Engineering Geological Aspects of Landslides

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Abstract: It is clear that the fundamental predisposing factors for many landslides are geological and this has been illustrated by many case studies in Hong Kong over the last 25 years. The nature of the soil and rocks and anisotropic structure relative to slope geometry provide the setting for failure to occur. Heavy rainfall is generally the trigger. Whilst man's influence is often an important contributing factor to many landslides, geological factors generally control the hydrogeological conditions within the slope and the available shear strength though the ground mass.

Slope development (and landsliding) is part of an ongoing time-dependent process during which the rock mass deteriorates and readjusts to changing conditions. These conditions include especially stress changes and the development of inflow and through paths for water. Changes in shear strength can also occur in engineering time. In this paper, engineering geological factors influencing slope stability are considered with particular emphasis on Hong Kong conditions. The discussion is illustrated with reference to landslide case studies in Hong Kong and elsewhere.

1 INTRODUCTION

Studies in Hong Kong over the last forty years or so have contributed to a better understanding of weathering processes and especially to landsliding in weathered rock masses in sub-tropical regions.

The prime focus for the vast majority of the geotechnical community in Hong Kong, especially since the establishment of the Geotechnical Control Office (GCO now GEO) in 1978, has however been slope safety. There has therefore been more concentration on managing risk and trying to stabilize slopes than in researching the mechanics of slope failure. Gradually though a better understanding has emerged.

Several of the early suppositions are more questioned today as further evidence has been collected. For example Ruxton (1980) essentially dismissed the concept of "ripening" of slopes because of the several thousand years it would take for chemical weathering to alter the degree of weathering significantly. That is to ignore the more general physical weathering processes (e.g. fracturing, internal erosion and migration of weathering products) that probably occur in engineering time in slopes. Lumb (1975) in his state-of-the-art paper on slope failures in Hong Kong made no reference to geological factors and argued that:

"natural slopes show no signs of creep",

"all failures are first-time slips" and,

"no significant seepage is ever noticed from the scarp after slip".

Koo & Lumb (1981) stated that:
"since slope failures associated with rains inevitably occur during or at the end of a rainstorm, but not several days after rain ceased, it can quite confidently be concluded that a rise in groundwater level need not be considered as a potential cause of instability."

These statements have not stood the test of time and this paper is aimed at documenting some of the factors important to slope stability in weathered rocks that have gradually become better understood.

Currently, an essentially geomorphological view, in which landslides are seen as part of overall slope development has become better accepted. Some of the ideas were alluded to by early workers (e.g. Hansen, 1984). Ruxton (op cit.) suggested that many areas of slope in Hong Kong can be considered to be in a metastable condition and this statement would have support nowadays.

It is the author's view that most slope failures are essentially unique, caused by local geological or hydrogeological conditions as discussed later. This recognition does little to help the Geotechnical Engineering Office in the onerous task of dealing with the many thousands of potentially dangerous slopes in Hong Kong given the inevitable constraints on resources. The approach adopted over the years since the establishment of the GCO has essentially been pragmatic and empirical becoming ever more so with the introduction of formal guidance on the use of "prescriptive measures" for stabilising slopes (Wong et al, 1999). The most common engineering geological settings are guarded against by such designs.

In Hong Kong a formal acceptance of design is based on an analysed Factor of Safety (GCO, 1984). Lumb (1976) addressed some of the problems of the "Factor of Safety" approach and advocated that engineers think instead in terms of probability:

"forcing the designer to consider the reliability of all his data and to face up to the consequences of his being wrong".

Lumb was essentially advocating the design of slopes through formal consideration of risk. This has latterly become a more popular approach in Hong Kong although more on a broad, planning scale than site specific (HKIE, 1999). It should be recognised however that different levels or risk are implicit with the selection of Factors of Safety. The concept of a Factor of Safety reflects the difficulties in establishing reliable local geotechnical and hydrogeological conditions for individual slopes. In fact there is considerable doubt that adopting a higher Factor of Safety can compensate for a poor appreciation of geology and hydrogeology and to the author's knowledge this dilemma has never been fully thought through or discussed. Following study of several major landslides in 1982 (GCO, 1983a), it was concluded:

"Six of the eight cut slopes that failed had been investigated by drilling in recent years. In five of these cases, important aspects that controlled the failure were missed. In only one case were the true geological conditions recognised but even then the groundwater levels were underestimated considerably. In all cases where piezometric data were available and the groundwater level was known by other means, albeit approximately (e.g. observed seepage), the piezometric data did not reflect peak water pressure at the failure surface. This was principally due to failure to observe rapid transient rises and falls in water levels. A further problem was that many of the piezometers were installed at levels where they could not detect the critical perched water tables which developed."

and

"It is recommended that high risk slopes should be investigated in more detail than at present. Lack of investigation data cannot be compensated by a higher factor of safety as the major problem appears to be in investigation and interpretation rather than in numerical analyses."

This paper is an attempt at reviewing some of the slope failure mechanisms in weathered rocks. It is hoped that a better understanding of processes and fundamental controls on stability will complement the essentially pragmatic and intended robust engineering approach adopted in Hong Kong. That approach may disregard geological subtleties and perhaps results generally in over-conservatism. Fortunately, particularly adverse geological situations are relatively rarely present. The author is convinced that many slopes in Hong Kong would remain safe indefinitely without any preventive measures yet the odd one has conditions predisposing it to failure. From experience, the routine type of inspections or investigations generally adopted would often miss those conditions. Similarly, prescriptive designs whilst generally conservative may be insufficient to cope with the worst geological / hydrogeological scenarios if they are not identified as such.

2 LANDSLIDES IN HONG KONG

2.1 *Introduction*

Landslides have been a major issue in Hong Kong since at least the 1950's as the population grew following the 2nd World War and more and more inherently geotechnically hazardous ground had to be developed. The vast majority of landslides occur during or shortly after heavy rainfall as illustrated by the rainfall distribution and no. of incidents reported to the Geotechnical Engineering Office in 1997, a record year for rainfall since records began in 1884 (Figure 1).

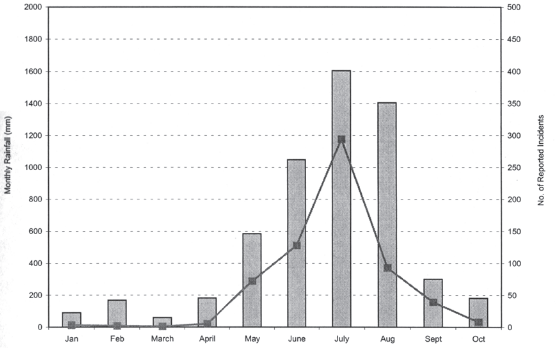


Figure 1. Monthly rainfall versus reported incidents (mostly landslides), 1997

Most landslides in Hong Kong are relatively small, less than 50 m^3 in volume, involving failure of the upper, weakest part of the regolith, and occur at the height of rainstorms. Small rock blocks may fail due to the development of cleft water pressures on joints. The erosion or failure of surrounding soil may undermine boulders. Such failures can have significant consequences despite their small size. However they are generally not geologically complex, nor do they reflect deep groundwater changes and therefore will not be addressed in this paper.

2.2 *Common Types of Landslide*

Landslides through Strong Rock

Slope failure in grade III or better rock most commonly occurs through sliding on single adverse discontinuities (rather than wedges or, especially rarely, toppling). Many of those known to the author in Hong Kong have occurred along sheeting joints and the characteristics of such failures will be addressed below. Other failures occur where shear strength on joints is especially low, for example where they are coated or infilled with clays. Such failure mechanisms are well understood even if persistence and scale effects remain difficult problems and subject to some debate (Hencher et al, 1993). One practical solution with respect to field roughness is to use a dilation-corrected shear strength for design and adopt a low Factor of Safety, in recognition that a lower bound strength is being used Hencher (1995).

Failures can also occur through strong rock that is "closely" jointed (relative to the size of slope) even though the joint pattern is not adverse with respect to the usually expected modes of failure (Hoek & Bray, 1981). Such failures are very difficult to predict or deal with and, in fact, modelling indicates that the mode of failure can alter just through a change in joint spacing as illustrated in Figure 2 (Al Harthi & Hencher, 1993; Hencher et al 1995; Liao & Hencher, 1997).

In Hong Kong the failure at Tin Wan Hill Road in 1983 was judged by the investigators to be a generalised failure through the closely fractured rock mass, mainly because of the lack of a clear kinematic mechanism (few obviously adverse discontinuities were identified). Furthermore the mass movement was unusual with essentially a "bulging", of the rock mass (Figure 3a). Figure 3b shows some of the initial signs of distress. Whilst a clear tension scarp was formed at the rear of the distressed zone, at the toe there were discrete rock falls and movements rather than overall detachment. To the right of the slope (facing) there was no apparent movement. To back-analyse the failure, the newly developed (then) Hoek-Brown criterion was used to provide mass strength parameters (see Hoek at al, 1995). The case is reported by Irfan et al. (1987).

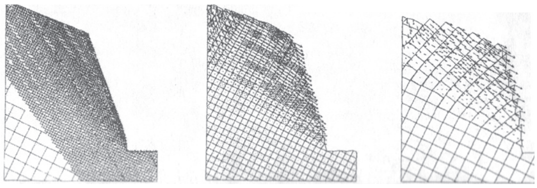


Figure 2. UDEC models showing changing style of failure, dependent solely on discontinuity spacing (after Hencher et al 1995)

Figure 3a. General distress in slope, Tin Wan Hill Road, 1983

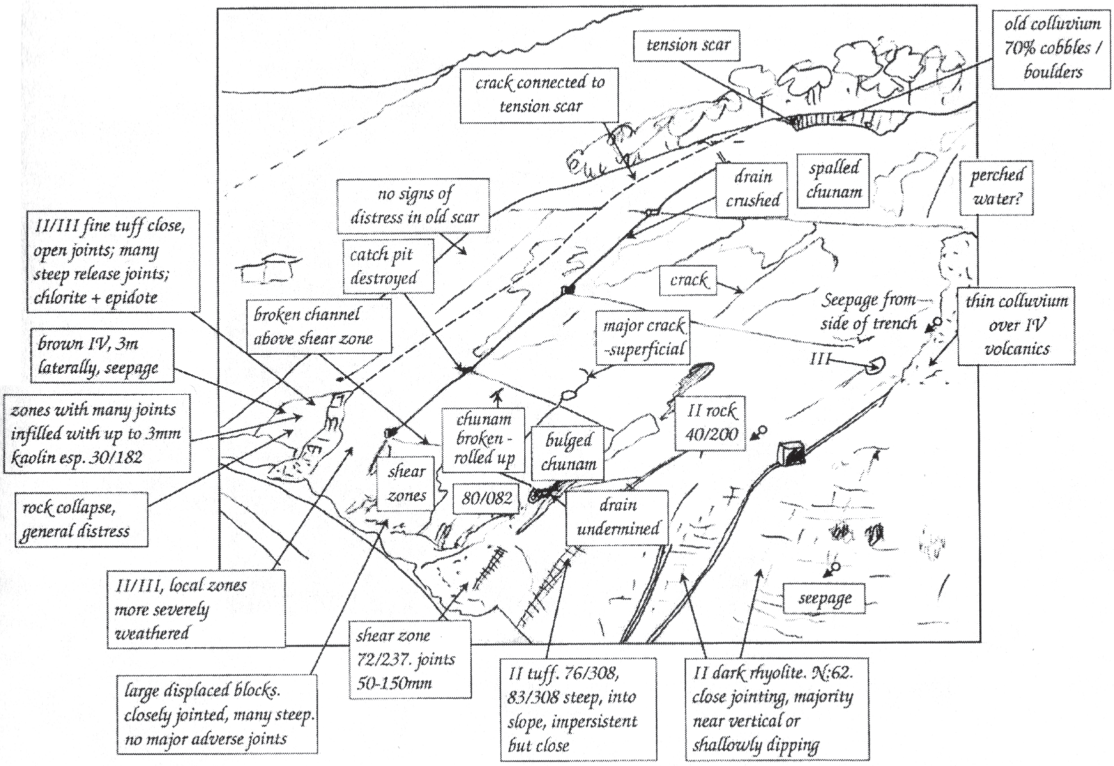


Figure 3b. Field observations, November 1983

Another example of this type of failure is that at Aznalcollar open pit mine in Spain (Hencher et al, 1995) (Figures 4 & 5). One section of the slope was continually on the move (several mm per day), speeding up following heavy rainfall, whilst another, apparently similar section remained apparently stable. The latter slope was of most concern because it was feared that a sudden, brittle type of failure might occur and careful monitoring had to be set up to try to get some advanced warning of imminent failure. The rock mass is predominantly fairly closely fractured slate with steeply dipping cleavage (much steeper than the failing slope which has an overall angle of only about 33 degrees).

Until relatively recently it has been impossible to analyse such complex geological conditions realistically; the only real option was to apply the Hoek-Brown general mass strength criteria as for the Tin Wan Hill Road case discussed above. The development of sophisticated software and availability of cheap, powerful computing facilities however now enables such analysis. Numerical modelling studies of the unstable slope at Aznalcollar were carried out based on the broad geological structure and geometry of the pit, both of which were reasonably well known. Using realistic parameters and Mohr-Coulomb behaviour for joint shear strength, the observed displacements within the slope were reproduced fairly realistically within the models. The broad correlation between observed data and model behaviour allowed some confidence that the mechanisms were being dealt with correctly. The model therefore provides a basis for exploring the sensitivity of the slope to changing conditions.

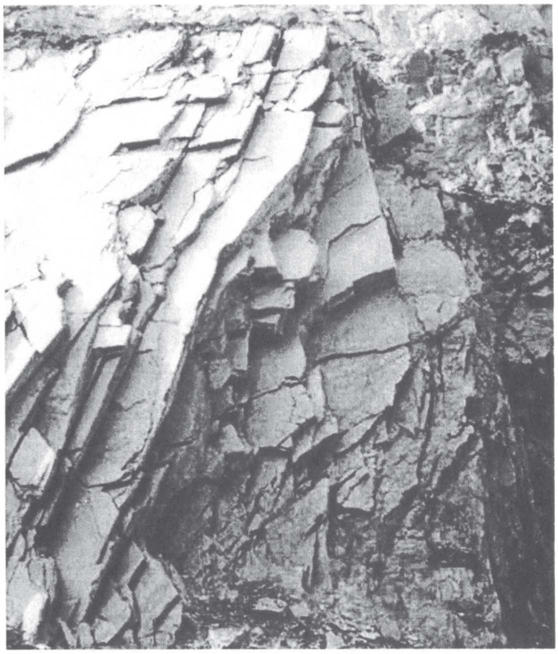


Figure 4. Typical cleaved rocks at Aznalcollar open pit mine

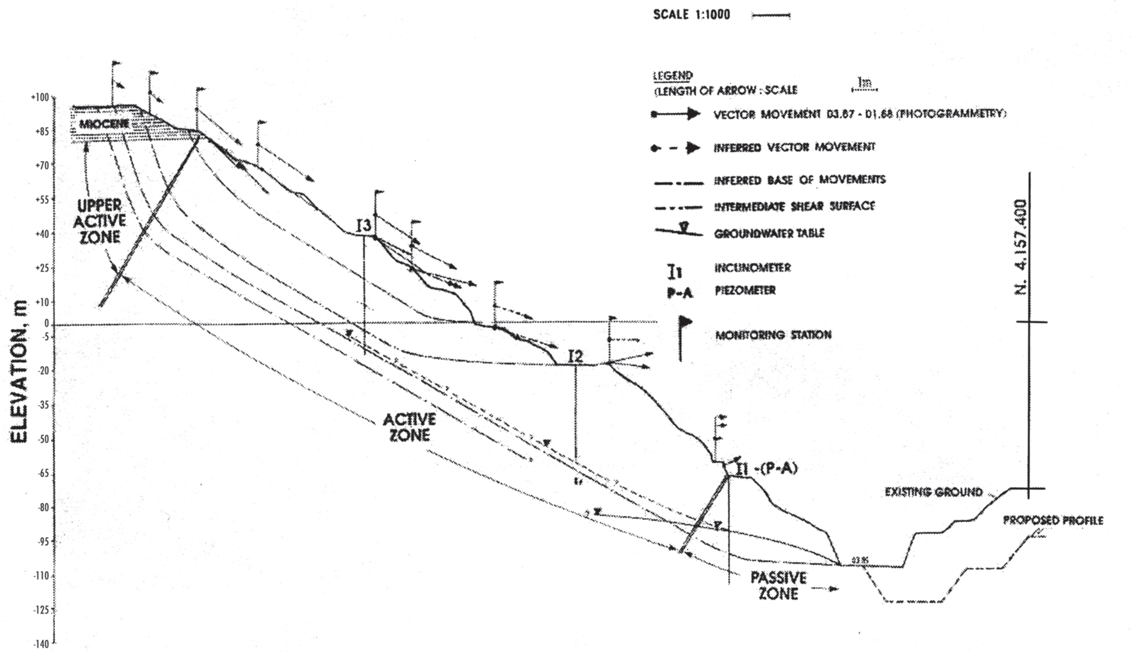


Figure 5. Section through failing slope (Hencher et al, 1995)

Structurally Controlled Failure through Weak Rock (Weathering Grades IV & V)

The main thing that distinguishes weathered rocks (soil-like) to other soils is the geological fabric remnant from the parent rock. That includes small-scale texture but also relict structure (Figure 6). It is commonplace for failures through weak weathered rocks to be controlled by adverse discontinuities and the need to consider such slopes as rock (i.e. look for sliding mechanisms on discontinuities) is too rarely addressed properly. Such discontinuities may have lower strengths than the parent material, even where the rock is highly or completely decomposed. Often those discontinuities form the focus for clay accumulation that restricts groundwater inflow or

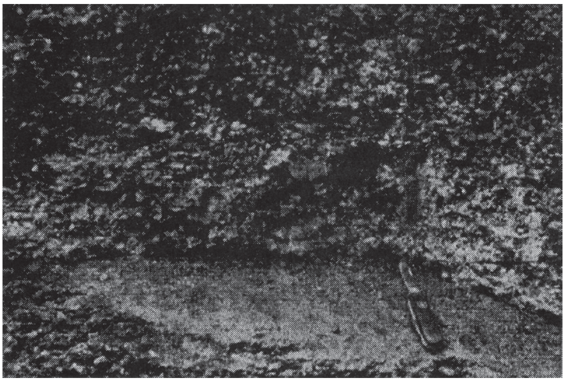


Figure 6. Relict joint through highly weathered granite

throughflow and leads to the local development of adverse water pressures. Such discontinuities are also commonly the sites for piping to develop which often control the hydrogeological conditions within the weathered rock mass as discussed later (Brand et al, 1986).

Through Mass Failure in Weak Rock (Weathering Grades IV & V - Not Structurally Controlled)

Once the rock material weakens sufficiently, failure can take place through the mass in a soil-like manner without following pre-defined structural weaknesses, (see discussion of modes of failure in Hencher & McNicholl, 1995). Even then however, the presence of relict discontinuities can cause a general reduction in mass strength below that of intact samples (e.g. McGown et al, 1980). Quite often failure surfaces may involve part sliding on or release by discontinuities as well as failure through the intact weakened rock material. An example from Hong Kong is shown in Figure 7.

3 CONTRIBUTING FACTORS

3.1 *Overall Factors*

The main contributing geological factors in Hong Kong are structure, especially jointing and minor intrusions and the depth of weathering. The other contributing factors are steep terrain (gravitational stresses), high intensity rainfall and man's influences.

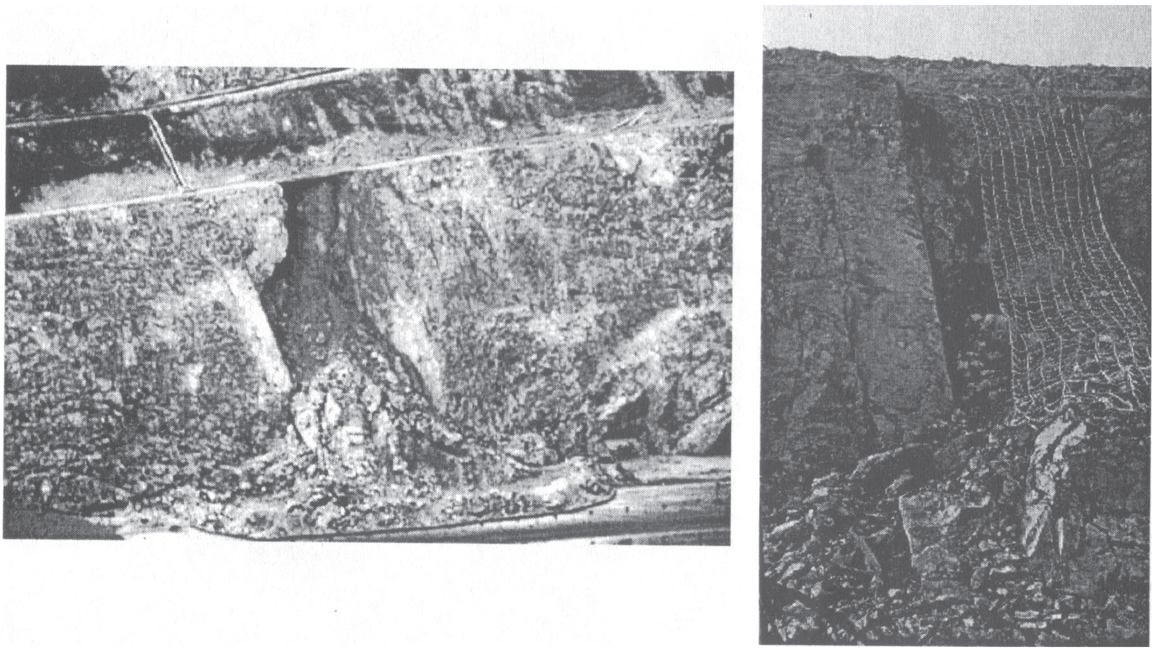


Figure 7. Failure through intact weak rock at the toe with sliding and release on joints a contributing factor, Tsing Yi, 1982

3.1.1 *Basic geology*

The overall geology of Hong Kong is fairly well understood. The distribution of the main rock types - granites and volcanics - were clearly established by the 1960's (Allen & Stephens, 1971). There have however been considerable advances in knowledge of genesis of the various rock types (see thematic papers on The Geology of Hong Kong, introduced by Fletcher, 1997). Every now and then there are still surprises which can severely jeopardize engineering projects. For example the occurrence in the Territory of karstic limestone was unsuspected until the mid 1980's (Chan, 1990) but has caused problems for foundation design. Similarly the true extent and weak nature of the major Tolo Channel fault zone off shore, though suspected, was not clearly established until it was recently identified on magnetic surveys and encountered in tunnels at depth below the harbour. Most recently there have been reports that bored holes for piles at Tung Chung, Lantau are encountering unconsolidated sediments at great depth, apparently associated with deep rockhead depressions related to collapse structures (Fletcher, 2000; Kirk et al, 2000).

Each major rock type has its own characteristics with respect to jointing and typical weathering profile. It is the author's impression with respect to the main granite and volcanic suites, that the granite tends to show greater development of stress relief joints (sheeting) than the volcanics. Steep joints otherwise tend to dominate in the granites. The volcanic rocks show joints which are more variable (tectonic stress induced?) and tend to be more closely spaced in exposure (Hencher & Martin, 1982). They tend to be rather more planar than those in the granites.

Weathering depth is greater generally within the granitic rocks but the products are similar. That said perhaps chlorite is more commonly a product within the granites and this can have significance for landsliding.

Both rock suites produce clays on weathering, which accumulate as infill in joints and can influence hydrogeology and shear strength. Such infills do provide a potential indicator during investigation that the rock mass has moved. The investigator must then determine whether that movement is part of the general consolidation of the rock mass during weathering or forewarning slope failure (detachment). Slickensiding is associated with both types of movement. Barriers to water flow can be formed where fine-grained rocks (e.g. dolerite dykes) weather adjacent to coarse grained rock and this is often a contributing factor to landsliding (e.g. Hudson & Hencher, 1984 and see later discussion).

3.1.2 *Structural geology*

As noted above, discontinuities play a major role in many types of slope failure in Hong Kong. These range from faults that can be quite major features, to joints, which tend to be pervasive in rocks close to the surface of the Earth. The latter include cooling and tectonic joints as well as those generally attributed to stress relief. Table 1 includes a list of the most common discontinuity types encountered in Hong Kong.

Examples of close, adverse fractures which have no doubt developed due to surface unloading and which had a controlling influence on a natural terrain landslide are shown in Figure 8. In this example, the near surface joints (above the detachment plane) are all infilled with clay, which probably reflects long term slope deterioration and movement.

Figure 8. Natural terrain landslide scar. Note probable stress relief fractures parallel to terrain surface. Also note apparent change in structure above and below the light coloured grade II surface (central)

Generally concerning the influence of discontinuities on rock slope stability, it is perhaps worth remembering the classic figure, reproduced here as Figure 9. This demonstrates that intact rock (say grade III or better) can theoretically stand vertically to hundreds of metres without failing, providing there are no adverse discontinuities.

Characterising the fracture network in the rock mass is an important task for the engineering geologist whatever the project. This is never easy even with excellent exposure and ground investigation, but good practice can make the best of limited data and avoid common pitfalls.

Recommended standards for the description of discontinuities either in core or exposure concentrate on visible and particularly open discontinuities that exhibit no tensile strength. Fracture frequency and RQD, for example, are calculated only on the basis of open fractures (ISRM, 1978, GCO, 1988). It should be remembered however that all rocks contain incipient fractures that are often oriented with respect to some stress regime from geological history. The fractures may be invisible and only become evident following later stress changes for example on sampling, by

Table 1. Common discontinuity types in Hong Kong (modified from Hencher, 1987)

Discontinuity Type	Occurrence	Geotechnical Aspects
Tectonic Joints	Fractures resulting from tectonic stresses.	May form roughly parallel or orthogonal sets or occur in spectra (see Price & Cosgrove, 1990). Often relatively planar. As with other fractures they commonly only develop fully during exhumation (weathering etc.)
Cooling Joints	Often systematic, perpendicular to cooling surface in igneous rocks - especially rhyolites and granitic rocks. Doming joints occur in granites.	Steep orthogonal sets common in granites and often act as release surfaces and conduits for the development of cleft water pressures. Doming joints have characteristics similar to sheeting joints (see below) and may be indistinguishable. They might however be expected to be found at greater depths.
Sheeting Joints	Parallel to overall natural slope. More closely spaced close to ground surface (generally upper 10 metres or so). Most common in granitic rocks and tend to be locally developed (e.g. above Tuen Mun Highway and at Stanley). Reason for local occurrence is not clear. Suspected stress relief fractures are also commonly found associated with natural terrain failures.	Rough/wavy (tensile fractures) but often adverse. Short sections may increase in dip on an "up wave" within the rock mass, away from the point of exposure and measurement. Often persistent for many metres but terminate against cross-joints (being more recent than they are). Weathering concentrates along them, clay infills commonly develop in the down dips and they act as conduits for water flow.
Petrological Boundaries	Boundaries between different rock types (especially minor intrusions such as dolerite, basalt or rhyolite dykes)	May mark change in engineering properties although quite commonly, in the fresh state, boundaries are strong, welded and not a plane of weakness. Where the parent rocks are of different grain size and hence weathered products are of different permeability, boundaries may be barriers to water flow and result in localised water accumulation and perching.
Faults	Fractures along which displacement has occurred. May be associated with fractured rock and intense weathering.	Often extend for tens or hundreds of metres. Can be associated with weakened zones of several metres width with associated weathering and presence of groundwater. Often steeply dipping and therefore not directly adverse for sliding. More shallowly dipping thrust faults do occur however and can contribute to failures.

unloading on excavation or erosion of overburden or through dehydration. Such fractures may have a major influence on the properties of the rock mass.

The analysis of discontinuities for slope stability assessment is dealt with elsewhere (Hoek & Bray, 1981; Hencher, 1987; Priest, 1993) and it is not intended to consider that in detail here. It is noted however that in recent years there has been more and more reliance on software to analyse these data stereographically (typically using the software package DIPS (Rocscience Inc.)). In the author's opinion this can be a retrograde step. It is suspected that many of the engineers using such software do not understand the underlying principles of analysis. There is more danger than ever of critical discontinuities being under-considered as has always been the case since stereographic projection methods were first developed for rock slope analysis (Hoek & Bray, 1981; Hencher, 1985). Basic rules are:

1. Remember the limitations of the data
2. Do not contour few data. This will obscure the picture and give false confidence.
3. Always consider adversely oriented discontinuities in detail even if they are few relative to other data. The non-adverse data are of relatively minor interest.

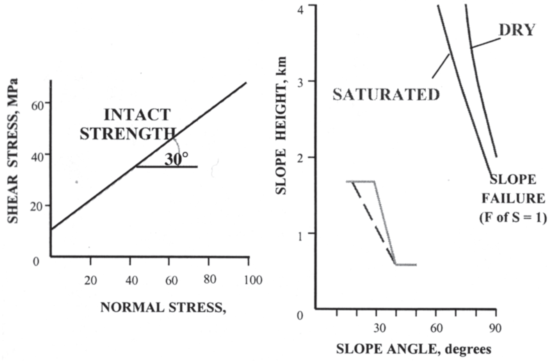


Figure 9. Safe heights for slopes in the absence of adverse discontinuities (after Hoek & Bray, 1981)

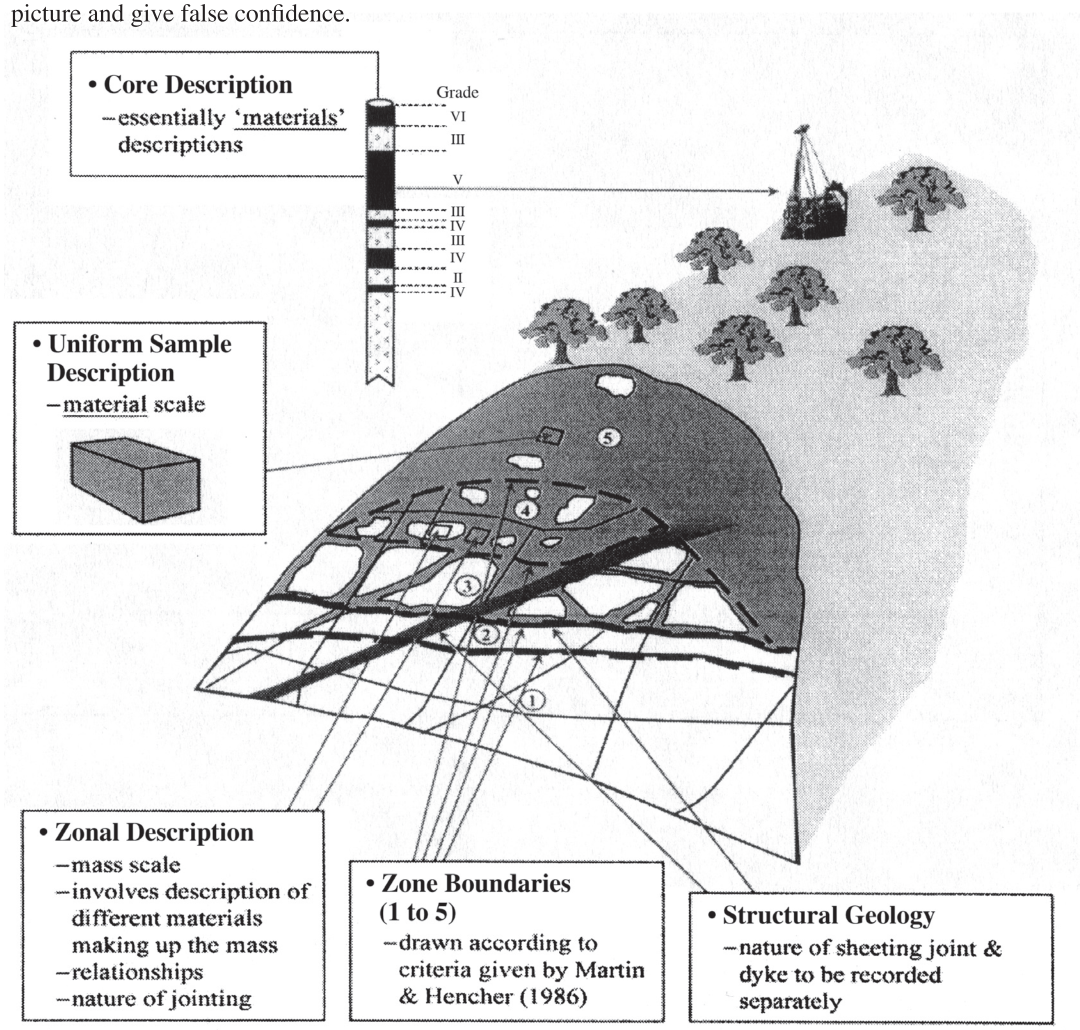


Figure 10. Scales of description

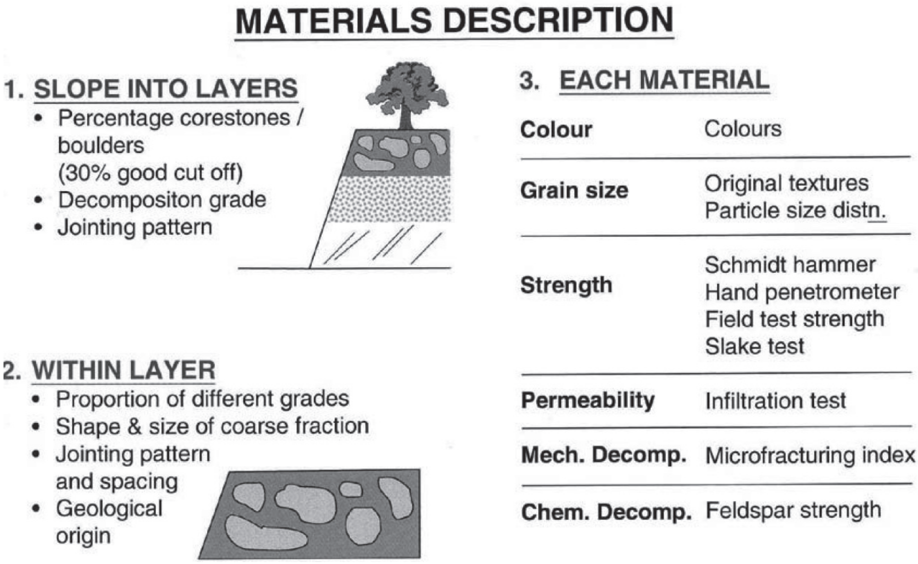


Figure 11. Systematic descrip tion of weathered rocks

This is a very real problem that should not be ignored as, too often, it is. Very recently the author was reviewing an interpretation of a stereoplot containing more than 1000 data points. The data had been contoured automatically (a process which takes no account of the geological reasons for distribution of the poles as discussed below). As a consequence the slope was interpreted as safe (contour centres not adverse) despite the fact that many tens of the original data were adversely oriented. There was no discussion on the significance of those adverse fractures. The paper referenced earlier (Hencher, 1985) was written following a major rock slope failure in Hong Kong where sliding took place on a single feature (daylighting fault). The data representing the subsequent detachment surface were overshadowed during analysis and checking by numerous other, essentially irrelevant data (GCO, 1983b).

There are potential advantages in considering the origin of the discontinuities in order better to understand the data and recognise any sampling bias. All fractures are the result of stresses and may be interpreted in that way as related sets (otherwise there would definitely be no justification for contouring data other than purely statistical representation). Such analysis is generally particularly revealing for sedimentary rocks, sometimes less so for igneous rocks. This subject is beyond the scope of this paper but is introduced by Pollard & Aydin (1988), Rawnsley et al (1990) and Price & Cosgrove (1990). Insights gained from interpretation of the geometry of discontinuity surfaces are illustrated by Ameen (1995) & Kulander et al (1990).

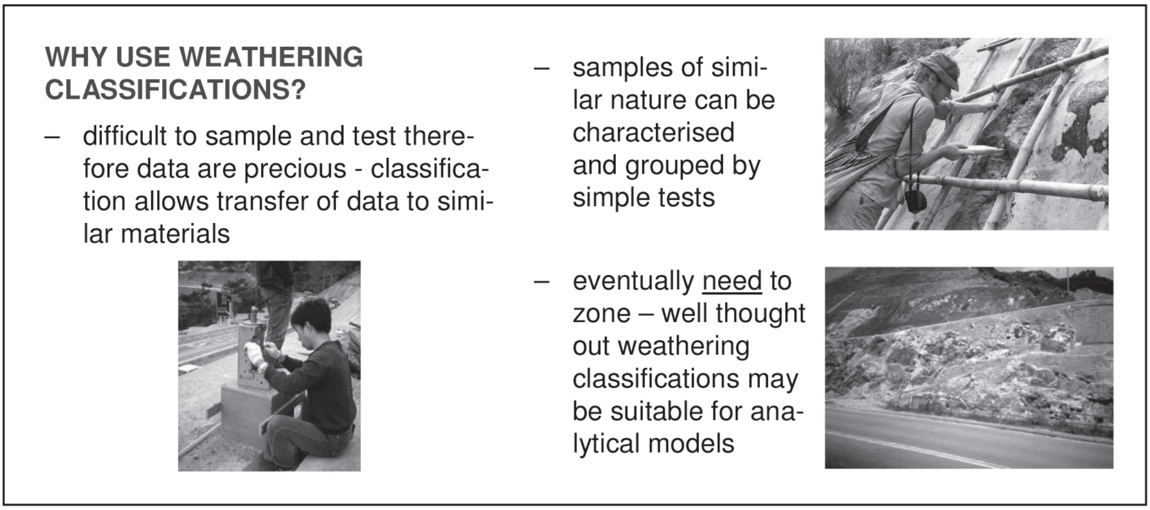


Figure 12. Why use weathering classifications?

3.1.3 Weathering

Deep weathering is the factor that distinguishes Hong Kong from many other advanced cities in the world and links it to others such as Rio de Janeiro. This factor makes the environment special and distinct from those where much of the fundamental research and theory in soil mechanics and rock mechanics has been carried out (the USA and Europe). Much of that work is not directly applicable to weathered rocks in Hong Kong. Weathering results in a severely weakened and often-heterogeneous rock mass, the characterisation of which is extremely important in understanding and predicting landslides (Deere & Patton, 1971).

The concepts of different scales of description and characterisation are fundamental to engineering geology and especially when dealing with weathering. Figures 10 and 11 illustrate some important aspects of systematic description of weathered rocks.

Hong Kong geologists and engineering geologists have played a major role in establishing a classification methodology for weathered rocks at an international level since the pioneering and insightful work of Ruxton & Berry (1957). The first edition of the Geotechnical Manual for slopes (GCO, 1979) separated quite clearly the concepts of mass and material classifications though these had been muddled in other publications (see discussion in Anon, 1995). That said, there is currently almost a rote manner of applying classification as if it is description, which it is not. Classification should come only after description (and index testing as per Figure 11 - see also Martin, 1986). This raises the question whether it would be better not to use classifications at all and the author is tempted towards this view in that it would rule out the "easy option" of guessing a grade or class of rock. There are however good reasons for classification as discussed in Martin & Hencher (1986) and summarised in Figure 12.

The recommendations of a working party on the description and classification of weathered rocks (Engineering Geology Group of the Geological Society of London) (Anon, 1995) are summarised in part in Figure 13. Not shown in that figure is the prime recommendation (mandatory) of the Working Party which is to describe what is seen, using non-technical language. It is recommended to avoid the use of standard classification terms such as "highly weathered", when doing so. It is also recommended that classifications are only used if deemed advantageous and where it is clear that such a

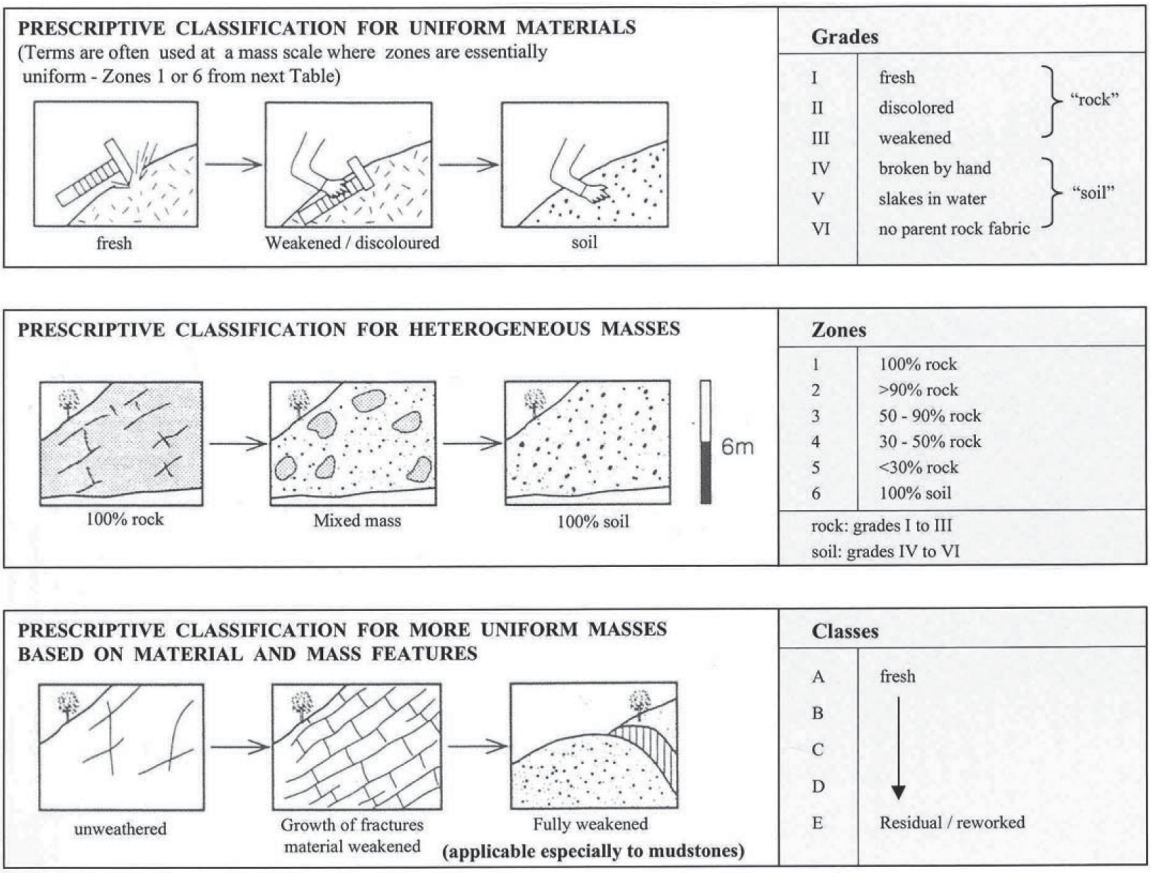


Figure 13. Prescriptive weathering classifications (simplified from Anon, 1995)

classification is truly applicable.

The scheme for heterogeneous masses in Figure 13 differs slightly from that in Geoguide 3 (GCO, 1988) in that zone 6 is defined as 100% soil (any combination of grades IV to VI) whereas the Geoguide 3 scheme has the 100% soil zone defined as "residual soil" (grade VI only). The Geoguide scheme presents a dilemma where dealing with a thick zone of soil-like material of grades IV and V. It would be necessary to classify that zone as partially weathered 0-30%, even though there are no corestones of rock present. The author prefers the Anon 1995 scheme with the Zone 6 classification indicating that the full zone comprises material that can be broken by hand. That indication is then supplemented by a description of the materials making up that zone.

3.1.4 Weathering at the material scale

Through weathering, rock breaks down eventually to soil. In doing so the minerals making up the rock change chemically, much to clay. Clays are minerals of essentially the same chemistry as the parent minerals (primarily feldspars) but are stable at low temperatures and pressures. Clays are much weaker than the parent minerals and are prone to softening, leaching and erosion. As weathering takes place chemical bonds between the various minerals making up the rock (e.g. feldspar welded to quartz) are weakened and voids develop. By the time a fresh granite (dry density = 2.7 Mg/m^3) reaches a "completely decomposed" state it has lost more than half of its mass (say dry density $\cong$ 1.2 Mg/m^3). The rest is holes! (Clays have much the same specific gravity as feldspar).

This is very significant. Fresh granites have uniaxial compressive strengths of perhaps 150 MPa; volcanics up to 400 MPa or even more. Completely decomposed rocks have strengths of perhaps 1 MPa or even less.

To illustrate the importance of weathering to shear strength, data are presented in Figure 14, collected following a failure on Tuen Mun Highway (Hencher & Martin, 1984). The data are analysed in detail in GCO (1983c). Block samples were collected from below the failure scar and tested in direct shear and triaxially. Triaxial test results are omitted from Figure 14 for clarity but generally provided further support to the discussion below. The samples tested were all within the range highly to completely decomposed (on the basis of field index tests) but the raw shear test data exhibited considerable scatter in terms of peak strength (Figure 14a). Once one takes account of the dry density of the samples, however, a clear pattern emerges. Those with highest density have the highest peak strength (Figure 14a) as might have been anticipated (Wong, 1982). It was also apparent that the densest samples also showed the greatest amount of dilatency during shear. An attempt was therefore made to "correct" the data for dilatency in the same way as for rock joints (Rowe, 1962; Hencher & Richards, 1982, 1989). The corrected data in Figure 14a from all samples provided a well-defined "basic friction angle" which is close to the dilation-corrected strength of rock joints through granite (whatever the weathering grade) (Hencher & Richards, 1982). Clearly the amount of extra strength available due to dilation was dependent upon dry density (reflecting degree of weathering) but also stress level. At high enough stress levels, dilatency would be inhibited whatever the density of the sample (Figure 14b). It is interesting that these data indicate that the strength above basic can be interpreted as stress dependent rather than cohesional. This does not mean that true cohesion does not exist in weathered rocks (say grade IV) which, no doubt, it does.

Ebuk (1990) and Ebuk et al (1993) give further illustration of the fairly subtle changes in shear strength associated with progressive weathering particularly at the weak end (grades IV to VI).

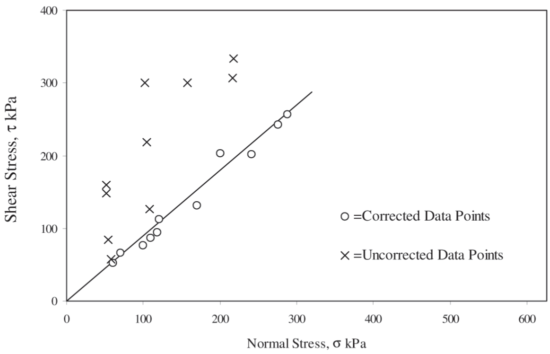
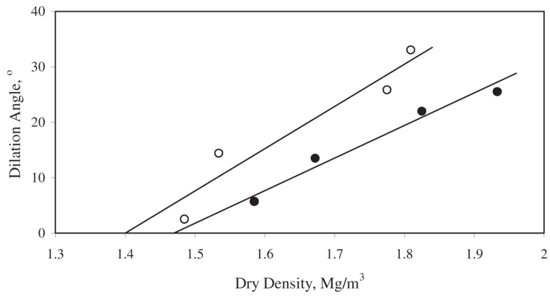


Figure 14a. Measured peak strengths and data "corrected" for dilation



14b. Dilation angle vs dry density of sample for given normal stress levels

3.1.5 Mass weathering

The material scale is the scale relevant to sample description in drill core and most testing. Where the weathering profile is uniform then such data may be applicable over a larger scale. Quite often it is taken that the whole zone is relatively weak even in the knowledge that there are stronger parts in the mass. Generally core stones add to the strength and stiffness of the mass rather than detract (West et al, 1992; Irfan & Tang, 1993). Designers tend to use friction angles of between 35 and 40 degrees plus a small (< 10 kPa) cohesion for analysis of zones of predominantly grade V or IV materials. That is usually conservative but not so where adverse, very weak infilled or coated structural discontinuities are present. The recent failure at Shek Kip Mei (Fugro et al, 2000) is a case in point with sliding on a very persistent, clay coated, planar discontinuity dipping at less than 10 degrees. A failure at Yip Kan Street in 1983 occurred on a dry day, partially through sliding on joints very thinly coated with chlorite and dipping at only 20 degrees (GCO 1983d; Brand et al, 1983). A photograph of the cleaned off failure surface is shown in Figure 15.

It should be noted that discontinuities have much wider ranges of strength than completely weathered rock (Hencher & Richards, 1989). Most natural rock joints have dilation-corrected friction angles of about 38 degrees (like intact grades IV and V granite in Hong Kong), possibly because this reflects a fundamental brittle-plastic behaviour property (Papaliangas et al, 1996). Where infilled however the strength can be as low as 10 or 12 degrees (rarely). In Hong Kong the lower bound is generally about 20 degrees (chlorite, kaolin) although lower values have been reported (Koo, 1982).

Figure 15. Almost planar failure surface at Yip Kan Street dipping at only 20 degrees (GCO, 1983d)

3.1.6 Hydrothermal alteration

Hydrothermal alteration can weaken rock in a similar way to weathering (Hencher et al, 1990). The main differences are:

1. Location: Hydrothermal alteration is not restricted to rock close to the earth's surface (generally the upper 60 m or so in Hong Kong). Very recently a 8 m wide zone of severely weakened rock (equivalent to weathering grades IV & V) was encountered at depths of almost 200 m during tunnel construction. The zone was associated with mineral veins which implies the zone was weakened by hydrothermal fluids rather than true weathering.
2. Physical properties: Whilst hydrothermally altered rock is weakened chemically, as in weathering, the author postulates that there has not been the same long-term through flow of water and hence transfer and loss of mass. This is indicated by the observation that hydrothermal deposits can have higher clay content than weathered rocks of similar grade as reflected by higher densities. One of the consequences is that hydrothermally altered granites can be mined as sources of clay unlike most weathered granites.

In Hong Kong, there are few known examples of landslides where hydrothermal alteration was a

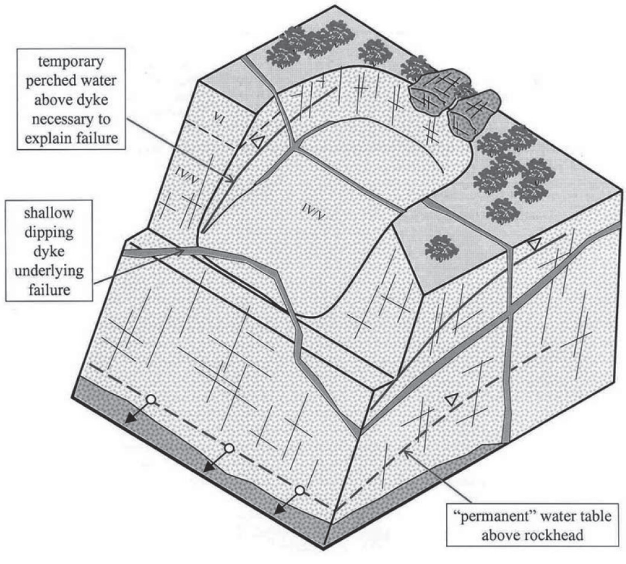


Figure 16a. Landslide at Tuen Mun Highway, 1982

Figure 16b. Block model of geology of landslide area (modified from Hencher & Martin, 1984)

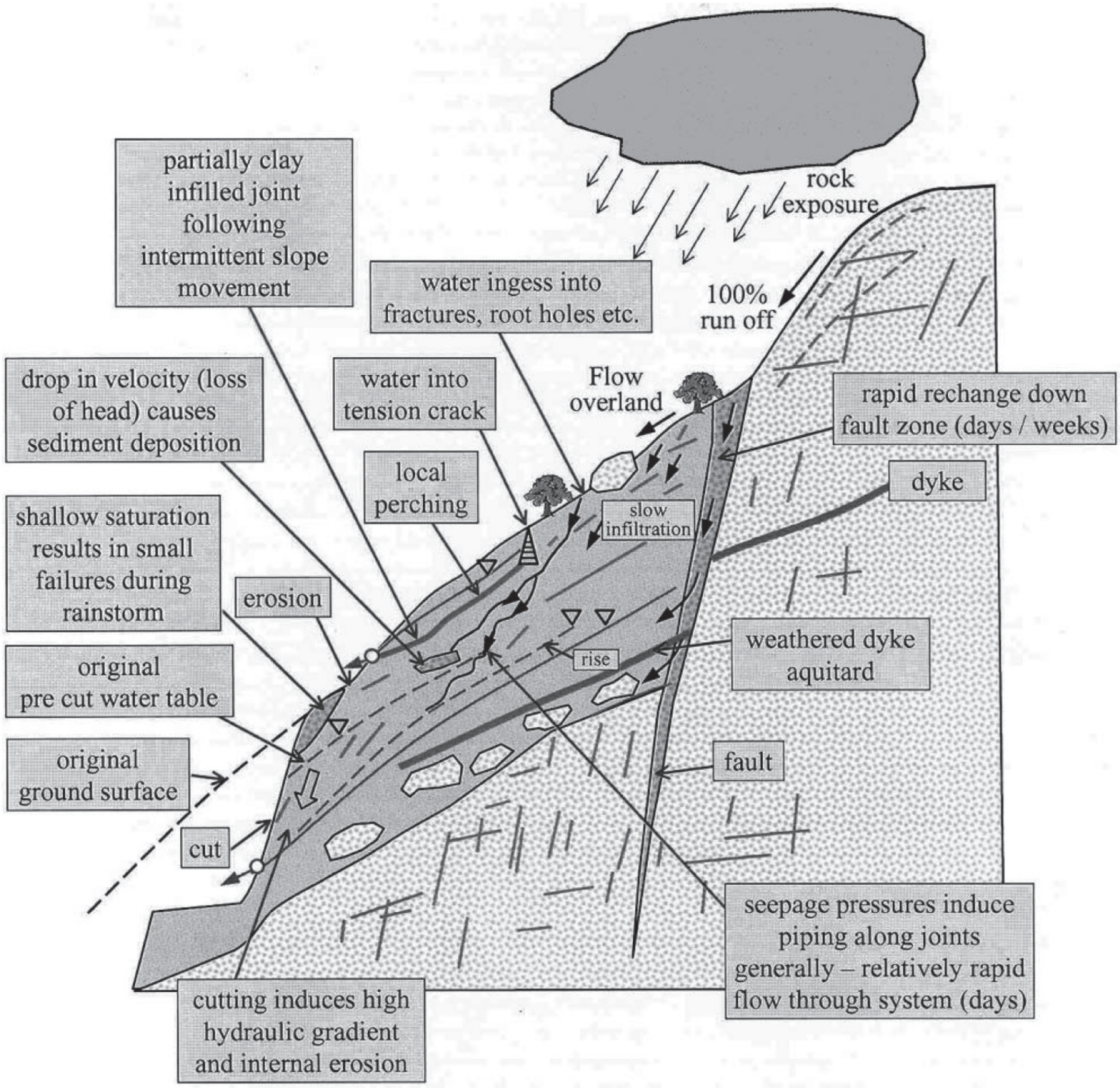


Figure 17. Hydrogeological mechanisms - each with its own time frame

significant contributing factor although in a couple of cases extensive kaolinisation may have played a role.

3.1.7 Other mass features

The accumulation of clays on joints during the weathering and deterioration of rock masses has long been recognised in Hong Kong and was associated with at least three of the major failures of 1982 (GCO, 1983a; Hencher et al, 1984). Buttling (1986) also reviews one of the 1982 landslides where there were numerous clay-infilled joints, many slickensided. The slickensides probably reflected accommodation mass movement rather than slope instability. Only relatively recently, following the serious failures at Shum Wan Road, and Fei Tsui Road that caused fatalities (GEO, 1996a & 1996b) has this been investigated in any depth by GEO (Kirk et al, 1997; Parry et al, 2000). Since then, as noted earlier, a failure has occurred at Shek Kip Mei with a large part of the slip surface dipping at less than 10 degrees (planar, slickensided) and infilled with thin kaolin and manganese dioxide (Fugro et al, 2000). The origin of this very persistent, flat lying clay-filled discontinuity was not addressed in the report and clearly there is still considerable work to be done on this topic in Hong Kong. It is evident that much of the clay is infill rather than replacement. The voids being infilled are the result of dilation during movement of the mass rather than erosion or shrinking.

Dykes are commonly involved in failures, most generally because their weathered products can be finer grained and therefore less permeable than the country rock. Hencher & Martin (1984) and Hudson

& Hencher (1984) give examples. Au (1986) reviewed several cases. Figure 16 shows a failure that occurred on Tuen Mun Highway in 1982 together with a block model interpretation of geological conditions that, it was believed, led to the development of perched water.

4 HYDROGEOLOGICAL CONTROLS

4.1 *Introduction*

The fact that most landslides in Hong Kong (and elsewhere) are associated with heavy rainfall is quite clear (Figure 1). Attempts have been made to correlate the occurrence of landsliding with antecedent rainfall with some success (Lumb, 1975; Brand et al, 1984).

Such statistical studies do little to explain the mechanisms of failure but give some clues. As a reference point a good aquifer (better than grade IV/V granite) might have a permeability of 10^{-5} m/sec. That translates to about 1 metre a day movement of water. It must be concluded therefore that failures during heavy rainstorms are probably due to shallow surface saturation or result from more rapid ingress and through flow as discussed below. Other factors such as erosion also play a role.

Figure 18. Large pipe with underground stream through weathered granodiorite, Stanley

In fact there is a delay in many large landslides, which fairly obviously relates to the time taken for surface water to infiltrate to the groundwater pressure system. Malone (1998) discusses some examples of delayed failures.

The general hydrological controls of groundwater are illustrated in Figure 17. Okunishi & Okimara (1987) present the concept of a series of pipes connected to sinks to explain the delayed movement of water through the ground (and delayed onset of failure).

The intense urban development of Hong Kong also adds considerable complexity to the hydrogeology of sites as discussed by Nash & Dale (1984).

4.2 *Inflow and Through Flow*

The routes for surface water to infiltrate relatively quickly into slopes include open joints and piping induced by seepage pressures. There is abundant evidence of both mechanisms in the weathered profiles of Hong Kong.

Pipe systems have been observed in numerous failures including that at Chaiwan in 1982 (GCO, 1983e) and Lai Ping Estate (Sun & Campbell, 1999). Despite their common occurrence they are very poorly understood nor investigated. A problem of such localised, channelised flow is that it is very difficult to investigate using typical "hit or miss" G.I. techniques. Piezometers, which do not tap into the pipe system, will give a wrong indication of conditions. On the contrary, where the hydrogeological model is well understood then major insights can be gained through intelligent instrumentation and interpretation (e.g. Cowland & Richards, 1985).

Pipes can be large (of the order of metres) and associated with the development of a full underground stream network, which meanders through the rock mass, sometimes eroding and sometimes depositing sediments. An example of an active, underground stream (through weathered granodiorite behind a failed retaining wall) is shown in Figure 18.

Pipe systems change with time. Some collapse and others get choked with sediments. Sometimes the sedimentary structures encountered are very well developed - for example beautifully graded sands which clearly indicate sedimentation into an underground sink of still water.

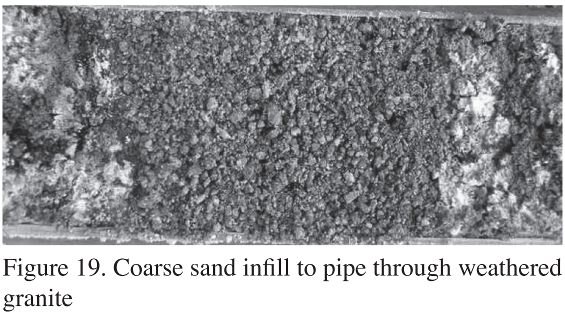


Figure 19. Coarse sand infill to pipe through weathered granite

An example of a sorted single sized sand layer, within granite at depth, and interpreted as a choked pipe is given in Figure 19.

4.3 *Hydrogeological Readjustment to Cutting*

One factor that, to the author's knowledge has not been considered in the literature is the readjustment of hydrogeology to slope works - especially cutting.

Clearly, when cutting a slope, the hydrogeological pattern will need to adjust. The larger the cutting the bigger the change. Generally cutting will mean that natural flow paths through the mass will be lowered and outflow points will be created in the new cutting. This will increase the hydraulic gradient and hence potential for erosion within the profile. Overall the mass will consequently become more permeable.

5 CONCLUSIONS

It is clear that many of the landslides in Hong Kong are the result of adverse engineer geological situations. Failures simply resulting from overstressing weak, uniform rock as commonly modelled for analysis are rare. Whilst in hindsight it is often relatively easy to identify the reasons for a failure, the predisposing complex site conditions that eventually result in failure are much more difficult to predict or identify using available ground investigation techniques.

There is still a lot more that can be done to understand the factors that control landsliding in Hong Kong. Hencher et al (1984) reviewed the state of knowledge then with respect to slope stability in Hong Kong and concluded that the poorest understood factor was groundwater. This probably remains true today. The authors then noted that:

"the post failure investigation of landslides, which includes back analysis, is potentially the most fruitful means of advancing our knowledge."

The establishment of a Landslide Investigation Division in the GEO in the late 1990s was a definite move in the right direction. Particular areas for study include the nature, distribution and development of discontinuities and all aspects of the hydrogeological mechanisms that lead to failure. A better understanding of these factors should provide benefit through better focused and more cost effective ground investigations and ultimately safer slopes.

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