982 v. reported incidents.

2005, 2006). An important and common condition, contributing to shallow landslides, is perching of local water above aquicludes at geological discontinuities and bands of clay concentration (Au 1986; Kirk *et al.* 1997; Irfan 1998). Such factors in the activity of weathered profiles as leaching, washing out and redeposition of fines, formation of pipes followed by their collapse and self re-establishment together with gradual intermittent slope movements are all very important contributors to the hydrogeological conditions and a general 'ripening' of slopes as the factor of safety diminishes over many years (de Mello 1972; Hencher 2006; Malone 1998).

Landslides and rainfall

Almost all landslides in Hong Kong are associated with periods of high rainfall, which is highly seasonal. Intense storms are to be anticipated from about April to September, although intense storms sometimes occur outside that period and similarly cause extensive failures (e.g. Wong & Ho 1995). The strong link between landsliding and rainfall may be inferred from Figure 17, which gives data for 1997, a record high yearly rainfall for Hong Kong. Lumb (1975) related the occurrence of landslides to rainfall over the preceding 15 day period and rainfall on the day of the majority of landslides. Analysis of calls to emergency services later identified the importance of short-period rainfall intensity of about 70 mm h^{-1} or more, which often coincides with the onset of numerous failures (Brand *et al.* 1984), although this criterion alone does not correlate particularly well with landslide occurrence: according to Malone

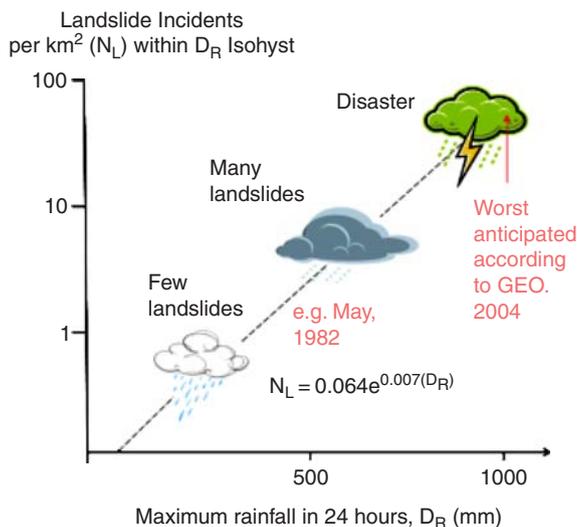


Fig. 19. Twenty-four hour rainfall v. reported incidents (after Hencher *et al.* 2006).

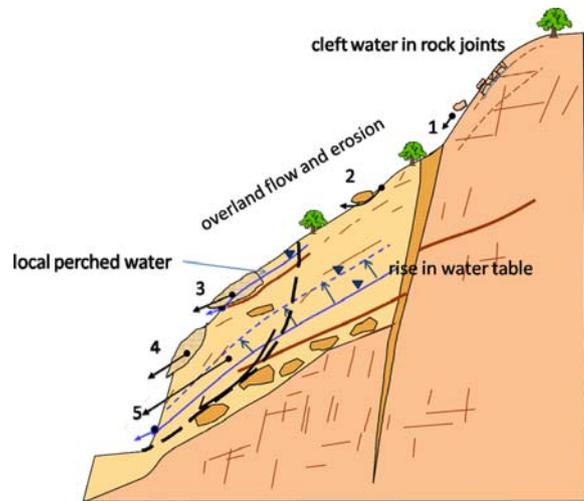


Fig. 20. Typical modes of failure: 1, rock fall; 2, washouts and boulder falls; 3, translational slide triggered by perched water; sometimes above aquiclude, sometimes above rock head or on sheeting joint; 4, shallow failure at crest or in face of cut slope; 5, deep-seated failure.

(1996), over one-third of such rainstorms between 1979 to 1995 did not trigger landslides.

Two of the intense storms listed by Malone (1996) occurred in the same year, 1982, and caused large numbers of landslides, including many in man-made slopes. Eleven of the most significant ones were investigated in some detail (Hencher 1983b). One of the things that was most striking about the landslides caused by those storms was the way in which they were geographically discrete. Areas devastated by the first storm in May 1982 were relatively untouched by the second storm in August and vice versa. The same was observed for landslides triggered by Typhoon Rusa in Korea in 2002 (Lee & Hencher 2007): the area devastated by landsliding was very discrete. Following the 1982 storms it was noted that in some natural terrain, sides of valleys facing in one direction were scarred by many landslides whereas the opposing valley sides were unscarred, which was probably an orographic effect. It is recalled that along one road, in Tsing Yi Island, almost every cut slope showed some signs of distress. An interpretation is that the intense storm had 'tested' each slope and found at least one section with an insufficient reserve of strength to resist the triggering action. Following those storms in 1982, landslide incidents reported to the Geotechnical Control Office were plotted against maps showing the maximum 24 h rainfall as in Figure 18. Analysis of these and other data by counting the number of incidents within each isohyet and dividing by area allowed a plot to be developed showing intensity of landslides per square kilometre v. maximum 24 h rainfall (Fig. 19). For the 1982 rainstorms, in areas where the 24 h rainfall exceeded about 500 mm, the

Table 1. *Hydrogeological processes and their link to timing of landslides*

<i>Timing</i>	<i>Typical size</i>	<i>Hydrogeological process</i>	<i>Example</i>	<i>Comments</i>	
I Early during intense storm	Small to medium	Ia	Surface flow causing erosion and undermining	Gulleying, shallow washouts, boulder fall	Convergence of flow towards topographic hollows
		Ib	Water pressure build-up in rock joint	Rock fall Rock slab failure above adversely oriented joint	May be indications of progressive, intermittent failure before final detachment
		Ic	Loss of suction or softening	Shallow face failure in steep, cut slope	Where stability relies upon apparent cohesion
		Id	Shallow perched water	Shallow slip of soil (colluvium or saprolite) over more competent rock	Very common type of failure in natural terrain (typically less than 2 m depth)
II Medium term late in storm or delayed	Medium to large	IIa	Deeper perched water table	Perching above aquiclude within saprolite	Aquiclude may be clay-infilled discontinuity or geological unit of lower permeability such as a weathered sill or infilled fault
		IIb	Rapid infiltration and throughflow via piping or along other high-permeability channels at depth	Through natural pipes at base of thick colluvial deposits Along permeable fault or shear zone	Where linked to higher catchment or source of recharge, can result in large failures with pore pressures maintained until final detachment despite 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 zone at top of rock head channelling water from high topography to location of landslide	May be caused by delayed flow along channels
		IIIb	May be apparently triggered by only minor rainfall	Progressive failure leads to increased vulnerability	Delay can be because of complex mechanism that takes time to develop

density of reported incidents was about 5–10. Extrapolating to the worst rainfall anticipated for Hong Kong (GEO 2004) indicates a density of incidents in the areas of extreme rainfall of perhaps 20–50 km⁻². Brand *et al.* (1984) reported that for 24 h rainfall less than 100 mm in Hong Kong only a few minor landslide ‘events’ would be anticipated.

It is acknowledged that the above analysis is crude not least because there is no definition of reported ‘incident’, which might range from a minor rock fall to a deep-seated landslide. Also, the incidents on which Figure 18 is based are only those reported to GCO/GEO and therefore biased to those affecting urban areas and infrastructure. No doubt the concentration would be higher if one were to count all natural terrain landslides and partial detachments. By comparison, a recent study of Malaysian cut slopes in weathered granite that appear superficially very similar to those of Hong Kong identified that large, serious landslides can be triggered in that country at much lower rainfall intensities than would be associated with similar incidents in Hong Kong. The reason for this is not clear, but it does indicate that the relationship in Figure 19 is not generally applicable, probably because, in some way, terrain susceptibility is in balance with local climate (Corominas 2000). Attempts have been made to define relationships for the onset of landsliding using rainfall intensity and duration normalized for mean annual precipitation (MAP) or ‘rainy-day normal’ (RDN) for different climatic regimes but these have met with little success (Guzetti *et al.* 2008). Clearly, there remains research to be done on susceptibilities and the underlying mechanisms and predisposing factors that control the response of a particular terrain to rainfall intensity. Perhaps the Malaysian granite saprolite has different density profiles for equivalent weathering grades compared with Hong Kong, as is certainly true of the hydrothermal weathering profiles from granite in the UK compared with weathered granite from Hong Kong, where, for example, Grade V material is much denser than the equivalent material from Hong Kong (Hencher *et al.* 1990). It is to be anticipated that such differences in the weathered profile characteristics will have knock-on effects on permeability, wetting rates, suction and true cohesion and hence the impact of particular types of rain storms, which vary in their intensity and duration.

Landslide mechanisms and occurrence

The landslides that occur in the weathered terrain of Hong Kong are varied because of the relatively complex geology and structure for a small area and the diverse geomorphological environments, which range from steep rock cliffs to deeply weathered foothills (Fig. 20). Furthermore, there is potential for natural terrain landslides of all types and for failures in man-made cuts and embankments. Malone (2000) identified many of the settings contributing to the occurrence of landslides in Hong Kong.

One of the chief aspects of Hong Kong landslides is the link to severe storms, and therefore a classification based on the hydrogeological factors leading to the failure is an attractive concept. It is evident that there are many different ways that water can influence stability, ranging from surface erosion to wetting infiltration and loss of suction and rise in water pressure, locally above an aquiclude or more generally through a rise in water table. It is also immediately obvious that the time frame for these various influences may be very different. Erosion will probably happen during a storm but rises in a deep groundwater table will probably be delayed by hours if not days and weeks, as illustrated in data from GCO (1982) discussed by Jiao *et al.* (2006). So (1971) reported that for the severe rainstorm of June 1966, the majority of landslides occurred during the intense rainfall but landslides continued to occur for more than 2 weeks. This has since been confirmed for many rainstorms, with deep-seated landslides often occurring many days after an intense rainstorm (e.g. Hudson & Hencher 1984).

Table 1 summarizes the main hydrogeological factors that trigger landslides in Hong Kong, grouped according to timing with respect to a major storm (which may last for several days in Hong Kong).

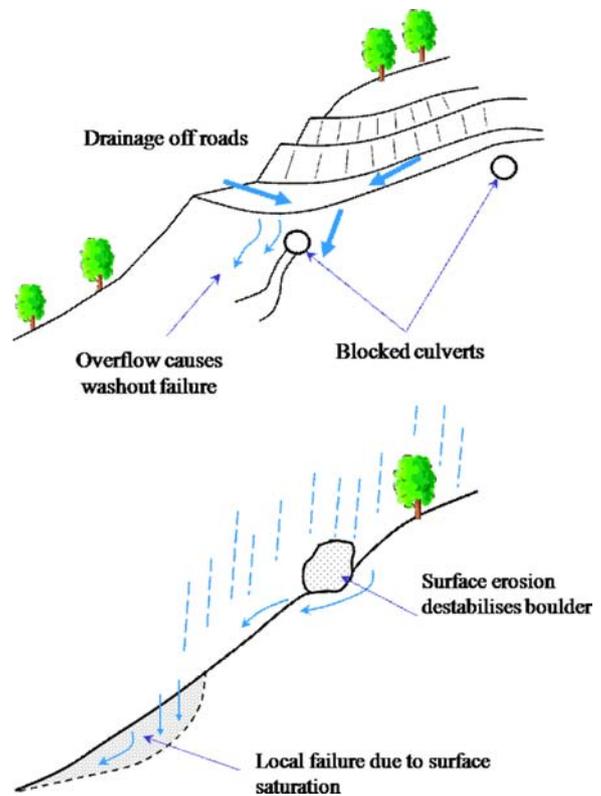


Fig. 21. Shallow failures generally caused by concentrated surface flow, either natural (below) or due to human influence (above).



Fig. 22. Washing out of newly constructed fill slope on Lantau Island following blockage of drains and flooding of the road above combined with an inability of surface channels to carry such large quantities of water.

Landslides that occur relatively early during an intense storm

Shallow washouts, erosion and rockfall (Types Ia and Ib)

Shallow landslides caused by erosion or shallow processes such as cleft water pressures behind loose rock blocks are the commonest types of failure in Hong Kong and probably the most significant in terms of risk. Even a very minor rockfall from a steep roadside slope can cause a serious incident where it affects traffic. Almost 50% of landslides reported to GEO in Hong Kong have volumes less than 5 m³ according to Premchitt *et al.* (1994). They typically occur during or very shortly after severe rain storms. Seventy-four rock and boulder falls incidents were reported between 1978 and 1995 with nine reported fatalities since 1926. Some of the processes are illustrated in Figure 21. Figure 22 shows a recently constructed fill slope damaged by surface flooding, and Figure 23 shows the fatal Shum Wan Road landslide triggered by concentrated surface water flow channelled into the landslide area following partial failure of a small fill slope supporting the passing-bay on the road above (GEO 1996). The concentration of surface water towards topographic depressions has been discussed by Anderson *et al.* (1983).

Loss of suction (Type Ic)

Suction may provide additional apparent cohesion of the order of a few tens of kPa to a slope in its partially saturated

condition, which is of the same order as true cohesion owing to relict bonding in completely weathered rocks (Fredlund 1981; Shen 1998). Suction probably plays a role in many landslides although it is generally difficult to prove as a primary candidate because of the many other factors and lack of definitive monitoring. The landslide in Figure 24 was, however, judged to be such a case, largely because there was no catchment above the slope, which made it unlikely that there was any positive pore pressure development (Hencher 1983c; Hencher *et al.* 1984).

Shallow perched water table (Type Id)

Landslides involving a thin soil slab overlying rock head or within a rock sheeting joint are very common forms of failure both in Hong Kong and Korea (Lee & Hencher 2007). Because of their shallow nature, infiltration and the build-up of water pressure can be rapid during a storm, so that this type of failure will be triggered early on. Figure 25 illustrates the mechanism. The case example is from a detailed study of a slope above a sheeting joint that had been evidently deteriorating progressively over many years prior to final detachment. Full details have been given by Halcrow China Ltd. (2001) and illustrated by Hencher (2006). This was a particularly illuminating case demonstrating the progressive loss of shear strength with intermittent movements, and one conclusion was that evidence of the kind of deterioration seen at that site could be



Fig. 23. Site of the Shum Wan Road landslide of 1995 that killed two people and was considered to have been triggered by flow down roads at the head of the landslide exacerbated by blocked drains (GEO 1996). Photograph following preliminary remediation works and with continuing ground investigation.

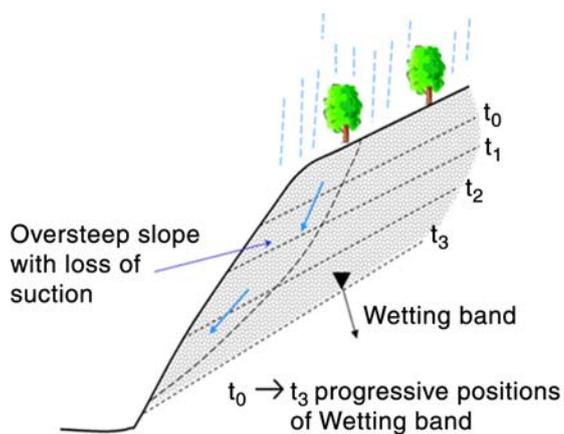


Fig. 24. Loss of suction as a result of wetting (saturation) of partially saturated material. Photographs on the right are of Chung Hom Kok failure in highly decomposed granite (Schmidt hammer rebound values up to 17) before and after failure (Hencher 1983c; Hencher *et al.* 1984).

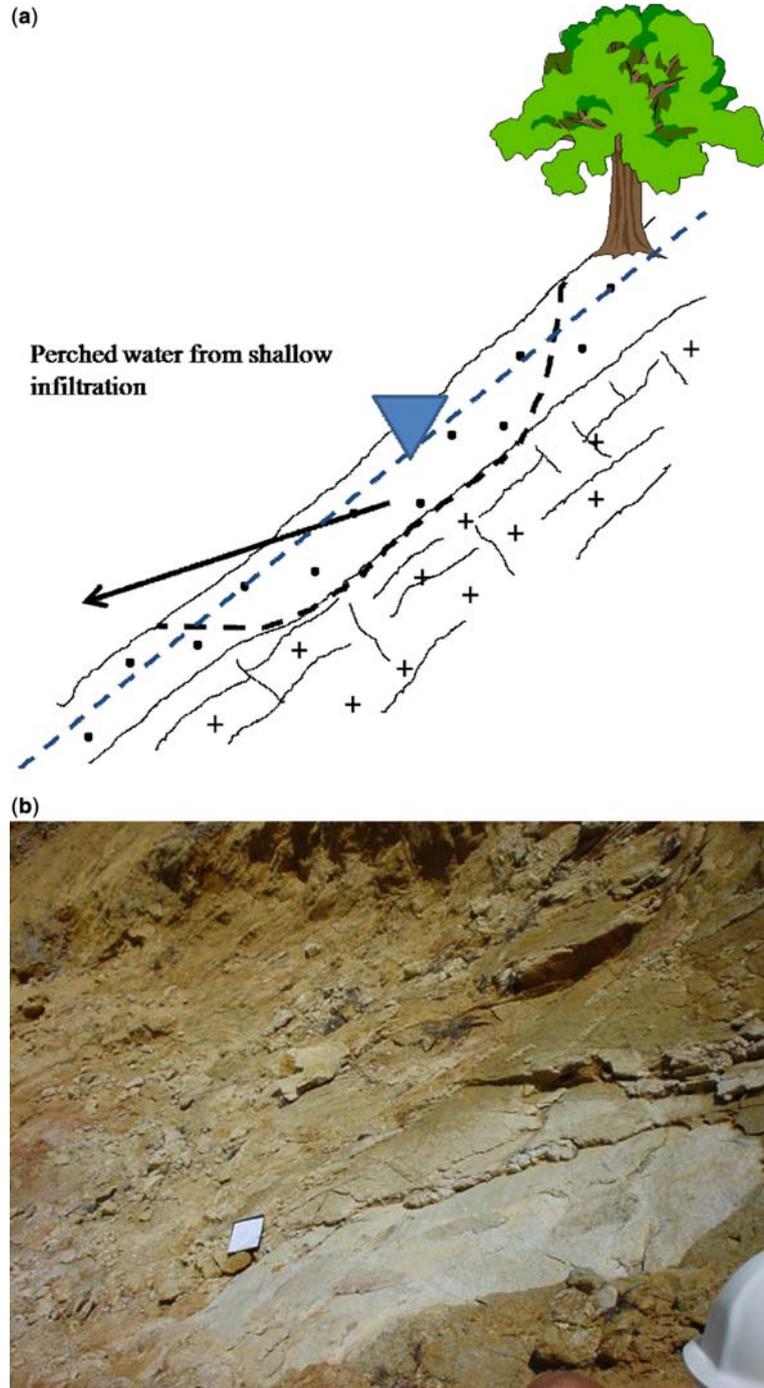


Fig. 25. (a) Schematic representation of perching of water above shallow rock head. (b) Debris trail from landslide above Leung King Estate (Halcrow China Ltd. 2001). In the foreground, in front of the clip board is exposed the pale grey, underlying wall of an extensive sheeting joint. The rock above the sheeting joint is discoloured as the result of many years of intermittent movement and deterioration prior to final detachment, as explained in detail by Halcrow China Ltd. (2003) and Hencher (2006).

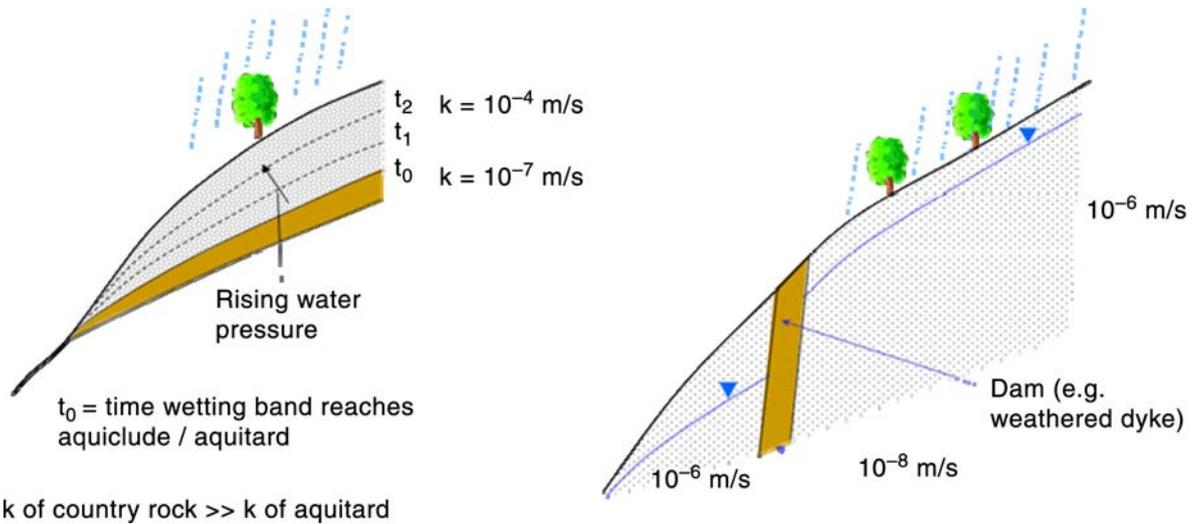


Fig. 26. (a) Perched water above deep aquitard. (b) Daming of ground water as a result of permeability contrasts.

taken, elsewhere, to indicate a slope progressively moving towards collapse.

Landslides occurring in the medium term

Perching at depth within the weathered rock profile or partitioning causing damming of ground water (Type IIa)
This group is differentiated from Type Id on the basis of scale and timing although the mechanisms are essentially

the same. This type of landslide is common and is caused because infiltration is restricted by the presence of a low-permeability layer so that water pressure can build up above that layer. The concepts are illustrated in Figure 26. Such failures may be delayed because of the time it takes for infiltration to occur, although in many cases it is suspected that pre-existing tension cracks and other flaws might have facilitated relatively fast infiltration; much faster than that generally envisaged adopting normal

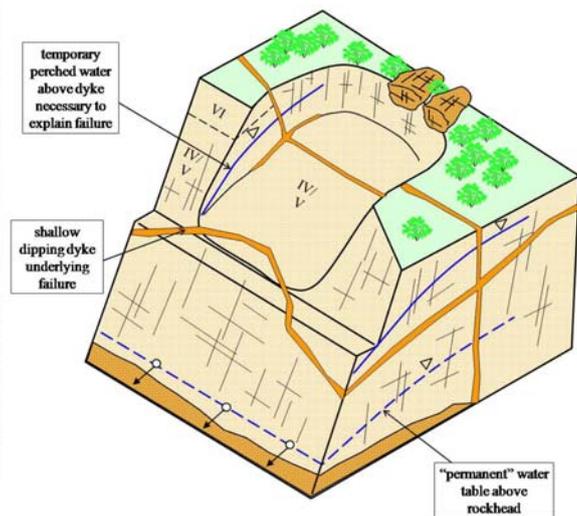


Fig. 27. Tuen Mun Highway landslide, 1982. The landslide was discussed in detail by Hencher (1983a, 2000) and Martin & Hencher (1984).



Fig. 28. Landslide in a section of Ching Cheung Road, 1982, that failed 4 days after heavy rain. A steeply dipping, thick decomposed dolerite dyke was mapped across the failure scarp with water seepage from above, after the failure.

permeability values, for example as discussed by Ruxton (1980) and Iverson (2000). Weathered rock profiles have many such features: persistent discontinuities can become filled with clay, derived from weathering of the rock above and around (Parry *et al.* 2000). Dykes and sills of fine-grained rock such as basalt and dolerite will weather differently compared with the host parent rock, say granite, with a resultant permeability contrast at the interfaces.

Examples of this type of failure have been reported by Hencher (1983*a, d*), Hudson & Hencher (1984), Martin & Hencher (1984) and Au (1986). The slope illustrated in Figure 27 is on the Tuen Mun Highway in Hong Kong. Post-failure investigation and analysis established that positive pore-water pressure was necessary to explain the landslide yet a piezometer through the landslide scar and field observation established that the main groundwater level a few days post-failure was much deeper than the failure surface. A series of decomposed dolerite dykes with lower permeability than the granitic country rock were mapped through the slope with a disposition such that the development of perched water was likely during high rainfall, and it was deduced that this was the triggering factor for the failure (Hencher 1983*a*). An example of groundwater being partitioned as in Figure 26*b* was identified at Ching Cheung Road (Fig. 28) (Hencher 1983*e*; Hudson & Hencher 1984). A thick dyke with water seeping above it was mapped within the failure scar, and

its presence was used to explain various unusual aspects of this failure, which occurred on a dry day, 4 days after an intense storm.

High throughflow along permeable channels (Type IIb)

Some landslides are associated with rapid throughflow of water along highly conductive layers as illustrated in Figure 29. These will affect the pore pressure distribution within a slope and the timing of water pressure development, as demonstrated through careful instrumentation and monitoring along a sheeting joint by Richards & Cowland (1986). Such zones can comprise preferentially fractured layers such as faults or shear zones, or pipes, which can coalesce to become underground stream systems (Hencher *et al.* 2008). Examples of failures associated with such highly transmissive zones include the Chai Wan 1982 landslide (Hencher 1983*f*; Hencher *et al.* 1984), and the landslides of South Bay Close (Hencher 1983*g*) and Lai Ping Road (Sun & Campbell 1999; Koor & Campbell 2005). In many such cases the transmissive feature leading into the back of the landslide can be seen issuing large volumes of water long after the landslide has occurred and rainstorm has passed, which illustrates an important component of the landslide mechanism. In the case of a shallow failure (e.g. Type I), initial dilation of the sliding mass can result in a reduction of water pressures leading to cessation of the movement. In the case of these deeper-seated failures, fed by underground stream systems, there is a much larger

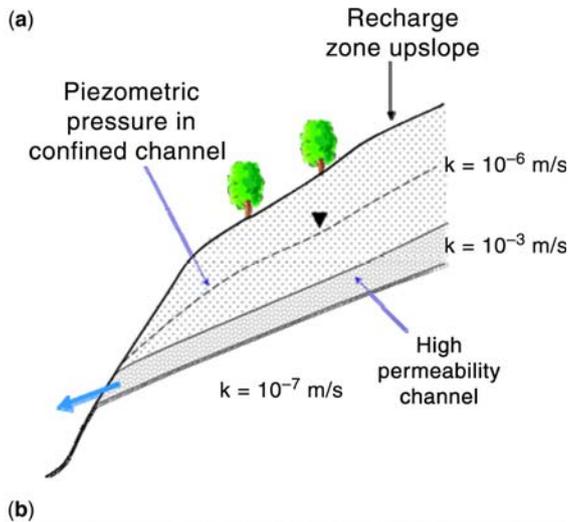


Fig. 29. Above, high-permeability zone allowing rapid through flow and build-up of potentially artesian pore pressure. Below, photograph of slope on Chai Wan Road, 1982 with large pipes at boundary between colluvium and underlying volcanic rock.

source of water available that can drive the failure to a full collapse.

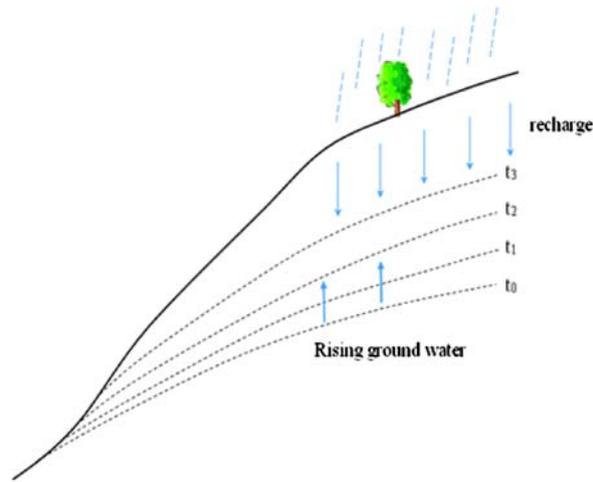
Delayed failures

General rise in deep water table (Type IIIa)

Perhaps the simplest concept of hydrogeological control of landslides involves infiltration leading to a general wetting and an eventual rise in the main groundwater table with increased water pressure and then failure. Lumb (1975) discussed infiltration rates in detail and calculated that only the upper few metres could become saturated following continuous heavy rainfall for more than half a day in granite and rather longer in volcanic rocks. Rises in deeper-seated groundwater table will take even longer (Fig. 14) and a delayed response may therefore be expected for deep-seated landslides. Well-documented cases are remarkably rare for Hong Kong, despite this being identified long ago as an area of knowledge that might be improved considerably through systematic study (Sweeney & Robertson 1979; Hencher *et al.* 1984; Brand 1985). Jiao *et al.* (2005, 2006) have recently revisited some of the data from the early 1980s as well as more recent cases in an attempt to analyse the driving factors for large-scale, deep-seated landslides. One example of a deep-seated failure illustrating most of the key characteristics (evidence of deep recharge through a transient and continuously changing natural pipe system and delayed response of piezometric head to rainfall and delayed failure) is illustrated in Figure 30. This failure was described in detail by Halcrow Asia Partnership (1998) and Hencher (2000, 2006).

The failure illustrated in Figure 31 comprised the dilation and partial detachment of a section of a cut slope in 1982 (Choot 1983). Water was seen issuing from the toe of the distressed area several days after rainfall, and an area to the left and above the failure was observed to be very wet and vegetated. A few days later water issue ceased from the zone of the failure. It was deduced that heavy rainfall on the natural hillside above the slope had flowed towards an old river valley, choked with boulders, which emerged in the upper left side of the cut slope (the wet and vegetated zone). During formation of the slope the valley cross-section had been dammed by a hard surface cover. Consequently, as water flowed down the old river, water pressure built up behind the concrete cover and this in turn led to a rise in water pressure within the relict joints in the adjacent zone of cut slope where the failure took place. The reduced effective stress and consequent decrease in shear strength combined with active cleft water pressure led to some initial translational movement on relict joints (about 0.5 m at the toe). The translation movement along the adverse joint sets involved dilation of the rock mass and increased permeability, and this in turn resulted in a drop in driving water pressure and cessation of movement as illustrated in Figure 31.

(a)



(b)

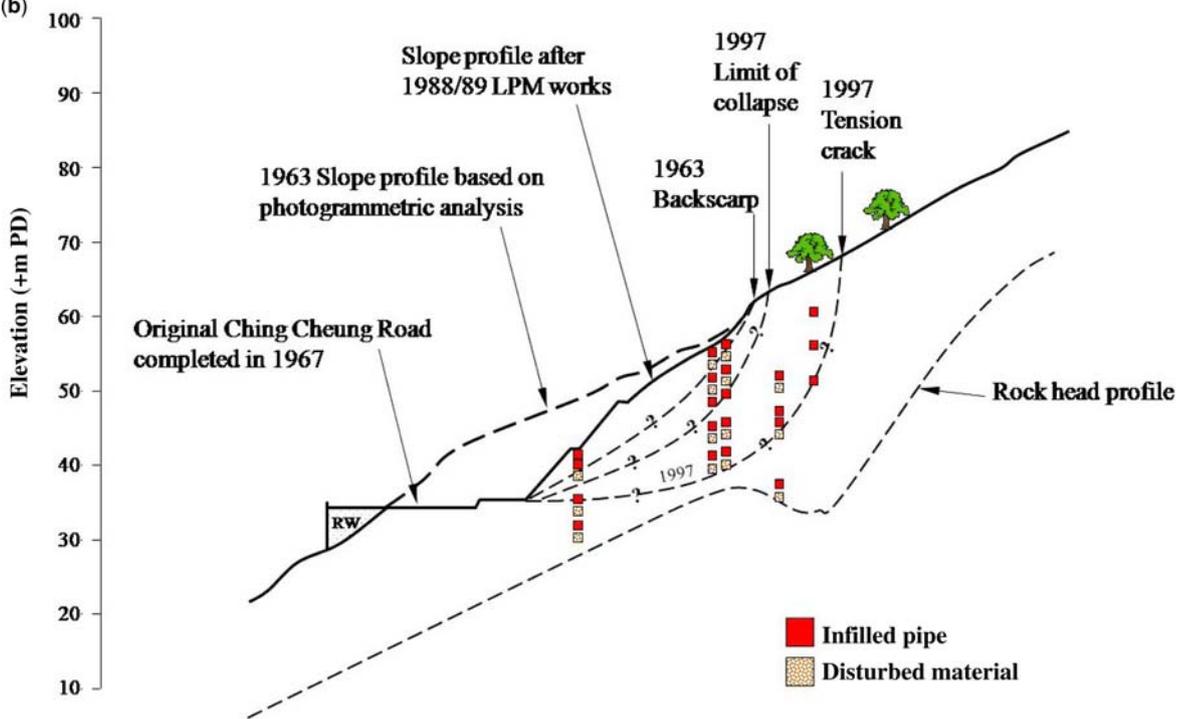


Fig. 30. (a) Rise in groundwater table from time t_0 to t_3 . (b) Cross-section of the Ching Cheung Road landslide of 1997. (Note the number of choked natural pipes sampled in each borehole and that they extend to considerable depth (even below the 1997 slip surface), which indicates the length of recharge path to the groundwater table.)

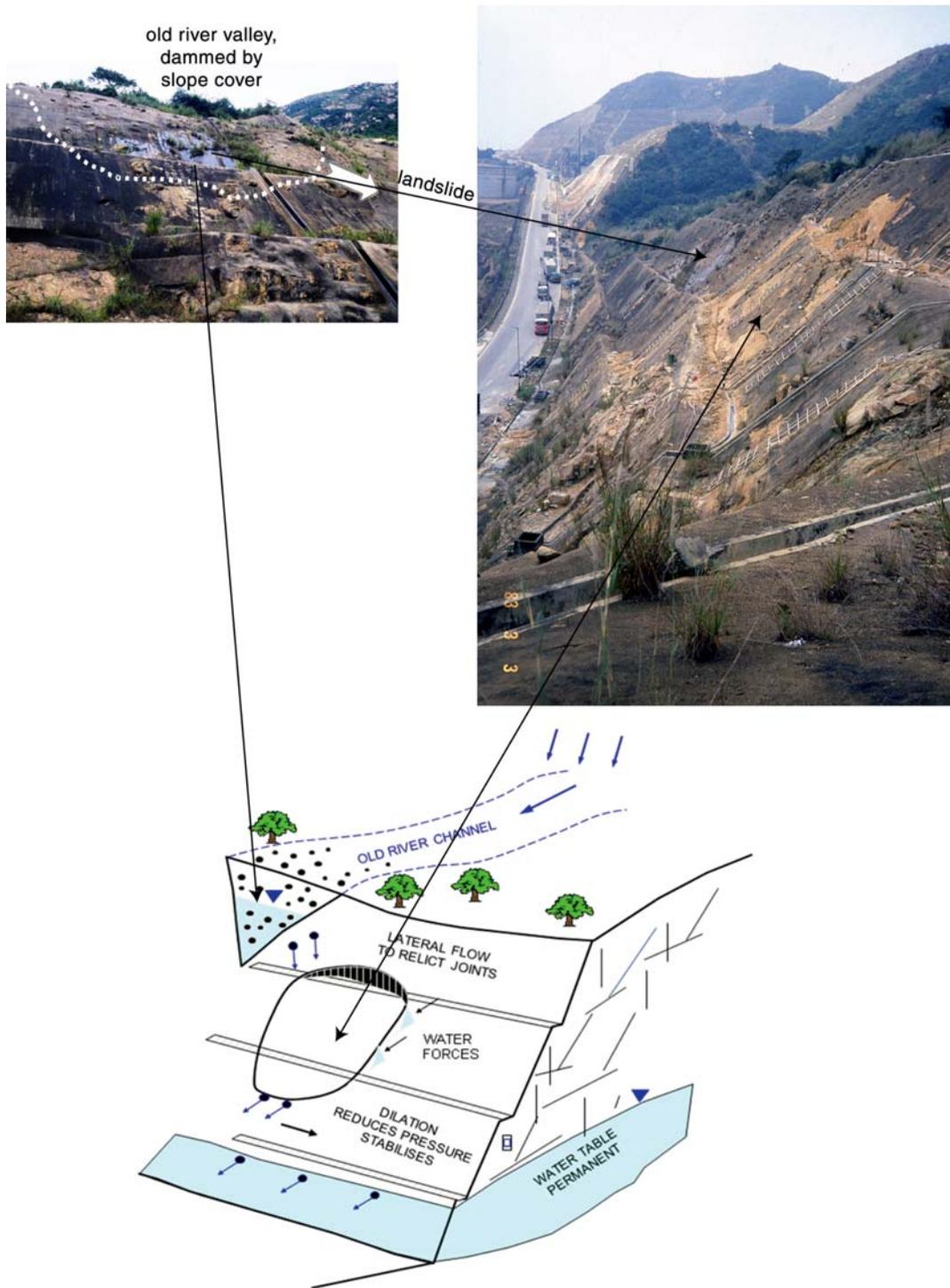


Fig. 31. Tsing Yi (2) landslide.

Other examples of delayed rises in deep groundwater level have been given by Insley & McNicholl (1982) and Jiao (2006).

Progressive deterioration (Type IIIb)

Finally, very large and disastrous failures can occur late in a storm or triggered by some later event, sometimes triggered by relatively minor rainfall. This can happen because the slope has deteriorated progressively over a period, making it susceptible to a final trigger. In the case of the Ching Cheung landslide of 1997 (Halcrow Asia Partnership 1998; Hencher 2000, 2006), the first major movement occurred as a delayed failure, several days after a rainstorm, a month before the final detachment that blocked both sides of a dual carriageway. Fortunately there were no injuries. The famous Po Shan landslide of 1972 occurred after 3 days of heavy rainfall and numerous collapses and settlement giving some warning of the final landslide that destroyed a block of flats and killed 67 people (Vail & Attewill 1976). Careful mapping and investigation of the Lai Ping landslide of 1997 demonstrated that it had apparently been moving intermittently for 20 years (Sun & Campbell 1999; Koor & Campbell 2005).

Conclusions

Landslides occur every year in Hong Kong and these are almost always associated with intense rainstorms. Shallow failures, including minor rock falls, are the most common and generally occur during the storm when the intensity of rainfall is highest, and pose the greatest risk because of their frequency. Deeper-seated landslides are often delayed, even many days after the rainstorm that is subsequently identified as the triggering factor. It is suggested that the timing of landslides directly relates to the hydrogeological factors triggering each landslide. Recent investigations of landslides in Hong Kong have identified the importance of precursory movements and continuing deterioration prior to the final failure, which lends support to the 'ripening' concept of de Mello (1972). The deterioration generally involves dilation and enhanced permeability with the development of underground stream systems and sedimentation. These features can be sought in ground investigations, giving a potential tool for identifying imminent landsliding. Large, deep-seated landslides pose a major threat and many of these are delayed. One category involves rising deep groundwater, sometimes linked to hydraulic systems much higher up a hill slope. A second category of large landslides involves a period of deterioration and movement that need to be monitored and managed. The situation may be irretrievable through normal landslide preventive measures but should allow the risk to the public to be minimized.

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