Hydrogeology of landslides in weathered profiles

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ABSTRACT: This paper provides an introduction to the hydrogeological processes that cause landslides. An equation is presented which predicts that the number of landslides increases approximately 10 fold for doubling of 24hr rainfall intensity. Numerical approaches for modelling infiltration and through-flow are discussed and the paper explains methods for preventing landslides through control of groundwater in engineering works.

1. INTRODUCTION

This paper identifies some of the hydrogeological mechanisms and processes that lead to landsliding and how these may be analysed and dealt with in practice.

2. TRIGGERING OF LANDSLIDES BY RAINFALL

Intense rainfall is one of the main triggers of landsliding. Many of those landslides actually occur at peak intensity. Brand et al (1984) studied the timing of reported landslide incidents in Hong Kong empirically and found a correlation between the reporting of many incidents to the emergency services and rainfall intensity exceeding 70 mm/hour. There are cases however where landslides and especially deep-seated landslides occur long after the main storm has ceased and this generally reflects the hydrogeological mechanisms (e.g. Hudson & Hencher, 1984).

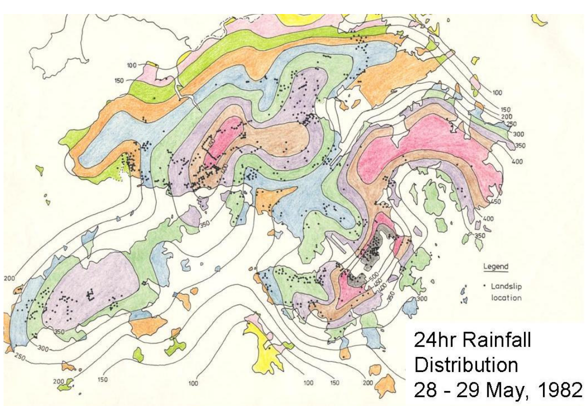

Figure 1. 100mm isohyets and landslide incident locations. 24hr rainfall from 3pm 28th May 1982

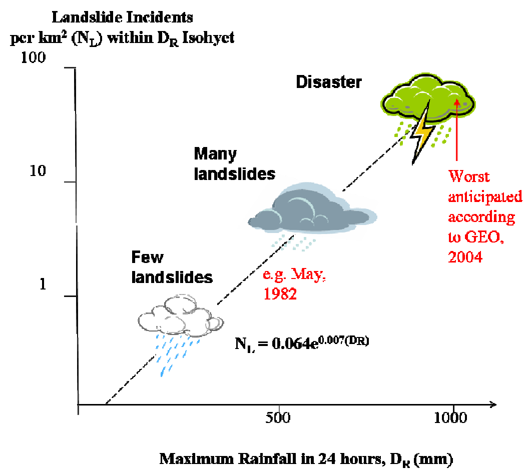

Figure 2. Number of landslides vs 24 hour rainfall

Hencher (2006) argues that, due to progressive deterioration, at any particular time in a hilly environment there is an “inventory” of slopes at different states of instability waiting to be triggered according to the intensity of the rainstorm. In general, the more intense the rainfall, the higher will be the number of landslides. The number of reported incidents (mostly man-made slope failures) within particular rainfall isohyets were analysed for two major storms in Hong Kong in 1982 and a general relationship derived:

$$N_L = 0.064\, e^{0.007(D_R)} \quad \ldots\ldots\ldots\ldots\ldots \quad (1)$$

where N_L is the number of reported landslide incidents per km^2 within the 24 hour peak rainfall isohyets (D_R) interpolated at 100mm intervals. The data from one of these storms from which the relationship is derived are shown in Figure 1.
The relationship is illustrated in Figure 2 and has been tested against mapped landslides triggered by severe storms in the USA (Pomeroy, 1981) and on data reported from

another major rainstorm in Hong Kong in November 1993 in which 230 incidents are predicted given the distribution of rainfall intensities as compared to the reported number of 253. This is a reasonably close prediction given the ill-defined nature of "incidents" reported, the probable geographical dependency of the relationship and the lack of certainty regarding timing of the landslides. Data presented by Yu et al (2004) also fit the trend indicated in Figure 1 quite well. The fact that such a relationship can be derived with a high degree of correlation supports the concept of an inventory of slopes with different susceptibilities to intensity of rainfall at any particular time. It is also indicative in that it predicts an approximate 10-fold increase in number of incidents for a doubling of 24-hour rainfall intensity.

3. MECHANISMS OF LANDSLIDES TRIGGERED BY RAINFALL

3.1. Surface failures

These include the results of surface erosion, undermining of boulders and minor rock fall. Premchitt et al (1994) report that approximately 50% of incidents in Hong Kong are less than $5m^3$ in volume and that more than 50% of incidents occur within 2 hours of maximum intensity of rainfall.

3.2. Shallow landslides

These include rockslides and small landslides induced by general gravity-driven infiltration (wetting) or pore pressure diffusion. They may also result from general saturation, increase in density and loss of suction. They may occur during rainstorms but may be delayed until water has travelled to the susceptible location. According to Premchitt et al (op cit) some 10% of landslides in Hong Kong are delayed by more than 16 hours.

3.3. Deep-seated landslides

These are triggered by rising groundwater or the development of significant perched water tables. They might also conceivably be caused by internal erosion such as severe soil piping. Such large failures are often delayed. Where a large, deep-seated slope failure does coincide with intense rainfall this may reflect the final detachment following a long process of deterioration involving many previous rainstorms as discussed by Hencher (2006).

4. QUANTIFICATION OF GROUND-WATER PRESSURE BUILD-UP

Attempts to quantify the process tend to be simple and assume uniform ground conditions and properties, albeit that even the behaviour of the simplest profile will be highly dependent on the variability in soil/rock and on pre-existing saturation states. The wetting band theory first proposed by Lumb (1962) may be used for estimating the likely depth of ground that might be affected by a rainstorm. More sophisticated attempts have been made to model infiltration and pressure diffusion processes in pressure head response and the triggering of landslides mathematically (see Iverson, 2000). Such methods are useful in visualising mechanisms but rely on generalised parameters such as hydraulic diffusivity which are difficult to define for weathered rock profiles.

It is often argued that it is more realistic to instrument a site and then to extrapolate rainfall response to a "design" rainstorm (GCO, 1984). However, instrumenting slopes to measure critical water pressures is not easy. Hencher (1983) found that measured piezometric data in several failed slopes were rarely indicative of the groundwater conditions that caused the landslide. Six of eight cut slopes that failed and were studied in detail had been previously investigated by drilling and instrumented to measure groundwater conditions. Hencher (op cit) concluded that in five of these cases, important geological features that controlled the failure were missed. In only one case were the true geological conditions recognized 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 of the monitoring system to measure rapid transient rises and falls in water levels. A further problem was that many piezometers were installed at locations where they could not detect the critical perched water tables which developed and triggered failure. Several of these cases are discussed in more detail in Hencher et al (1984).

There are few examples of well instrumented slopes in weathered rock in the literature. Cowland & Richards (1985) is an exception where they monitored pressure surges along sheeting joints during storms.

5. HYDROGEOLOGICAL PROCESSES AND MECHANISMS

Figure 3 is a schematic representation of hydrogeological processes in hillsides which illustrates that infiltration, rising groundwater and the development of perched water tables all take time. As noted by Pope (1982), peaks in water level in superficial colluvial deposits can occur within a few hours of rainfall whereas a peak rise of 8m in underlying decomposed granite can take several days to develop. Similar data are presented and discussed by Jiao & Malone (2000).

The simple case of a generalised wetting front infiltrating under gravity through essentially uniform saprolite to recharge the seasonal water table as envisaged in many numerical simulations and representations is rare. In fact infiltration and throughflow tends to be controlled by geological structure; perched water tables are the norm rather than the exception, particularly with respect to shallow and intermediate depth landslides.

Vagaries of hydrogeological conditions such as the control exerted by natural pipes (Figure 4), which are commonplace, discrete joints in rock (Figure 5) and permeable zones underlying less permeable material (Jiao & Malone, 2000) make it difficult to predict actual groundwater pressures. Numerical techniques allow groundwater to be modelled reasonably realistically but are not definitive because of poorly-defined ground models (Hencher, 1996).

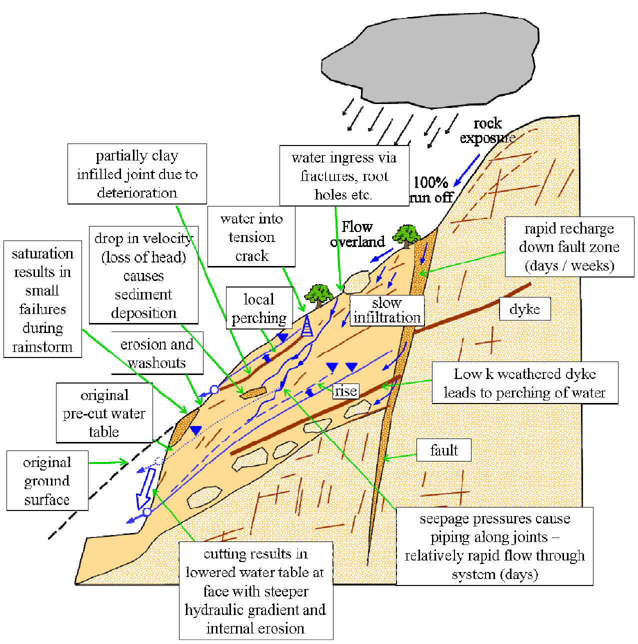

Figure 3. Hydrogeological mechanisms (after Hencher, 2000)

Figure 4. Natural pipes at interface between Grade V and Grade IV granite, Hong Kong

Figure 5. Discrete channel flow from short section of a rock discontinuity

6. NUMERICAL MODELLING

Whilst numerical representation of hydrogeological processes may be challenged by a lack of realistic data and the complexity of the real geology, such modelling can give good insights into the processes and the importance of factors that might otherwise be overlooked. The process is illustrated with reference to the CHASM software. The procedure adopted to model the hydrological system is a forward explicit finite difference scheme in which the slope is divided into a series of rectangular columns, each subdivided into regular cells (Anderson et al., 1996). The model simulates surface detention storage, infiltration, evaporation, and unsaturated and saturated flow regimes. Rainfall is allowed to infiltrate into the top cells governed by the infiltration capacity.

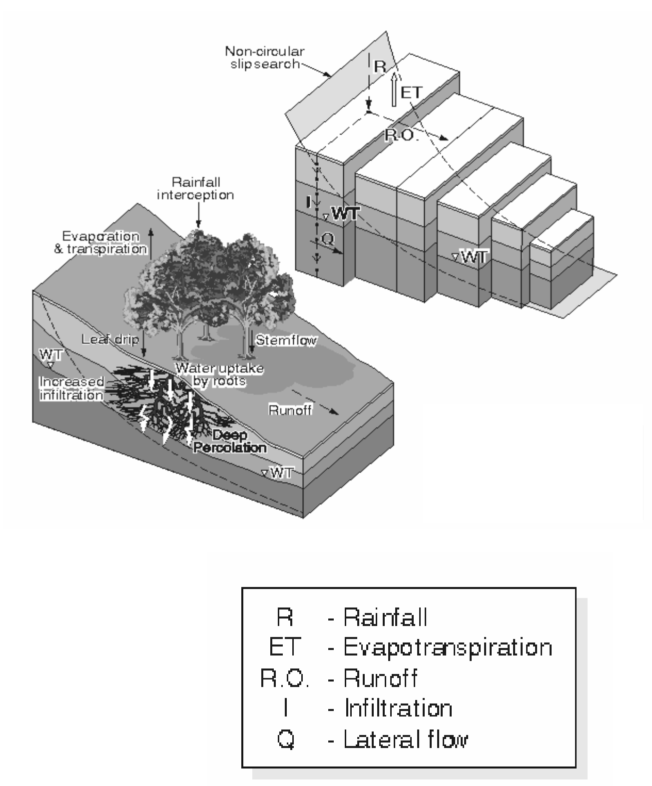

Figure 6. Integrated model structure (CHASM)

Within the integrated model structure (see Figure 6), the hydrological scheme can be modified to represent slope plan curvature (convexity and concavity), thereby allowing investigation into different topographic scenarios. The specification of curvature is geometrically consistent with the slope plan index measure provided by the Geotechnical Control Office Hong Kong CHASE report (Hudson et al, 1981). The soil water flux regime is computed in the same manner as the two-dimensional scheme described above.

However, down-slope saturated fluxes are enhanced (slope plan convergence) or reduced (slope plan divergence) in accordance with the down-slope cell breadth changes specified.

Integration of the unsaturated and saturated flow regimes within the model allows determination of the pressure head field within the slope domain and subsequent input into stability analysis. An important component of the numerical scheme is the full inclusion of a surface cover model. The mechanisms whereby vegetation influences slope stability may be broadly classified as either hydrological or mechanical in nature (Table 1).

Table 1. Effects of vegetation on slope stability (based on Greenway, 1987)

No.	Factor	Type*
1	Reduction in soil suction and raising of groundwater levels by infiltration	H, A
2	Interception of rainfall by foliage, producing ‘canopy’ runoff and absorptive/evaporative losses which reduce ‘effective’ rainfall	H, B
3	Reinforcement by roots, increasing soil shear strength	M, B
4	Depletion of soil moisture by root uptake and transpiration	H, B
5	Surcharge weight of trees that increase normal and downhill force components	M, A/B
6	Root wedging of surficial rock; uprooting in typhoon winds	M, A
7	Restraint by trees on the fall of loose boulders, and on soil by anchoring, buttressing and arching	M, B
*H	= hydrological factor	A = adverse to stability
M	= mechanical factor	B = beneficial to stability

Table 2. Hypothetical slope form and material properties

Property	Parameter value
Slope angle	1:1.5 (~ 37º)
Slope height	20 m
Effective soil cohesion	2 kPa
Effective angle of internal friction	35º
Saturated/unsaturated bulk density	19/18 kNm^{-3}
Saturated hydraulic conductivity	5×10^{-6} ms^{-1}
Initial surface suction	-2 m
Initial water table height	50% (from slope toe)

To illustrate the full potential of the integrated model structure, reference is made to a hypothetical slope configuration with assumed geometric and material properties (summarised in Table 2).

Application of the integrated model demonstrates the potential impact of vegetation cover and slope plan curvature on slope stability. For this purpose 5 different curve radii are adopted, representing the range of slope plan curvatures specified in the CHASE report, Hudson et al (1981).

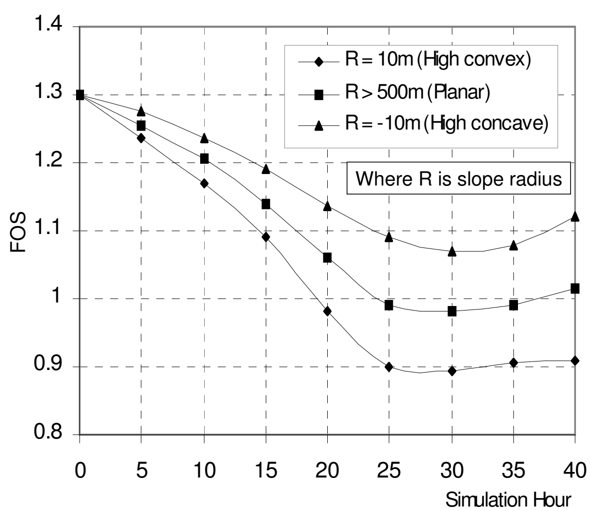

Figure 7. FOS change with time for various slope plan curvatures

To illustrate the sensitivity of the integrated model, a 1 in 10 year, 24-hour return period storm for Hong Kong (Hong Kong Government 1982, p108) is imposed on the top boundary (15.46 mm/hr). Progression of the wetting front towards the water table results in a time-dependent decrease in the Factor of Safety (FOS), associated with increasing pore-water pressures within the soil. Figure 7 indicates the importance of plan curvature, a result that has also been demonstrated in reality with respect to landslide susceptibility (Halcrow China Limited, 2003). Analysis shows that failure to incorporate the effects of slope plan concavity may result in a 15% overestimation in the Factor of Safety compared to the standard Bishop approach. Conversely, by not considering the effects of slope plan convexity the FOS may be underestimated by up to 12%.

7. PREVENTING FAILURES CAUSED BY RAINFALL

7.1 Surface failures

Uncontrolled surface runoff and erosion are often the dominant failure mechanisms rather than landsliding per se. Liquefaction failures, i.e. sudden collapse of a loose soil mass under high saturation in a 'flow slide' manner, are an exception to the dominant washout-type movements and occur mainly in loose fill.

The most effective measures to prevent such shallow failures are to add surface drainage channels and to increase the durability of the surface cover or reduce the erodibility of surficial soils, e.g. by fill compaction, or by addition of a more durable surface such as shotcrete or a vegetated cover with a geotextile (Ho, 2004). Attention to surface drainage detailing, e.g. to ensure adequate capacity and prevention of splash and overspilling at channel junctions and changes in direction, is of great importance (Au & Suen, 1996). A convenient list of factors requiring attention is given by Hui et al (2006).

Public concern over slope appearance in Hong Kong, especially the former liberal use of hard shotcrete surfacing, led to renewed interest in bio-engineering techniques in the late 1990s and publication of new guidelines (GEO, 2000). However, assessing the effects of a permeable vegetated cover on slope stability, and the relative pros and cons in comparison with a hard surface cover involves much judgement (Martin et al., 2001). Uncertainties in the depth of root reinforcement mean that designers rarely rely on the mechanical effects of vegetation to strengthen the ground: the main engineering benefit is to help control surface erosion. Conversion of old hard surface covers to new vegetated covers is highly desirable on aesthetic grounds but may lead to increased hazard of shallow failure through adverse near-surface hydrogeology.

Even with close attention to drainage detailing, it is difficult to completely eliminate the risk of minor washout and sliding failures, e.g. between the heads of soil nails now commonly used to enhance stability. Such failures may be of little consequence in rural areas, but in high-risk dense urban settings, where there is no alternative, hard slope surfaces are still used, on safety grounds.

7.2 Shallow landslides

Shallow landslides caused by infiltration and perching on less permeable horizons, or a rise in base groundwater, can be prevented by a range of subsurface drainage measures. Trench (counterfort), cut-off and shallow raking drains are commonly used preventive measures but require much judgement to optimise their depth and layout, especially in variable saprolitic soil profiles. Installation of drains on a standard grid layout or at evenly-spaced centres is the norm. Where possible, an observational approach over one or two wet seasons is much preferred, with a view to locating drains preferentially at sites of seepage, flowing groundwater, or known zones of high groundwater pressure (Martin & Siu, 1996). Raking (sub-horizontal) drains in particular

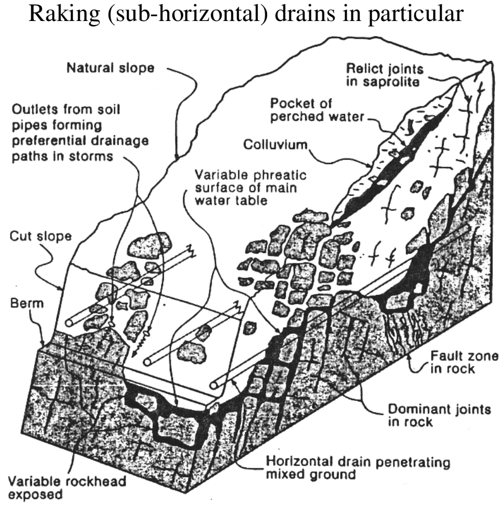

Figure 8. Variable hydrogeological conditions in Hong Kong slopes (from Martin & Siu, 1996)

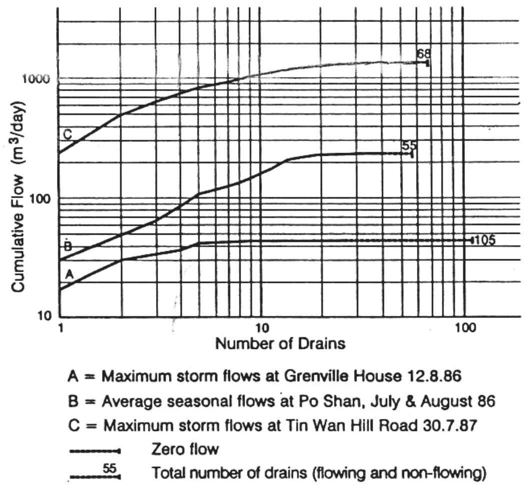

Figure 9. Variability of drain flows at three sites in Hong Kong (from Martin & Siu, 1996)

have been commonly applied as landslide preventive measures in Hong Kong since the 1970s and are of two basic types: (a) 'designed' drains installed to reduce groundwater pressures so that a specified factor of safety or margin of stability is achieved, and (b) 'prescriptive' drains installed to provide some additional unquantified improvement to slope stability by reducing groundwater pressures below that achieved by natural drainage. Inherent highly variable hydrogeological conditions in saprolitic and colluvial soils means that groundwater 'compartmentalisation' is the norm and explains the common finding of highly variable drain flows within single sites (Figure 8).

Cases studied in detail typically show that less than 20% of the drains at a site produce over 90% of total measured flows (Figure 9). Designed drains were employed for slope stabilisation at a small number (around 15) sites in Hong Kong in the 1970s-1980s. Requirements for monitoring and maintenance published in 1991 (Works Branch, 1991) reduced the popularity of these drains. An early 1990s review summarised by Martin & Siu (1996) found that these drains had generally caused significant lowering of groundwater levels (in the range 3 to 15 m) in a variety of geological settings and there was evidence to suggest that problems of long-term clogging were not of major concern.

A more recent review has identified occasional piezometric readings suggestive of declining drain performance at some sites. Given the increased emphasis on more robust landslide preventive measures in recent practice (Ho et al; 2003), designed drains are no longer in common use, and in some cases are being supplemented by other measures (e.g. addition of soil nailing). In contrast, prescriptive raking drains are commonly used as part of a range of landslide preventive measures and have now been installed on hundreds of soil cut slopes in Hong Kong.

7.3 Deep-seated landslides

Large failures induced by a rising groundwater table or thick perched water are amenable to a wider range of subsurface preventive drainage measures, including vertical drainage wells, galleries/adits/tunnels, syphon drains and pressure relief walls (Forrester, 2001; Ho, 2004). Deep raking drains may also be used. For example, in the mid 1980s raking drains up to 90 m long were used in saprolites on a natural hillside at Po Shan in Hong Kong as a designed drainage system. This scheme is now in the process of being supplemented by deeper drainage tunnels and the addition of soil nails to enhance slope stability at the site.

8. CONCLUSIONS

The vast majority of landslides in Hong Kong are caused by intense rainfall. The number of reported landslide incidents increases approximately 10 fold for a doubling of 24-hour intensity. It is demonstrated that numerical modelling of hydrogeology of weathered rock profiles can give useful insights into the controlling factors. Control of hydrogeology by surface and subsurface drainage can prevent rainfall-induced landslides, but successful design and construction of such measures requires much judgement due to inherently variable ground conditions.

9. ACKNOWLEDGEMENTS

This paper is published by permission of the Director of the Civil Engineering Department, Government of the Hong Kong SAR.

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