

A confined groundwater zone in weathered igneous rocks and its impact on slope stability

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Abstract

Landslides associated with hillside cuttings in igneous rock saprolites are a serious natural hazard in Hong Kong and have been extensively studied by government agencies and local universities for many years from the perspective of soil and rock engineering. A review of the case studies for some major landslides, especially deep-seated landslides, shows certain puzzling features. First, a number of failed slopes had failed again after they were cut back to a gentler angle designed to be safe based on theoretical calculations. Second, some of the failures were postulated to have been caused by the occurrence of a high groundwater table after rainfall, but weepholes in some slopes were dry and piezometers did not show much response to the rainfall.

An attempt is made to offer explanations of the hydrogeological characteristics and failure features of these deep-seated landslides. A conceptual model is proposed to explain the failure mechanisms. It is believed that a confined groundwater zone may exist in the weathered igneous rock profile due to a highly fractured zone. In Hong Kong the saprolite has been treated as an aquifer while the bedrock is considered as an impermeable boundary, with the focus of research on the saprolite above the bedrock. This paper will demonstrate that, at least in some slopes, the saprolite is more like an aquitard and that the bedrock can be essentially a confined aquifer. The high pore pressure during exceptionally heavy rainfall periods may be responsible for a significant reduction in slope stability. An examination of the cross sections of some well-known landslides in Hong Kong revealed a chair-shaped rockhead profile. The discussion in this paper has implications on slope remedial work design. The artesian water in the bedrock at times of exceptionally heavy rainfall is the key factor in slope failure and should be the focus of slope stability studies. An effective dewatering system is needed. Other traditional measures such as regrading the slope may lessen stability.

1 Introduction

Landslides occur frequently in Hong Kong's hillsides of weathered igneous rocks during heavy rainfall periods. The mechanisms of the slope failure have been the subject of extensive research in government agencies and local universities since the 1970's. The previous studies have led to many archived reports and lots of insights and experience on slope movements, failure mitigation, and remedial work design. Although it is well recognized that groundwater can be a dominant factor in slope stability (Terzaghi, 1950), the study on the impact of hydrogeological condition on slope stability is relatively weak. This paper will summarize some hydrogeological characteristics and common failure features of some deep-seated landslides. An attempt will be made to relate the failure features to the hydrogeological conditions. A conceptual model of failures based on the hydrogeological study will be proposed to provide some insights on the slope failure mechanisms and remedial work design.

2 Hydrogeology and failure features of some deep-seated landslides in Hong Kong

2.1 Hydrogeological features of some deep-seated landslide sites

In Hong Kong, a large portion of the major landslides, especially the deep-seated landslides, are associated with complex hydrogeological conditions (GEO, 1993). About 10 reports are reviewed for this study. Although none of the sites have any systematic hydrogeological studies, reports of three landslides have a fairly detailed description about hydrogeology. These three landslides are Tsing Yi (1) (GCO, 1983), Tsuen Mum Highway Chainage 550 (GCO, 1984), and Siu Sai Wan (GEO, 1993), respectively. After a review on the hydrogeology of the three sites, some interesting or even puzzling hydrogeological features are summarised below:

- After rainfall, the slopes are obviously waterlogged, but the weepholes or shallow horizontal drains in some slopes were dry, as was the case in TY and SSW.
- The fact that the weepholes did not issue water does not appear to mean that there was no water inside the slope since deeper horizontal drains showed that water was certainly present in the slopes.
- At SSW, surface water in the stream channels disappeared in the upper part of the slope, indicating that there may be a more permeable zone through which the surface water recharges the groundwater.
- At TY and TMHC the water level of the piezometers in the completely decomposed igneous rock appeared to be rather 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 TY 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 SSW, in general, piezometers above bedrock showed practically no response to rainfall, while those in or near the bedrock showed a stronger response to rainfall.
- The groundwater level in the bedrock appeared to be higher than that revealed by the shallow piezometers, as indicated by the seepage points at SSW. There appeared to be an upward groundwater flow from the bedrock. The investigation report of SSW 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”.

2.2 Cuttings and failures

Most of the slopes with deep-seated landslides were cut back due to road construction or housing development. The angle of the cutting slope was, however, fairly gentle. The slope surfaces were usually less than 35 degrees, which was designed to be safe based on the theoretical calculation of factor of safety. Some slopes showed a minor failure after road construction. Consequently, remedial works were carried out and the slope was cut back to a theoretical safer angle. Other measures, such as shotcrete, rock or soil nails and horizontal drains, were also used. However, a much larger failure occurred a few years later, such as the cases of TMHC and SSW. This suggests that cutting back of the slope did not improve its stability, or at least, not to the extent that was indicated by theoretical calculations. It appears that the stability was decreased when the slope was cut back.

2.3 Shape of the bedrock in some slope failures

All the slip surfaces appear to be controlled by the boundary between completely decomposed rocks and moderately decomposed rocks. After examining the cross sections of the landslide sites, a strikingly common feature is observed. That is, the rockhead profile is chair-shaped. Figure 1 presents the interface of the saprolite and the bedrock in 8 well-known failures in Hong Kong (GCO, 1983; GCO, 1984; GCO, 1986; GCO, 1989; GEO, 1993; GEO, 1998a; GEO, 1998b; GEO, 2000). While the interface is generally parallel to the slope surface, at the toe of the slope, the interface becomes rather flat (Figures 1C, 1E, 1F, 1H), or depressed slightly (Figures 1A, 1B, 1D, 1G). The saprolite in most of the slopes becomes thin toward the toe of the slope. The sliding surface is usually located above the flat or depressed areas. It is unclear if this shape is simply a coincidence or has some important implication on the failure mechanisms.

3. Hydraulic conductivity profile distribution in weathered igneous rocks

The key to understanding the hydrogeological features of the failure sites discussed above is to study the hydraulic conductivity distribution of the weathered igneous profile in the slope. The weathered profile of igneous rock in Hong Kong is divided into 6 grades and noted from Grades I to VI. They are: fresh, slightly decomposed, moderately decomposed, highly decomposed, completely decomposed and residual soil (GEO, 1997). Grades I to III are usually called bedrock and Grades IV to VI engineering soil. The first and most comprehensive study related to hillslope hydrogeology in Hong Kong was conducted about 20 years ago (GCO, 1982). A conclusion was made that the hydraulic conductivity decreases progressively as the depth increases or the rock becomes less decomposed. This pattern has been widely used in Hong Kong. In groundwater modelling for slope stability studies in Hong Kong, the soil above the bedrock has been represented by an unconfined aquifer while the bedrock as an impermeable boundary (Lerner, 1986; Tung et al., 1999)

Whilst this pattern may be correct for some slopes, it may not apply universally. Recently, it has been demonstrated, by a vertical hydraulic conductivity profile measured in a construction site and piezometric response to rainfall in a slope in the Mid-Levels area, that at least in some places, there is a highly permeable zone in the bedrock around the interface of the highly decomposed rocks and the bedrock (Jiao and Malone, 2000). The existence of such a zone was also confirmed by groundwater conditions in the south portal of Aberdeen Tunnel when it was constructed. It was noted that “a sharp interface between the sound and decomposed monzonite produced water inflows that could only be controlled by pumping” (Bevan, 1984). It was further realized that a confined water zone existed at the interface : “It appeared that an artesian condition could exist in the lower part of the hillside where the base of the hill was covered by residual soil and colluvium, and the main source of water and water pressure was from the more permeable zone at the weathered rock and fresh rock contact. Following rains, this zone could have sharply increased piezometric levels because of its continuity in an uphill direction, where it could be charged by infiltration in areas of thin colluvial or residual soil cover” (Twist and Tonge, 1979). Although the highly permeable zone was recorded in tunnelling more than 20 years ago, only recently has this phenomenon been related to slope stability studies in Hong Kong (Jiao and Malone, 2000).

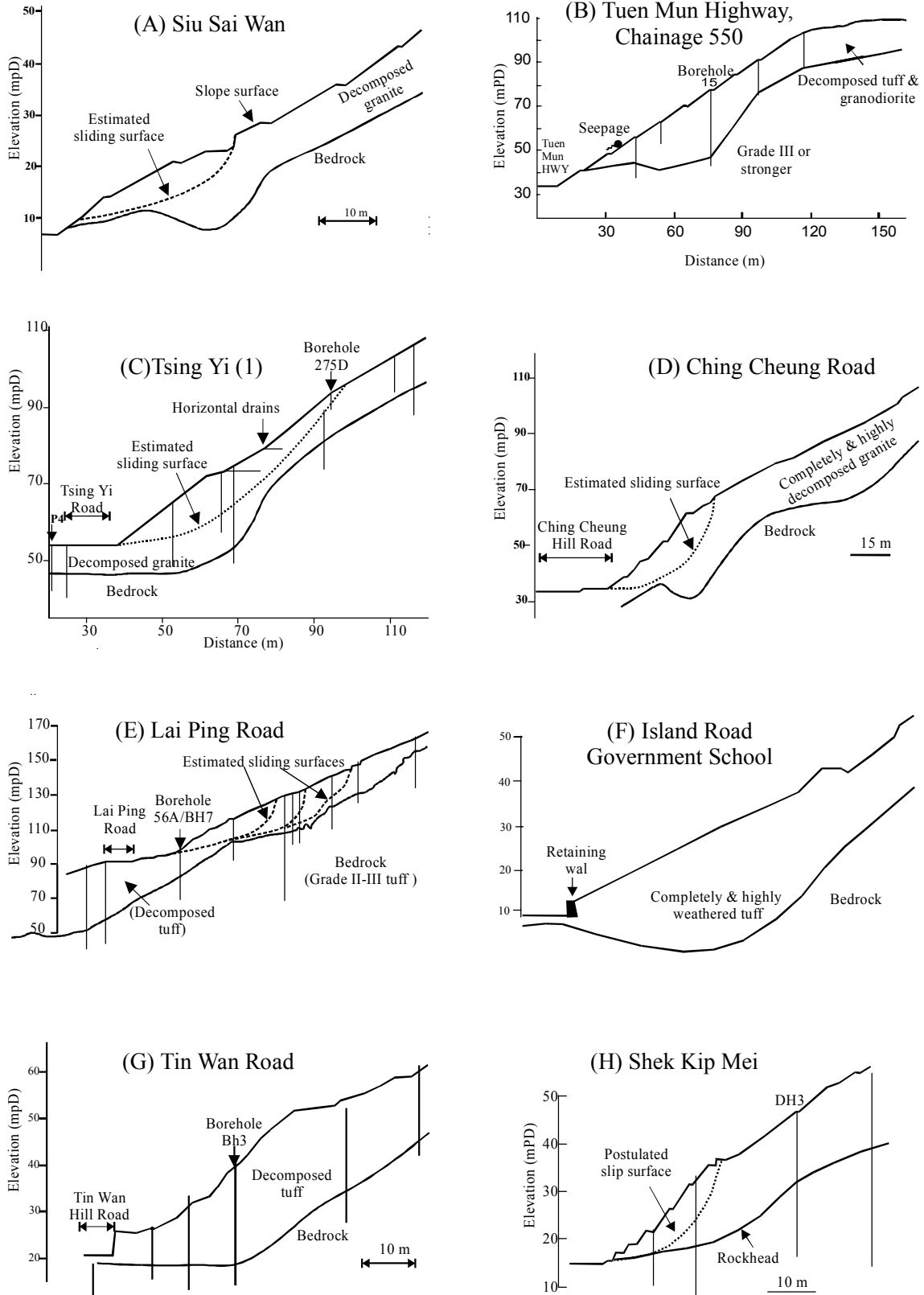


Figure 1 Chair-shaped rockhead in cross-sections of some well-documented landslides in Hong Kong

4. A conceptual model of slope failure

Based on the previous discussion about the hydraulic conductivity distribution and the shape of the rockhead, a model is proposed in Figure 2. The completely to highly decomposed materials (Grades IV-VI) near the surface are believed to behave like a relative aquitard while the moderately to slightly decomposed materials or commonly called bedrock (Grades II-III) are treated as a confined aquifer. This aquifer should not be considered as the typical confined aquifer in the traditional hydrogeology. It may be only half-full or even dry in the dry seasons. It may become fully confined only at times of heavy rainfall.

4.1 Implication of the conceptual model on slope hydrogeology

When the highly permeable zone is confined in exceptionally heavy rainfall days, the pore pressure may be very high, groundwater in the bedrock can be squeezed out through the relic joints in the overlying Grades IV-VI materials where the thickness of the saprolite is small. Due to the chair-shaped rockhead, the thickness of the Grades IV-VI is usually small near the bottom of the slope or above mid-level of the slope. Soil pipes may be formed at areas where the saprolite is thin and has relic joints, as shown in Figure 2. Some water may also escape at toe of the slope where the slope is cut or where a natural valley, stream, or the sea is located. Water may also escape in the form of distributed leakage through the soil body of Grade IV-VI.

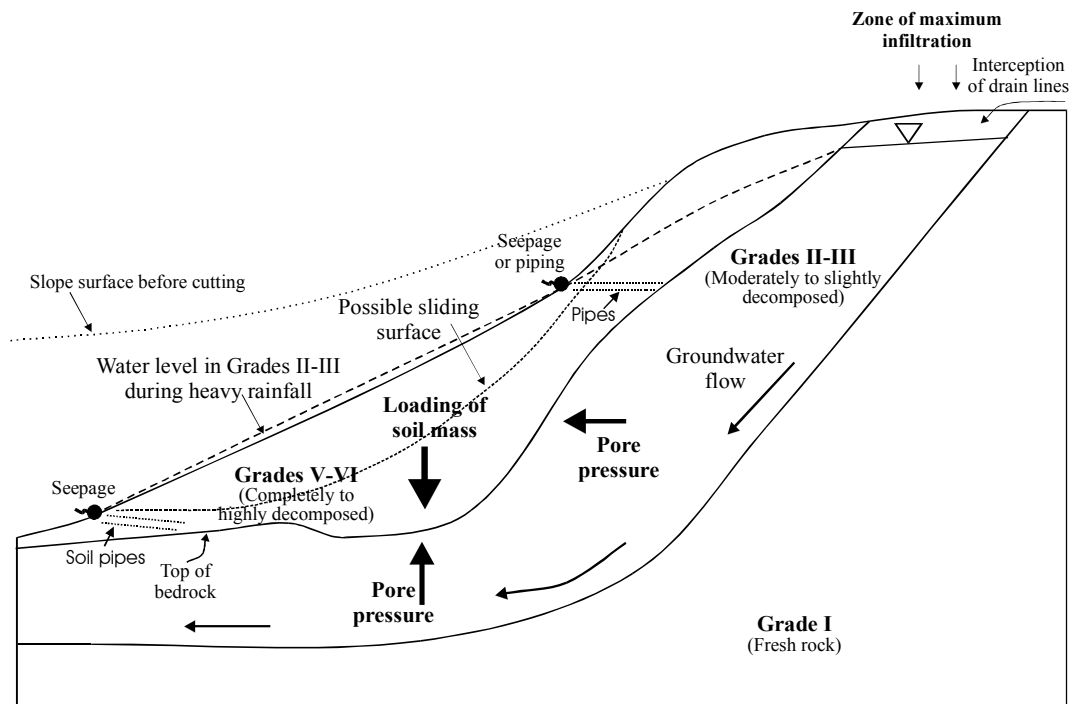


Figure 2 A conceptual model of some deep-seated landslides in cut slopes of weathered igneous rocks in Hong Kong

A piezometer in the saprolite will still show a measurable water level, but its response to rainfall is usually small or rather random, depending mainly on the local hydraulic condition

around the piezometer and the degree to which the soil is disturbed due to installation of the piezometer. Usually piezometers in this zone cannot provide a reasonable pattern of water level.

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 as the case in SSW. A piezometer in this zone will be therefore more sensitive to rainfall than that installed in the overlying saprolite. For a fractured aquifer, the transmissivity can be great, but the storativity may be generally low. Therefore, the pressure can build up quickly in heavy rainfall periods and can dissipate quickly after rainfall, if the slope has a good drainage system. 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 which matters.

4.2 Implication of the conceptual model on slope stability

The more permeable zone is usually parallel to the slope surface and outcrops at the crest of the slope. Consequently, a significant pressure build-up can be generated in exceptionally heavy rainfall. The pressure build-up and the rate of build-up depend on rain intensity, the elevation of the recharge zone, and the rate at which the groundwater can escape at the toe of the slope. When the fractured aquifer is filled with water, a significant pore pressure can be acted at the bottom of the saprolite (Figure 2). The pore water pressure from the bottom will reduce the effective stress of the soil body.

The cutting has two effects: reducing the loading of the soil mass and increasing the hydraulic conductivity of the bedrock after stress release. The joints in the bedrock may be open or open more widely due to stress release. This may lead to a significant increase in hydraulic conductivity. In addition, the connection between different sets or zones of fractures may be created or enhanced due to stress release. Consequently patches of originally independent groundwater zones caused by poor hydraulic connection among the fractures in the bedrock may be combined into a well connected aquifer system with a unified hydraulic head distribution.

Another effect is the change of the loading of the soil mass. Before cutting, the pore pressure from the bottom may be insignificant compared to the loading of the soil mass. After being cut, the soil mass is considerably reduced and the upward pore pressure becomes relatively more significant. When the pore pressure is low, the shearing resistance is likely to be considerably greater than the shearing stresses and the slope will be stable. However, because of high precipitation, the pore water pressure may rise and the shearing resistance may become significantly reduced. If the shearing resistance decreases to the value of the average shearing stress, the slope above the bedrock will fail even it may still possess an adequate factor of safety against sliding along any curved surface located above the bedrock.

If there is a confined zone below the saprolite, the stability of the slope may depend on not only the strength of the saprolite and the angle of the slope, but also to a large extent the pore water pressure in the bedrock. Probably no reliable opinion can be formed concerning the factor of safety of the slope with respect to sliding unless the pore water pressure is known.

5. Summary

This paper summarizes the hydrogeology and failure features at some landslides in Hong Kong. It is believed that a confined zone may exist in the weathered igneous rock profile due to a highly permeable zone. An examination of the cross sections of some well-known landslides in Hong Kong revealed a chair-shaped rockhead profile at these sites. On the basis of the hydrogeological characteristics of the landslide sites and the shape of the bedrock, a conceptual model is proposed to explain the puzzling hydrogeological features and the failure mechanisms. It has been widely accepted in Hong Kong that the saprolite is treated as an aquifer while the bedrock is considered to be an impermeable boundary. This paper demonstrates that the saprolite is more like an aquitard and that the bedrock can be essentially a confined aquifer.

This model can also explain why most deep-seated landslides failed after the slopes were cut back. Cutting back reduces the soil loading required to balance the underneath pore pressure and enhances the hydraulic conductivity of the fractured groundwater zone by generating more fractures after stress release. This paper also illustrates that the chair shape of the rockhead profile appears to be a common feature for some of the deep-seated landslides in Hong Kong. Further studies are required to see if the shape is simply a coincidence or has a significant adverse effect on the mechanisms of slope stability.

The discussion in this paper has implications on slope remedial work design. While in Hong Kong the focus of research has been only in the materials above the bedrock, this paper showed that the artesian water in the bedrock at times of exceptionally heavy rainfall is the key factor in slope failure and should be the focus of slope stability studies. An effective dewatering system is needed to increase the stability of the slopes. Other traditional measures such as shotcrete, shallow weepholes, cutting back the slopes etc. may be less useful. In fact, a shotcreted surface without effective horizontal drains will make things worse since it reduces the overall hydraulic conductivity of the slope surface and increases the pressure build-up inside the slope. Regrading the slope with a chair shaped bedrock surface will also decrease the slope stability.

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