DESIGN AND CONSTRUCTION ISSUES FOR EXCAVATION AND TUNNELLING IN SOME TROPICALLY WEATHERED ROCKS AND SOILS

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ABSTRACT

In tropical areas, weathering is common down to several tens of metres, and can occur to depths of over a hundred metres. Tunnels and excavations in such areas are therefore very likely to encounter weathered rock. Weathering involves progressive weakening of the rock, ultimately to a soil-like condition. Despite this soil-like nature, the weathered rock retains many structural features of the original rock. This means that the behaviour may be significantly different from an apparently similar deposited soil. Both the pattern of weathering development and this retained structure are important in understanding the behaviour of weathered rocks. Some of the issues involved in tunnelling and underground excavation in tropically weathered rocks are illustrated with examples of observed performance in four selected rocks found in Hong Kong and Singapore. The four selected rocks consist of two granitic rock formations and two sedimentary rock formations. The development of weathering in these rocks is contrasted, and related to the nature of the fresh rock. The observed behaviour of the weaker and more soil-like weathering grades of the rocks is discussed in terms of the 'Tunnelman's classification'. Particular issues discussed include: mixed face conditions, abrasion, assessment of strength, swelling, relic joints, erosion, hardpans and collapse.

INTRODUCTION

Rocks affected by tropical weathering are prevalent over a significant proportion of the earth's surface. Although such rocks are widespread in tropical and sub-tropical areas, they are also found in more temperate areas where conditions favour weathering. Figure 1, after the FAO world soil map, shows areas where tropically weathered rocks are commonly found.

Over the last 45 years, much effort has been devoted to developing systems of description and classification suitable for weathered rocks. Publications have included several major working party reports prepared for the Geological Society of London and the International Society of Engineering Geologists (Anon 1977, 1979, 1990 and 1995). Although these reports primarily focus on the description and classification of weathered rocks, it is clear from them that the engineering behaviour of tropically weathered rocks can be very different from the behaviour of the original fresh rock. The behaviour of the soil-like materials that are the final result of tropical weathering can also differ in important ways from that of deposited soils. The nature and behaviour of the weathered rocks are affected not just by the nature of the parent rock but also by factors such as climatic conditions and topography.

The aim of this paper is to review some of the particular design and construction issues presented when excavating or tunnelling in tropically weathered rocks and soils. Because of the great variety of rocks subject to tropical weathering, it would be difficult to provide an adequate overview on a broad scope. It is therefore proposed to limit this review to selected weathered rocks and construction work of which the authors have personal experience. This is a severe restriction, as it effectively limits the review to underground construction in weathered rocks in the city-state of Singapore and the Special Administrative Zone of Hong Kong. However, the very rapid development and associated construction work in these two cities provides ample case records of excavations and tunnelling to refer to. Reference will also be made to some related experience outside Singapore and Hong Kong. The review will also be limited to four main

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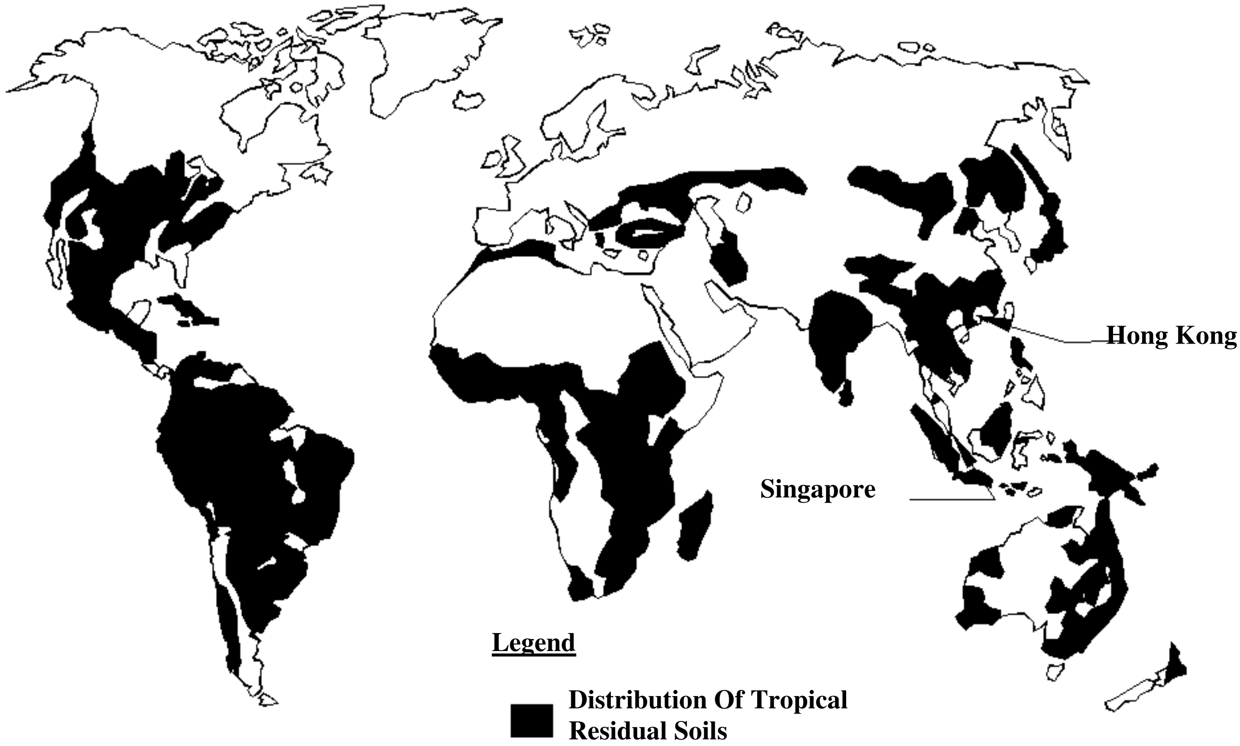


Figure 1 : Tropical Residual Soils (based on F.A.O World Soil Map)

rock formations. The rocks to be discussed have very different characteristics, both prior to and during tropical weathering. They were chosen to illustrate the variation in the nature of weathered rocks, even when weathered under similar climatic conditions.

It is acknowledged that the scope of this paper is limited by the choices made above. The selected rocks do not exhibit certain types of behaviour that can be associated with weathering. Where this behaviour is important for underground construction, it will be included with a brief summary and references to other published material.

TROPICAL WEATHERING

General Principles /Processes

Most rocks close to the earth's surface are generally weathered to some degree due to the effects of stress relief, the passage of groundwater and changes in temperature. Weathering involves physical disintegration and /or chemical attack as minerals break down to more stable forms – especially to clays and oxides. Selby (1993) provides a well-illustrated review of weathering processes.

Physical disintegration dominates in cold climates whilst chemical decomposition is the main factor in warmer climates. Often, however, both processes occur in unison – chemically decomposed rocks are commonly far more closely fractured and jointed than their parent rocks in the fresh state.

In tropical areas, the rock is often altered so severely that it is disintegrated or chemically altered to the state of a soil so that it can be broken and crumbled by hand, sometimes to depths of tens or, rarely, hundreds of metres. The weathered rock mass will retain relic structure from its geological past, which will often control its engineering behaviour. This is a major distinction from a sedimented soil such as a sand or clay. Relict discontinuities, in particular, will define the pattern of weathering throughout the mass, lead to anisotropic strength and control the through-flow of water. Examples of weak, weathered profiles are given in Figures 2 and 3.

This combination of sometimes soil-like material strength, combined with a discontinuity network, means that engineering in weathered profiles requires an appreciation of principles of both soil and rock mechanics. Regarding the ground as a soil, simply because the material is very weak will be to underestimate the

Figure 2 : Cut slope in fairly uniform Grade IV Granite (Zone 6)

importance of relict structure. Similarly the texture of the weathered rock (porosity etc.) may be quite different to that expected from, say, a transported sand deposit of similar apparent density, and lead to problems for sampling, testing and the integrity of the engineering works.

Figure 3 : Irregular weathered profile in granite, Lamma Island, Hong Kong. Note paler Grade II granite in centre, flanked by weaker Grade II to IV

Systems Of Classification / Nomenclature

Engineering geological description can be carried out at scales ranging from that of the individual mineral grains up to the scale of the engineering works themselves. Generally, however, characterisation and classification is carried out at two scales:

Materials, and

Masses

The *Materials Scale* is the scale at which small samples are described, for example from drill core. It is the scale at which index tests and laboratory tests are carried out. Later in the design process, properties need to be assessed at the scale of the project. These properties include material properties, scaled up as necessary and taking account the physical nature of the ground (geological structure and distribution of materials of different strengths) at the *Mass Scale*. A geotechnical model is created, which comprises zones or layers

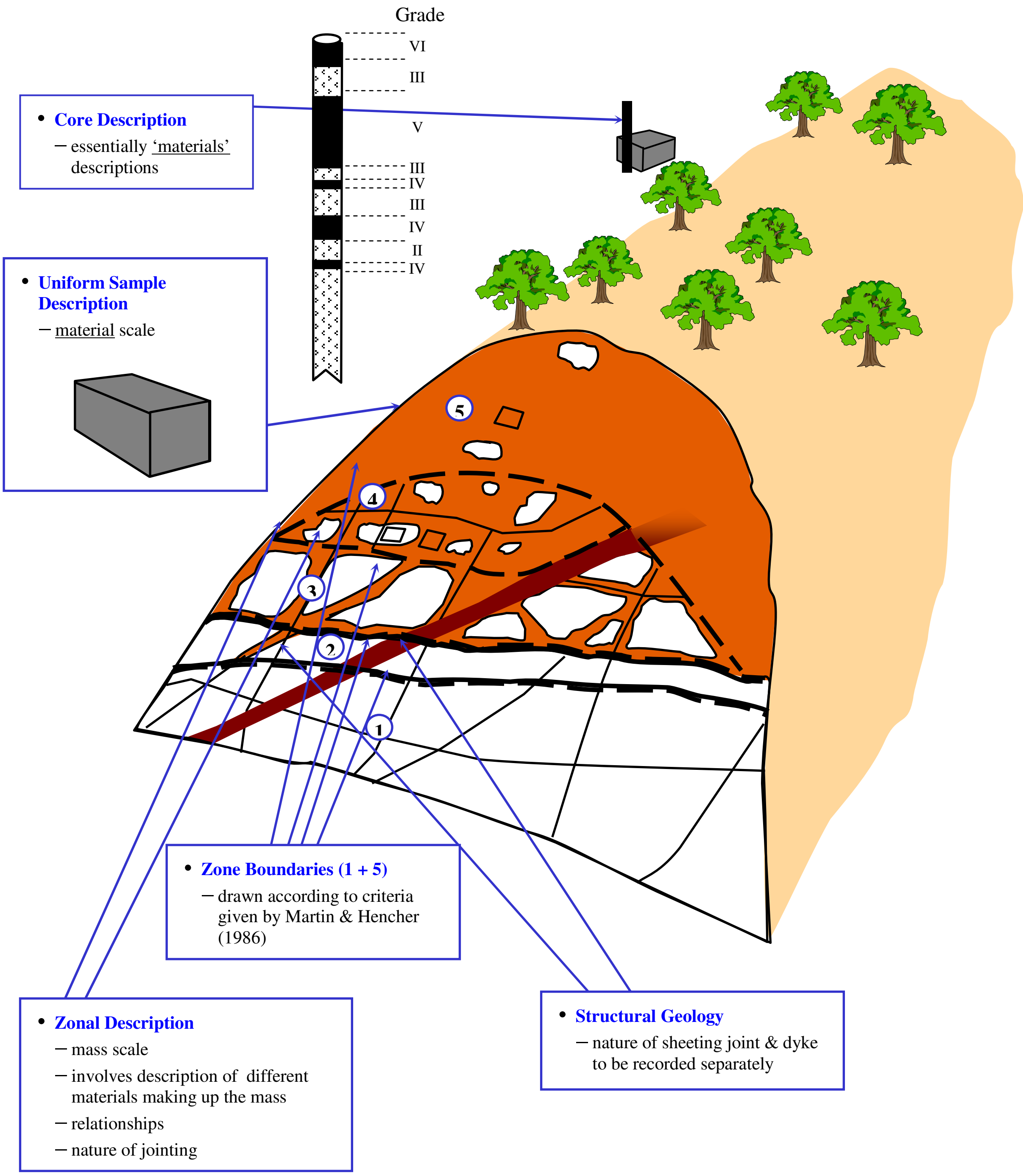


Figure 4 : Scales of Description

which are considered to have engineering properties different from those of adjacent layers or zones. The concept of description at different scales is illustrated in Figure 4.

The progressive nature of weathering, generally with intensity increasing towards the ground surface, means that degree of weathering, on a mass scale, is often a useful way to differentiate between different zones. That said, weathering patterns and profiles are often complex, unpredictable and cannot be extrapolated. This is mainly because the groundwater paths that result in local intensity of weathering are themselves complex – controlled by fractures and lithological variability resulting from the geological history of the rock mass.

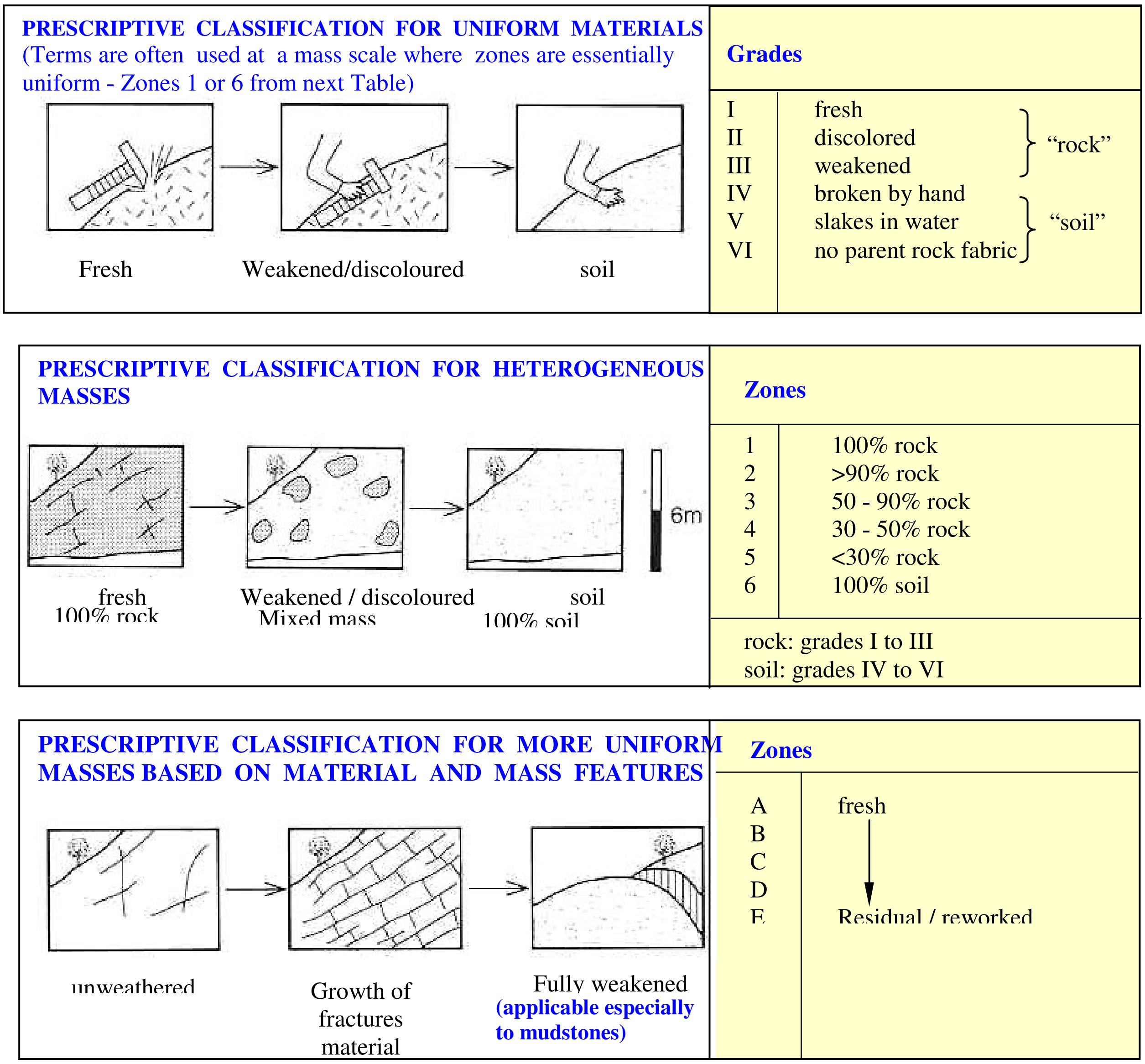


Figure 5 : Prescriptive Classifications for weathered rocks

Many methods of classification have been developed over the last 50 years and this has led to considerable confusion in the literature with different authors and even Authorities such as ISRM, ISSMFE, IAEG recommending the same terms to describe different conditions. This can lead to misunderstanding, ultimately claims and disputes, and difficulties with works because the designer has wrongly interpreted the site data. The situation was reviewed recently by a Working Party of the Engineering Group of the Geological Society of London (Anon, 1995) and various recommendations for methodology of description and standardised terminology made. Those findings have been incorporated in the recent re-issue of The British Standard for Site Investigations (BS:5930, 1999) and it is hoped that the rationale and schemes recommended will be adopted more widely in the near future. The schemes are illustrated schematically in Figure 5.

The most generally applicable and by far the most useful method of classification of most weathered rocks is that based on, essentially, strength as originally devised by Moye (1955). The classification is based on simple, repeatable index tests such as the slake test (Figure 6).

Figure 6 : Example of Simple Index Test (Slake) used to Distinguish Grade IV from Grade V by Immersion in Water. Slaked samples are Grade V.

It is the authors' experience, that this simple scale can be usefully applied to very many weathered rock types. When describing larger masses, where they comprise a mix of hard and softer materials, then that can be dealt with simply by describing the distribution of the various weathering grades of material. For example: *"The upper 15 metres comprise predominantly completely decomposed granite (grade V) with 20-40%, generally rounded corestones of strong to very strong rock (grades III and better) of typical diameter less than 2 metres."* One would then go on to describe each material and mass structure (e.g. discontinuity spacing) fully (Figure 4). If the layer to be described is not too heterogeneous (commonly the case) then concentrate on describing the predominant material in that layer / zone. It is the authors opinion that formal zonal schemes (mass scale classifications) are often too inflexible to be of great use in creating models although they can be useful for primary, shorthand description and discussion (Anon, 1995). Also the principles on which the classifications are based can be helpful in establishing the ground models at site-specific level even if the formal classifications are not particularly applicable or helpful in establishing the fundamental engineering nature and likely problems to be faced in the project works. The philosophy of mass and material scale classification is discussed by Martin & Hencher (1986).

SELECTED WEATHERED ROCKS

Most of the examples of underground construction and tunnelling discussed below concern four particular rock formations. These comprise two granitic rocks: the "Hong Kong" Granite and the Bukit Timah Granite, and two sedimentary rocks: the Jurong Formation and the Old Alluvium. The latter three rock formations are found in the Republic of Singapore. It will be demonstrated that these four formations differ significantly in how they weather and how they behave when weathered. These differences arise from a number of factors including the nature of the original rock and climatic and topographic conditions.

Hong Kong Granite

The term Hong Kong Granite has long been used for the granite which outcrops around the main harbour area of the Special Administrative Zone, although the term is now defunct because of difficulties in distinguishing that granite from others which occur in Hong Kong. The granite batholith was intruded into older volcanic rocks in the late Jurassic/Cretaceous period, the volcanic rocks in the harbour area having been stripped away, exposing the granite (Figure 7). The granite is predominantly fine to medium grained (typically 2mm) and is associated sometimes with granodiorite, quartz syenite and other igneous rocks.

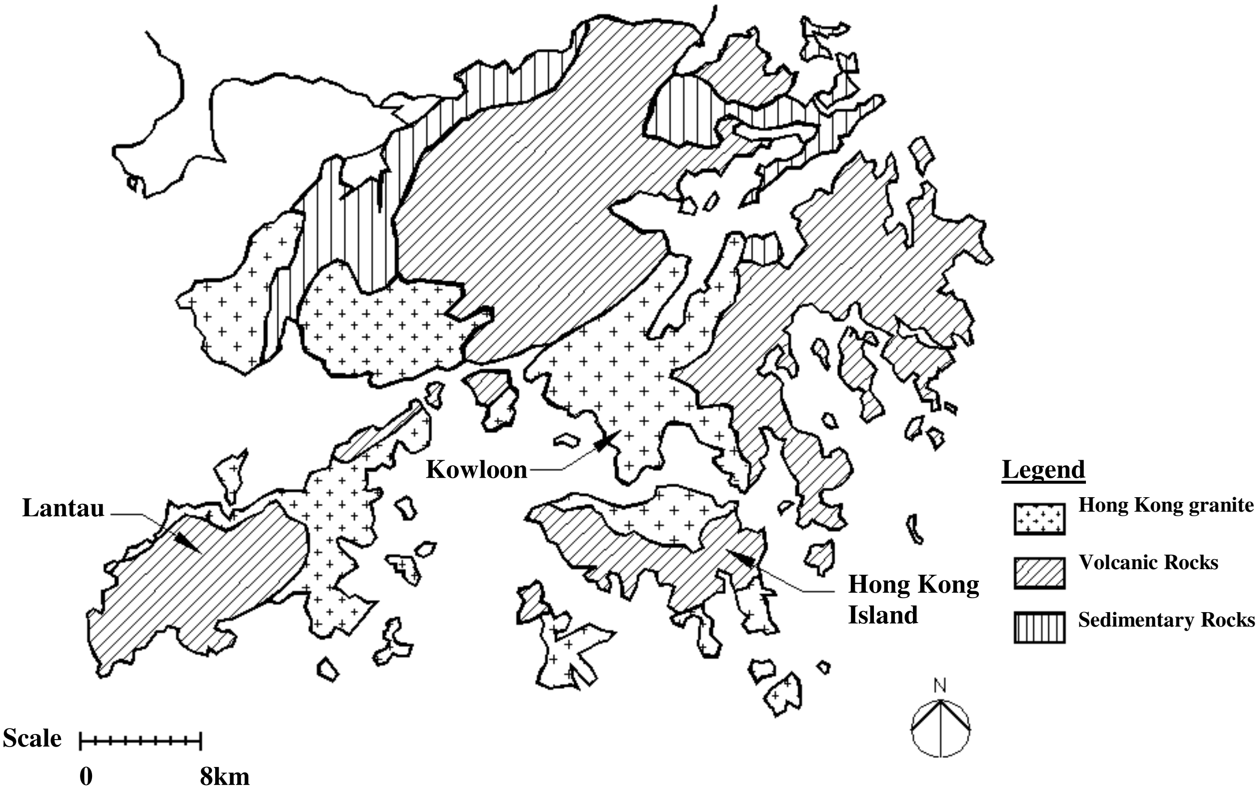


Figure 7 : Hong Kong (after Lumb, 1962)

Weathering of the granite to a depth of 30m to 80m below current ground surface is common. Locally, deeper weathering has been found, particularly associated with faults. Under the harbour weathered rock has been encountered in tunnels to a depth of at least 140m below sea level. Of the total depth of the weathered mantle, a significant proportion is generally Zones 5 and 6, with grades IV and V predominating within those zones.

The weathering classifications for strong rocks recommended in Anon (1995) and in BS 5930 (1999) are similar to those commonly used in Hong Kong and outlined in Anon (1988). Experience with the Hong Kong Granite has been a significant factor in the development of the current systems of classification and nomenclature. As the mass of the Hong Kong Granite weathers it typically develops most or all of the zones shown in Figure 4. Both the material and mass classifications are used routinely and usefully within soil and rock descriptions.

Bukit Timah Granite

The Bukit Timah Granite is a generic term applied to a suite of igneous rocks, principally granite, microgranite and grandodiorite found in the centre of Singapore (Figure 8). The granite in the North West of Singapore, near Mandai, has been the subject of particular study prior to cavern construction (Zhao et al. 1995). The nature of the weathered rocks in this area contrasts in some respect from the weathered Hong Kong Granite described above. Although there is often a thick weathered mantle, the majority of the weathered material encountered is usually residual soil (Grade VI). Table 1 shows the results of three test boreholes in the Mandai area, showing the preponderance of Grade VI material, with very limited depths of completely weathered (Grade V) material encountered. Also evident in these borehole records, and in exposures in quarries on the Mandai area, is a sudden transition from Grade V to Grade I or II rock. There is little evidence in the quarries or boreholes of the classic strong rock weathering profile as shown in Figure 4. The weathering appears to be stratified in roughly horizontal layers with little evidence of corestones, as shown in Figure 9 (Zhao 1993). Major penetration of weathering below the general zonal boundaries is usually limited to a few large joints and faults. The predominance of Grade VI material in the weathered material found at Mandai is a common feature throughout the Bukit Timah Granite. However, the weathering profile found in the Mandai area is not necessarily representative of other areas of the Bukit Timah Granite. Core boulders were reported in the weathered granite during the construction of the Bukit

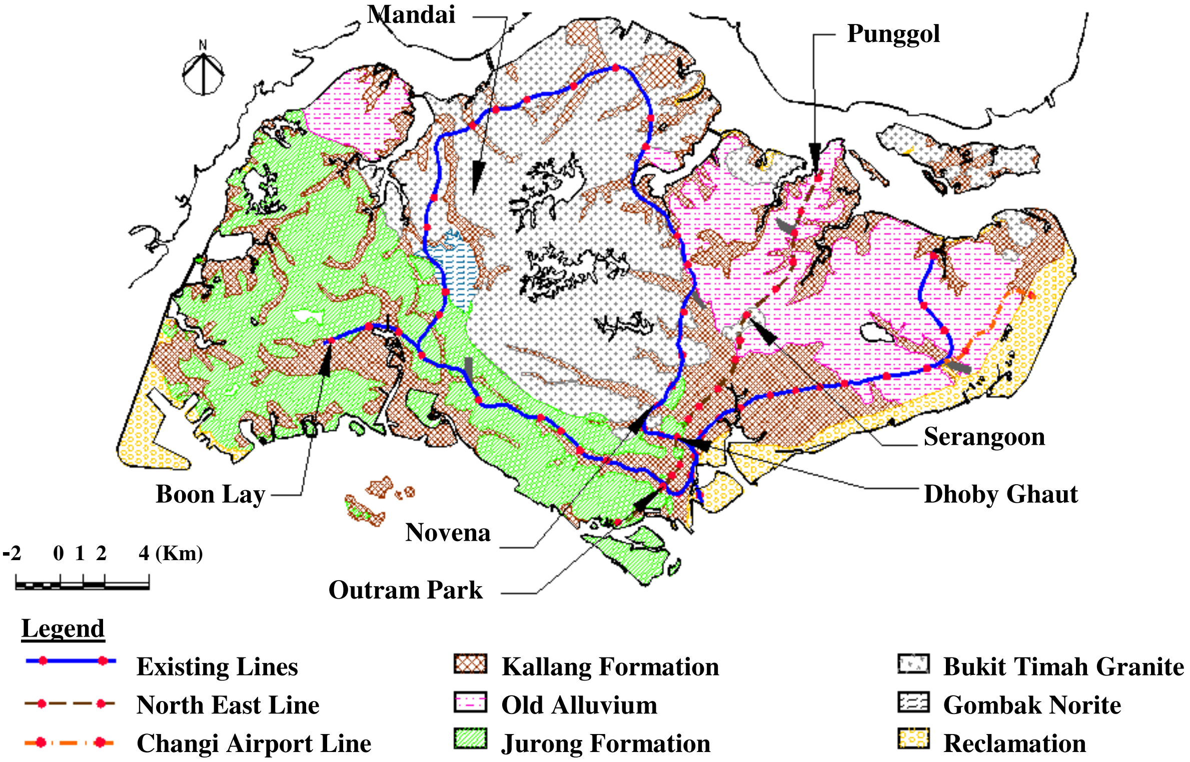


Figure 8 : Singapore

Timah Expressway. Towards the east of the area where the Formation is found, in the Serangoon area, core boulders are also found, and the weathering pattern is generally of the type shown in Figure 4.

Table 1 : Summary of three boreholes drilled in the Mandai area for cavern feasibility study (after Zhao et al. 1995)

Borehole 2		**Borehole 7**		**Borehole 11**	
Depth (m)	Weathering Grade	Depth (m)	Weathering Grade	Depth (m)	Weathering Grade
0-0.5	Top soil	0-1.0	Top soil	0-2.2	Fill
0.5-10.0	VI	1.0-18.1	VI	2.2-26.4	VI
!0.0-18.2	V	18.1-22.0	V	26.7-38.4	V
18.2-29.0	I	22.0-24.3	II	38.4-43.1	Fault zone
29.0-30.3	II	24.3-31.9	Fault zone	43.1-50.0	II
30.3-100	I	31.9-33.8	II	50.0-58.0	III
		33.8-90.0	I	58.0-68.3	II

The differences between the weathering of Bukit Timah Granite and Hong Kong Granite, and within different areas of the Bukit Timah Granite, can be ascribed to variations in climate, topography and the nature of the rock itself. The average annual temperature and rainfall in the two cities is compared in Table 2. The major differences are the annual average temperature and the seasonal nature of rainfall in Hong Kong. The high temperature and consistent monthly rainfall in Singapore are likely to be the major factors in the relative thickness of the Residual Soil there. Another factor may be the relative lack of topography. The highest point in Singapore is Bukit Timah Hill at 161m above mean sea level. The urban areas of Singapore are typically 5m to 10m above mean sea level, and hills over 30m are rare. In contrast the

Figure 9 : Weathering profiles in the Bukit Timah Granite observed at a quarry in the Mandai area of Singapore

topography in Hong Kong consists largely of steep hills, rising to up to 900m above sea level. In the steeper Hong Kong hillsides, much of the Residual Soil of the Hong Kong Granite would have been removed, either by erosion or in the frequent slope failures.

The sharp transition from Grade V to Grade I or Grade II material in the Mandai area appears to be due to the very low permeability of the rock mass in the area; Zhao (1993) gives an average value of rock mass permeability of less than 10^{-9} m/s. In the Serangoon Road area, the Bukit Timah granite exhibits the typical strong rock weathering profile, with corestones, as shown in Figure 4. The measured mass permeability of the Grade I/II rock in this area is typically between 10^{-6} and 10^{-7} m/s. This value is similar to the typical permeability for Hong Kong Granite (10^{-5} to 10^{-7} m/s), with similar results in terms of the development of the weathering profile.

Table 2 : Climatic conditions in Hong Kong and Singapore

	HONG KONG	SINGAPORE
Mean Annual Temperature (^{O}C) Annual Temperature range (^{O}C) (Monthly mean)	20.9 13 to 32	26.9 23 to 34
Mean monthly rainfall (mm) Monthly rainfall range (mm)	185 23 to 391	200 170 to 260

Jurong Formation

The Jurong formation underlies much of the western and southwestern areas of Singapore (Figure 8). The Formation consists of a sequence of Sedimentary Rocks of Late Triassic to early Jurassic age. The Formation includes beds of siltstone, mudstone, sandstone, conglomerate and limestone. The rocks have been heavily folded and faulted, and some metamorphism is apparent.

Much of the underground construction work that has encountered the Jurong Formation has been in the Central Business district, often close to the Jurong Formation/ Bukit Timah Granite interface. In this area the rocks of the Jurong Formation dip steeply, typically at between 50^{o} to 80^{o}, and comprise largely mudstone, siltstone and sandstone beds. Beds of quartzite have been recorded (Shirlaw et al. 1990) within the generally slightly metamorphosed rock. The conglomerates and limestone beds have so far only been recorded at and to the west of the World Trade Centre and Mount Faber.

Table 3 : Ranges of Unconfined Compression Strength for sedimentary rocks in Singapore

Formation	Rock Type	UCS Range (MPa)
Jurong	Conglomerate and Meta-conglomerate	32-102
Jurong	Sandstone and Quartzite	35-185
Jurong	Siltstone and meta-siltstone	21-53
Jurong	Mudstone and meta-mudstone	2 to 36
Jurong	Limestone and low grade marble	45 to 162
Old Alluvium	Sandstone	1 to 6
Old Alluvium	Mudstone	1 to 2

As shown in Table 3, most of the sandstone and siltstone beds of the Jurong Formation are moderately strong to very strong when fresh. The mudstone beds are weak to moderately strong. Due to the folding, many of the beds are heavily fractured even when fresh. Some of the boreholes drilled for a cavern study showed RQD values at around 10% even at a depth of 100m, Zhao et al. (1999). As the mudstone and siltstone rocks weather the mass of the rock loses strength at the same time as the rock mass fragments. The action of weathering on the mudstone and the siltstone beds further increases the fracturing. At an advanced stage of weathering the rock reduces to a mass of gravel size lithorelics. The weathering of the sandstone and quartzite beds is much more variable. Some of the sandstone beds are moderately strong when fresh. These beds can weather to the degree of adjacent mudstone or siltstone beds. However, the quartzite beds, in particular, are very resistant to weathering. They are generally either massive or contain only infrequent joints. So there are two variables in the weathering of the beds: the nature of the particular rock, and the initial degree of fracturing induced by folding. With the individual beds dipping steeply, this combination results in a very high degree of variation in ground conditions. Figure 10 shows local conditions mapped in a tunnel, with weak, highly weathered, fractured mudstone in direct contact with a steeply dipping bed of very strong quartzite.

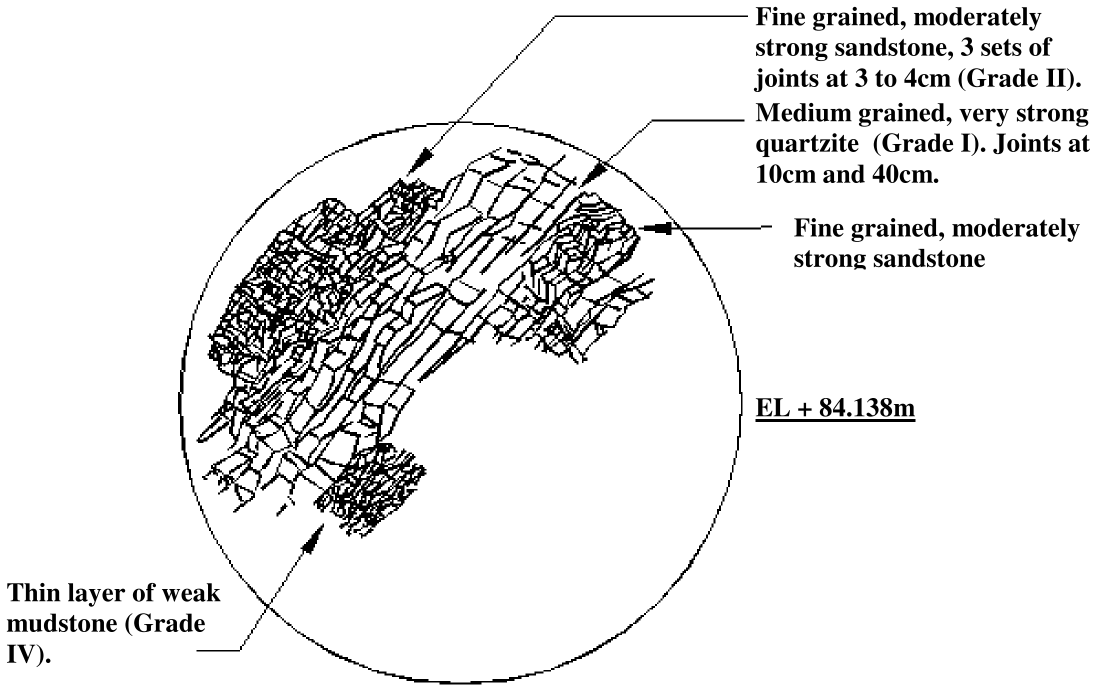


Figure 10 : Quartzite bed encountered in tunnel face, Jurong Formation, Singapore

The description of the weathering of the Jurong Formation rocks has been problematic. The formation includes both strong and weak rocks. As the strength of the fresh rock varies considerably, it is difficult to establish simple criteria for the degree of weathering. Traditionally, the site investigation industry in Singapore has combined the 6 weathering Grades into 3 composite grades. The composite grades are:

S1, for fresh and slightly weathered rock
S2, for moderately weathered and highly weathered rock
S4 for completely weathered rock and residual soil

The use of composite grades is allowed under BS 5930 (1999), although the recommended combinations are different from those traditionally used in Singapore. Poh et al. (1987) recommended the use of the full 6 weathering grades in the Jurong Formation, and against the use of the traditional composite grades. For engineering purposes, the 3 composite grades do not distinguish adequately between the behaviour of rock of different degrees of weathering, and many local consultants now subdivide the 3 composite grades, effectively returning to the use of 6 weathering grades. As the majority of the rocks of the Jurong Formation were moderately strong to very strong when fresh, it is reasonable to apply the full 6 grades of weathering, and these will be used for this paper.

In the Jurong Formation the weathering mainly penetrates down beds rather than individual joints, so core boulders are not generally found. Zonal descriptions are therefore not appropriate, and will not be used.

It is common to include in the Jurong Formation a colluvial deposit known as the 'Singapore Boulder Bed', Pitts (1984). This deposit, which occurs under much of the Central Business District, consists of often large quartzite boulders in a matrix of hard clayey silt. When first recorded, by Nowson (1954), it was thought to be weathered Jurong Formation rock, with the boulders being core boulders of the type found in weathered igneous rocks. However, subsequent work has shown this deposit to be a colluvial deposit originating locally from the Rimau Facies rocks of the Jurong Formation, Han et al. (1994). Boulders of up to 250m^3 in size and up to 185MPa in unconfined compressive strength have been recorded in this deposit. The clayey silt matrix has an undrained shear strength of typically 250kPa to 1MPa. Although not technically a weathered rock, some reference to tunnelling in the Boulder Bed will be made as it provides an interesting comparison with tunnelling experience in weathered igneous rock with core boulders.

The Jurong Formation also includes beds of limestone and dolomite. The weathering characteristics of the limestones and dolomites are very different from the clastic rocks, Guo and Zhao (1998). So far, very little underground work has been carried out in these rocks in Singapore, although they have been proposed as suitable for cavern construction (Zhao et al 1999). Because of this limited experience, these two carbonate rocks are not discussed further in this paper.

Old Alluvium

The Old Alluvium underlies much of the eastern area of Singapore. It is of Pleistocene age. The Old Alluvium has been found to a depth of 149m below mean sea level, and forms a series of low hills 20 to 30 m high in the eastern half of Singapore. According to Anon (1976) it was laid down in the last Wurm

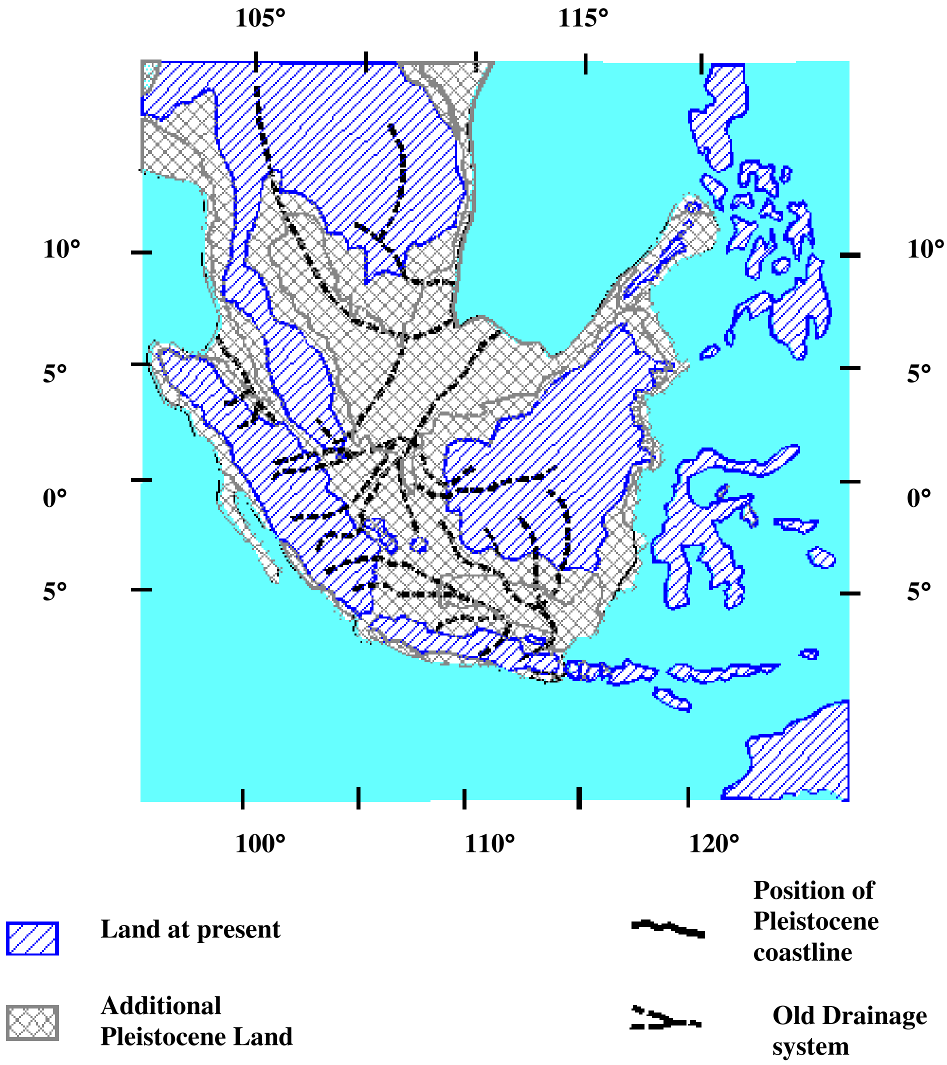


Figure 11 : Pleistocene land and drainage systems (after Gupta et al. 1987)

glaciation, when the level of the South China Sea was at least 150m lower than the current level. Gupta et al. (1987) suggest that the area between Peninsula Malaysia and the island of Borneo formed a massive drainage basin leading to the much reduced South China Sea (Figure 12). As sea levels rose again, a massive thickness of alluvial material was deposited into this basin. The alluvial material appears to consist of mechanically weathered granite eroded from the mountains of what are now Indonesia and Malaysia. Although much of the deposit consists of slightly rounded quartz particles, up to 10% or more of the deposit at depth consists of fresh feldspars. Based on exposures in old sand quarries in Singapore, the majority of the deposit consists of beds of well-graded sand with some gravel and up to 30% fines. Smaller beds of uniform sand and of clayey silt are also found. Since deposition the material has been cemented, so that the sand has become weak feldspathic sandstone, and the clayey silt beds, very weak mudstone. It has been suggested that the cementing material is silica (Anon 1976). Typical unconfined compressive strength values are given in Table 3.

The Old Alluvium contains very occasional joints. These are so infrequent that the material is generally massive. Typical values of permeability are in the range of 10^{-7} to 10^{-8} for the sandstone and less than 10^{-8} for the mudstone. Because of the general lack of joints, the permeability of the rock is due to flow through the weak rock mass rather than along joints.

Following deposition and cementation, the Old Alluvium has been subject to tropical weathering. Weathering leads to both loss of cementation and decomposition of the feldspars. Due to the general absence of joints the weathering proceeds down from the ground surface with a weathering front that typically has a profile similar to the ground surface.

Due to the low strength of the Old Alluvium, the recommended approach for weak rocks in BS5930 (1999) can be applied to it, although the rock does not appear to develop increased fracturing with weathering. The main evidence for weathering is colour change and loss of strength. Due to the low intact strength of the Old Alluvium, the Standard Penetration Test is commonly used to differentiate the various classes of weathered rock. Typical ranges of SPT for the weathering classes are shown in Table 4.

Table 4 : Classification for Old Alluvium

Class	Descriptor	Characteristics	Typical SPT, Blows/300mm
A	Unweathered	Original strength	>50
B	Partially Weathered	Slightly reduced strength	
C	Distinctly weathered	Further weakened	30 to 50
D	Destructured	Greatly weakened, often mottled, bedding disturbed	10 to 30
E	Residual	Bedding destroyed	>10

CONSTRUCTION ISSUES – GENERAL BEHAVIOUR

Weathered rocks are complex materials that can behave in a way that is quite distinct from fresh rocks or alluvial soils. Depending on the nature of the original rock and the conditions under which it weathers, some or all of the following may be observed:

- A high degree of local variation in material properties due to uneven penetration of weathering
- Residual cementation even in materials which appear soil-like
- A high degree of fracturing
- Mass permeability values which are much higher than would be expected based on fines content
- The development of swelling clay minerals as part of the weathering process
- Slaking materials
- Collapsible materials
- Localised change in properties, especially where affected by hydrothermal changes

For underground construction, a primary issue is how a material behaves when exposed below the ground water table. Although this behaviour can be predicted from engineering properties, classification in terms of the 'Tunnelman's Classification', Heuer (1974), based on field observation, is still of considerable value. This is particularly so for weathered rocks where the application of principles based on conventional soil mechanics can be debatable, because of factors such as those listed above. The 'Tunnelman's classification' is very limited for cohesive materials, where undrained strength is dominant during tunnel excavation. For cohesive soils the classification can be expanded by reference to the stability number of the tunnel (Broms and Bennermark 1967). The first part of this review will assess the behaviour of the selected weathered rocks, for various weathering grades, in terms of the 'Tunnelman's classification', expanded where necessary by reference to stability numbers. This will be based largely on experience with tunnelling with open face shields and the New Austrian Tunnelling Method (NATM), as applied in soils and weak rocks. After the reviewing the general behaviour of the weathered rocks, a number of construction issues specific to weathered rocks will be covered in some detail.

The majority of the tunnelling described below involved shield tunnelling, by open face or Earth Pressure Balance (EPB) machines. The shield tunnelling was carried out while erecting segmental precast concrete linings within the tailskin of the shield. This discussion will focus on stability at the tunnel face and ground movements associated with the construction of the tunnels, rather than the choice and design of the permanent tunnel support. For excavations, however, there will be some discussion of the choice of temporary ground support systems in the various conditions.

Hong Kong Granite

The majority of the experience of tunnelling through weathered Hong Kong Granite has come from the construction of the Hong Kong Mass Transit Railway. A high proportion of this tunnelling was through completely weathered granite (Grade V). The behaviour of this material was investigated in a trial shaft and tunnel reported by Haswell and Umney (1978). When exposed below the water table in free air, the Grade V weathered granite behaves a 'flowing ground'. This was confirmed by two major tunnel inflows experienced during the construction of the Hong Kong MTR, at North Nathan Road on the initial system and at Hennessy Road during the construction of the Island Line. Both inflows were huge, resulting in massive craters in the roads above. The inflows occurred under similar conditions, with a tunnel in Zone 3 granite approaching a known transition into Zone 6 (mainly Grade V) granite. The tunnels were taken close to the interface in free air, and the inflows occurred while the face was still in the Zone 3 granite. Failure appears to have started along seams of Grade V rock connected to the main area of Zone 6 rock. A key factor in both inflows seems to have been how close the face was to the transition to a full face of Grade V rock, which in both cases was a few metres. Grade V rock was often encountered in thin seams in tunnels being driven in predominantly less weathered rock in free air. Provided that these seams were reasonably thin, and that there was no large extent of Grade V (i.e. Zone 6) rock close to the tunnel, no major inflow or loss of ground resulted. The tunnelling for the MTR construction was mainly at depths of up to 30m below ground surface, and the behaviour described above is for this experience. At greater depths, the higher water head is likely to provide more adverse behaviour.

Almost all of the tunnelling, by open face shield or NATM, in Grade V Granite was carried out in compressed air or in ground treated with silicate grouts. Compressed air pressures were typically set to balance the ground water pressure at or just below the axis level of the tunnel. The Grade V granite has a small residual bonding between the angular grains of quartz and feldspar, with many of the latter having been decomposed to kaolin agglomerations. Typical effective stress parameters used for the Grade V Granite in design are a c' of 8kPa and a ϕ' of $37^{O.}$ Under compressed air the Grade V material generally stood as a vertical face in the typically 6m to 8m diameter tunnels. However, the relic joints of the original rock, filled with fine weathering products, acted as planes of weakness. Under compressed air, the effect of the relic joints on stability was limited. Occasionally large pieces of intact Grade V material would slip at the exposed face due to the presence on an adversely orientated relic joint. As a result some support was usually provided to the face and crown, usually by face grids and extendable hoods, as a safety measure. The Grade V material was weathered to a soil-like consistency, and was readily excavated with a pneumatic spade or back-hoe.

The 'Tunnelman's classification' is based on soils, and does not cover rock behaviour. The Grade V Granite exhibits predominantly soil-like properties, and has therefore been discussed in the context of the classification. The Grade I, II and III materials behave as rocks, albeit progressively weakened by the weathering, particularly along the joints. The Grade IV material (highly decomposed granite) is material which can be cored with good recovery, but where the cores can be broken by hand. At this level of weathering the rock is microfractured by the weathering process. Due to the combined effect of microfracturing and alteration of the feldspars, the permeability of the Grade IV is generally high. Water inflow when tunnelling in this grade of weathered granite can be high. However, experience has shown that the Grade IV material usually has sufficient strength for the seepage not to cause instability. Tunnels have been successfully advanced in the Grade IV material in free air, although effective support has to be introduced rapidly after excavation.

The discussion on the classification of the behaviour of weathered granite given above has been based mainly on the various weathering grades. This is because for tunnelling in soil or in mixed face conditions it is the behaviour of the weakest or most mobile material that generally governs the need for, and magnitude of, the support pressure that is needed at the tunnel face. However, there are other effects that the various zones have on tunnelling, and these will be discussed below.

Bukit Timah Granite

Because of the predominance of Residual Soil (Grade VI) in the weathered mantle in Singapore, most of the open face tunnelling has been in this material. Open face tunnelling has been carried out using open face shields, drum diggers (unpressurised TBMs) and the NATM. The Grade VI residual soil has a relatively low permeability and high clay content, and is mostly excavated in free air. The Grade VI material typically has an undrained shear strength of about 100kPa at a depth of 20m (Poh et al. 1985). This strength gives a stability number of 4 for an unsupported tunnel face. As observed in the tunnels, this gives reasonable stability provided the tunnel is supported quickly.

Dykes of fresh microgranite and dolerite have been encountered during tunnelling in the residual soil (Poh et al. 1987). These dykes were fractured and heavily waterbearing. Although the dyke rock was strong, large settlements were recorded due to both tunnel advance and dewatering, Shirlaw and Doran (1988). This will be discussed further below.

Generally, only a relatively thin band of Grade V material is found between the residual soil and the less weathered grades of rock. This Grade is much more permeable than the residual soil. From the limited exposures that have been encountered, mostly for cross-passage construction, the Grade V Bukit Timah Granite, like the Grade V Hong Kong Granite, acts as flowing ground when exposed below the water table. Because of the limited amount of both the Grade V and Grade IV that have been encountered it is difficult to distinguish their behaviour. Grades I,II and III Bukit Timah Granite behave as rock.

Jurong Formation

Several tunnels have been successfully completed in the residual soil and completely weathered (Grades VI and V) Jurong Formation, using open face shields in free air. The Grade VI and V mudstone and siltstone have significant, short term, undrained shear strength, of typically 150 kPa. This strength gives a stability number for an unsupported face, at a depth of 20m, of 2.7. This is consistent with the observed stability of the tunnels. The stability of the tunnel face was, however, dependant on adequate cover to weaker, more recent deposits. Grade V weathered sandstone is typically very dense and has some, small, residual cementation. When encountered in the tunnel face, the Grade V sandstone has behaved as a slow to fast ravelling material, Hulme and Burchell (1992), and face timbering has been necessary to maintain heading stability.

The highly weathered (Grade IV) and moderately weathered (Grade III) Jurong Formation rocks are hard to distinguish. The rocks of these weathering grades are often fractured, and permeable. Generally, they behave as slow to fast ravelling ground. In certain circumstances the highly weathered rock can behave like running ground. With the discontinuities are very closely spaced, the weathered mudstone and siltstones can form a mass of gravel size fragments. With an adverse joint orientation and with weathering products on the joint surfaces, the rock can be highly unstable on exposure in a tunnel face. Similar behaviour has also been observed in fault zones in the rock. Under these conditions open face tunnelling has been very difficult, with the need to use both compressed air and full face timbering. Even so, large (50 to 400mm) settlements have been recorded at the surface (Hulme et al. 1990). In contrast to the poor behaviour of the Grade IV and III rocks of the Jurong formation, the Grade I and II rocks are generally stable provided that support is provided reasonably close to the tunnel face.

Free air tunnelling has also been carried out successfully in the Singapore Boulder Bed. Both NATM and open face shields have been used in this deposit. The matrix is a hard clayey silt with an undrained shear strength estimated by Shirlaw et al. (1990) to be at least 250kPa. This gives a stability number for a 20m deep tunnel of less than 2, consistent with the observed behaviour during tunnelling.

Old Alluvium

There has been relatively little experience of open face tunnelling in the weathered Old Alluvium. Buttling and Shirlaw (1988) record the construction of a cross-passage, which was partly in the Class C Old Alluvium, at a depth of 16.5m below the ground water table. The Class C Old Alluvium was hard and stable on first exposure, but deteriorated over-night and required chemical grouting to stabilise it, so that the cross-passage could be excavated. The Class C and D Old Alluvium are typically well graded and exhibit a very small residual cementation. The permeability of the material is typically about 10^{-6} m/s, similar to a silt. The rapid deterioration of the material after exposure is similar to the behaviour of dense silts. Another factor in the rapid deterioration of the material could be loss of cementation under conditions of groundwater seepage, as suggested in Anon (1976).

In contrast to the weathered Old Alluvium, the unweathered Old Alluvium has proved to be a generally stable medium for open face tunnelling. Figure 12 shows an 8.44m excavated diameter NATM tunnel that was constructed as advance works for the Singapore Deep Tunnel Sewerage System.

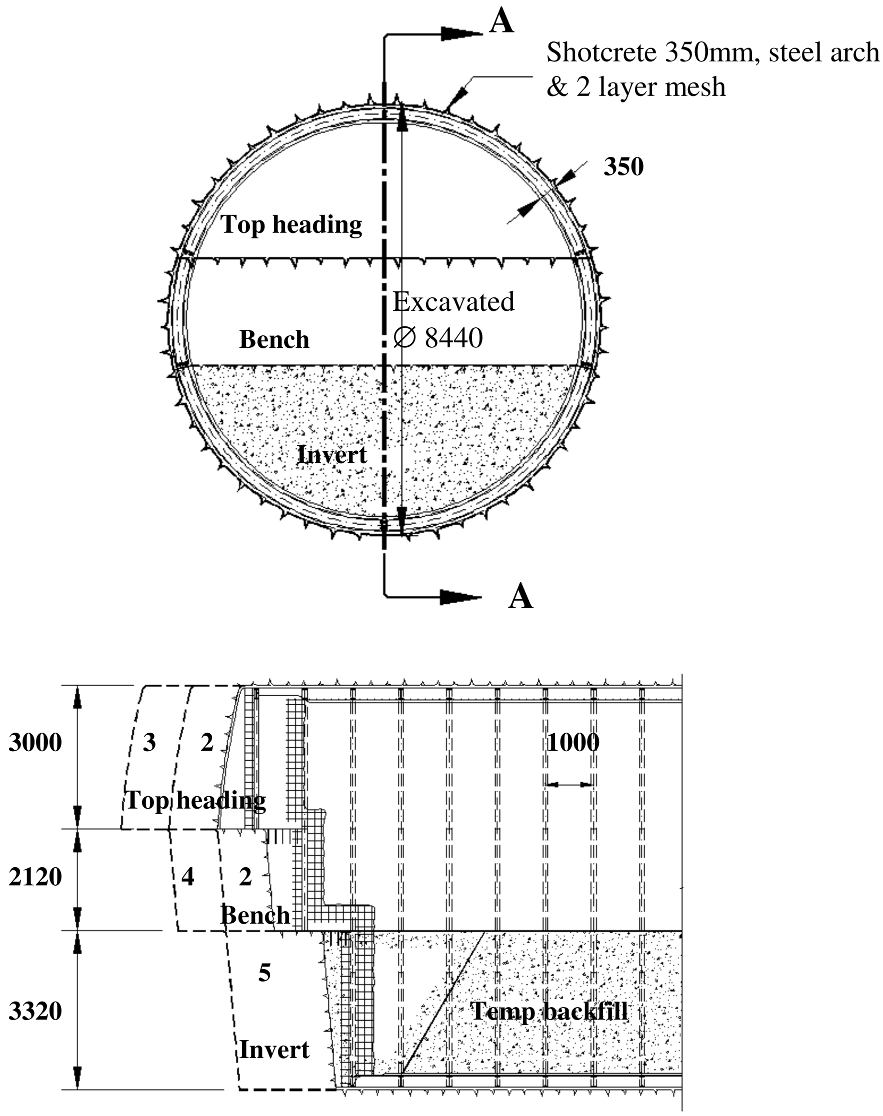


Figure 12 : NATM tunnel carried out in Class A Old Alluvium

The tunnel was constructed in free air, with shotcrete support. There was minimal seepage during construction and the maximum surface settlement was 25mm. Apart from this large NATM tunnel, 8 crosspassages with a typical external diameter of about 4m, have been successfully excavated through the unweathered Old Alluvium, in free air and up to 20m below the ground water table. So far, all of the evidence from tunnelling shows the unweathered Old Alluvium to be a stable material when exposed below the water table. Some of the very weak sandstones of the deposit are derived from poorly graded sands, and there is some evidence, from pile construction, that these very weak sandstones are unstable below the water table, as they rapidly become flowing ground. The evidence for this is, however, limited.

Support systems for deep excavations

A major factor in the choice of excavation support systems is the stability of the ground when exposed. In potentially flowing, running or rapidly squeezing ground it is necessary to use continuous walling systems, such as diaphragm, secant pile or sheetpile walls. In contrast, potentially ravelling ground can be effectively supported using soldier piles, while more stable ground can be supported using soldier piles or can be cut to steep slopes, possibly using anchors or soil nails to further improve overall stability. However, the choice of support system in an urban environment needs to consider the potential for settlement, both due to wall movement and due to consolidation. Consolidation settlements can be large where piezometric pressures fall significantly during excavation, particularly where there is a significant depth of compressible recent deposits overlying the weathered rock. Where an excavation is to be made in recent deposits overlying weathered rock it is therefore common to use diaphragm, secant or sheetpile walls for the excavation, even if the weathered rock does not need this type of support if only stability is considered.

Table 5 summarises the excavation support systems for the 31 underground stations constructed in Singapore. It can be seen that the use of discontinuous walling systems or slopes has been relatively infrequent, and generally only in areas where weathered rocks extend almost to the ground surface.

The behaviour of the completely decomposed Hong Kong Granite as flowing ground below the water table means that most excavations in Hong Kong are carried out within continuous walling systems.

Table 5 : Support systems used for the construction of the 31 underground stations in Singapore

Secant Piles	Diaphragm Wall	Sheet Pile	Soldier Pile & Lagging	Slopes
Chinatown, *M*	Braddell, *Granite (VI)* Newton, *M* Somerset, (Part) *M* Lavender, *M* Bugis, *M* Hougang (part) *OA* Kovan *OA* Potong Pasir *M* Boon Keng *OA* Farrer Park *M* Little India *Jurong (III to VI)* Clarke Quay *M*	Toa Payoh *Granite (VI)* Novena *M* Marina Bay *M* Somerset (part) *M* Dhoby Ghaut (N-S) *M*	Raffles Place *Boulder Bed* Outram Park (E-W) *Jurong (IV to VI)* Tiong Bahru *Jurong (V to VI)* Serangoon *Granite (VI)* Woodleigh *OA* Dhoby Ghaut (NEL) *Jurong (III to VI)* Outram Park (NEL) *Jurong (III to VI)* Harbourfront *Jurong (III to VI)*	Orchard *Granite (VI)* City Hall *Jurong (Boulder Bed, VI)* Tanjong Pagar *Jurong (III to IV)* Punggol *OA* Sengkang *OA* Buangkok *OA* Hougang (part) *OA*

Key: Lines: (N-S) North –South Line
(E-W) East West Line
(NEL) North East Line

Predominant ground conditions: *M* *Marine Clay*
OA *Old Alluvium*
Granite (Grades)
Jurong (Grades)

DESIGN AND CONSTRUCTION ISSUES

Some of the major engineering problems with weathered rocks and soils are discussed in the 1990 report of the Geological Society Engineering Group Working Party (Anon 1990). The issues discussed in that report are related primarily to piling, site investigation and site formation. For major underground construction, similar general issues apply, but the details can be significantly different. A number of cases will be presented below to illustrate some of the particular issues of underground construction in weathered rocks.

As discussed above, there is a major limitation in discussing only the selected weathered rocks. The particular climatic conditions in Hong Kong and Singapore preclude certain results of weathering which are found in other areas of the world. Reference is therefore made to some published experience in other weathered rocks to illustrate the potential issues involved.

Permeability

For tunnelling and underground construction below the water table, the permeability of the ground is a major factor in determining the behaviour of the ground and the type of construction methods that need to be used. It is common, for deposited soils, to assess the permeability of the soil by correlating with the gradation of the soils. Common formulae for this correlation are the Hazen, Terzaghi and Rose formulae (Baker 1983). The simplest is the Hazen formula, which relates the permeability of a soil to the size of the smallest 15% of the constituent particles. Figure 13 shows a typical range of gradations for Hong Kong Grade V granite, where the testing has been carried out conventionally, using dispersant. The fines content is much higher than would be the case for an alluvial soil with the same range of permeability as the Grade V Granite (10^{-5} to 10^{-7}m/s). The difference between the permeability of the weathered granite and an alluvial soil of similar gradation is that the silt and clay size fraction of the weathered granite are mostly agglomerated. This effect of the residual rock structure means that most of the fine particles act like sand or gravel size particles, resulting in larger pores than would be the case for a similar alluvial soil. So weathered granite has a permeability and behaviour of a sand or silty sand, even though the grading curves presented in Figure 13 would not indicate this behaviour. For this reason, it is now common to carry out gradation testing for weathered rocks without the use of dispersants.

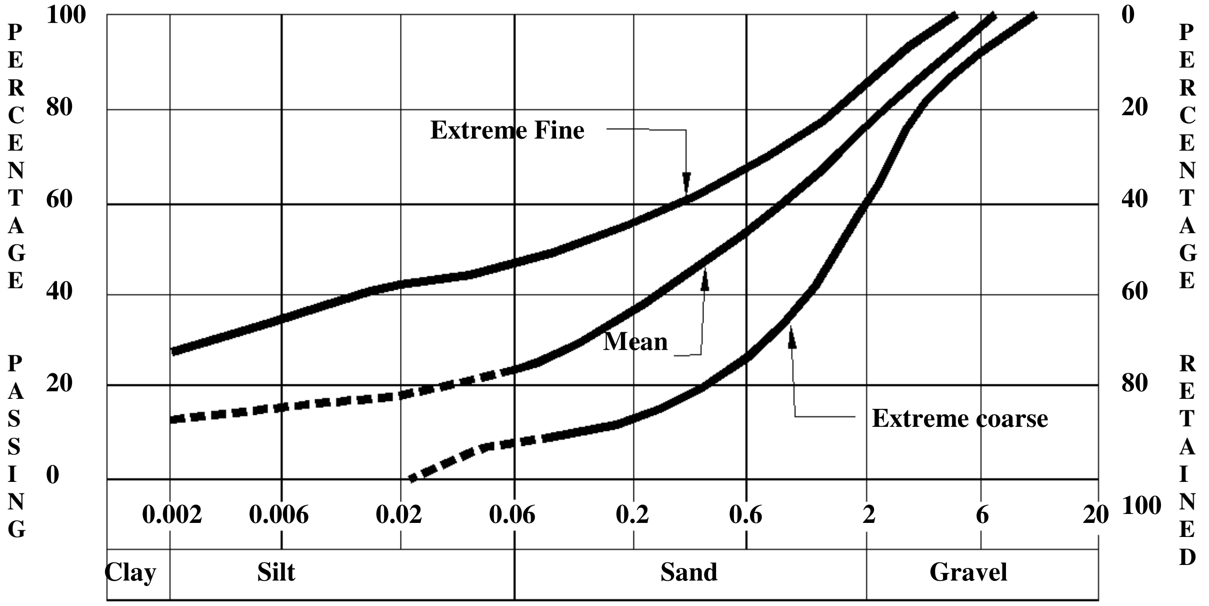


Figure 13 : Grading range for 71 samples of completely weathered granite (Grade V), Hong Kong (after Bruce and Shirlaw, 1985)

Residual soil (Grade VI) is material which has lost the structure of the original rock. The agglomerations of clay and silt size particles are mostly broken up and dispersed through the soil. As a result, residual soil is generally significantly less permeable than the Grade V completely decomposed rock that it derived from. This can be seen in the significant difference between the response to tunnelling of Grade V and Grade VI Bukit Timah Granite in Singapore.

Another implication of the relatively high permeability of the Hong Kong Grade V granite is that it can be grouted with chemical grouts. As described by Haswell and Umney (1978), Bruce and Shirlaw (1985) and Shirlaw and Cater (1986), pre-treatment by cement grouts followed by a main treatment using a silicate/reagent grout has proved effective in stabilising the Grade V Hong Kong Granite. This was commonly carried out to allow free air tunnelling below the water table, although it was also used as a means of protecting buildings (Shirlaw 1987). Over 1 kilometre of tunnelling has been successfully carried out in grouted Grade V granite using open face shields or NATM, in free air. Figure 14 shows a typical treatment pattern and initial grout injection for ground stabilisation ahead of tunnelling.

It is common to assess soil behaviour in terms of either sand ($>10^{-5}$ m/s) or clay ($<10^{-8}$ m/s) behaviour. This is because the pore pressures during construction are determined by steady state seepage in the case of

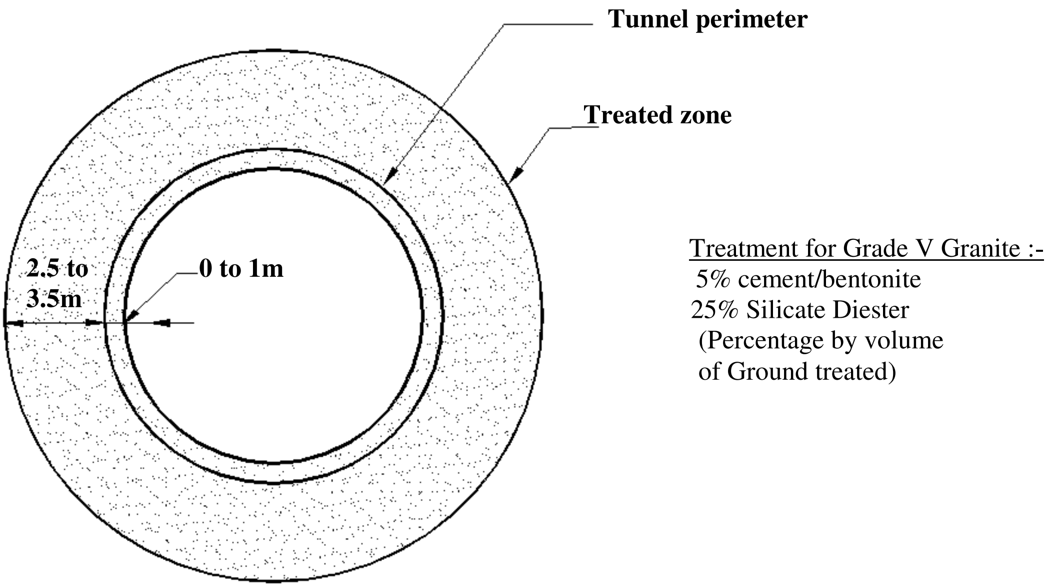


Figure 14 : Typical pattern of grouting for tunnels in completely weathered granite (Grade V) in Hong Kong.

sands, and by the pore pressure response to excavation in the case of clays. For this reason analysis is commonly carried out using effective stress parameters (drained analysis) for sands and total stress (undrained) for clays. Many residual soils and weathered rocks, including the selected ones, exhibit values for mass permeability which fall between these two convenient values (see Figure 15). The issue of the type of analysis appropriate for weathered rocks is discussed further below.

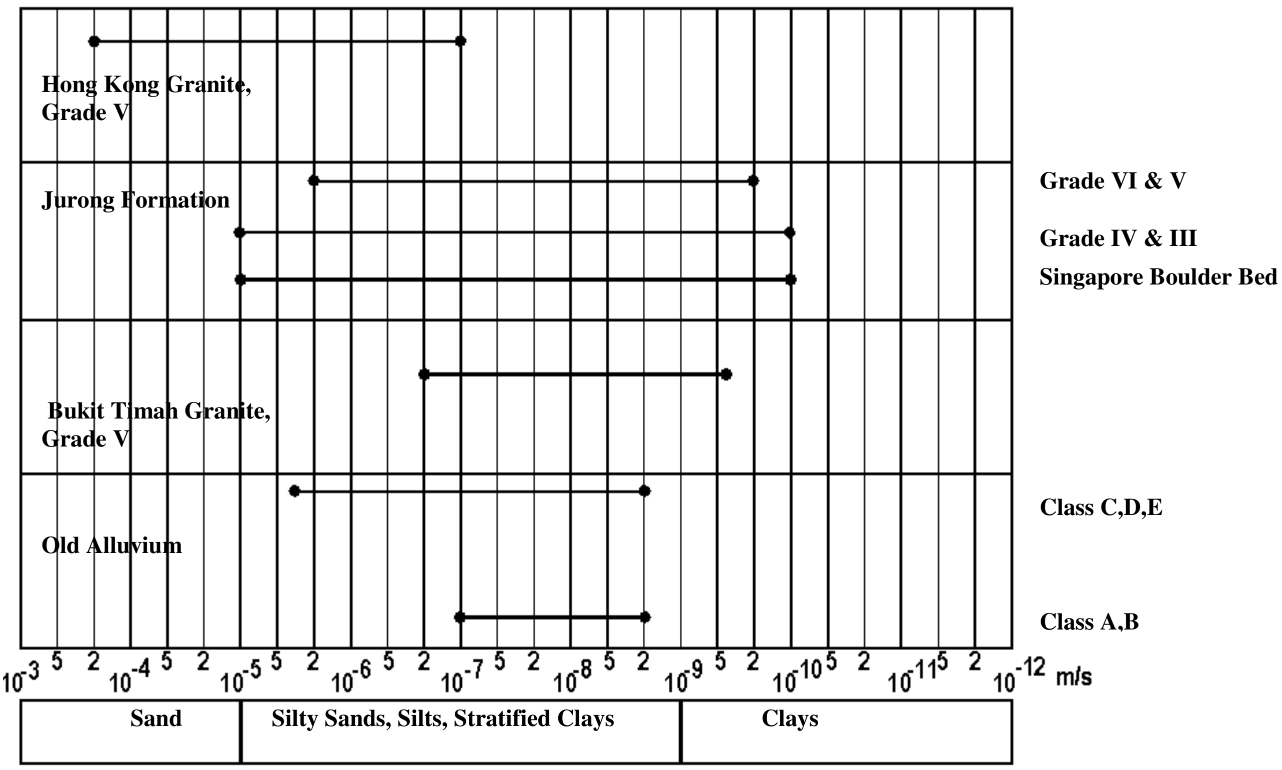


Figure 15 : Ranges of permeability for the selected weathered rocks

Mixed Face Conditions

Mixed face conditions provide a particular challenge to tunnelling. While mixed face conditions can be found in a variety of geological conditions, deep tropical weathering leads to conditions where a mixed face is particularly likely to be encountered. Buried valleys, typically up to 40m deep, eroded into the weathered rock and infilled with recent deposits, are common in both Hong Kong and Singapore. Willis and Shirlaw (1984) describe tunnelling through such a valley on Hong Kong Island. Figure 16 shows a section along the recently constructed North East Line of the Singapore MRT. It can be seen that a number of buried valleys cut across the line. The line runs right across Singapore Island, from South West to North East, and the conditions encountered can be considered typical for Singapore. When tunnelling in these conditions, tunnels that are less than 30m in depth (typical for subway tunnels) are likely to encounter a number of mixed faces comprising weathered rock and recent deposits. However, mixed face conditions are also common within weathered rock masses. In strong rocks, tunnelling in Zones 5 to 3 involves a continuously changing mixture of strong rock and much more weathered and weaker material. Mixed face conditions in the variably metamorphosed and weathered rocks of the Jurong Formation have already been shown in Figure 10. Based on experience, mixed conditions are potentially problematic with respect to tunnel stability, settlement over tunnels and for the construction of retaining walls.

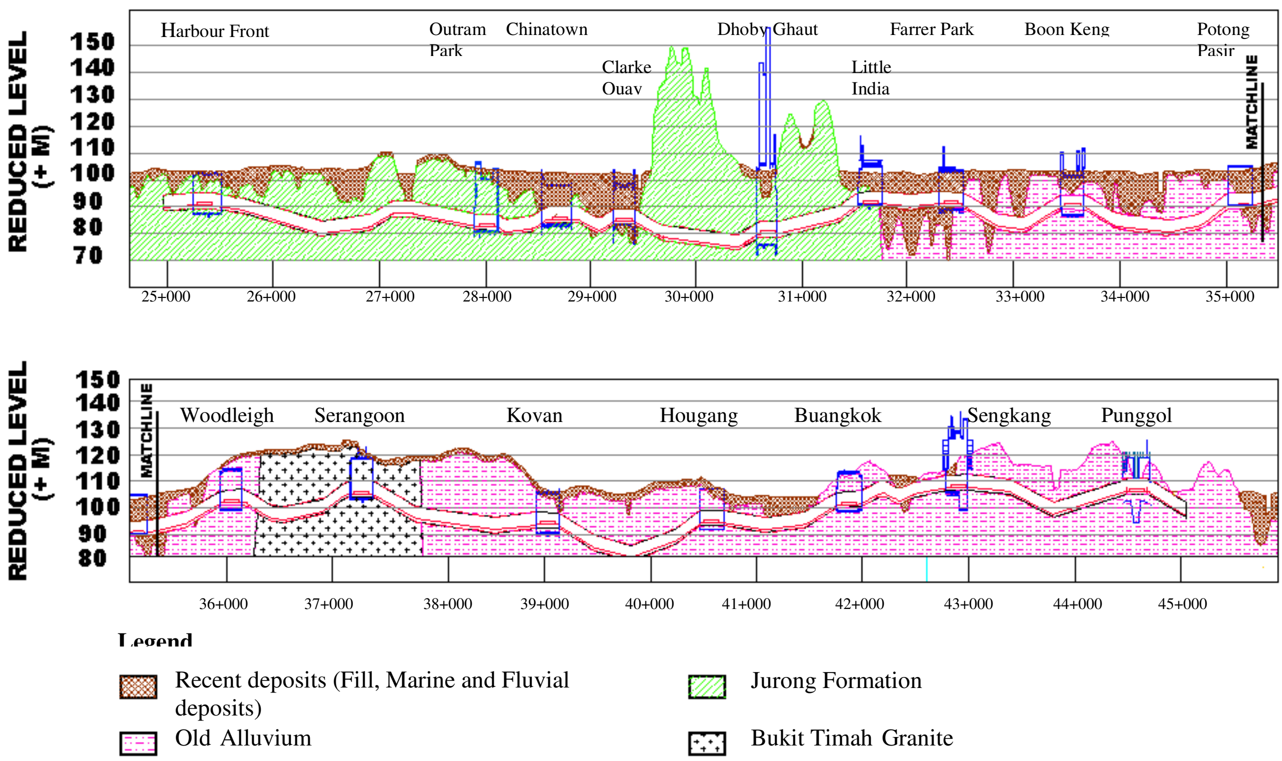


Figure 16 : General stratigraphy along the North East line in Singapore

Tunnel Stability

A mixed face is generally considered in terms of a combination of a strong material, such as rock, and a much weaker material, such as a soil. However, for stability, the major issue is one of relative mobility of the materials, rather than just strength. A mixed face of strong boulders and hard clay presents problems in terms of rate of excavation, but generally not in terms of heading stability. However, a combination of strong, stable rock with a more mobile material, such as a flowing, rapidly squeezing, or fast ravelling material provides conditions where the overall stability of the heading can be very difficult to control as well as difficult to excavate. Two cases of major inflows at such interfaces, in Hong Kong, have already been given above. Those inflows resulted from the use of conventional rock tunnelling methods too close to the transition from rock-like to soil-like conditions. The inflows resulted from a reluctance to apply compressed air while the tunnel was still in rock. Ironically, this particular type of mixed face condition has become problematic with the introduction of modern tunnelling technology. This is best demonstrated by giving an example of the type of problems this type of interface causes.

Along Upper Serangoon Road, near Serangoon Station, the tunnels for the North-East line have encountered a buried ridge of weathered Bukit Timah Granite. The tunnels are generally in the residual soil (Grade VI), and this has proved, as previously, a good tunnelling medium. However, at two locations the tunnels pass through areas of less weathered rock. One of these locations is shown in Figure 17. The Bukit Timah Granite in this area exhibits the classic strong rock weathering with zones of weathering of the type shown in Figure 5. The tunnels have been driven with two 6.58m OD Earth Pressure Balance machines (EPBM). The presence of rock along the alignment was identified before the machines were ordered, and the cutting head was equipped with both picks for soft ground and disc cutters for rock. The axis level of the two parallel bored tunnels is about 24m below ground level, and the centre to centre separation of the tunnels about 21m. A relatively thin band of Grade V granite was found between the residual soil and rock of Zones 3. For pressurised machines such as EPBMs there is little opportunity to log the tunnel face, so most of the information comes from the interpretation of the boreholes carried out in the area. The face condition through much of this area consisted of a varying mixture of completely weathered rock (Grade V) and less weathered rock. Except when tunnelling in the Grade VI granite, there was heavy water make due to the relatively high permeability of the weathered rock.

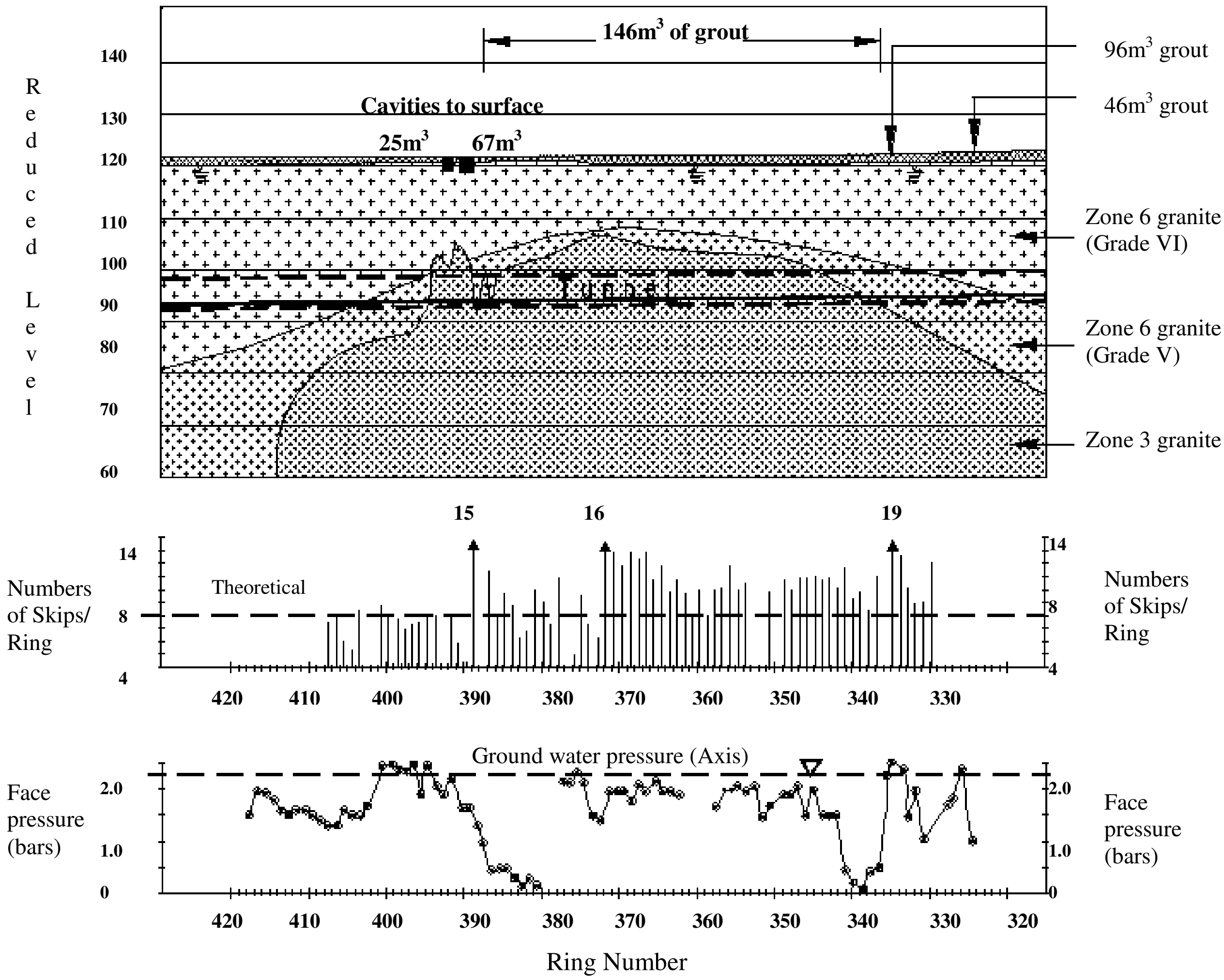


Figure 17 : EPB Tunnelling through buried ridge of weathered granite, Serangoon area of Singapore

These conditions proved extremely difficult for EPBM tunnelling, despite prior knowledge of the conditions. For successful EPBM tunnelling, the excavated soil has to be turned into a viscous, low permeability plug in the plenum chamber behind the cutter head (Refer to Figure 24 for a typical EPBM layout). This plug is maintained at the required pressure by controlling the volume of material removed via the screw conveyor and the rate of advance (and therefore volume of excavated material entering the chamber). Working in a mixture of Grade V weathered granite, which behaved as flowing ground under seepage pressures, and less weathered granite, presented two major problems for EPB operation. The problems related to the nature of the material in the chamber and the behaviour of the material at the face. The disc cutters with which the machine was equipped successfully cut the strong, less weathered granite. However, the spoil after cutting consisted largely of gravel and cobble size fragments of granite. Much of the more weathered Grade V granite entering the chamber consisted of sand size quartz particles. The material in the chamber was therefore neither plastic nor of low permeability. Initially only bentonite was added to this mixture as a conditioning agent, but this proved to have little beneficial effect. During the later stages of the tunnelling through this area a mixture of sand, sawdust, flyash, polymer and bentonite was injected into the chamber, and this did improve the characteristics of the spoil.

While the disc cutters could excavate the less weathered granite, progress was relatively slow, at typically 1 to 2 rings of 1.5m length per day. The contrasting mobility of the strong granite and the Grade V Granite resulted in overexcavation of the much more mobile Grade V material. Surface settlement markers were placed at about 25m centres along the road above the tunnels. The settlement records over the Southbound tunnel, the first to enter the area, are shown in Figure 18.

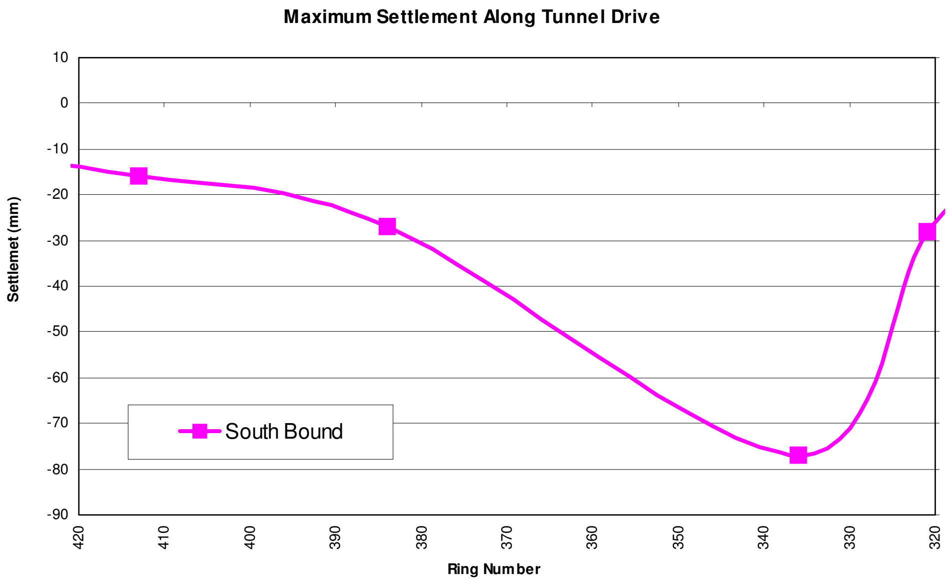


Figure 18 : Recorded surface settlement after South Bound tunnel cleared the weathered granite ridge, Serangoon area, Singapore

It can be seen that there was a local area of settlement as the machine entered the mixed face area. The settlement was much higher than the previous area where the tunnel was wholly in Grade VI material. However, the settlement records do not present the full picture of the over excavation during tunnelling. A regular check on the number of skips removed showed that overexcavation was taking place through much of the tunnelling where there was a mixed face. This overexcavation resulted in voids that migrated up through the overlying Grade VI Granite. Grouting was carried out from the surface. This filled many of these voids before they could migrate to the surface. However, in two instances, over the Southbound tunnel, the voids did reach the surface. Figure 18 shows the approximate location of the voids and their size, based on the volume of grout used. Also shown on Figure 17 is the volume of grout injected from the surface to fill voids before they migrated to the ground surface. All of the grouting was under gravity, so the volumes given can only represent voids. It can be seen that, while overexcavation was a problem throughout this area, the largest voids occurred as the machine entered and left the area of less weathered rock. The typical face pressures for each advance are also shown in Figure 18. It can be seen that it was particularly difficult to maintain the face pressure during the two transitions into and out of the Zone 3 rock. This is consistent with the observation that there was significant over excavation and resulting voids in these areas. Figures 17 and 18 show the behaviour of the Southbound tunnel, which was the first to reach the area. The parallel Northbound tunnel passed through the area about 50m behind the Southbound. Despite knowing the exact nature and behaviour of the weathered rock, the tunnelling for the Northbound drive followed the same general pattern as the Southbound. Large volumes of grout were injected from the surface to fill voids created by overexcavation, and one void migrated to the road surface. This void to ground surface occurred as the machine entered the transition to Zone 3 rock.

Similar problems had occurred on an earlier section of the Singapore MRT. Tunnels which were being constructed using drum diggers through the weathered Bukit Timah Granite encountered dykes of fresh dolorite in the otherwise Grade VI granite. Large localised ground loss occurred, leading to local collapse of the road pavement overlying the tunnels on at least 3 occasions. Ground water inflows also lead to consolidation settlement of up to 160mm, and extending almost 200m ahead of the tunnel face (Shirlaw and Doran, 1988).

Similar problems were also experienced during EPBM tunnelling in the weathered Jurong Formation, particularly in two conditions:

1) When the tunnelling encountered a mixed face of highly fractured, highly weathered mudstone or siltstone and massive, very strong, unweathered quartzite. The highly fractured, weak and weathered rock is a ravelling material, and the vibrations resulting from the machine while cutting the quartzite accentuated the ravelling. The resulting problem was similar to that experienced in the granite ridge at Upper Serangoon Road, with significant loss of ground locally where the mixed face was encountered.

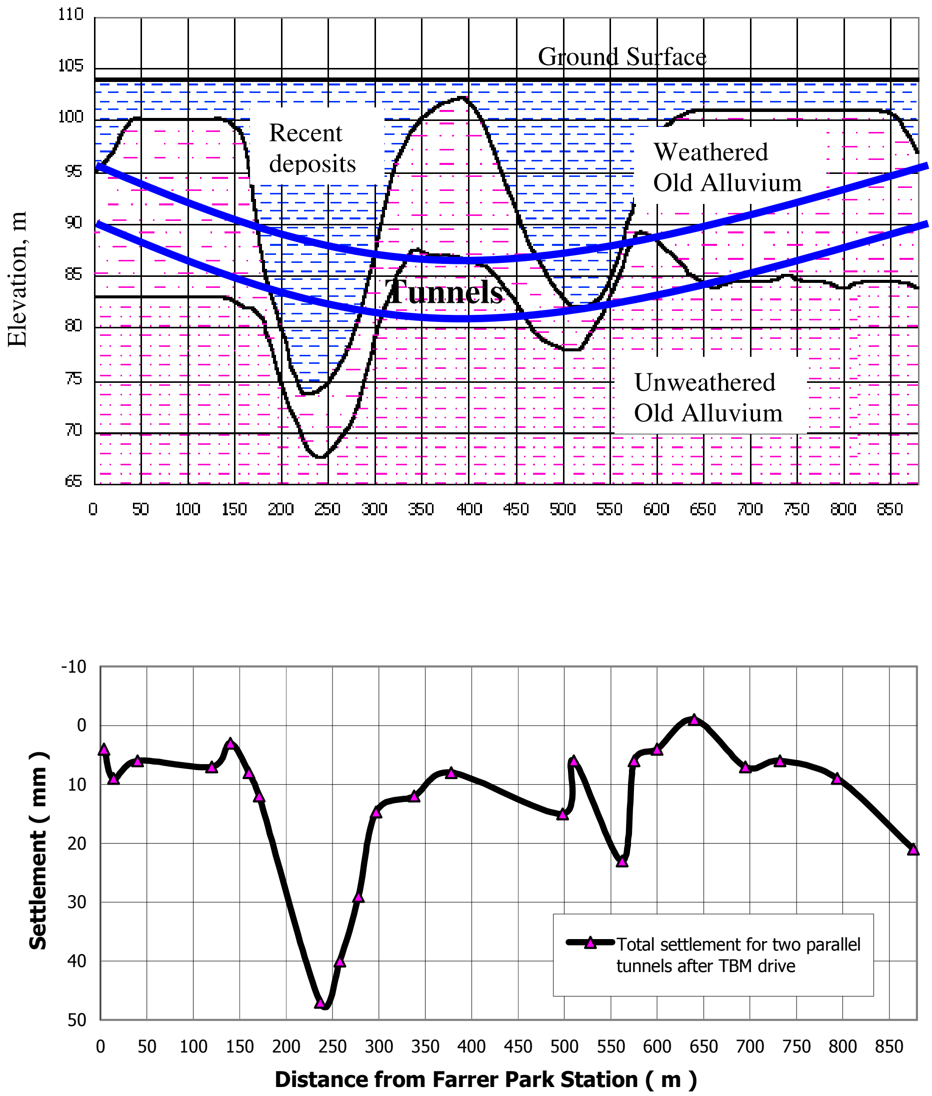


Figure 19 : Surface settlement after two tunnels completed using EPB shields between Farrer Park and Boon Keng

2) When tunnelling out of weathered rock into buried valleys of recent deposits, such as fluvial sand or marine clay. These recent deposits require a support pressure at least equal to the full water pressure; otherwise they flow or squeeze very rapidly. On a number of occasions during North East line construction such valleys have been encountered with the chamber either empty or underpressurised, resulting in significant ground losses. In theory these ground losses could have been avoided by advancing into the buried valleys with the machine fully pressurised. However, there was great reluctance by the operators to do this, due to the abrasion and heat resulting from pressurised tunnelling in the weathered rock. Heat and abrasion are in themselves major issues for EPB tunnelling in weathered rocks, and so will be discussed separately below.

The problems associated with mixed face tunnelling were inversely proportional to the strength of the rock encountered. In contrast to the problems experienced with tunnelling through the granite ridge at Serangoon, the transition between the weathered Old Alluvium to/from the more recent deposits and between the weathered Old Alluvium and the fresh Old Alluvium has been trouble free. Figure 19 shows the tunnelling through these interfaces between Farrer Park and Boon Keng Stations, and the measured surface settlements. It can be seen that the ground was well controlled through the interfaces. There was no indication of the type of high localised ground losses that occurred in the mixed face conditions in the stronger Bukit Timah Granite or Jurong Formation rocks. The relative ease of these interfaces was in part due to the nature of the Old Alluvium. The very weak to weak Old Alluvium did not provide the contrast in resistance that the granite/weathered granite interface provided at Upper Serangoon road. In addition, the pattern of weathering in the unjointed Old Alluvium is such as to provide a relatively smooth transition from the unstable recent deposits, throughout the potentially flowing weathered Old Alluvium into the generally stable unweathered Old Alluvium. In contrast the classic ‘strong rock’ weathering experienced in the granite resulted in a constantly changing mixture of intact rock and Grade V rock.

Settlement over tunnels

Some of the problems experienced with EPBM tunnelling in mixed face conditions have been discussed above. These problems included instability at the face of the tunnel leading to ground loss and surface settlement. Settlement problems related to tunnelling through mixed conditions have also been recorded for quite different reasons.

In both Hong Kong and Singapore, tunnels have been driven through mixed conditions using both open face shields and NATM. In Hong Kong the mixed conditions consisted of a mass of core boulders in a matrix of Grade V granite (i.e. weathering Zone 5). As the Grade V granite constituted a significant proportion of the face area, compressed air had to be used to maintain the stability of the face. The compressed air pressure was typically set to balance the hydrostatic pressure at or just below the level of the

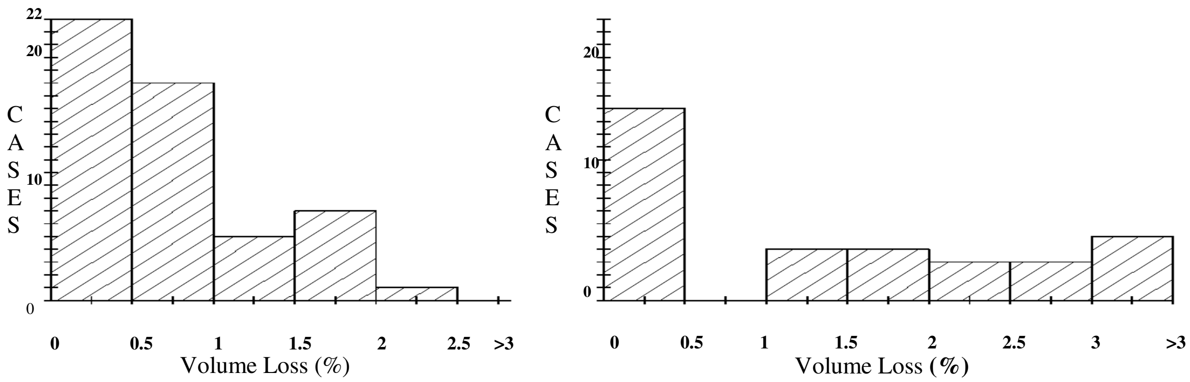


Figure 20 : Comparison of recorded Volume losses over shield driven tunnels through completely weathered granite (Zone 6), on left, with tunnels through completely weathered granite with core boulders (Zone 5), on right, in Hong Kong, based on Cater et al. (1984)

tunnel axis. Although the face was stable, the measured settlement over the tunnels was up to 3.5% volume loss. Both the maximum settlement and the range of the recorded settlements was significantly higher than for tunnels driven using identical methods but through only Grade V Granite (Figure 20). The contrast with tunnels driven through Grade V Granite using NATM was even more marked, as the volume loss was kept to less than 0.5% (Shirlaw 1990).

In Singapore Shirlaw et al. (1987) compare the settlements due to open face shield tunnelling through the Singapore Boulder Bed with those from NATM tunnelling. The range of measured Volume Loss for the two tunnelling methods are summarised in Figure 21. As discussed above, the Boulder Bed consists of very strong quartzite boulders in a hard clayey silt matrix. The faces of the tunnels were stable even in free air. However, the range of volume loss, and the maximum volume loss were much higher in the shield driven tunnels than the NATM tunnels.

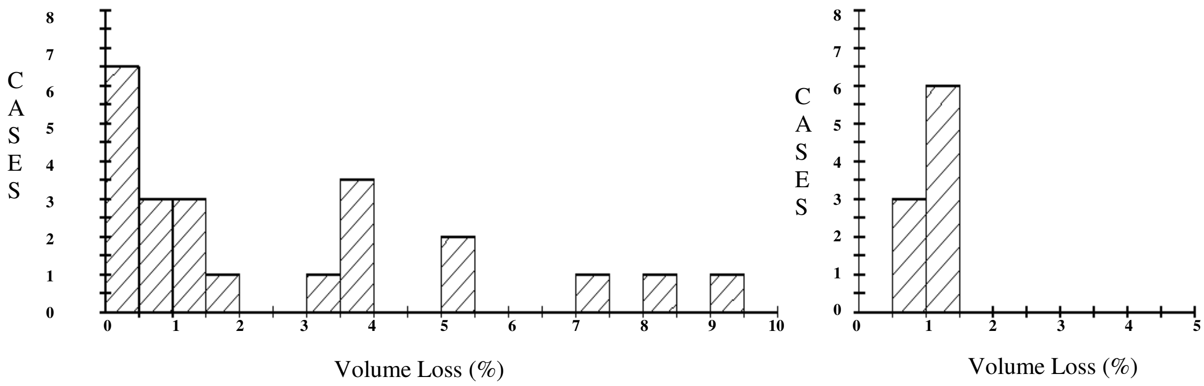


Figure 21 : Comparison of recorded Volume losses over tunnels driven through the Singapore Boulder Bed using open face shields (left) and NATM (right), based on Shirlaw et al. (1987)

The data from Hong Kong and Singapore show that the high, and very variable settlements recorded over the open face shields were specific to the mixed conditions, consisting of large boulders in a matrix of weathered rock or hard clayey silt. This problem was clearly not due to problems at the face, as NATM driven tunnels could be taken through the same conditions with significantly lower and more consistent values for Volume Loss. Inspection of the records for the annular grouting around the segmental linings of the shield driven tunnels showed that the settlement resulted from delayed grouting of the tail gap. Excavation of the boulders was by blasting or percussive methods, although the smaller boulders could were removed as a whole. The excavation of the boulders resulted in a very uneven excavated profile, with significant overbreak around the shields. The tunnelling crews delayed full grouting of the rings due to concern over the grout running forward and setting on the shields, or breaking through to the face. Set grout on the shield skin will increase shove forces, make steering difficult and may ultimately lock the shield into place. Despite the general stability of the ground at the tunnel face, the ground around the partially grouted rings gradually came down and filled the annular gap. This is an illustration of how the settlement over tunnels is not due solely to the nature of the ground; the settlement is a result of the interaction of the ground, the tunnelling method and the implementation of the tunnelling method by the tunnelling crew.

Mixed Conditions in Excavations

The installation of retaining walls can be difficult in mixed conditions. While weak rocks, such as the Old Alluvium, can be readily excavated using conventional machinery, Strong or very Strong rocks can be slow and difficult to excavate. Where the transition from soil like materials, such as Grade V weathered granite, to strong rock is abrupt, then walls can be chiselled or cut a short distance into the rock to provide a secure toe. However, tropical weathering of the ‘Strong Rock’ type often results in a transition that is complicated, and not abrupt (see Figure 4).

Various techniques have been used in Hong Kong to minimise the need to take retaining walls through rock of weathering Zones 5 to 2. These techniques include:

- For diaphragm walls it is common to drill a borehole at every panel, to obtain exact information in order to establish the founding level and the nature of the rock below that founding level
- For walls which found above final excavation level, the use of chemical grouting outside and below the wall, to stabilise weathered material in joints and to reduce overall permeability (Figure 22)

- For walls which found bellow final excavation level, the use of conventional rock grouting techniques to provide a deep cut-off (see Morton and Leonard, 1980)
- The installation of ducts in walls to allow drilling for grouting and/or the installation of dowels to help key the base of the wall into the underlying rock.

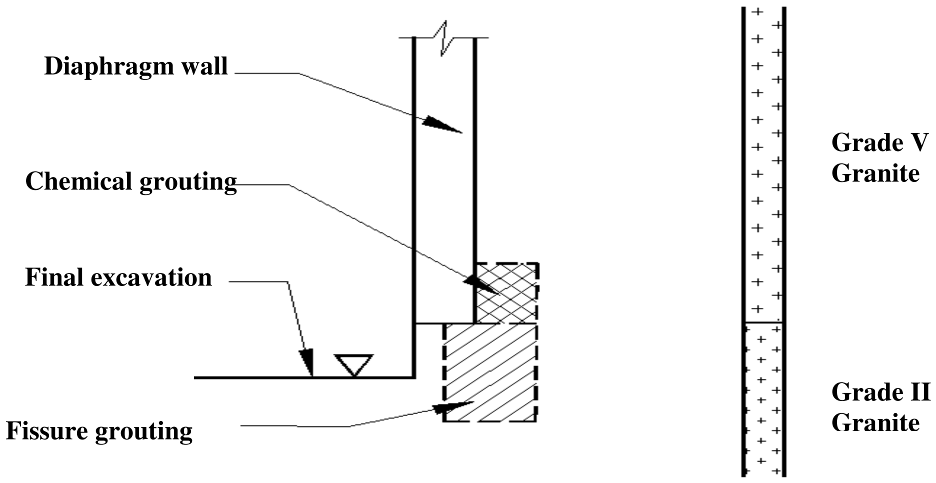


Figure 22 : Grouting for diaphragm wall founded above final excavation level

Abrasion and Heat

As described above, the use of earth pressure balance type machine is problematic through mixed faces of mobile/immobile materials. In tropically weathered rocks this type of interface is particularly prevalent. The difficulties of working in these mixed faces is compounded by the abrasion and associated heat from machine tunnelling in this type of material.

All of the selected weathered rocks have a high quartz content, except for the mudstone and siltstone

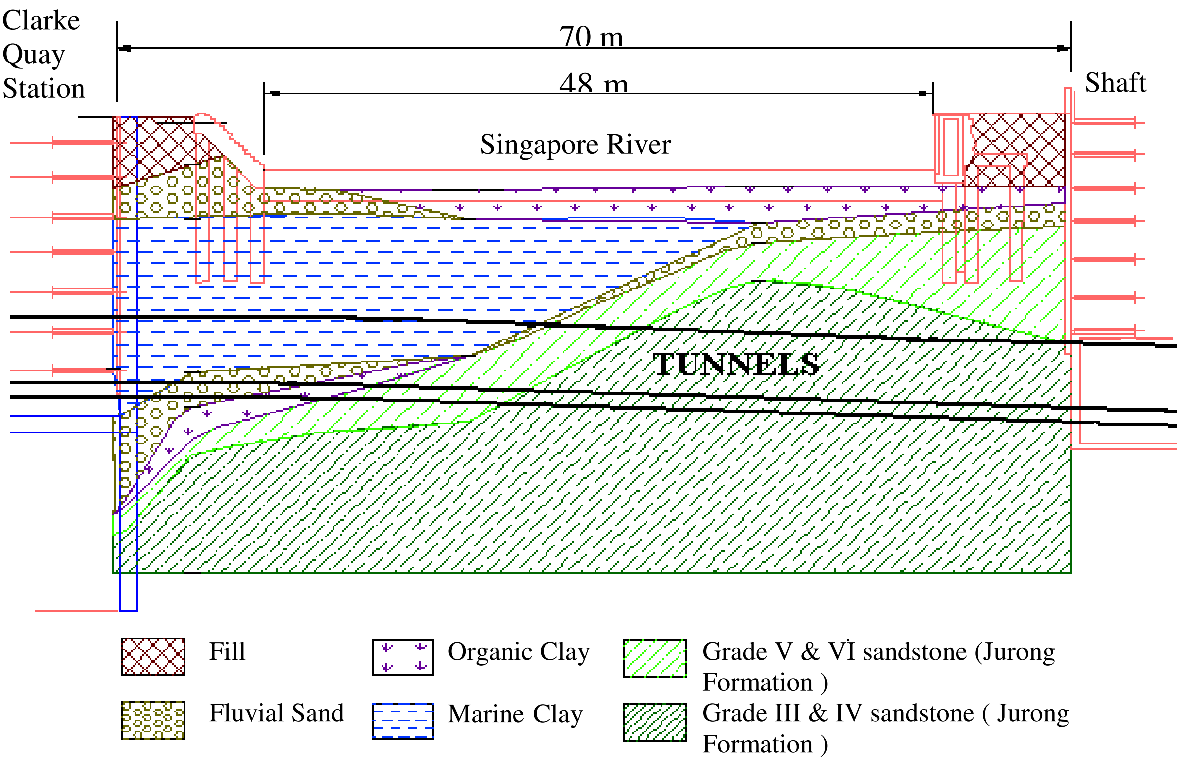


Figure 23 : Elevation showing the tunnels driven under the Singapore River

rocks of the Jurong Formation. Typical quartz contents for the weathered Hong Kong and Bukit Timah Granite are in the range 38% and 30% respectively. The sandstones and quartzites of the Jurong Formation consist largely of quartz, as does the sandstone of the Old Alluvium. For the igneous rocks the quartz crystals are angular while for the sedimentary rocks the quartz crystals are generally more rounded. Abrasion of the cutting tools and machine surfaces is high even when simply excavating the weathered rock.

Excavation in the weathered and fresh rocks in Earth Pressure Balance mode has lead to extremely rapid abrasion of the cutting tools. When excavated, the weathered rock is degraded into quartz particles in a wet slurry of the clay and silt size particles. This forms an excellent grinding paste. Tests carried out on the Old Alluvium showed that it had a Cerchar Abrasivity Index of 1 to 1.5 (slightly to moderately abrasive) when intact, but 1.5 to 5 'very abrasive' when broken down into a slurry, Peart (1999). In earth pressure balance mode, this slurry fills the chamber and the area between the cutting head and the excavated face. The cutting tools and the head are therefore surrounded by highly abrasive material. Another area, for EPB shields, of particular concern for abrasion is the screw conveyor. The practical implications of this abrasiveness are best illustrated by giving a couple of examples of the effect of this abrasion.

As part of the construction of the North East Line, the line had to cross the Singapore River. The river is not a large one: at the point of crossing the width is just 48m and the depth at average sea level is 3m. However, the ground conditions gave some concern over the crossing. The two 5.8m I.D. tunnels were driven from the east bank of the river to Clarke Quay Station on the west bank. As shown in Figure 23 the total length of each drive was only 70m. One 6.53m (external diameter) machine, shown in Figure 24, was used to construct the two sections of tunnel; the southbound tunnel was driven from the shaft to the station where the shield was turned around and launched back to the shaft. The current course of the Singapore River is at the foot of Fort Canning Hill and on the edge of a buried valley infilled with marine clays. Prior to the deposition of the marine clay, there was a spur of weathered sandstone from Fort Canning Hill at the location of the tunnels. On the Fort Canning Hill side of the river, the tunnelling was in this, now buried, spur. On the Clarke Quay station side of the river the tunnelling was in marine clay and fluvial sands. The tunnelling therefore involved going from weathered rock to marine clay on the Southbound tunnel and the reverse on the Northbound tunnel. Both transitions were made under the river.

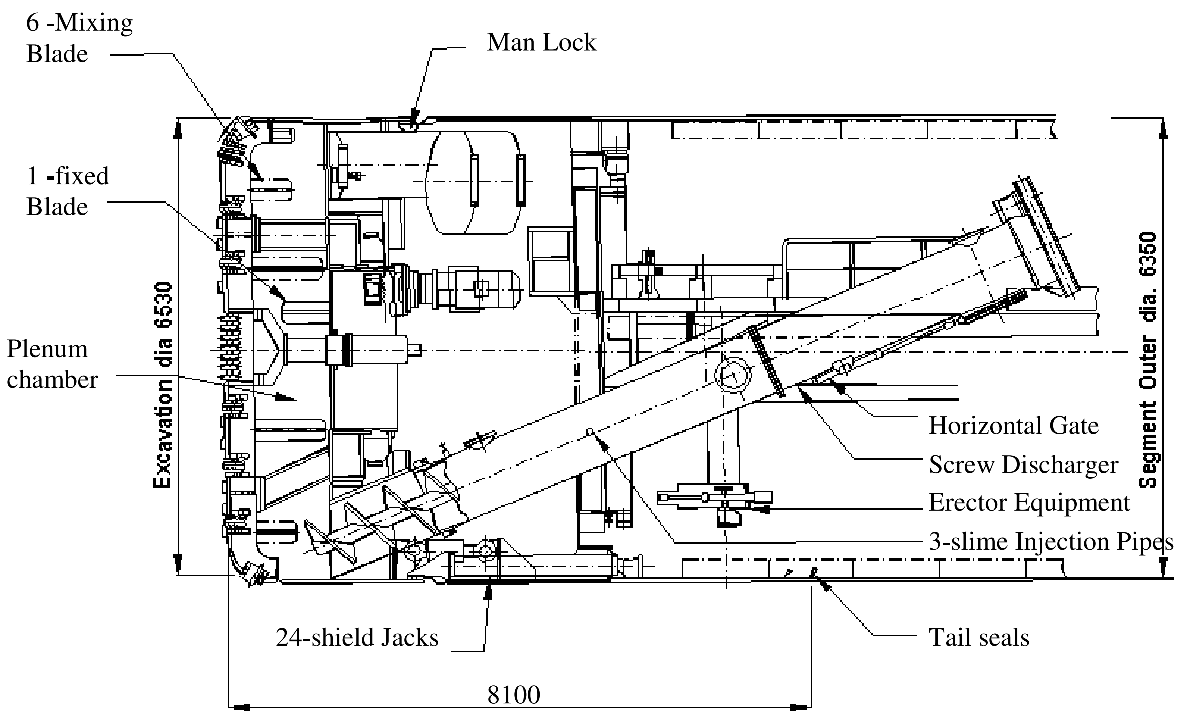


Figure 24 : Earth Pressure Balance shield used to tunnel across the Singapore River

Due to the obvious risks involved in tunnelling through this interface under the river, particular care was given to controlling the face pressures. The face pressure used in the weathered rock was about 1 bar, except for the 10m adjacent to the interface. For this 10m, the interface zone and in the marine clay, the face pressure was typically 1.5 to 2 bars. These pressures proved effective in controlling the ground movements; lines of piezometers had been placed on the river bed as a form of settlement monitoring, and these showed little movement during the tunnelling.

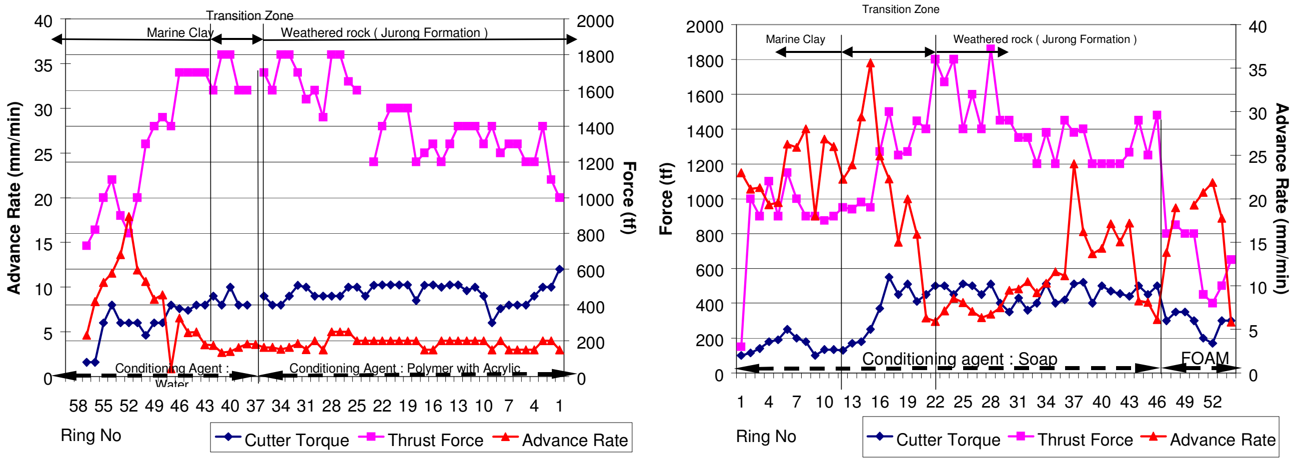


Figure 25 : Torque, thrust and advance rate for tunnelling under the Singapore River. South Bound left, North Bound right

The cutter torque and thrust force required to achieve this pressure are shown in Figure 25. Maintaining the face pressure while the tunnel was wholly or partly in the weathered sandstone meant that the EPB shield was operating at almost maximum torque. It also resulted in very high temperatures in the head and the material in the plenum chamber. A maximum spoil temperature of 71^{O}C was measured; one tunnel worker received burns when spoil splashed onto him. The continuous operation at high torque in the abrasive weathered sandstone also resulted in extensive wear to the cutting tools. Almost all of the discs had to be replaced before relaunching the shield for the North Bound drive.

The high abrasion and temperature recorded in the South Bound drive were in large part due to the nature of the ground and the need to maintain a high face pressure because of the weathered sandstone/soft clay interface. However, there was another factor: the contractor’s choice of conditioning agent for the spoil in the Plenum Chamber. For the South Bound drive and most of the North Bound, either water or

Figure 26 : Abrasion of cutting tools after first drive under the Singapore River

polyacrylamide were used as the conditioning agent. For the last 10m of the North bound tunnel the contractor switched to foam. This had a dramatic effect in reducing the torque required to rotate the cutting head, and the temperature of the spoil, as shown in Figure 25.

The tunnelling through the highly weathered sandstone/marine clay interface under the river provides an interesting comparison to the other cases given above. Unlike the relatively fresh granite at Upper Serangoon Road, the highly weathered sandstone could be abraded by the machine to the point where it could be conditioned to form a slurry. However, the resulting slurry was itself highly abrasive, as seen from the condition of the cutting tools after just 70m of tunnelling (see Figure 26).

Figure 27 : Abrasion of spoke after passing under Kallang River

As recorded above, the Old Alluvium interfaces proved to be relatively benign in terms of recorded surface settlement. However, the Old Alluvium has a very high quartz content, and the abrasiveness based on laboratory testing was high to very high. Tunnelling in the Fresh Old Alluvium has generally been carried out with EPB machines operating without applying a high face pressure. Under these conditions the cutting tools have been abraded, but relatively slowly. Abrasion has been much higher when operating in pressurised EPB mode. As an example, a section of tunnel was driven along Upper Serangoon road, passing under old shophouses and the Kallang River. In this section the tunnel was mainly in the weathered Old Alluvium, and in places there was little or no cover to recent alluvial sands or soft marine clay. Due to the presence of, first, the structures, and then the river over the tunnels, and the presence of soft soils in or just above the tunnel crown, the EPB machines were operated at 300 to 400 kPa face pressure, representing 90% to 105% of full overburden pressure. The machine heads were inspected after the tunnels had passed under the river, at which point they had been operating in full EPB mode for 300m. Severe abrasion was found to most of the cutting tools and for one machine the spokes that held the cutting tools were also significantly abraded (Figure 27). This illustrates the potential increase in abrasion when working in full Earth Pressure Balance mode.

Assessment of Strength for Design

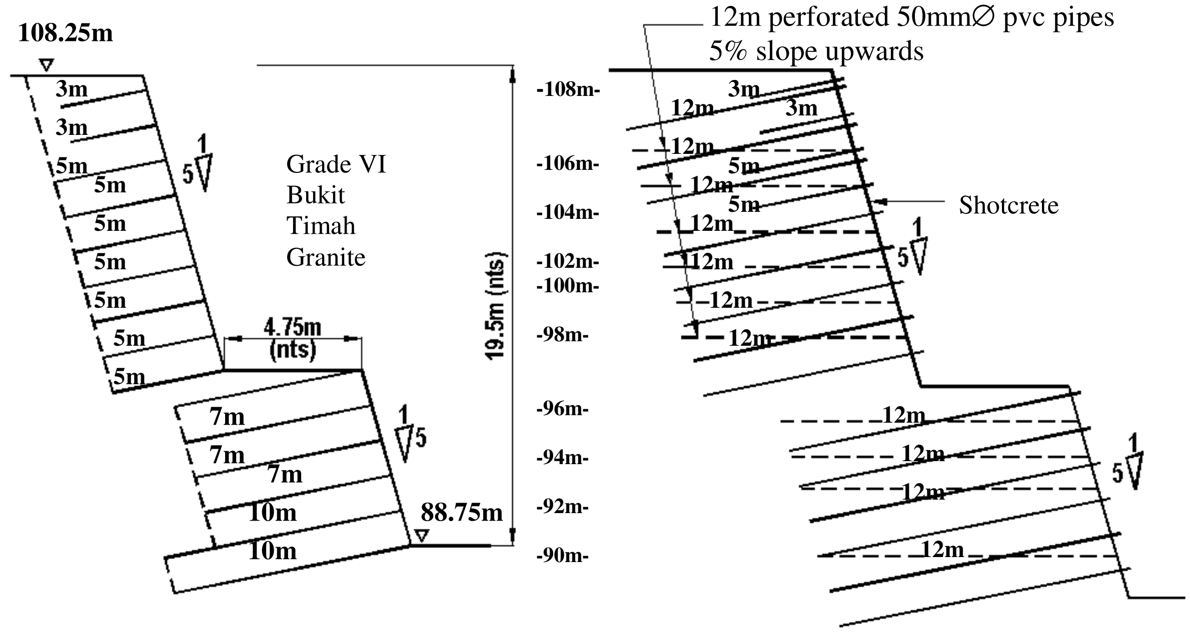
Assessing the appropriate strength to use for design in weathered rocks can be complex, and only a limited discussion can be given here. The discussion will be limited to three particular areas:

- The use of effective or total stress parameters for the grades of weathering which exhibit soil like behaviour, i.e. highly or completely weathered rocks and Residual Soils
- The variability of strength due to the way the weathering process penetrates the rock mass
- Factors other than strength which can affect design in weathered rocks

As discussed above, most of the Grade IV, V and VI weathered rocks selected for review are of a permeability intermediate between sands and clays. In the review of open face tunnelling it was clear that materials with a relatively high permeability, >10^{-7} m/s, behaved in a drained manner i.e. seepage pressures dominated. The materials with a permeability less than 10^{-8} m/s typically behaved in an undrained manner.

Deep excavations are usually open for much longer than a tunnel face. Due to this, materials which can be considered ‘undrained’ in a tunnel may be ‘drained’ in the case of an excavation. Hulme et al. (1990) give three examples of failures or incipient failures of temporary excavation support systems. The support systems had to be extensively modified to allow successful completion of the excavations. The excavations were in Residual Soil (Grade VI) Bukit Timah Granite, Grades V and VI of the Jurong Formation, and Grades V and VI of the Jurong Formation, respectively. The first two of these excavations were initially designed using total stress parameters. Figure 28 shows one of the excavations, at Orchard Station. The redesign, after failure, was based on effective stress parameters. The third excavation was originally designed using effective stress parameters was redesigned using a lower value for c’ in the highly weathered, highly fractured sedimentary rock. Based on the evidence, materials with a permeability equal to or greater than 10^{-8} m/s should be considered as ‘drained’ materials in deep excavations. This observation covers all of the soil like weathered rocks selected for review in this paper. It is consistent with the methods for determining the appropriate basis of design given in Clough and Schmidt (1981).

The residual soils and completely weathered rocks covered in this paper are soil like materials, and sampling and testing are typically carried out as for soils. They usually have some degree of relic mineral bonding and cementation, and both the drilling and the testing have to be carried out with care to measure this cohesive component of strength. However, there is usually a significant scatter in the results of even the



a) Original Design

b) Revised Design After Failure

Figure 28 : Nailed slope in Grade VI Bukit Timah Granite, design before failure (a) and as successfully completed (b)

most careful drilling and testing. This is because of the way that weathering penetrates the rock mass. Figure 5 shows the typical development of weathering in strong rocks. The weathering proceeds down the joints and then progressively into the rock between the joints. As demonstrated by Howat (1986), even an apparently homogeneous mass of Grade V Hong Kong Granite retains some of this structure, with weaker material close to the relic joints and stronger material in between the joints. Anon (1982) showed that the effective strength parameters for Grade V granite could be related directly to the degree of weathering of the feldspars. So, although there is usually a general trend of increasing strength with depth in weathered granite, at any given depth there is significant variation in strength due to the uneven pattern with which weathering develops. This variation can also be seen in the Bukit Timah Granite (Poh et al. 1985). As a result of this variability of the materials, estimates of strength for design are typically taken at the lower end of the measured range.

There is a similar difficulty in terms of assessing appropriate design parameters in the often weak, sedimentary rocks, typically with closely to very closely spaced discontinuities, of the Jurong Formation. As discussed in terms of tunnel behaviour, above, the highly weathered rock is typically fractured to the point where it can behave like a granular mass. In the weakest and most fractured rock, core recovery is generally poor even when using a triple tube core barrel. It is also difficult to find pieces of rock large enough for testing, whether by unconfined compression or by point load test. However, the designer is faced with deriving appropriate parameters for the design of temporary works for both tunnelling and excavations in this material. Figure 29 shows the results of Standard Penetration Testing and coring in weathered Jurong Formation rock along some 600m of cut-and-cover excavation for Harbourfront station. The high degree of variation in the results can be seen. This variation results from the difference in the original nature of the beds in the Formation, and the different rates at which weathering penetrates down the steeply dipping beds. Any assessment of strength has to allow for the variability of the material, and estimates are therefore typically conservative.

In the Jurong Formation, effective stress parameters for the completely weathered rock (Grade V) are typically taken as $c'=0$ and $\phi'=30^O$, based on triaxial testing. Use of these parameters effectively ignores any residual cementation, as being too uncertain to quantify. Methods such as those outlined by Hoek and Brown (1997) can be used to obtain effective stress parameters for the Grade IV and III rocks. The strength envelope for the Grade IV rock is probably curved; except at low stress levels, parameters used for design are typically $c'=40$kPa and $\phi'=30^O$. These parameters are based on values for Geological Strength Index (GSI) and Unconfined Compression Strength (UCS) that are appropriate for the poorer rock found. The

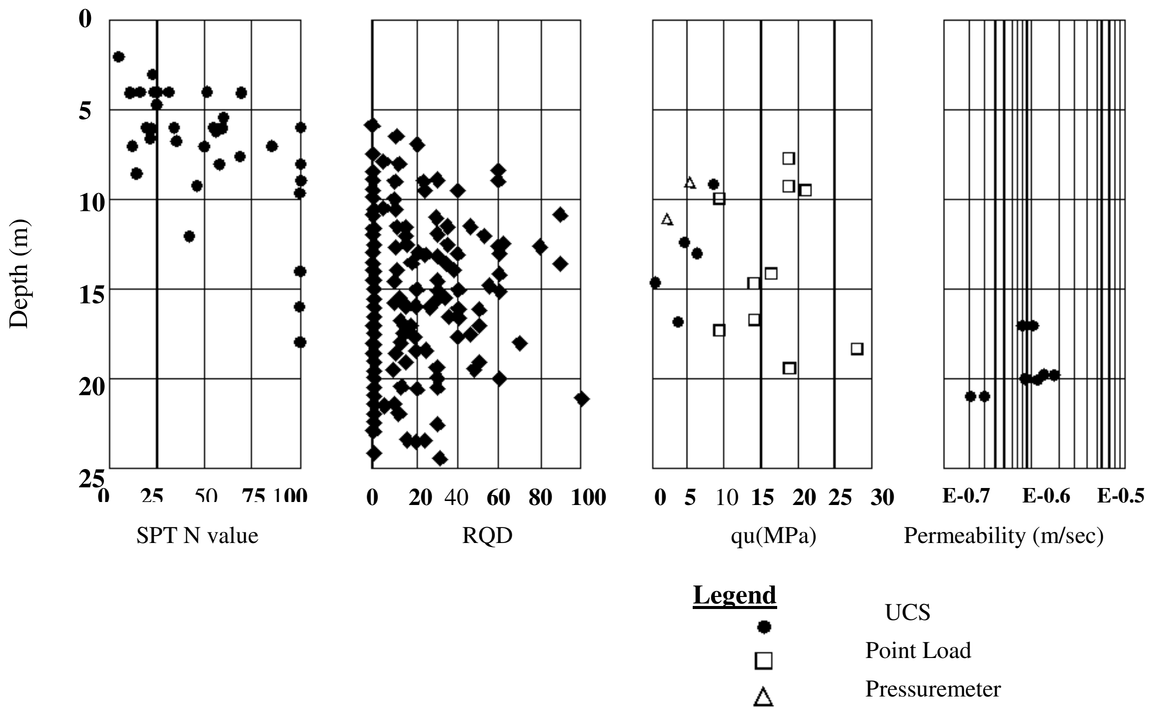


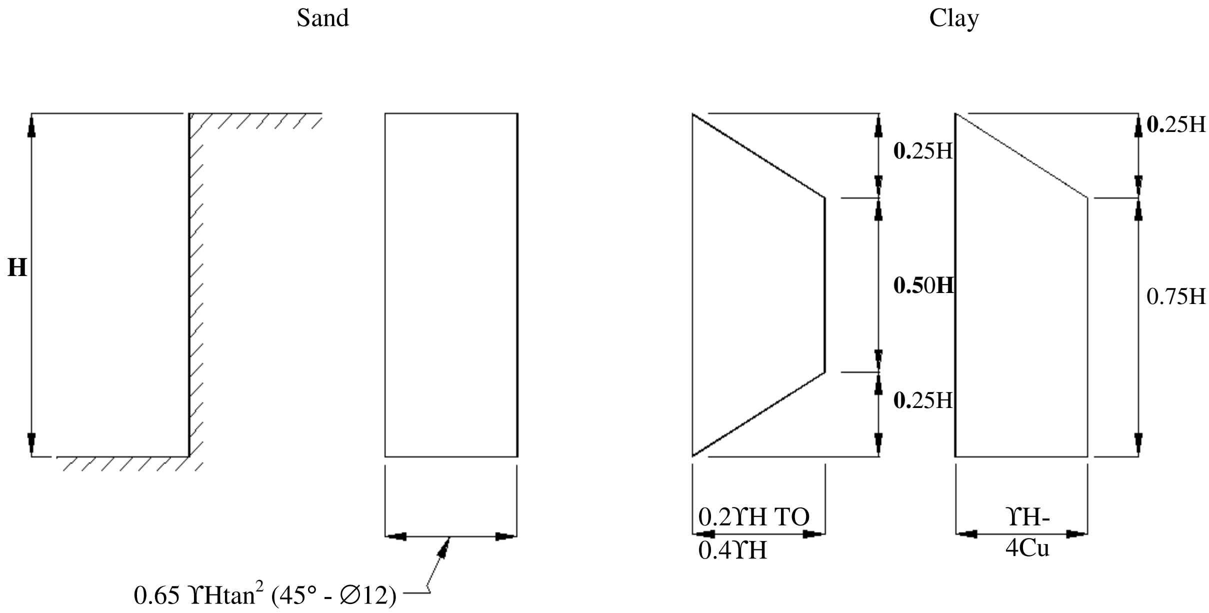
Figure 29 : Results of testing of weathered Jurong Formation, Harbourfront Station, Singapore

variability in the measured strength of the weathered rocks of the Hong Kong Granite, Bukit Timah Granite and Jurong Formation results from the uneven penetration of weathering into the rock. In contrast, weathering penetrates relatively evenly into the largely unjointed and horizontally bedded weak rocks of the Old Alluvium. Orihara et al. have been able to establish good and consistent correlation between the results of Standard Penetration testing (used as a measure of degree of weathering) and effective stress parameters for the Old Alluvium.

The scatter of test results due to the uneven penetration of the weathering is due to effects which can be on quite a small scale. In both the crystalline and the sedimentary rocks significant variation can occur over a horizontal distance of a few metres or less. It is difficult or impossible to try to refine the assessment of the design parameters to allow for such localised variation. However, larger scale features can have a major effect on the way that weathering penetrates the rock mass, and can be the cause of some of the more extreme values measured. Faults, dykes and geothermal alteration of the original rock can have a major effect on the subsequent weathering. It is common to find local areas of deep weathering which are associated with faults. Dykes may weather more or less quickly than the rock mass, leading to a sudden change in the degree of weathering and consequent behaviour in a tunnel or excavation. Geothermal alteration can also change the rate at which rock weathers, and the nature of the weathered rock. This can lead to sudden and very significant changes in behaviour. These features are generally vertical or subvertical, and may not be identified by vertical boreholes. Inclined or horizontal boreholes, and geophysical methods, are among the techniques that can be used to identify such features.

However, the use of such parameters for the design of support systems for deep excavations can be unsafe unless other geological factors are considered. This can be demonstrated by comparing the measured strut loads for soldier pile supported excavations for various grades of weathered rock and with theoretical earth loads that would be obtained from the parameters given above.

For supported deep temporary retaining systems, it is the struts and/or anchors which are usually critical to ensure the overall stability of the retaining system. The walls are important to limit deflections, but are unlikely to fail if there are sufficient struts or anchors. For the struts and /or anchors an alternative to design using conventional Rankine or Coulomb earth pressure distributions is to rely on empirical data from similar excavations. This is a method developed by Peck, and outlined in Peck et al. (1974). In Singapore there is a significant amount of published information on the appropriate values to use to develop a ‘Peck’ diagram. Hwang et al. (1987) present strut load measurements and backcalculated ‘Peck’ diagrams for a number of excavations in weathered rocks for the Phase 1 MRT system. Data from the excavations for the mainly



a) Sketch of wall of cut
b) Diagram for cuts in dry or moist sand
c) Diagram for clays if ϒH/Cu is less than 4
d) Diagram for clays if ϒH/Cu is greater than 4 provided than ϒH/Cb does not exceed about 4 where Cu is the average undrained shear strength of the clay beside the cut, and Cb is the undrained shear strength of the clay below excavation level. (after Peck et al 1974)

Figure 30 : Apparent Earth Pressure diagrams for strutted excavations (after Peck, 1974)

underground Central Expressway was presented by Wong et al. (1997). As shown in Figure 30, Peck suggested two main constructions for apparent earth pressure diagrams. For cohesive materials he proposed a trapezoidal diagram. For granular materials he proposed a rectangular diagram, to which water pressure is added. It is interesting that the data from Singapore, some of which is reproduced in Figure 31 and 32, follows the trapezoidal form for cohesive materials. This is reasonable for the residual soils, which are similar to over consolidated clayey silts. However, strut loads measured in the apparently granular, highly fractured and highly weathered Jurong Formation also fit the ‘cohesive’ form. In the majority of the residual

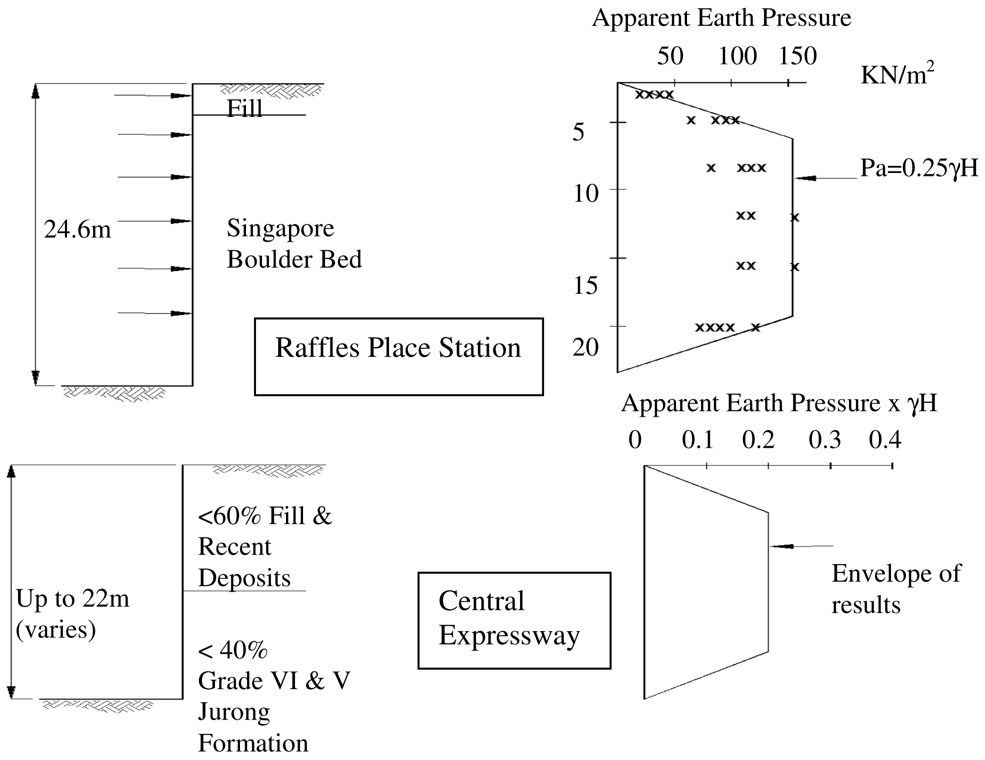


Figure 31 : Measured Apparent Earth pressure diagrams at Raffles Place Station (after Hwang et al. 1987) and for the Central Expressway (after Wong et al. 1997

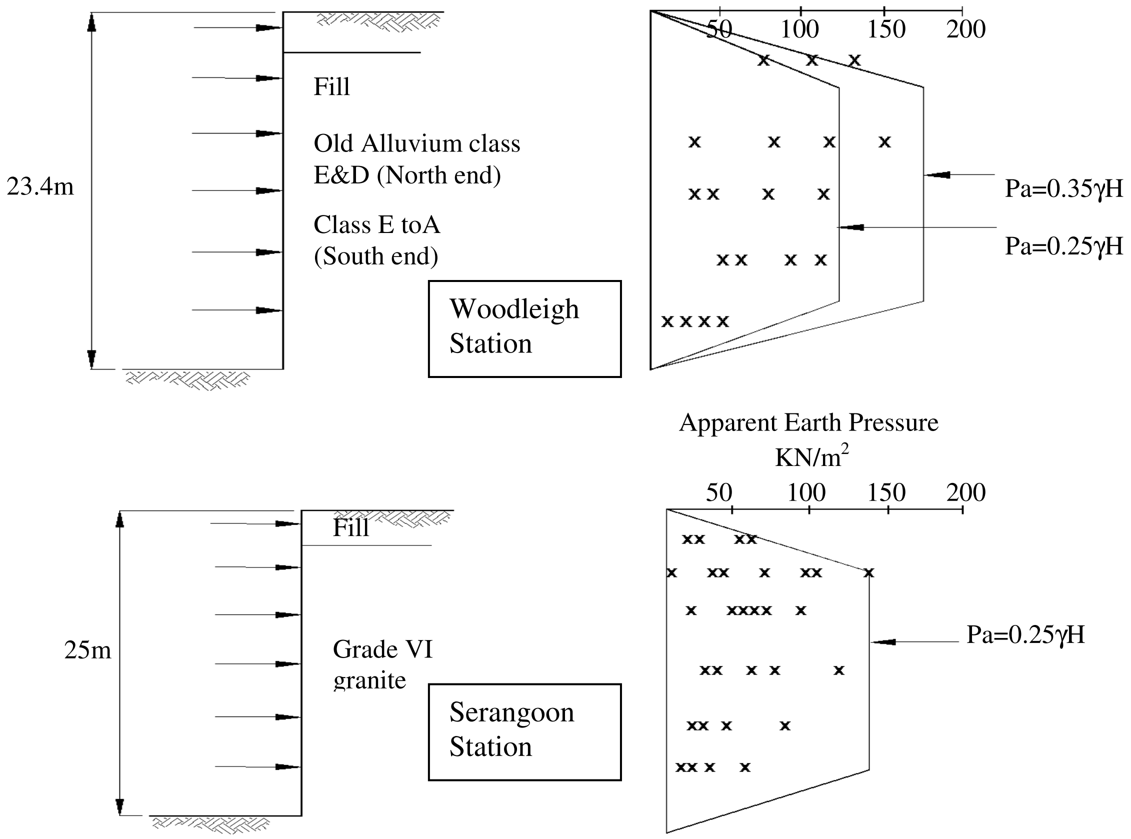


Figure 32 : Measured Apparent Earth pressure diagrams for Serangoon and Woodleigh Stations (after Coutts and Wang (2000)

soils and weathered rocks, a 'K' factor of 0.25 gives a reasonable upper bound for the measured strut loads. although there is a high degree of scatter in the results. Both the largest variation in strut loads and in absolute pressure have been experienced in the weathered Jurong Formation. Although Wong et al. (1994) recorded a 'K' factor of 0.2 for excavations in the Jurong Formation, Hwang et al. (1987) record a factor of 0.6 for an excavation at Outram Park. Just how remarkable a 'K' factor of 0.6 is, can be seen by comparing the measured apparent earth pressure diagrams at Outram Park with those for an excavation of similar depth in soft Marine Clay at Novena Station (Figure 33). It can be seen that the strut loads in the weathered rocks, which were sufficiently stable to allow excavation using soldier piles without loss of ground, were significantly higher than those measured in the soft, squeezing marine clay. Similar pressures have been measured in a more recent excavation in weathered Jurong Formation rock, at Dhoby Ghaut. These high pressures are in stark contrast to the exceptionally low pressures measured in lateritic soils in Brazil (Eisenstein and Negro (1985).

There are various potential factors that have been identified as contributing to the high strut loads measured in the Grades VI to III weathered Jurong Formation rocks. One, water pressures, will be discussed in this section. The other, the swelling behaviour of the rock, will be discussed separately, below.

Both of the excavations where high strut loads have been measured in the Grades VI to III rock of the Jurong Formation have been constructed using soldier piles and laggings. This is a permeable retaining

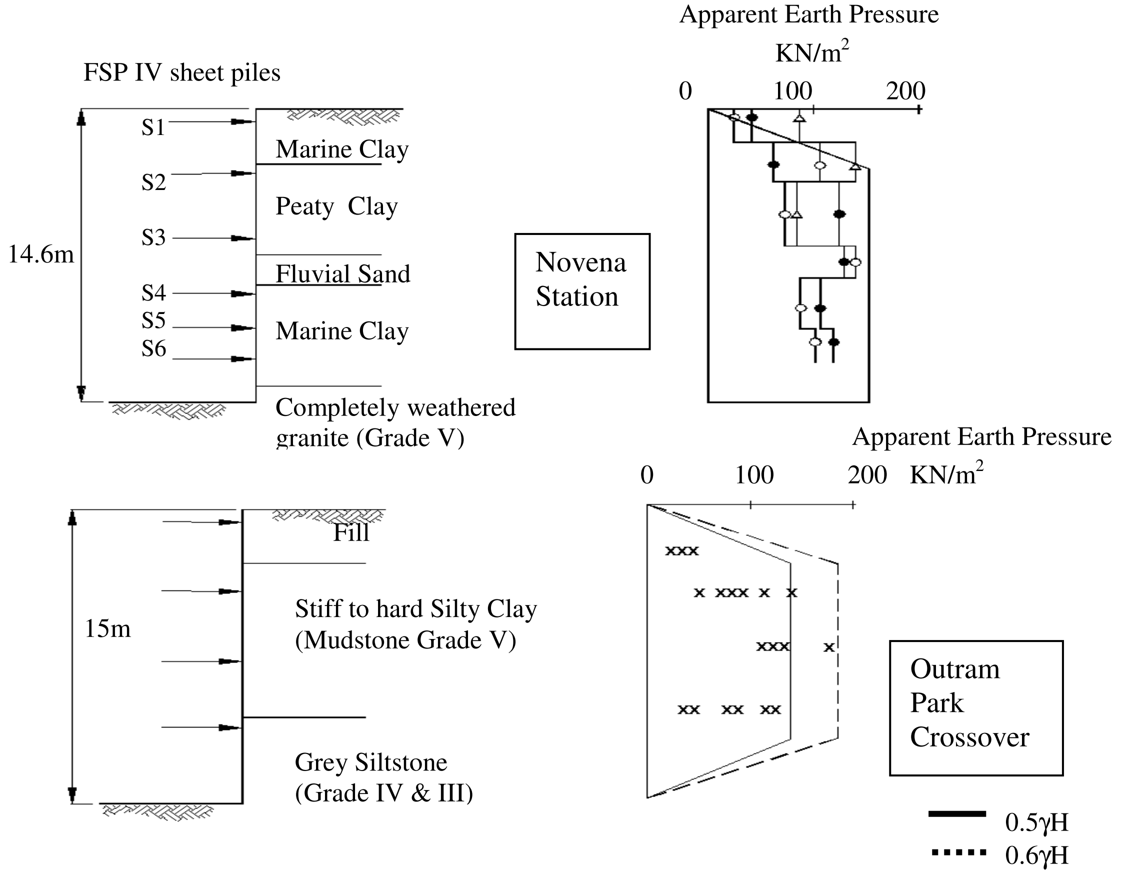


Figure 33 : Measured Apparent Earth pressure diagrams for Novena Station and Outram Park Crossover (after Hwang et al. 1987)

system, allowing the groundwater to drain into the excavation. As a consequence, only limited water pressures are normally considered when designing this type of support system (Anon 1971). However, in weathered rocks, geological features can result in higher water pressures than would be allowed for in a soil.

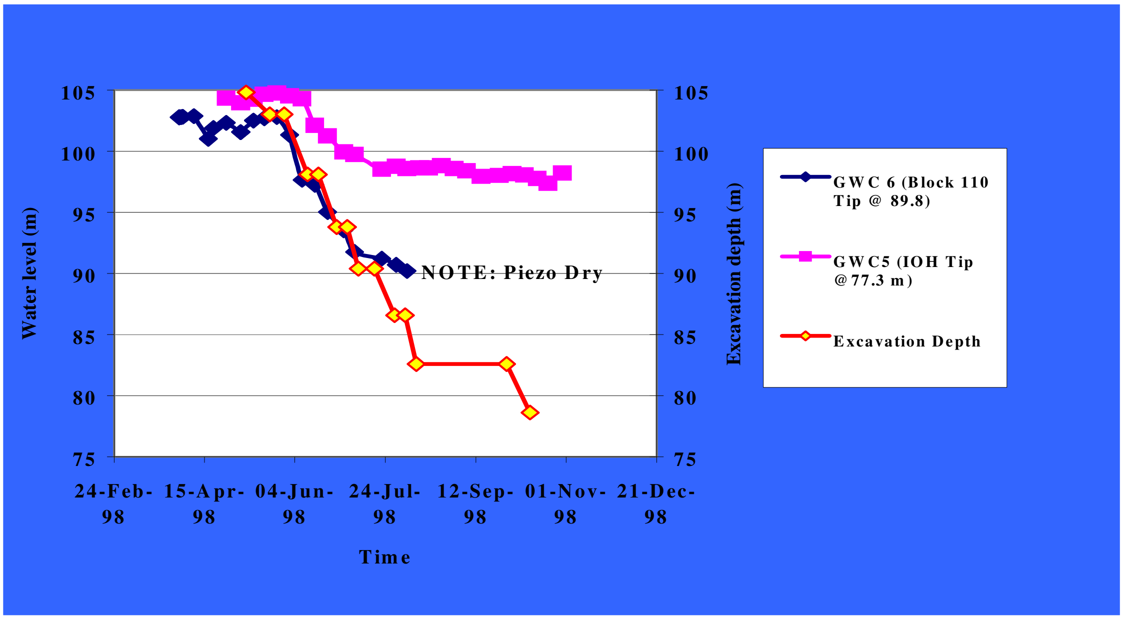


Figure 34 : Imbalance of water pressures on either side of an excavation in weathered Jurong Formation using a soldier pile retaining system

At one of the excavations where high strut loads were measured, at Dhoby Ghaut station, a fault was known to run parallel to one side of the excavation (see below). The fault was water charged and probably acted as a constant head reservoir, putting a high hydraulic head on the excavation support system. The presence of the nearby fault was also evident in slickensiding of the joint surfaces of the rock in the excavation, reducing joint roughness and effective friction angles. In a more recent excavation at Outram Park, it was found that there was a major imbalance of measured groundwater levels across the excavation (Figure 34). It is probable that this imbalance was due to the steeply dipping nature of the strata; a single bed of less permeable rock could have acted as a dam, maintaining a much higher ground water level on one side of the excavation than on the other.

Although factors such as water pressure, slickensiding and adverse joint orientation may all have played a part in the high strut loads measured in the excavations in the Grade IV and III weathered Jurong Formation, it is unlikely that these factors are sufficient by themselves to cause the measured loads.

Swelling/Shrinkage

One of the potential results of tropical weathering, in some rocks, is the presence of swelling clay minerals, particularly smectite. As discussed in Anon (1990), soils containing swelling clay minerals are a potential problem for light structures founded in the zone of seasonal change of moisture content. Although Anon (1990) also states that ‘most problems occur within about one metre below the surface’, swelling behaviour can also influence the behaviour of deep excavations and tunnels.

Swelling clay minerals are not the only cause of swelling in weathered rocks. Extreme dessication can also lead to swelling behaviour. For example Al-Shamani and Al-Mhadib (1999) record highly expansive behaviour in a highly weathered shale, although the clay minerals consisted mainly of kaolin and illite. Rocks not affected by weathering can also exhibit swelling behaviour, for example the Queenston shale discussed by Hefny et al. (1996). This paper however, covers only weathered rocks, and the four selected rocks are generally fully saturated. Almost all of the tunnels and excavations described are below sea level.

Of the selected weathered rocks, smectites, mostly montmorillorite, have been identified in both the Jurong Formation and the Old Alluvium. In the Jurong Formation, Lo et al. (1988) identify smectites in

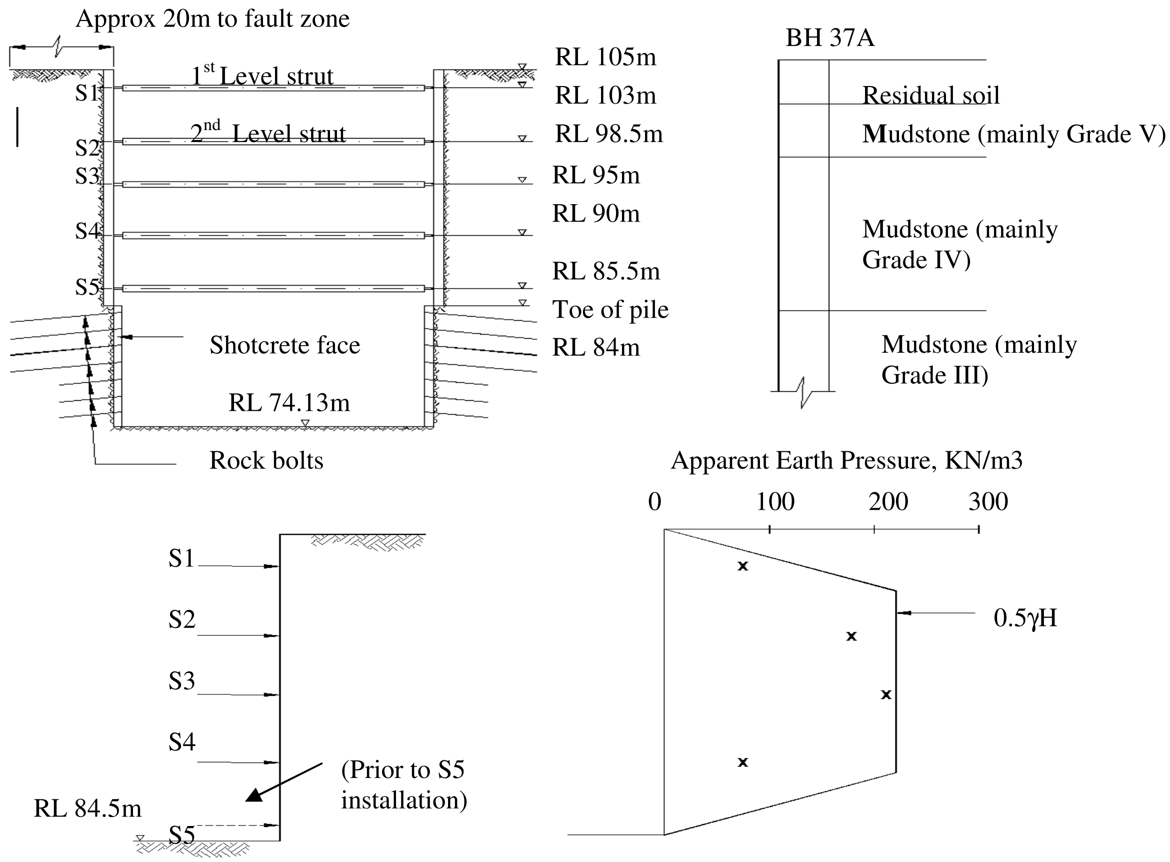


Figure 35 : Dhoby Ghaut Station, North End. Typical section and measured Apparent Earth Pressure after excavating to 20.5m.

shaley mudstones during assessment of some slopes formed in the Jurong Formation. In the Old Alluvium, Gupta et al. (1987) record a significant proportion of smectites in the weathered mudstone beds; the proportion of smectite in the clay fraction was up to 50%.

Swelling behaviour was noted during site investigation for one of the excavations in the Jurong Formation where high strut loads were measured. The swelling behaviour was noted in two relatively thin bands of weathered mudstone. The 31.5m deep excavation, at Dhoby Ghaut, is shown in Figure 35. The support system consisted of strutted soldier piles down to a depth of 21m, with the remainder of the cut stabilised by rock bolts and shotcrete. This combination of support systems slightly complicates the assessment of the loads that developed in the strutting system. As a first stage in the assessment, the strut loads when the excavation level was 20.5m below ground surface are also presented in Figure 35. At this stage excavation had been carried out for the 5th strut level, but the struts at this level had not been installed, and the excavation had not passed below the toe of the soldier piles. At this point the strut loads were within a trapezoidal envelope defined by a ‘K’ factor of 0.5, similar to the measurements at Outram Park described above. As the maximum strut loads presented are only for the period of excavation, they are not strictly comparable with the other published data, which are for loading throughout the periods of excavation, construction and strut removal. Had the final excavation level been 20.5m, then it is likely that a higher ‘K’ factor would have been measured. The measurements do, however, reconfirm the potential for very high strut loads for excavations in the weathered Jurong Formation rocks. The struts were preloaded, but to only 300KN per strut, less than 5% of the capacity of most of the struts installed. When the excavation at the north end of Dhoby Ghaut progressed down to final excavation level of 31.5m below ground level, the loads in the struts continued to increase. Several of the struts approached their ultimate capacity, and additional struts had to be installed to ensure the safety of the excavation. Figure 36 shows the total load measured on one bay of 5 struts. The spacing between each bay of struts was 7m. It can be seen that the total load in the bay was about 15,000 KN when the excavation reached 20.5m.

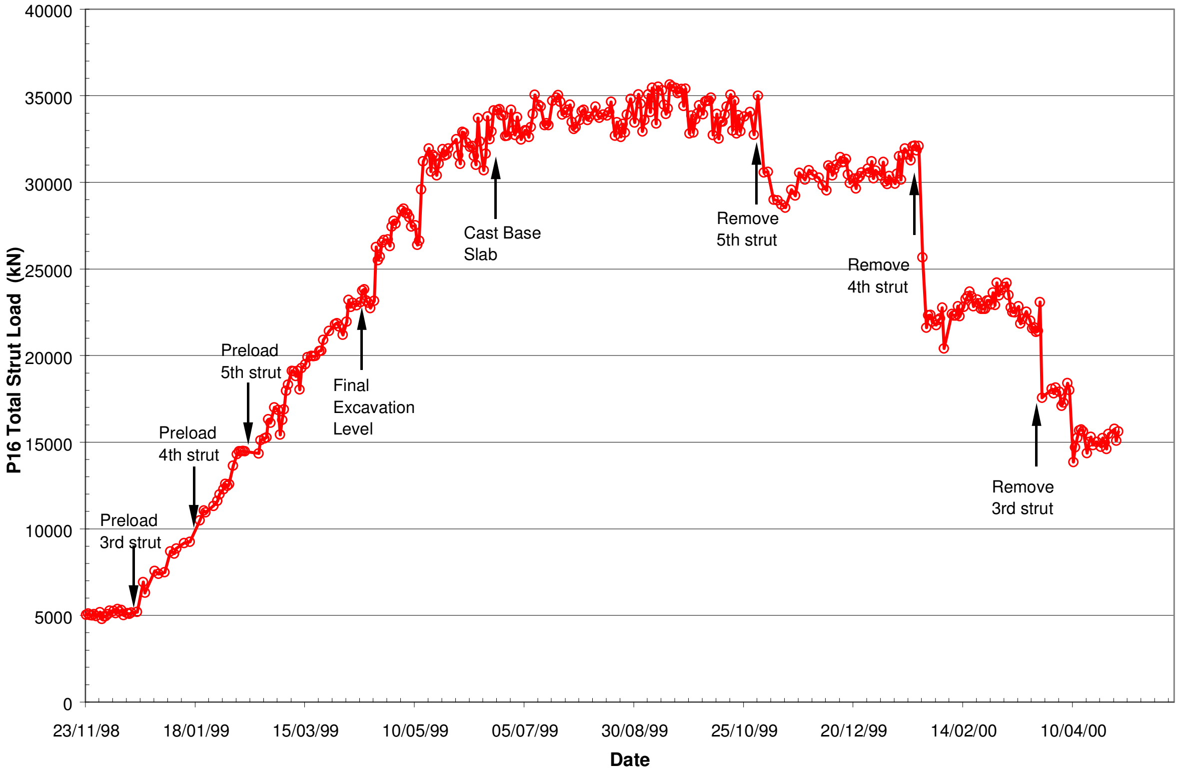


Figure 36 : Total strut loads measured at Dhoby Ghaut Station, north end

The load on the strutting system continued to increase during further excavation with a total load of about 23,000KN at final excavation level. The load on the system then continued to increase until shortly before the base slab was cast in this section, with a peak load (including that in the additional struts) of about 35,000KN. It is notable that:

1) The development of the load was almost linear with time, whether excavation was being carried out in the area or not.
2) The build-up in load stopped suddenly on about 11 June 1999, about 3 weeks before the base slab was cast.

Inclinometers had been installed on both sides of the excavation, close to the monitored bay of struts. The deflection of the inclinometers is shown in Figure 37. It can be seen that:

1) There was very little movement, less than 5mm, during the excavation down to 20.5m, on both sides of the excavation
2) During excavation down to the base of the excavation the west side of the excavation moved up to 15mm into the excavation, while the east side of the excavation was pushed back 5mm to its installed position.
3) Following excavation to the final level, both sides of the excavation moved in by about another 5mm.
4) Between excavation to 20.5m and the load levelling off in June 1999, there was an almost uniform inward movement along the soldier piles, with all of the struts shortening by about 15mm. This value is consistent with the strain needed to produce the measured loads in the struts.
5) There is a sharp kink in the inclinometer plot at about 24m below ground surface. Assuming that all of the ground load down to this level was transferred into the struts, then the total pressure on the retaining system was equal to 0.83 of the total overburden pressure. This can be compared with the estimated K_O value of 0.8.

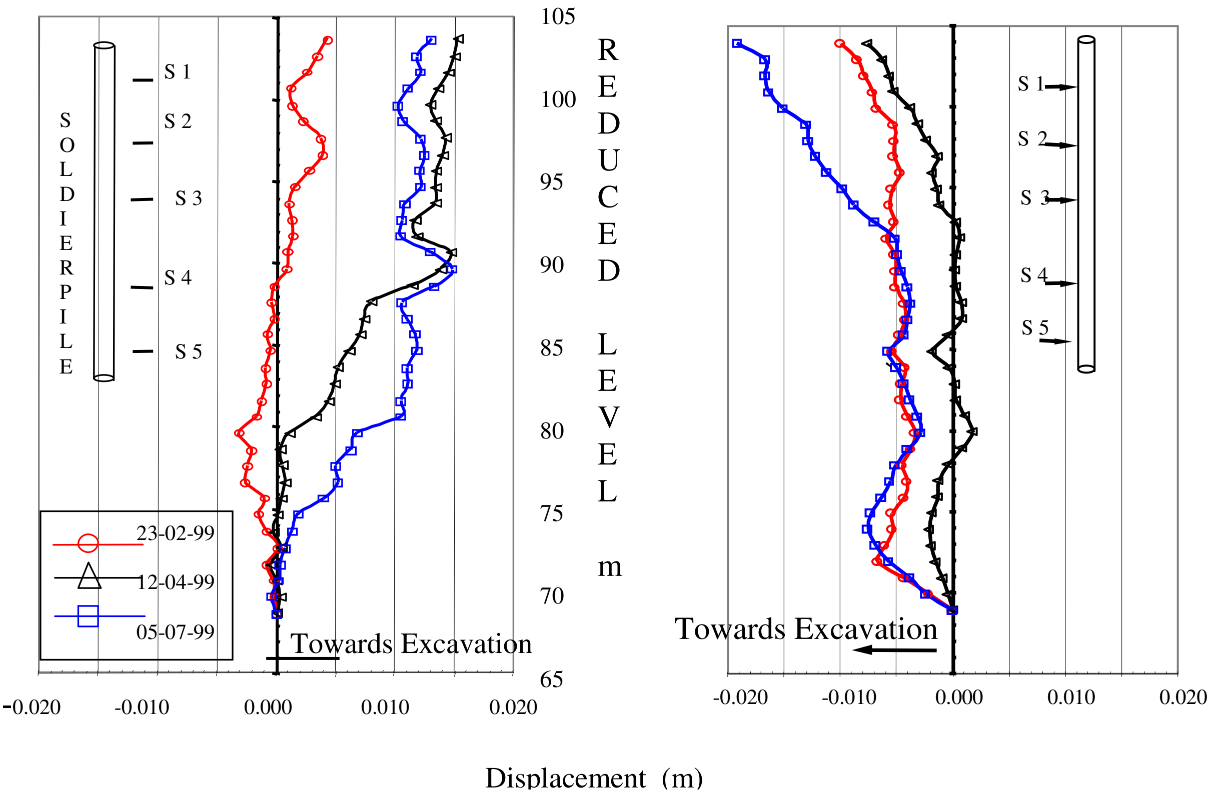


Figure 37 : Lateral movement of retaining system at Dhoby Ghaut, north end, based on inclinometers on both sides of the excavation

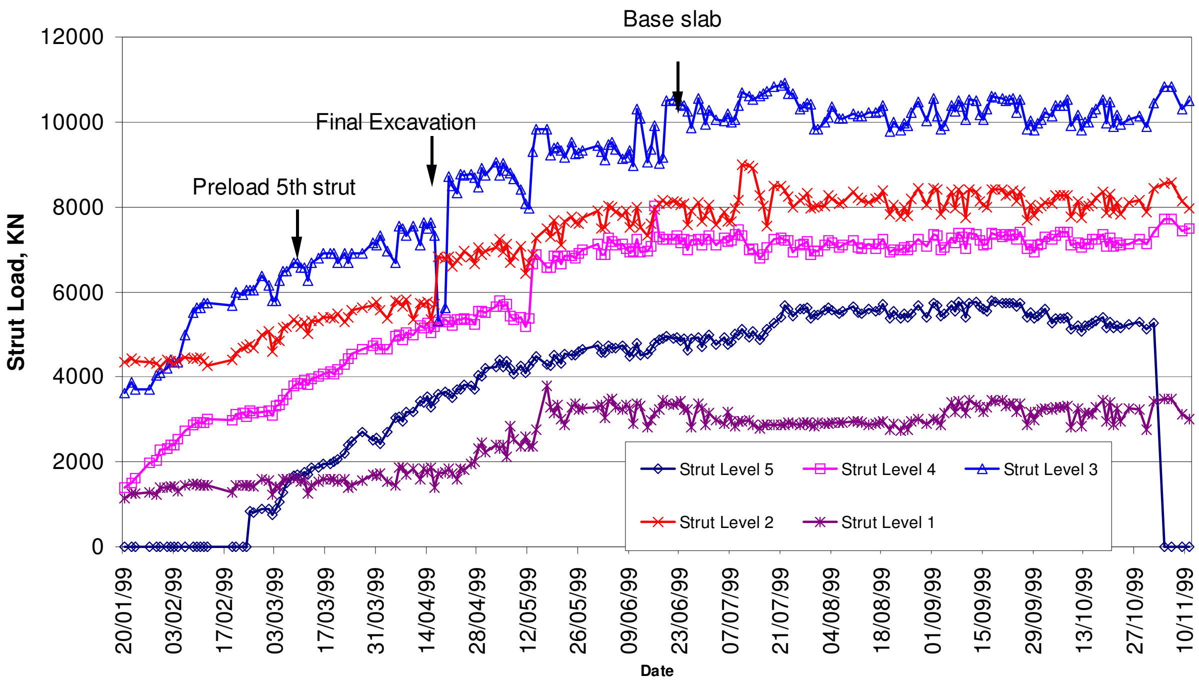


Figure 38 : Load measured at each strut level, Dhoby Ghaut Station, north end

Figure 38 shows the build-up of load on individual struts. It can be seen that all of the struts continued to gain load during the excavation below the 5th strut level, and even after excavation in the area was complete. The amount of the final load was clearly influenced by the use of relatively short, very stiff struts that effectively restrained the sides of the excavation. However, the pattern of load development suggest that this could not have been the only factor, and that the swelling behaviour noted in the adjacent borehole was a major factor in the high strut loads that were measured. In other areas of the same site similar behaviour was not observed, although similar excavation methods were used, also in weathered rock of the Jurong Formation.

In the Old Alluvium, it is also the weathered mudstones that can contain a significant proportion of smectite. However, the measured strut loads in the Old Alluvium are not noticeably influenced by the presence of the smectite. This is probably because the weathered mudstone beds are thin, horizontal and form a small proportion of the overall Old Alluvium. The earth pressures are therefore governed by the, predominantly quartz, weathered sandstone beds.

Relic Joints

Joints and other discontinuities are pervasive in most rocks close to the surface of the earth. It is apparent, though poorly documented that joints extend and develop as weathering progresses (Hencher, 1985). Aligned, stress-induced micro cracks can coalesce to form incipient joints which will eventually develop into fully persistent open fractures. As part of the process the wall rock weakens and may be coated by minerals. As material is eroded from the walls, voids may develop. Voids may also develop through dilational movements. These voids may become infilled with weathering products, most notably clays which may have a low shear strength Kirk et al (1997).

By definition, (BS 5930, 1999) all grades of weathered rock up to grade VI (residual soil) retain relict texture and structure from the parent rock. Both are extremely important in influencing engineering behaviour.

Joints can often be characterised as roughly parallel sets, the geometry of which relate to the stress conditions at time of fracture initiation. If adversely oriented they allow blocks to slide or topple into excavations. Examples of adverse joints in weak weathered profiles are given in Figures 38 and 39.

Figure 38 : Relic joint in completely weathered granite (Grade V)

Figure 39 : Relic Release Joints in the Rear of a Landslide through Grade IV Granite

Such joints can have a very wide range of strengths. Most rough (naturally) textured discontinuities through silicate rocks will have sliding angles of greater than 40 degrees (Papaliangas et al, 1995) and much higher where there is interlocking of macro-scale roughness or impersistence. Such strengths are as high as or stronger than intact material shear strength of the weakest grade V, completely decomposed granite (typical design values for such material are $c' = 8$ kPa, $\phi' = 37°$). However coated, infilled or unusually smoothed joints (due to movement) can have strengths far lower than this. Friction angles of between 17 and 22 degrees are typical for persistent, planar chlorite and kaolin infilled discontinuities respectively. Values even lower (10 to 14 degrees) can apply to some clays and polished surfaces in mudstones.

Clearly when dealing with weathered rocks, it may be necessary to investigate and analyse the situation using both soil mechanics and rock mechanics approaches (Hencher & McNicholl, 1995).

Joints will have an overall mass weakening effect so that failure may be could through a combination of weak material and partially adverse discontinuities. An example of such failure is shown in Figures 41and 42. The bottom line is that relic joints should not be ignored. During a recent design review for a major excavation in weathered

Figure 40 : Aerial view of landslide through fractured, weak granite

granite profiles in Korea, one of the authors noted that the designers had analysed all the slopes using Rankine theory, as if the material was a transported sand. Whilst this assumption led to extremely conservative design for much of the excavation, if adverse, low strength discontinuities were present the design would be unsafe. The review called for a complete re-investigation and design to allow for such failure mechanisms.

For tunnels, some of the effects of joints in weathered rock have already been discussed above, in terms of the general response to tunnelling of the selected weathered rocks. In the Grade II and IV siltstone and mudstone beds of the Jurong Formation, it is the very high degree of fracturing of the rock, partly caused by weathering, that leads to the fast ravelling behaviour observed in the tunnels. In the Grade V Hong Kong granite, the relic joints are often filled with weathering products and act like ‘greasy backs’. Just how important the joints are in controlling behaviour can be seen in the behaviour of the unweathered Old Alluvium. Despite the low strength of the rock, the generally massive rock has proved to be an excellent tunnelling medium.

For supported excavations, the frequency, roughness and angle of the joints are a major factor in determining the load in the support system. Methods of deriving design parameters, such as those given by Hoek and Brown (1997) allow for these factors.

Figure 41 Failure Partly Controlled by Relic Discontinuities (same failure as Figure 40)

Erosion

Completely weathered rocks typically have little cementation, and their relic rock structure results in a granular texture. This makes them prone to erosion when exposed. This may be a major problem with excavations that are open for a long time, but is less likely to be a significant problem for temporary excavations. For supported excavations, the support system usually provides some protection from erosion to the ground during excavation. For unsupported excavations, erosion is likely if no slope protection is provided. However, if the excavation is to be backfilled, some erosion of the slopes in the short term is unlikely to be a major concern.

Of the selected weathered rocks, the weathered Old Alluvium is particularly prone to erosion. Weathering results in a loss of almost all of the original cementation, leaving a material consisting predominantly of quartz particles. This material erodes rapidly, quickly forming deep gullies in exposed slopes. In contrast the fresh Old Alluvium has sufficient cementation to resist erosion. Protection of slopes using turf or plastic sheeting is generally sufficient to minimise erosion.

A particular problem related to erosion has been loss of ground at locations where utilities cross supported excavations. Due to the presence of the utility, a gap has to be left in the sheetpile or soldier pile wall. It is common for the utility, the utility protection or backfill to act as a water path. Unless great care is taken to seal around the utility, the concentration of flow at the gap can result in rapid erosion and loss of ground outside the excavation.

Hardpans

Hardpans are layers of soil that are cemented by the precipitation of iron or alumina. This typically occurs in zones of fluctuating groundwater. Hardpans typically have significant strength because of this cementation.

Hardpans do occur in Hong Kong, but most commonly in recent deposits rather than in the weathered rocks. In Singapore thin (<0.5m) layers of hardpan have been encountered in the weathered Old Alluvium. The amount of groundwater fluctuation in Singapore is relatively small, due to the regular and almost even spread of rainfall throughout the year. This accounts for the limited thickness of the hardpans that have been encountered.

The thin layers of hardpan that have been encountered in tunnelling and excavation in Hong Kong and Singapore have not, as far as the authors are aware, caused any significant problems. The layers are more difficult to excavate than the surrounding soil, but this is not significant if the layers are thin. Successive layers of hardpan have been an inconvenience during site investigation in the weathered Old Alluvium. The layers of hardpan restricted the use of cone penetration testing, which is otherwise a useful tool for investigating the Old Alluvium. However, this was a relatively minor inconvenience compared with some of the other aspects of weathered rock behaviour discussed in this paper.

Collapse

Many partially saturated, completely weathered, rocks and residual soils exhibit collapse behaviour, Anon 1990. Under certain conditions, the clay minerals resulting from weathering may be gradually leached out by long term ground water flow. This leaves a very open soil structure of low density, which is meta-stable.

As far as the authors' are aware, collapse behaviour has not been recorded as a major problem in the four selected rocks. This is probably because of the climatic and topographical conditions in Hong Kong and Singapore.

Collapsible soils have been encountered in excavations and tunnelling in South Africa and Brazil. The meta-stable structure of these soils is liable to collapse when subjected to stress changes. When they collapse, the soil becomes denser. This can lead to unusual patterns of settlement during tunnelling or excavation. Farrias and Assis (1996) record examples of settlements measured over tunnels in Brazil. Extensometers placed along the tunnel route showed that the stress changes induced by the tunnelling caused the meta-stable clay to collapse. This behaviour developed progressively as the effect of the tunnelling migrated to the ground surface. As a result, the measured surface settlement was over 160mm, compared with a subsurface settlement of less than 150mm 2m above the tunnel crown and less than 75mm of convergence of the tunnel lining. This behaviour is the complete opposite to the progression of settlement through ordinary soils, where the maximum ground movement reduces between the tunnel crown and the ground surface.

DISCUSSION

Most of the issues for design and construction discussed above arise out of the structure of weathered rocks. The issues can be divided into those that arise out of material scale and mass scale structures.

At a materials scale, weathered crystalline rocks retain the structure of the fresh rock. The relic crystalline structure can result in the weathered rock having a significantly higher permeability than an alluvial soil of similar clay and silt content. Such materials are also prone to piping leading to channelised flow not represented by generalised permeability values. These conditions can lead to instability in excavations and tunnels taken below the water table in the more weathered grades of rock. On a small scale, intense leaching of weathered rocks can lead to the development of a very open structure which is meta-stable, and prone to collapse. Typically completely decomposed granite in Hong Kong has only half the density of fresh rock (more than 50% is voids). Such rock slakes (disintegrates in water) by definition. Such weathered rocks, which commonly have a high clay content, are prone to slumping and erosion in excavations if not properly surface protected.

On a mass scale the uneven development of weathering through the rock mass results in the potential for mixed conditions. Such mixed conditions contain both strong and stable materials and weak and unstable materials. Dealing with such mixed conditions is a particular problem in tunnelling, and can cause difficulties in excavations. Mixed conditions can lead to highly varying surface settlements over tunnels. The settlements can be due to loss of ground at the face or due to the difficulties in grouting the tail void where the excavated profile is very uneven. The uneven development of weathering, even in apparently homogeneous completely weathered rock, is one of the reasons for scatter in the results of testing used to establish strength and stiffness. .

It is common for weathering to penetrate the rocks mass along joints and other discontinuities; this is one of the causes of the uneven development of weathering discussed above. The joints and other discontinuities are another issue in excavation and tunnelling in weathered rocks, as they form planes of weakness in the rock mass, even when weathered down to a soil-like consistency.

Also on a mass scale are structural features in the original rock such as faults, dykes and zones of hydrothermal alteration. Such features can weather at a quite different rate to the adjacent rock. This can lead to very sudden changes in ground conditions, which can be particularly problematic for tunnelling. This in turn can lead to high, localised settlements.

Although there are other issues in tunnelling and excavation in tropically weathered soils, such as swelling behaviour and hardpans, it can be seen that the majority of the issues relate directly to the original structure of the rock and how that structure affects the development of the weathering.

CONCLUSIONS

There is great variety in both the development of tropical weathering and in the behaviour of the four rock formations that have been reviewed in this paper. This variation is evident from the examples given, despite the very limited number of rock formations reviewed and the limited variation in climatic conditions that have produced the weathering in the four selected rock formations. There is a degree of similarity in the basic principles and processes involved in the weathering, but the end result can be very different as far as underground construction is concerned. It is therefore unwise to extrapolate the behaviour of one weathered rock based on the behaviour of another, even for the same type of rock. This can be seen in the differences between the Bukit Timah Granite in Singapore and the Hong Kong Granite.

Although the residual soils and completely and highly weathered rocks can be described as ‘soil-like’ materials, their nature and behaviour can be significantly different from deposited soils. These differences are because of the way the weathered rock retains some vestigial features of the original rock. These features can be on a material or mass scale. Material features include residual cementation and bonding, and a pore structure developed from the original rock structure. Mass scale features include joints, faults, dykes and geothermal alteration that can significantly affect the development of the weathering.

For the design and construction of excavations and tunnels in weathered rocks, there are a number of general issues that have been discussed above. These issues include: permeability, mixed face conditions, abrasion and heat, assessment of strength for design, swelling and shrinkage, relic discontinuities, erosion, hardpans and collapse. Most of these issues are not unique to tropically weathered rocks. They are issues, however, which are either particularly important in weathered rocks or where the nature of the issue is different from that in transported soils or fresh rock.

For construction, one of the most difficult features of weathered rocks is the potential for mixed conditions which include flowing or ravelling ground in conjunction with rock that is strong and difficult to excavate. Such conditions are often found in weathered rocks, due to uneven penetration of weathering into the rock mass. It would be wise when planning a tunnel route to account for this fact and to consciously opt for either predominantly soft (shallow) or hard (deep) rock conditions to minimise the difficulties resulting from the mixed ground. The easily eroded nature of many weathered rocks also leads to interfaces between the rock and weaker, more recent deposits. These conditions are particularly problematic for tunnelling.

Uneven penetration of the weathering also commonly leads to a high degree of scatter in the results of testing for the strength of weathered rocks. Scatter due to local variation in the degree of weathering of the rock is a common feature, but is difficult to refine further. Larger scale features, such as faults, dykes and geothermal alteration can lead to sudden changes in properties and behaviour over a significant length of tunnel or wall.

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