

# **An Hypothesis Concerning a Confined Groundwater Zone in Slopes of Weathered Igneous Rocks**

J. J. Jiao and A. W. Malone

Department of Earth Sciences, University of Hong Kong, Hong Kong

## **Synopsis**

In this paper an attempt is made to offer insights into local slope failure mechanisms from the perspective of hydrogeology. The hypothesis examined envisages that the hydraulic conductivity distribution in a weathered profile includes a relatively high hydraulic conductivity zone associated with the jointed rock mass near rockhead. There is evidence locally for such a condition. The groundwater flow regime in such a high hydraulic conductivity zone may be confined, in the sense of a 'confined aquifer', resulting in higher pore pressures during exceptionally heavy rainfall periods than might otherwise be expected. These high pore pressures may be responsible for a significant reduction in slope stability. The paper will conclude that, while slope stability studies in Hong Kong so far have tended to focus on perching within the regolith, in places a critical hydraulic boundary condition may exist at the base of the regolith.

## **Keywords**

Landslide, slope failure, hydrogeology, hydraulic conductivity, confined aquifer

## **1 Introduction**

Slope failure has been the subject of local research for decades from the perspective of soil and rock engineering. Although it is well recognized that groundwater can be a dominant factor in slope stability (Terzaghi, 1950), the study of the impact of regional hydrogeological conditions on slope stability in Hong Kong is relatively undeveloped. An attempt will be made here to examine one hydrogeological characteristic of the rock weathering profile that may influence stability.

## **2. Hydraulic conductivity profile and piezometric response in weathered igneous rock**

There is some limited information available relating to hydraulic conductivity profiles in Hong Kong. A review of this information may provide insights on the hydrogeological characteristics of weathering profiles.

### ***2.1 Hydraulic conductivity profile from a construction site***

The first and still the most comprehensive study related to hillside hydrogeology in Hong Kong was the Mid-levels Study (GCO, 1982). Over 400 boreholes were installed in the Mid-levels area

between Glenealy and the University of Hong Kong and many hydraulic conductivity tests were conducted. The test data were grouped based on the depth from the ground surface or the degree of weathering and the conclusion was drawn that the hydraulic conductivity decreases progressively as the depth increases or as the rock becomes less decomposed. This pattern has been adopted in GEO manuals and is widely used in Hong Kong. Groundwater modelling studies assumed that rockhead is an impermeable boundary (Lerner, 1986; GEO, 1996).

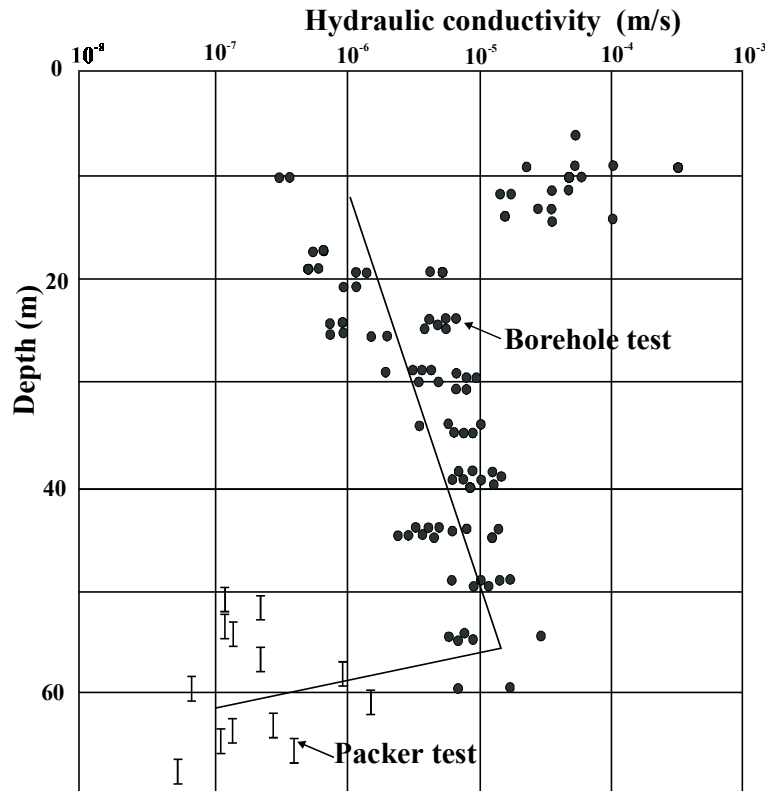


Figure 1: Variation of hydraulic conductivity with depth at the construction site in Wanchai, Hong Kong (from Davies, 1987)

Whilst the above pattern may be correct for some slopes, it may not apply universally. Davies (1987) presented hydraulic conductivity data from a small construction site ( $60 \times 40 \text{ m}^2$ ) in Wanchai, Hong Kong. The site, now occupied by the MTRC Wanchai station, was described as being underlain by fill, marine deposits and alluvium, residual soil, completely decomposed granite, highly decomposed granite, and granite bedrock. The measured hydraulic conductivity profile is reproduced in Figure 1. The hydraulic conductivity of the fill material at the top is greater than  $10^{-5} \text{ m/s}$ . Below the fill material, the hydraulic conductivity increases with depth, achieves a maximum around a depth of 50 m (which corresponds to Grade III), and then decreases with depth in the Grades I and II rock.

These results are not unreasonable. It could well be that the zone beneath rockhead dominated by Grade III rock may indeed form the most permeable zone in the entire weathering profile due to the presence here of well developed jointing systems which are hydraulically conductive.

## 2.2 Highly permeable zone in bedrock indicated by piezometric response

The weathering profile at this formerly coastal site in Wanchai may not be characteristic of that in the hillside and borehole hydraulic conductivity tests are prone to uncertainties of various kinds. More reliable observations of hillside hydrogeological characteristics are needed. Since the hydraulic conductivity characteristics of the weathering profile will be reflected by the piezometric response to rainfall, the response at different depths within the profile may give insights into the distribution of hydraulic conductivity with depth.

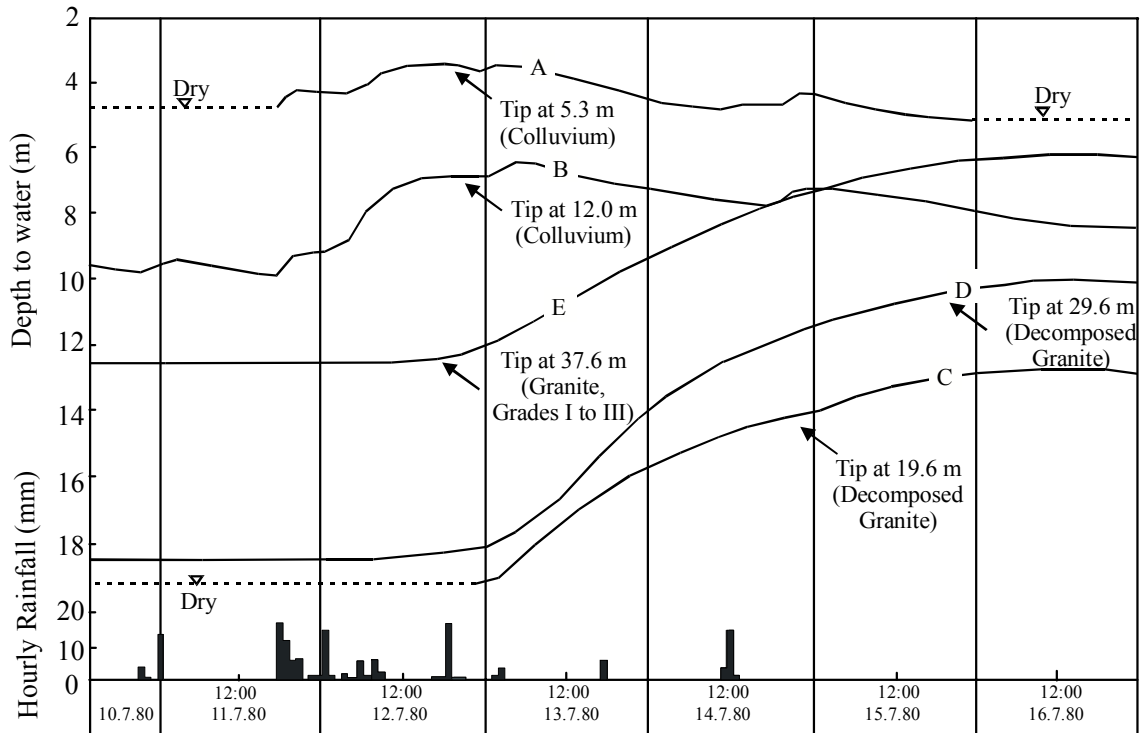


Figure 2 Piezometric response in response to rainfall in Mid-Level, Hong Kong (from GCO, 1982)

Figure 2 shows the piezometric response to rainfall with depth near Scenecliff, No 35, Conduit Road in the Mid-levels between July 10 and 16, 1980 (GCO, 1982). As shown in the figure, the tips of the piezometers are located in what is described as colluvium, decomposed granite, and granite bedrock. More detailed information on the geology of the site and location of the piezometer groups can be found in GCO (1982). Before the rainfall began, Points D and E were in the regional saturated zone. Point B had a measurable water level and therefore was in a local saturated zone. The two saturated zones were separated, since Point C was dry. Most of the rain fell on July 11 and 12. The water level at Points A and B showed a fairly immediate rise. By the end of July 12, Point E, at the lowest elevation, began to rise, then Point D, followed by Point C. Point E began to rise when Point C was still dry. As infiltration proceeded, the two saturated zones met. When the water level at Points A and B began to decline, the water level at Points D, C, E increased quickly and reached a maximum by July 16, by which time there had been no rain for two days.

The most plausible hypothesis to explain the above observations is as follows:

- 1) The significant early rise in pressure at Point E in the bedrock is mainly caused by pressure transmission through 'Grade III' after infiltration in the remote upper part of the slope, which suggests that there is a rather permeable zone near the bedrock.
- 2) There was a significant delay in pressure response near the bedrock to rainfall.
- 3) The change in hydraulic head in the bedrock was much greater than that in the saprolite. A considerable vertical upward flow was generated after rainfall.
- 4) The bedrock and the saprolite near the bedrock became confined after July 13.

If the above hypothesis is correct, a high conductivity zone exists at rockhead in this part of the Mid-levels area.

### ***2.3 Highly permeable zone in igneous rocks discussed in literature***

Considering the large amount of geotechnical work that has been carried out in Hong Kong it might have been expected that the presence of a high permeability zone at rockhead in the local weathering profile would have been reported before if the condition is commonplace. Perhaps it is not commonplace in Hong Kong or perhaps it has gone unrecorded.

Looking outside the narrow confines of Hong Kong it is interesting to note that a highly permeable zone in the weathering profile of igneous rocks was reported in literature in the middle of the last century. The sequence of previous and impervious layers in slopes in residual soils is described by Terzaghi and Peck (1967, p432) in their classic textbook as follows:

“Within the zone of weathering of the insoluble types of rock, it is by no means uncommon for the coefficient of permeability of the weathered rock to increase from very small values near the ground surface to maximum values close to the boundary between weathered and sound rock. Thus the zone of rock weathering forms a relatively impervious skin resting on a pervious layer. If water enters the previous layer through a gap in the skin or through open fissures in the sound rock, artesian conditions may develop in the pervious zone and the impervious top layer may slide down the slope even if the inclination is very gentle.”

This sequence was later described in detail by Deere and Patton (1971) who regard the more permeable zone in the middle of a weathering profile of intrusive igneous rocks as a commonplace occurrence. They stated that “this zone is commonly very permeable and water losses are often noted by drillers when they reach this zone”.

### **3. A conceptual model**

Based on the previous discussion, a conceptual hydrogeological model is proposed. The zones of the weathering profile near the surface where completely and highly decomposed materials (Grades V & IV) predominate behave as an aquitard. The zone commonly called bedrock where moderately and slightly decomposed materials (Grades III-II) predominate is a confined aquifer. This aquifer should not be understood as the typical confined aquifer used in traditional

hydrogeology. It may be only half-full or even completely dry in the dry season, but may become fully confined following periods of heavy rainfall.

The bedrock is essentially a fracture aquifer with low storativity. In many cases, it outcrops at the upper part of the hillside and forms a zone of maximum infiltration. It may also intercept the surface drainage lines. A piezometer in this zone will be therefore more sensitive to rainfall than one that installed in the overlying saprolite. For a fractured aquifer, the hydraulic conductivity can be great, but the storativity is generally low. Therefore, the pressure can build up quickly in heavy rainfall periods and can dissipate quickly after rainfall. It is worthwhile to note that, for slope instability, it is not the amount of groundwater, but the amount of pore pressure which is generated from groundwater that matters.

#### **4 Hydrogeological features of some slope failures in Hong Kong**

It is of interest to know if the hydrogeological characteristics of the sites of the landslides which have been investigated in detail show a confined aquifer at rockhead.

So far, the reports of ten major landslides have been examined. The reports of three of the landslides give a fairly detailed description of hydrogeology. The three sites are Tsing Yi (1) (GCO, 1983), Tuen Mun Highway Chainage 550 (GCO, 1984), and Siu Sai Wan (GEO, 1993), respectively.

To generalise the findings, weepholes or shallow horizontal drains were dry after rainfall in the slopes at Tsing Yi and Siu Sai Wan but deeper horizontal drains produced water. Perhaps the deeper drains connected with groundwater in the bedrock.

At Tsing Yi(1) and Tuen Mun Highway Chainage 550 water level of the piezometers in the completely decomposed igneous rock appeared to be stable and did not show much response to rainfall. For example, a shallow piezometer in the highly decomposed granite near the top of the cut slope at Tsing Yi showed a rise of about 1.5 to 2.0 m after a rainfall. However, the groundwater level in a piezometer installed in the bedrock near the toe of the slope showed a rise of 7 m in response to the same rainfall.

At Siu Sai Wan, in general, piezometers above bedrock showed practically no response to rainfall, while those in or near the bedrock showed a stronger response to rainfall. There appeared to be an upward groundwater flow from the bedrock. The investigation report (GEO, 1993) states that “there is a possible regional groundwater discharge effect which may give an upward component to the groundwater flow with resultant elevation of water pressure”.

#### **5. Discussion and conclusions**

The hypothesis presented here has implications for slope engineering, as well as for tunnelling, bored pile construction and deep excavations. At some sites water pressure rise in the bedrock at

times of exceptionally heavy rainfall may be a key factor in the failure of a slope and should be the focus of slope stability studies. In such a case, an effective dewatering system is needed. Other traditional remedial measures such as cutting back may lessen stability.

The documented piezometric response and hydraulic conductivity distribution at two well-studied sites were examined and then a conceptual model on slope hydrogeology was postulated. So far, in groundwater flow modelling for slope stability studies in Hong Kong, the saprolite has been treated as aquifer with perching horizons within it or at its base while the bedrock is treated as an impermeable boundary. This paper suggests that, at least in some slopes, the regolith may be an aquitard and the bedrock a confined aquifer zone.

### Acknowledgement

The study is supported by Committee on Research and Conference Grants (CRCG) at the University of Hong Kong.

### References

- Davies, J. A, 1987, Groundwater control in the design and construction of a deep excavation, in *Groundwater Effects in Geotechnical Engineering*: proceedings of the ninth European Conference on Soil Mechanics and Foundation Engineering, Dublin, 31 August-3 September 1987, editors, E.T. Hanrahan, T.L.L. Orr & T.F. Widdis, p139-144
- Deere, D. U. and F. D. Patton, 1971, Slope stability in residual soils, *Proc. 4<sup>th</sup> Panamerican Conf. Soil Mech.*, Puerto Rico, 1, p.87-170.
- Geotechnical Control Office, *1983 Landslide Case Study: Tuen Mun Highway, Chainage 550*, Special Project Report SPR 2/84, 1984.
- Geotechnical Control Office, *1983 Landslide Studies 1982: Case Study No. 8, Tsing Yi (1)*, SPR 9/83, 1983.
- Geotechnical Engineering Office, 1993, *Interim Report on Investigation of the Failure of Slopes 11SE-D/C 182 & 11 SE-D/C 183 Siu Sai Wan, Hong Kong*, SPR 3/93, Geotechnical Engineering Office, Civil Engineering Department, Hong Kong.
- Lerner, D.N., 1986, Predicting piezometric levels in steep slopes, *Groundwater in Engineering Geology*, Geological society, Engineering Geology special publication, No.3, London.
- Terzaghi, K., 1950, Mechanism of landslides, in *Application of Geology to Engineering Practice, Berkey Vol.*, Geological Society of America, p.83-123.
- Terzaghi, K. and R. B. Peck, 1967, *Soil Mechanics in Engineering Practice*, New York, John Wiley and Sons.
- Geotechnical Engineering Office, *Report on the Shumwan Road Landslide of 13<sup>th</sup> August 1995, Findings of the Landslide investigation*. Geotechnical Engineering Office, Hong Kong, 1996