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The Hydrogeology of Weathered Granites

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The weathering processes of granites are well documented and schemes for identification have been developed particularly in Hong Kong. However the development of permeability associated with these processes is not well documented. Permeability data associated with different stages of weathering have been identified and compared from Hong Kong, Singapore and other locations around the world.

The paper considers the available data and the difficulties in measuring permeability particularly based on simple laboratory tests. The impact of "clusters" within the matrix and sample preparation where grading tests are relied on to indicate permeability is discussed. The role of geology and deep water movement, in particular the development of jointing, is acknowledged in the frequently non homogeneous nature of weathering.

Suggested likely ranges for values of permeability for each of the grading categories are presented.

1 CLASSIFICATION OF GRANITES

The weathering of granites from fresh intact rock to residual soil commonly uses the classification scheme developed in Hong Kong (Geoguide 3, 1988) and adopted in the current British Standard for site investigations (BS 5930 1999). The key features of the basic rock weathering grades are outlined below:

Table 1: features of rock weathering grades

Grade I	Fresh Rock	No visible signs of decomposition, rings when struck by hammer.
Grade II	Discoloured rock	Staining near joint surfaces, not easily broken by hammer.
Grade III	Weakened rock	Completely stained, easily broken by geological hammer.
Grade IV	Weak rock	Does not slake when immersed in water. Can be broken by hand
Grade V	Completely weathered (or decomposed - CDG)	Original rock texture preserved, can be crumbled by hand, slakes when immersed in water.
Grade VI	Residual Soil	Original rock texture completely destroyed.

Whilst Geoguide 3 provides no comment on permeability, the descriptor that Grade IV does not slake in water but that Grade V does slake (i.e. intact samples will disaggregate under the influence of water) is particularly relevant in terms of the permeability and anticipated behaviour. For example, in critical excavations such as in tunnels below the water table.

Geoguide 3 includes two photographs of examples of Grade V and VI granites (Plate 11) which clearly show significant differences between them. It should be noted that a whole range of material must exist as a transition between these two distinct samples which serves to highlight the problems of describing and classifying such soils. Bruce and Shirlaw (1985) presented a range of grading curves for 71 samples of Grade V granite from Hong Kong as reproduced below.

The curves show an enormous range of grading representing material from clayey silty sand (which probably has clay like behaviour) to gravelly sand. Such a range is indicative of the range of weathering that can exist between the Grade V and Grade VI material as described above.

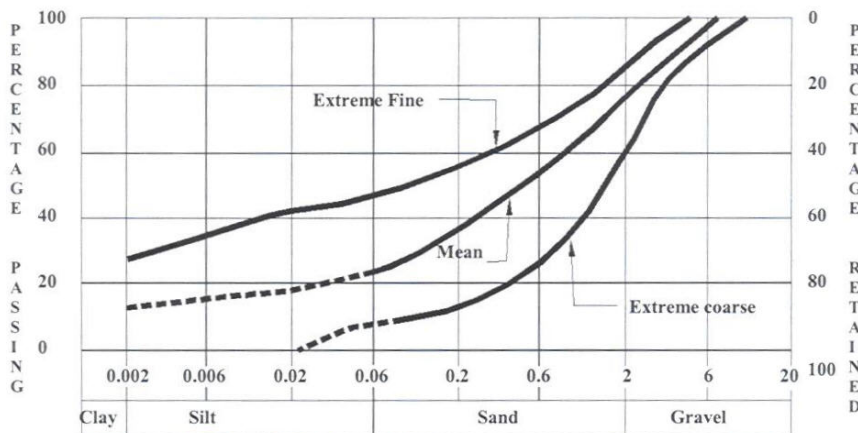


Figure 13 : Grading range for 71 samples of completely weathered granite (Grade V), Hong Kong (after Bruce and Shirlaw, 1985)

Figure 1: Grading range for 71 samples of Grade V granite

2 PERMEABILITY DATA

One conventional method of determining permeability from gradings is the Hazen formula based on experimental works using filter sands. The permeability is given by:

Permeability k (m/sec) = $D_{10}^2 \times 10^{-2}$ m/sec. Where D_{10} is particle size in millimetres where 10% passes the comparable sieve size.

Significantly the permeability implied by the gradings figure 1, using the conventional Hazen analysis implies a range of permeabilities between 2×10^{-4} m/sec and less than 10^{-9} m/sec for the extreme curves given in figure 1, with the permeability of the mean value being around 10^{-8} m/sec.

Such values are consistent with a large range of material types ranging from the impermeable clayey material to moderately highly permeable sands. It also implies that flow is likely to be spatially variable and dominated by flow from discrete zones.

Irfan and Dearman (1978) in a comprehensive set of laboratory data for a granite quarry at Hingston Down in SW England include permeability values for various granite grades as follows:

Grade II	Permeability range	10^{-8} to 10^{-11} m/sec.
Grade III/IV	Permeability range	10^{-9} m/sec.
Grade V	Permeability range	10^{-6} to 10^{-7} m/sec.

Irfan and Dearman also show data for increasing saturation moisture content and porosity with increase in weathering grade as follows:

Table 2:

GRADE	Saturation moisture content	Total Porosity
I	0.11 %	1.56 %
III	0.2 - 1.52 %	2.45 - 4.64 %
V	10.0 %	22.8 - 28.1 %

The total porosity value of some 25% for the Grade V granites indicates very clearly the significant void development associated with the weathering process and in particular leaching of fine

material. Such increases in porosity and moisture content might reasonably be expected to correlate with increasing permeability.

Lumb (1983) also produced data from Hong Kong to demonstrate the increase in porosity with weathering. Lumb states that, on average, Grades I and II material have an apparent porosity less than 5% and Grades III and IV have values between 5 and 30%. Lumb attributes much of this change to leaching which is accompanied by a density decrease.

Suzuki et al. (1995) reported on long term accelerated weathering simulation tests on granite cores. Cores of massive homogeneous granite from Ibaraki in Japan were immersed in water at 90°C for six years. Permeability tests showed an initial permeability of 1.8×10^{-11} m/sec, with a significant increase of several orders of magnitude at 3 years. Significant microcracking was seen on thin sections. Chemical weathering was also identified and linked to the microcracking.

It has been realised in recent years that in the weathering of granites to soils, small clusters of granite particles remain, particularly in the Grade V material. These clusters being bonded by stronger forces. Traditional methods of preparing samples for laboratory particle size analysis require that clays and other soils particles are separated by the use of Sodium Hexametaphosphate dispersant. This method has the effect of breaking down some of the clusters and producing results showing a higher proportion of clays and silts. There is therefore strong evidence that assessments of the permeability of highly weathered granites based on laboratory sizing tests where dispersants have been used are likely to be misleading.

Whilst these clusters predominate in Grade V material, progressive weathering leads to their breakdown to silts and clay sized particles such that by the time that the material has reached the Grade VI, residual soil stage, their behaviour is more that of a clay than a granular material. As a result the Grade VI residual soil is far less permeable than the Grade V material.

The parent material in a fresh state is substantially impermeable, so that the hydrogeology of Grade I and II material is entirely controlled by flow within joints and other discontinuities within the rock mass. Since permeability normally applies to a homogeneous material the use of the term permeability in relation to a rock mass with a few isolated joints can be misleading.

Where vertical and horizontal joint sets exist local weathering along joints ultimately leads to the formation of corestones, that is the where the central mass of rock remains unweathered and the joints are weathered and leached. An example of exposed granite corestones from Australia, where the joint sets can be clearly seen is shown in figure 2.

As weathering progresses in Grade III and IV material intergranular permeability and porosity will start to develop but fissure flow will still dominate. Shirlaw and Hencher (2000) have stated that *“chemically decomposed rocks are commonly far more closely fractured and jointed than their parent rocks in a fresh state”*. The reason for this appears to be related to stress release associated with relic structures and fracturing as a result of stresses caused by the expansion of material associated with weathering/ chemical changes. This will lead to a potentially large range of permeabilities from the largely intact rock with a permeability less than 10^{-9} m/sec to moderately permeable conditions, perhaps 10^{-5} m/sec or higher.

Where fracturing is intense and joints remain clean and unweathered, localised higher permeabilities have been observed. Thus the most permeable zones are often encountered in wells and boreholes in the top few metres of rock. This is consistent with the experience of water well drilling, particularly in the tropically weathered granitic rocks in Africa and Sri Lanka, where drilling just a few metres into the rockhead has been shown (Herbert et al. 1988) to be the most effective strategy for obtaining water supplies. The most permeable zones were in the lower part of the in situ weathered and disaggregated bedrock (equivalent to Grade V) and the underlying top of the bedrock where there were more fractures and an absence of clay infilling. Tests on a large number of wells show a permeability range of 10^{-5} to 10^{-7} m/sec in Zimbabwe and 10^{-4} to 10^{-6} m/sec in Sri Lanka.

Similar results from the Hawkesbury Sandstone in Sydney (Hewitt 2005) show the significance of depth and decreasing permeability with depth.



Figure 2: Example of granite corestones from Australia

When weathering reaches Grade V and the rock is completely weathered it might be expected that a relatively homogeneous, granular material results; however as is shown by the grading curves above this is not generally the case. Whilst intergranular permeability and porosity have developed i.e. the rock is a porous media, weathering changes mean that joints do not necessarily remain clean and open but may tend to become clogged with silt and clay sized particles. Alternatively clay particles may be leached out leading to more flow paths within the mass of the material leading to increases in permeability. These alternative scenarios may account for the variability observed in the permeability of the Grade V material.

This model is consistent with the grading curves for the 71 Grade V samples shown in the previous sections. However, there is in most cases a significant clay and silt fraction which conventional wisdom suggests leads to a lower permeability. In many cases however, as discussed in the preamble, the silt and clay minerals occur as clusters, which in turn are associated with higher permeability due more microfractures which are likely to be interconnected. Moderate permeabilities in the range 10^{-5} to 10^{-7} m/sec are likely to develop in this situation.

As weathering proceeds further towards the Grade VI condition proportionally more clay and silt will be present which will become more mobile leading to disaggregation of the clusters and the *“original rock texture completely destroyed”*, which is one of the prime descriptors of the Grade VI material. It is not surprising that as silt and clay becomes more disseminated and the microfractures become clogged and disappear that the permeability and porosity decrease rapidly. Permeabilities are likely to quickly reduce to 10^{-7} to 10^{-9} m/sec.

The weathering process in granite is complex with major and relic joints as well as microfracturing due to stress relief being key controls and variables. It is important to recognise that the increase in permeability associated with these various forms of joints allows water to flow and to introduce dissolved oxygen which is the driving force for the chemical reactions in the weathering process. Conversely in the massive unjointed fresh granites where the permeability is significantly less than 10^{-9} m/sec water flow does not take place and hence there is no weathering. The result is that corestones can be left within the mass of completely weathered rock.

Grade I material, i.e. fresh rock, has a permeability significantly less than 10^{-9} m/sec. However the presence of major jointing within the rock mass will produce locally very high permeabilities and with time, associated weathering.

Grade IV material tends to be the most highly fractured and has the highest porosity, it is therefore the most permeable of all the grades. Little data are available but permeabilities in the ranges 10^{-4} to 10^{-6} m/sec can be reasonably inferred.

Gradings of Grade V material can show an extremely large degree of variability, which may be consistent with the weathering process, but can also be influenced by the presence of clusters of fine particles which can be broken down in some laboratory test procedures. In practice Grade V material tends to be more permeable than would be expected from grading sieve analysis. There are considerable data which show that the permeability of the Grade V material is typically in the range 10^{-5} to 10^{-7} m/sec.

The Grade VI material is very different being a residual soil with the complete absence of the original rock fabric. In Singapore these materials tend to have a higher clay content and claylike behaviour, hence they tend to have a lower permeability of the order of 10^{-7} to 10^{-9} m/sec.

3 CONCLUSIONS

Using the standard Grades I to VI weathering grading system, Grades IV and V represent the most weathered rock. Samples of each may look similar with the original rock structure apparent and both can be broken by hand. The essential difference is that Grade IV does not slake in water whereas Grade V does.

If the weathering process can be said to be controlled by permeability, which itself is initially related to fracturing, it is not surprising that the permeability in weathered granites is likely to be highly variable and the material itself is likely to be variable.

In Grade V material, the silt and clay minerals typically occur in clusters, which in turn are associated with higher permeability due more microfractures which are likely to be interconnected. Moderate permeabilities in the range 10^{-5} to 10^{-7} m/sec are likely to develop in this situation.

As weathering proceeds further towards the Grade VI condition, clusters become disaggregated and "*original rock texture completely destroyed*", as silt and clay becomes more disseminated; the microfractures become clogged and disappear. The permeability and porosity decreases rapidly is likely to quickly reduce to 10^{-7} to 10^{-9} m/sec.

Consideration of published permeability data confirms that the highest permeabilities are found at the "rockhead" interface, that is in grades IV and V material as is predicted from the general review discussed above.

Assessed permeability and flow characteristics of the various granite grades, based principally on data from Singapore and Hong Kong are summarised below:

Grade	Description	Detail descriptors	Permeability	Flow Model
I	Fresh Rock	No visible signs of decomposition, rings when struck by hammer.	$<10^{-9}$ m/sec	Impermeable mass, only flow in major faults/joints
II	Discoloured rock	Staining near joint surfaces, not easily broken by hammer.	$<10^{-9}$ m/sec	Impermeable mass, only flow in faults and joints
III	Weakened rock	Completely stained, easily broken by geological hammer.	10^{-5} to 10^{-7} m/sec	Principally fissure flow in faults and joints.
IV	Weak rock	Does not slake when immersed in water. Can be broken by hand	10^{-4} to 10^{-6} m/sec	Fissure flow in joints, some microfracturing,
V	Completely weathered (decomposed - CDG)	Original rock texture preserved, can be crumbled by hand, slakes when immersed in water.	10^{-5} to 10^{-7} m/sec	Extensive microfracturing, and porous media flow developing.
VI	Residual Soil	Original rock texture completely destroyed.	10^{-7} to 10^{-9} m/sec	Porous media flow

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