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Saturated hydraulic conductivity (Ks) of earth materials in the weathering profile over a porphyritic biotite granite at the Kuala Lumpur - Karak Highway in Peninsular Malaysia

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Abstract: Three broad zones can be differentiated within the weathering profile over porphyritic biotite granite at Km 31 of the Kuala Lumpur - Karak Highway. The top Zone I (pedological soil) is 12 m thick and comprises A, B and C soil horizons; the C horizon (saprolite) being a clayey sand with indistinct relict bedrock textures. The intermediate Zone II (saprock) is some 30 m thick and consists of silty sands that indistinctly to distinctly preserve the minerals, textures and structures of the original granite. Zone II can be differentiated into four sub-zones; the upper II A and II B sub-zones marked by an absence of core boulders, whilst the lower II C and II D sub-zones have some to many core-boulders. The bottom Zone III (bedrock), whose upper surface is marked by an unconfined groundwater table, is a continuous granite outcrop with effects of weathering along and between discontinuity planes. Constant head permeability tests show saturated hydraulic conductivity (Ks) to vary with depth and texture; clayey sand from saprolite having a conductivity of 0.2420 cm/hr and silty sand from sub-zone II B, a conductivity of 0.7464 cm/hr. Silty sands from sub-zone II D have saturated hydraulic conductivity values of 1.5313, and 1.9585, cm/hr, whilst a silty sand from sub-zone II C has a conductivity of 4.1131 cm/hr due to it being collected at a relict pegmatite pod. Regression analyses show variable trends with low to moderate correlation coefficients (R^2 <0.600) for hydraulic conductivity versus index properties as clay and sand contents, but large correlation coefficients (R^2 >0.820) for hydraulic conductivity versus physical properties as dry unit weight and void ratio.

Keywords: Weathering profile, porphyritic biotite granite, saturated hydraulic conductivity

INTRODUCTION

The movement of water through earth materials is governed by the experimentally derived Darcy's Law [Q = KiA] which states that the discharge of water (Q) through a unit area of porous medium is directly proportional to the hydraulic gradient (i) normal to that area (A); K being the proportionality constant (Sharp, 2007). In Geology, the proportionality constant (K) has been known as the coefficient of permeability, though nowadays, it is referred to as the hydraulic conductivity. Hydraulic conductivity is defined as the rate of flow of water through a cross-sectional area under a unit hydraulic gradient at the prevailing temperature (Bates & Jackson, 1980).

The property or capacity of a porous rock, sediment or soil to transmit a fluid without impairment of the medium is termed permeability and can be considered to be a measure of the relative ease of flow under unequal pressure; the SI unit of measurement being m^2 (for saturated flow) (Bates & Jackson, 1980). The term intrinsic permeability, refers to the permeability of earth materials independent of fluid properties and is related to the hydraulic conductivity (K) by $K = k\rho g/\mu$, where k is the intrinsic permeability, ρ is the density of the liquid, g the acceleration due to gravity and μ is the dynamic viscosity of the liquid (Lewis *et al.*, 2006).

In Soil Science, intrinsic permeability (k) is considered to be a quantitative property of porous material that is controlled solely by pore geometry (USDA, 2018). Saturated hydraulic conductivity (Ks) furthermore, is considered to be a quantitative measure of a saturated soil's ability to transmit water when subjected to a hydraulic gradient and can be described as the ease with which pores of a saturated soil permit water movement (USDA, 2018). Saturated hydraulic conductivity is affected by both soil and fluid properties and depends on the soil pore geometry as well as the fluid viscosity and density. In contrast to hydraulic conductivity, intrinsic permeability is independent of fluid viscosity and density. In some cases in Soil Science, however, permeability (k) has been used as a synonym for saturated hydraulic conductivity (Ks), even though some other quantity was originally used to convey permeability (USDA, 2018). This misrepresentation led to some confusion and misapplication and is considered to be an important reason for use of the term saturated hydraulic conductivity (Ks) nowadays (USDA, 2018).

There is limited published data on the saturated hydraulic conductivity of earth materials in Malaysia where deep weathering profiles are found as a result of prolonged and pervasive weathering throughout most of the Cenozoic Era (Raj, 2009). The earliest data is from the

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Cameron Highlands Hydro-Electric Scheme where water absorption tests in boreholes in fresh to slightly weathered granite (Grades I and II) at depth yielded low coefficients of permeability (<0.18 cm/hr), and at shallow depths, moderate values (0.36 to 1.44 cm/hr) (Dickinson & Gerrard, 1963). Similar tests in fresh to slightly weathered meta-sedimentary bedrock yielded coefficients of permeability between 0.11 and 0.90 cm/hr, and in friable weathered schist, coefficients between 0.32 and 4.32 cm/hr. Field and laboratory tests furthermore, yielded coefficients of permeability between 0.36 and 3.60 cm/hr for moderately weathered granite (Grade III), between 1.62 and 32.40 cm/hr for highly weathered granite (Grades IV and V), and between 1.01 and 9.36 cm/hr for completely weathered granite (Grade VI) (Dickinson & Gerrard, 1963).

A study of water movement using dyes in soils at the Bukit Tarek Experimental Watershed found that the saturated hydraulic conductivity decreased with depth (Noguchi *et al.*, 1997). Measured values of hydraulic conductivity ranged from 16.88 to 146.52 cm/hr and were said to be much higher than those of other tropical soils. The study concluded that subsurface water flow may play an important role during stormflow generation, rather than saturation overland flow (Noguchi *et al.*, 1997).

In a study to evaluate the potential use of saprolite (soil horizon C) as a wastewater treatment in Malaysia, Hamdan *et al.* (2006) determined saturated hydraulic conductivity rates of 6.50, 1.10, 0.25 and 0.10, cm/hr for granite, schist, shale, and basalt, saprolites, respectively. Clay and sand contents as well as porosity, pore shape and pore size were found to influence the hydraulic conductivity; the study concluding that shale and basalt saprolites would be suitable for use in *in situ* wastewater treatment (Hamdan *et al*., 2006).

Samples from different depths at a weathering profile over quartz-mica schists in the Seremban area show saturated hydraulic conductivity to be primarily dependent upon the orientation of inherent relict foliation planes (Raj, 2020). Clayey silts from saprock (sub-zone II B) have saturated hydraulic conductivity values of 0.0611, and 0.0838, cm/hr with flow perpendicular, and about perpendicular, to relict foliation, respectively. Silts from saprock (sub-zone II C) furthermore, have conductivity values of 0.7365, and 0.3864, cm/hr with flow parallel, and steeply inclined, to relict foliation, respectively (Raj, 2020).

In Singapore, variations in index and engineering properties as well as micro-structural characteristics were said to be related to the degree of weathering in residual soils over the Bukit Timah Granite (Rahardjo *et al.*, 2004). A saturated coefficient of permeability of 0.00144 cm/hr was reported for granite saprolite (Grade VI), whilst values of 0.00212, and 0.00252, cm/hr, were reported for Grades V, and IV, granite saprock, respectively (Rahardjo *et al.*, 2004).

In the course of a study on the characterization of weathering profiles in Peninsular Malaysia, was investigated a profile over porphyritic biotite granite at Km 31 of the Kuala Lumpur - Karak Highway (Raj, 1983). In this paper are discussed the results of the laboratory determinations of the saturated hydraulic conductivity (Ks) of earth materials at various depths within the said profile.

METHODOLOGY

The investigated weathering profile is located at the slope cut at Km 31 of the Kuala Lumpur - Karak Highway and was exposed during earthworks for construction of the highway (Figure 1). Field mapping was first carried out to visually differentiate weathering zones and sub-zones, i.e. layers of earth materials with similar morphological features including colour, extent of preservation of original bedrock minerals, textures and structures, and litho-relicts (coreboulders) (Ollier, 1969). Two sets of constant volume samples were then collected at various depths within the exposed profile; one set for determination of physical and index properties of the earth materials, and the other for determination of the saturated hydraulic conductivity (Ks).

Brass tubes of 4.0 cm length and 7.6 cm internal diameter were used for the collection of undisturbed, constant volume samples at five different depths within the weathering profile (Figure 2). The tubes had a constant wall thickness of 0.3 cm, except towards one end where the lower 1.5 cm tapered to a wall thickness of 0.15 cm to provide a cutting edge. Prior to sampling, the tubes were externally greased to facilitate entry into the soil whilst surface materials were cleared to a depth of about 0.5 m to minimize surface disturbance. The exposed earth materials were also cut into an approximately cylindrical shape, slightly larger than the tube diameters, prior to sampling to reduce lateral compaction. A sampling tube with the cutting edge facing downwards was first driven into the weathered material by gently hammering on its' top, until the top was flush with the ground surface. A second tube, with its cutting edge facing upwards, was then placed on the first tube and this then driven deeper into the soil by hammering gently on the top of the second tube. A piece of wood was placed on top of the tubes when hammering to minimize damage to the tubes as well as disturbance to the samples. Both tubes were then dug out from the ground by excavating the earth materials surrounding, and under, the two tubes. The sample in the lower (first) tube was then trimmed until its upper and lower surfaces were flat and flush with the top and bottom of the tube. The sampling tube was then sealed with rubber end caps and taken to the laboratory for determination of the physical and index properties of the earth materials, as well as the saturated hydraulic conductivity.

Moisture contents, unit weights and densities of one set of the constant volume samples were determined before the specific gravity of the constituent mineral grains was measured using a pycnometer (GBRRL, 1959). Porosities were then calculated before the plastic limits of the fine fractions (<0.425 mm size) were determined by standard

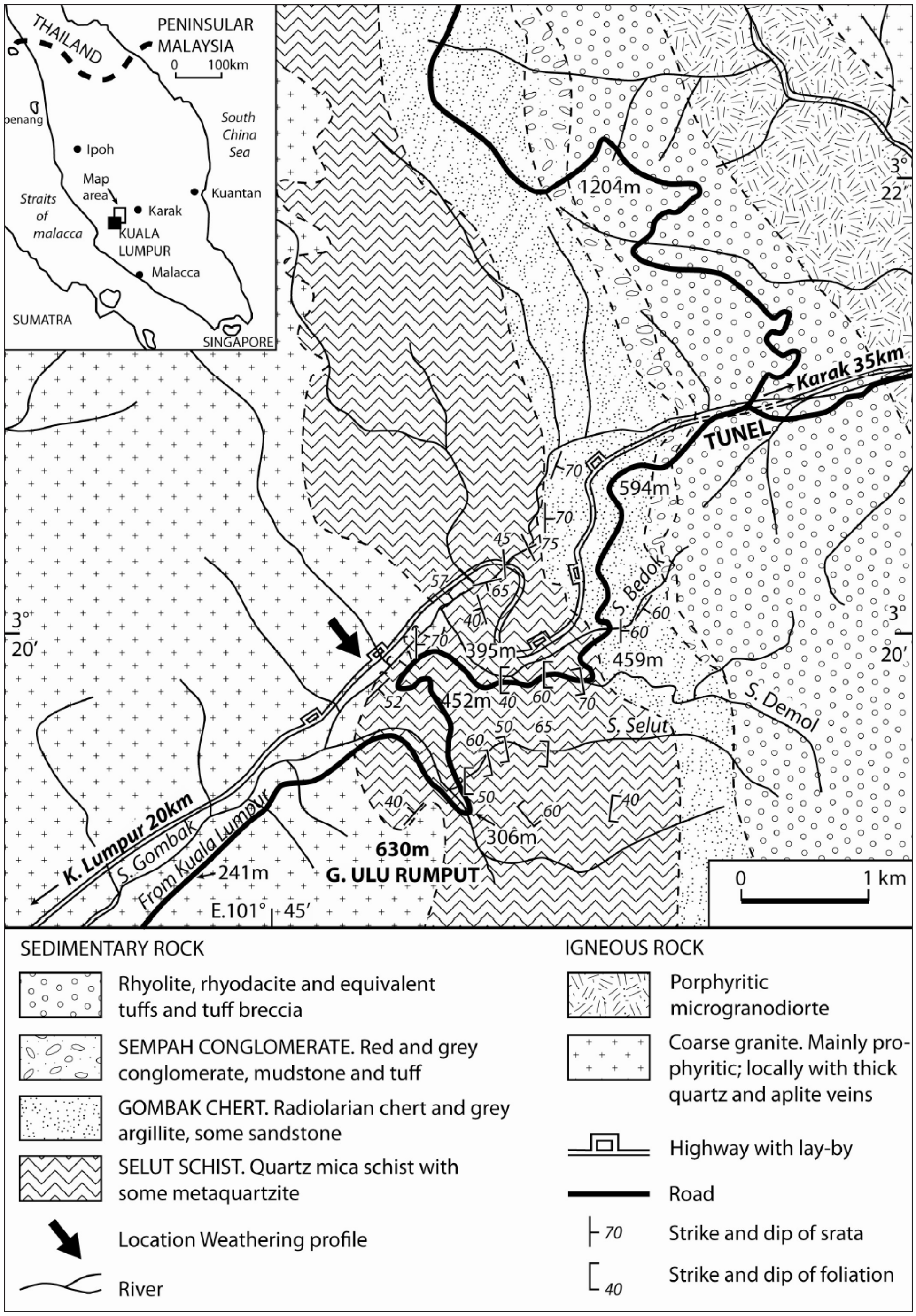

Figure 1: Geology map of the Genting Sempah area, Pahang and Selangor (Haile *et al*., 1977).

procedure (GBRRL, 1959). Particle size distributions of the samples were determined by employing the sieving and sedimentation methods for the coarse (>0.0625 mm diameter), and fine, fractions respectively (GBRRL, 1959). The main minerals present in the coarse silt to gravel sized fractions were identified with the aid of a binocular microscope, whilst X-ray diffraction analyses were carried out to identify the clay minerals present (Raj, 1983). It is to be noted that definitions of size limits for particles follows that of Wentworth (1922) where gravel refers to particles with diameters between 2 and 64 mm, sand to particles with diameters between 0.625 and 2.00 mm, silt to particles with diameters between 0.0039 and 0.0625 mm and clay to particles less than 0.0039 mm in diameter.

Saturated hydraulic conductivity (Ks) was measured by covering both ends of the sampling tube (from the second set) with filter paper and wire gauze screens before sealing it between araldite end caps. The araldite caps with

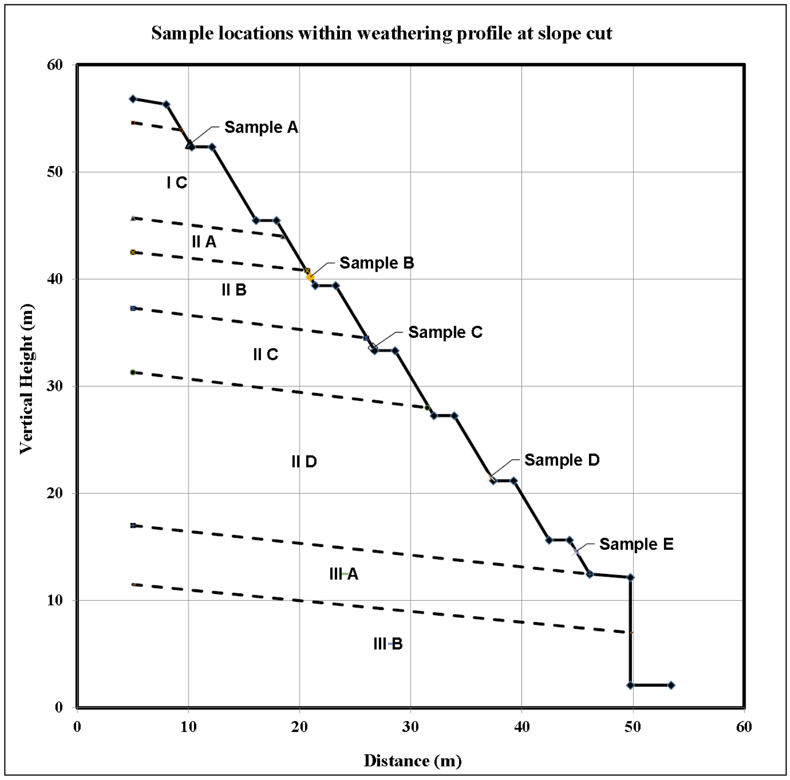

Figure 2: Sample locations within the weathering profile over the porphyritic biotite granite.

the enclosed sampling ring were then placed between two brass plates and held in place by three bolts and nuts. The outlet from the upper araldite cap was attached to a vacuum pump whilst the outlet from the lower cap was placed in a large water-filled beaker with its top water level on par with the top of the sample ring. The vacuum pump was then started and water allowed to flow through the sample until it emerged at the outlet of the upper araldite cap. The vacuum pump was stopped and the water-filled beaker raised to a known height. The discharge of water from the outlet of the top araldite cap was then measured over a period of up to 16 hours until a constant rate of discharge was recorded. From the known cross-sectional area (A) and length (L) of the sample, as well as the constant head (H) and rate of discharge (Q/t), the saturated hydraulic conductivity (Ks) was calculated. A schematic sketch of the set-up for the constant head permeability test is shown in Figure 3.

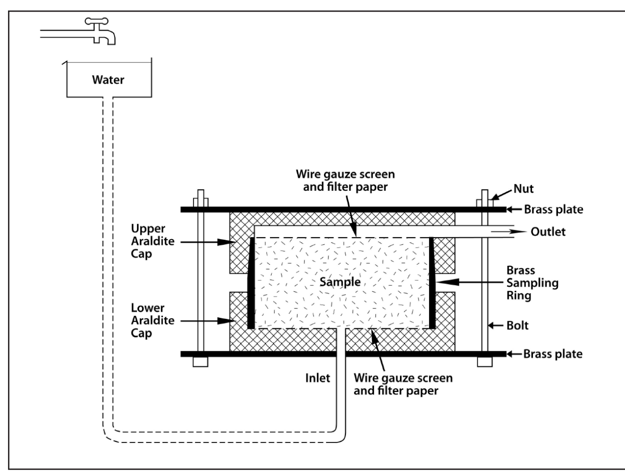

Figure 3: Schematic sketch of set-up for constant head permeability test.

GEOLOGICAL SETTING OF INVESTIGATED WEATHERING PROFILE

The investigated weathering profile is developed over a porphyritic biotite granite that forms part of the eastern lobe of the Late Triassic (199 - 210 Ma) Kuala Lumpur Granite (Figure 1). The granitic bedrock has given rise to a fluvially dissected, hilly to mountainous terrain of steep slopes and narrow, deep valleys that rise to over 1,000 m above sea-level. The bedrock continues to outcrop to the west over a distance of about 10 km, but to the east, is in contact with a sequence of schists, and sedimentary and volcanic rocks, that occur as a roof pendant within the Main Range Granite (Haile *et al.*, 1977).

The granitic bedrock exposed at the foot of the cut is strongly jointed and cut by a number of moderately to steeply dipping faults of variable strike. A number of epidote and quartz feldspar veins with tourmaline as well as aplite and leucocratic microgranite dykes are also seen. The grey bedrock is medium to coarse grained and usually porphyritic with large alkali feldspar phenocrysts (up to 4 cm in length). The essential minerals are quartz, alkali feldspar, plagioclase feldspar and biotite, whilst the accessory minerals include apatite, tourmaline and zircon. Quartz occurs as anhedral crystals, filling interstices in the groundmass and sometimes forms small phenocrysts. The alkali feldspars include microcline, orthoclase and perthites, and occur both as phenocrysts and as fine to medium grained crystals in the groundmass. The alkali feldspars sometimes contain quartz, biotite and plagioclase inclusions. The plagioclase feldspars, of an albite to andesine composition, are usually found as euhedral to subhedral, fine to medium grained crystals in the groundmass and are often sericitized. The biotites occur as fine to medium grained, generally euhedral crystals and are found both as disseminated grains and as aggregates within the bedrock material. Close to the faults, hydrothermal alteration of the plagioclase feldspar and biotite grains has occurred.

MORPHOLOGICAL ZONATION OF WEATHERING PROFILE

Field mapping shows vertical and lateral variations in the extent of preservation of the minerals, textures and structures of the original granitic bedrock; these variations allowing differentiation of three broad zones, i.e. an upper pedological soil (Zone I), an intermediate saprock (Zone II), and the underlying bedrock (Zone III). The zones are developed about parallel to the overlying ground surface and are of maximum thickness below the ridge crest but thin towards the valley sides. Descriptions of the different morphological zones (and sub-zones) are summarized in Table 1 and schematically shown in Figure 4 (Raj, 1985).

The presence of the three broad zones substantiates the view of Carroll (1970) that chemical weathering at the outer part of the lithosphere takes place in two stages; the first stage being the production of rotten rocks, on which the second stage, soil formation, takes place. The first stage is geochemical weathering, and is mostly the inorganic alteration of solid rocks, but in the second stage the effects of vegetation, both living and dead, together with the effects of metabolism of micro-organisms living in the geochemically altered rock materials, are added by the continued inorganic processes (Carroll, 1970). The pedological soil (Zone I) can thus be considered to result from alteration of bedrock by both geochemical and pedological processes, whilst the saprock (Zone II) results from alteration of bedrock by essentially geochemical processes. *In situ* development of the saprock (Zone II) furthermore, points to weathering (alteration) by gradual lowering of the unconfined groundwater table which is now located at its' (Zone II) bottom.

The pedological soil (Zone I) is up to 12 m thick with the A and B soil horizons (solum) consisting of friable to firm, sandy clay, whilst the C horizon (saprolite) comprises stiff to very stiff, clayey sand with indistinct to distinct relict granitic textures (Table 1). The saprock (Zone II)

Table 1: Field description of morphological zones and sub-zones within the weathering profile.

Sub-zone	Thickness (m)	Field Description	RM WG
I A	0.6	Brownish yellow (10YR6/8), sandy clay, porous, soft; friable dry; sub-angular blocky; many roots; boundary irregular, diffuse.	VI (6)
I B	1.0	Reddish yellow (7.5YR7/8), firm, sandy clay; friable, dry; sub-angular blocky; some roots; boundary wavy, sharp.	
I C	7.8	Yellowish red (5YR5/8), stiff to very stiff, clayey sand with some reddish yellow mottles; friable, dry; sub-angular blocky; indistinct to distinct relict bedrock texture; a few distinct relict quartz veins; boundary irregular, sharp.	
II A	4.5	Yellowish red (5YR5/8), friable, gravelly, silty sand with red & white mottles; thin bands & wedges of yellowish red clayey sand; distinct relict bedrock texture & quartz veins; some indistinct relict joint planes; boundary, irregular, diffuse.	V (5)
II B	6.0	White (10YR8/2), friable, gravelly silty sand with bands of yellowish red, gravelly silty sand; distinct relict bedrock texture, quartz veins & joint planes; boundary, irregular, diffuse.	
II C	7.3	Pinkish to yellowish red, friable, gravelly silty sand; distinct relict bedrock texture, quartz veins, joint & fault planes; some fresh core-boulders (20 - 40% by area); boundary, irregular, diffuse.	IV (4)
II D	13.9	Dominantly partly weathered to fresh, rounded core-boulders (>70% by area) surrounded by thin to broad bands of whitish, friable, gravelly silty sand with distinct relict bedrock textures, quartz veins, joint & fault planes; boundary, irregular, sharp.	III (3)
III A	5.0	Continuous granite outcrop with effects of weathering (including alteration of feldspars & formation of gravelly silty sand) along & between joint & fault planes; boundary, broken, diffuse.	II (2)
III B	>2.0	Continuous granite outcrop with effects of weathering along joint & fault planes only.	

Note: i) RMWG - Rock Mass Weathering Grade, ii) Colour based on Munsel Colour Chart

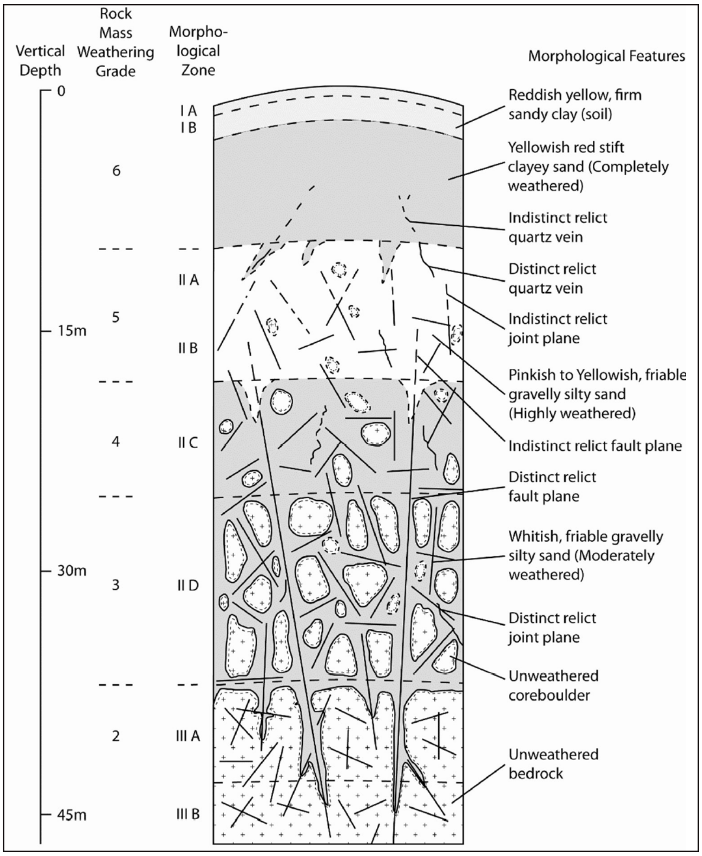

Figure 4: Schematic sketch of morphological features within the weathering profile over the porphyritic biotite granite.

is up to 30 m thick and consists mainly of silty sands that distinctly preserve the minerals, textures and structures of the original granite; the extent of preservation increasing with depth. This Zone can be separated into four sub-zones; the top two (II A and II B) devoid of core-boulders, whilst the lower two, II C and II D, have some (<40% by area), or many (>70% by area), core-boulders, respectively (Table 1). The bedrock (Zone III) is a continuous outcrop of granite with effects of weathering (marked by narrow to broad, strips of gravelly silty sand) along, and between, discontinuity planes (III A), or only along discontinuity planes (III B).

In terms of rock mass weathering grades as proposed by IAEG (1981) and GSL (1990), the pedological soil (Zone I) would be classified as rock mass weathering grade VI (6), whilst the bedrock zone (Zone III) would be defined as rock mass weathering grade II (2). In view of the litho-relicts (core-boulders) present, sub-zones II D, and II C, would constitute rock mass weathering grades III (3), and IV (4), respectively, whilst sub-zones II A and II B would be classified as rock mass weathering grade V (5) (Figure 4).

RESULTS

Descriptions of collected samples

Earth materials in the weathering profiles of humid tropical areas, indistinctly to distinctly

Table 2: Descriptions of samples collected for determination of saturated hydraulic conductivity (Ks).

Sample	Sub-zone	Vertical Depth	Description
Sample A	I C	3.70 m	Yellowish red, stiff, clayey sand with reddish yellow mottles & indistinct relict granite bedrock texture. Completely weathered granite. Coarse fraction of quartz grains & sericite flakes. Clay fraction of kaolinite. (USC - SC Class)
Sample B	II B	16.11 m	Pink to yellowish red, friable, silty sand with distinct relict bedrock texture. Very highly weathered granite. Coarse fraction of quartz grains & sericite flakes with some kaolinized feldspar fragments. Clay fraction of kaolinite. (USC - SM Class)
Sample C	II C	22.71 m	Light grey, friable, gravelly silty sand with distinct relict bedrock texture. Highly weathered granite. Coarse fraction of quartz grains & sericite flakes with many, large, kaolinized feldspar fragments. Relict pegmatite pod. Clay fraction of kaolinite. (USC - SM Class).
Sample D	II D	37.26 m	White to light grey, friable, gravelly silty sand with distinct relict bedrock texture. Moderately weathered granite. Coarse fraction of quartz grains & sericite flakes with some altered & fresh feldspar fragments. Clay fraction of kaolinite & illite. (USC - SM Class).
Sample E	II D	42.77 m	White to light grey, friable, silty sand with distinct relict bedrock texture. Moderately weathered granite. Coarse fraction of quartz grains & sericite flakes with many fresh feldspar fragments. Clay fraction of kaolinite & illite. (USC - SM Class).

Note: USC refers to Unified Soil Classification System (Wagner, 1957) preserve (as relict features) the minerals, textures and structures of the original bedrock material and mass (Raj, 2009). Descriptions therefore, must be provided of the earth materials from weathering profiles that are investigated in the field or tested in the laboratory. In the case of the collected samples, there can be seen distinct textural and compositional variations as they were collected at different depths within the weathering profile (Figure 2).

Sample A is from soil horizon I C (saprolite) which forms the parent material for the overlying soil horizons I A and I B (solum). The sample is a stiff, clayey sand which indistinctly retains the original granite texture and represents completely weathered bedrock material.

Samples B, C, D and E were collected from saprock and thus distinctly retain the texture of the original granite. The samples are best described as friable, silty sands that represent moderately to highly weathered granitic rock, except for sample C which was collected at a weathered pegmatite pod.

Physical properties of collected samples

The samples show variations in physical properties; sample A being the most dense, and sample C, the least dense, with dry unit weights of 15.99 kN/m^3, and 11.27 kN/m^3, and dry densities of 1,630, and 1,149, kg/m^3, respectively (Table 3). Samples B, D and E, have intermediate values of dry unit weight between 13.23 and 13.79 kN/m^3, and dry density between 1,376 and 1,406 kg/m^3 (Table 3).

Mineral grains in the samples show slight differences in specific gravity (SG) with samples A, B, D and E having values of 2.596 to 2.640 whilst sample C has a value of 2.520 (Table 3). These differences are considered to reflect the composition of the minerals present for fresh (unaltered) feldspars have a specific gravity between 2.60 and 2.80, whilst their main alteration product kaolinite has a specific gravity between 2.58 and 2.63 (Deer *et al.*, 1977). Large feldspar crystals in the original pegmatite pod (and subsequently altered to kaolinite) have thus given rise to the lower specific gravity of sample C.

The porosity of samples is variable; sample A with the minimum value (38.0%) and sample C with the maximum value (55.8%), whilst the other samples have intermediate values (46.3 to 48.7%) (Table 3). Values of void ratio are also distinctly variable with sample A having the minimum ratio (0.61), and sample C, the maximum ratio (1.26), whilst the other samples have intermediate ratios (0.82 to 0.95 (Table 3).

Moisture contents show a general decrease with depth; sample A with 15.2% and sample E with 7.0%, whilst samples B, C and D have contents of of 12.0%, 15.0% and 11.9%, respectively (Table 3).

Index properties of collected samples

Index properties show distinct differences; sample A from saprolite having a large clay content (32%) but the other samples from saprock having lower contents that decrease with depth from sample B (12%) through samples C (11%) and D (7%) to sample E (6%) (Table 4). Silt contents are similarly variable; sample A with a silt content of 14%, whilst samples B, C, D and E, have silt contents of 22%, 28%, 21% and 12%, respectively (Table 4).

Table 3: Physical properties of samples collected for determination of saturated hydraulic conductivity (Ks).

Sample	Vertical Depth	Dry Unit Weight (kN/m^3)	Dry Density (kg/m^3)	Mineral Grain SG	Porosity (%)	Void Ratio	Moisture Content (%)
A	3.70 m	15.99	1,630	2.640	38.0	0.61	15.2
B	16.11 m	13.50	1,376	2.596	47.0	0.89	13.0
C	22.71 m	11.27	1,149	2.520	55.8	1.26	15.0
D	37.26 m	13.23	1,398	2.626	48.7	0.95	11.9
E	42.77 m	13.79	1,406	2.620	46.3	0.82	7.0

Note: SG refers to specific gravity

Table 4: Index properties of samples collected for determination of saturated hydraulic conductivity (Ks).

Sample	Vertical Depth	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	Gravel & Sand (%)	Plastic Limit (%)
A	3.70 m	9	45	14	32	54	33.1
B	16.11 m	5	61	22	12	66	38.6
C	22.71 m	11	50	28	11	61	39.9
D	37.26 m	15	57	21	7	72	36.0
E	42.77 m	3	79	12	6	82	26.7

Sand contents are more variable as are the gravel contents (Table 4). Sample A has a sand content of 14%, whilst samples B, C, D and E, have contents of 61%, 50%, 57% and 79%, respectively (Table 4). Sample A furthermore, has a gravel content of 9%, whilst samples B, C, D, and E, have contents of 5%, 11%, 15% and 3%, respectively (Table 4). Sand and gravel contents together generally increase with depth from 54% in sample A through 66% and 61% in samples B and D, to 72% and 82% in samples D and E, respectively (Table 4).

Plastic limits show limited variation with values of between 26.7% and 38.6% for all samples (Table 4). Liquid limits, however, were not determined as high silt contents prevented creation of a proper groove with the standard Casagrande grooving tool.

In general, it can be said that increasing effects of weathering processes up the profile are marked by a decrease in silt contents and an increase in clay contents.

Discharge and saturated hydraulic conductivity (Ks)

The permeability tests were carried out with a constant head of 70.485 cm and involved measurement of the volume of water (cm^3) collected in fixed time periods (mins) at different elapsed times (in hours) from the start. The results of these tests are presented in Tables 5 to 9 in order to serve as reference for future work.

Sample A (from saprolite) shows a gradual decrease in discharge with time and reaches a constant value after some 12 hours elapsed time (Table 5). Sample B (from sub-zone II B in saprock) shows a similar gradual decrease in discharge with time and reaches a constant value after some 11 hours elapsed time (Table 6).

Sample C (from a weathered pegmatite pod in sub-zone II C) starts with a large discharge that remains fairly constant over a long period of elapsed time (13 hours); thus pointing to its very permeable character (Table 7).

Samples D and E (from sub-zone II D) start with fairly large discharges that gradually increase and become constant after some 7 hours of elapsed time (Tables 8 and 9). The high and constant discharges point to the very permeable character of the earth materials in sub-zone II D (saprock).

DISCUSSION

The constant head permeability tests show the saturated hydraulic conductivity (Ks) of earth materials within the weathering profile to vary with depth and dependent primarily upon their texture (Table 10). The hydraulic conductivity is therefore, dependent upon the degree of alteration (or weathering) of the original bedrock mass as reflected by the morphological zones and sub-zones that are based on differences in preservation of the minerals, textures and structures of the original bedrock.

Sample A (from sub-zone I C) is a clayey sand with the lowest values of hydraulic conductivity (0.2420 cm/hr), porosity (38.0%) and void ratio (0.61), but the highest

Table 5: Results of constant head permeability tests on Sample A from sub-zone I C.

Time from start (hours)	Discharge (cm^3/hr)	Saturated Hydraulic Conductivity (Ks) (cm/hr)
0.067	270.0	0.3378
0.200	262.5	0.3284
0.467	251.3	0.3143
4.517	230.0	0.2877
4.633	231.4	0.2895
4.850	223.8	0.2800
5.167	220.4	0.2757
11.533	197.7	0.2473
12.050	194.5	0.2433
12.683	193.4	0.2420

Table 6: Results of constant head permeability tests on Sample B from sub-zone II B.

Time from start (hours)	Discharge (cm^3/hr)	Saturated Hydraulic Conductivity (Ks) (cm/hr)
0.050	900.0	1.1259
0.167	831.4	1.0401
0.383	766.2	0.9584
4.467	720.0	0.9007
4.617	686.7	0.8590
4.833	669.2	0.8372
5.100	656.3	0.8209
11.183	624.0	0.7806
11.300	617.1	0.7720
11.600	596.7	0.7464

Table 7: Results of constant head permeability tests on Sample C from sub-zone II C.

Time from start (hours)	Discharge (cm^3/hr)	Saturated Hydraulic Conductivity (Ks) (cm/hr)
0.017	3300.0	4.1282
0.083	3270.0	4.0906
0.183	3250.0	4.0656
0.383	3165.0	3.9593
4.433	3200.0	4.0031
4.517	3252.0	4.0681
4.650	3232.5	4.0437
12.700	3240.0	4.0531
12.767	3270.0	4.0906
12.900	3270.0	4.0906
13.067	3288.0	4.1131

Table 8: Results of constant head permeability tests on Sample D from sub-zone II D.

Time from start (hours)	Discharge (cm^3/hr)	Saturated Hydraulic Conductivity (Ks) (cm/hr)
0.067	1320.0	1.6513
0.167	1310.0	1.6388
0.317	1326.7	1.6596
0.517	1335.0	1.6700
0.783	1346.3	1.6841
6.833	1560.0	1.9515
6.917	1536.0	1.9215
7.067	1553.3	1.9432
7.267	1555.0	1.9452
15.333	1575.0	1.9703
15.483	1553.3	1.9432
15.667	1570.9	1.9651
15.917	1564.0	1.9565

Table 9: Results of constant head permeability tests on Sample E from sub-zone II D.

Time from start (hours)	Discharge (cm^3/hr)	Saturated Hydraulic Conductivity (Ks) (cm/hr)
0.067	1095.0	1.3698
0.167	1107.0	1.3848
0.350	1105.6	1.3831
0.583	1117.3	1.3977
6.683	1100.0	1.3761
6.833	1103.3	1.3802
7.017	1110.0	1.3886
7.833	1223.9	1.5310
11.867	1245.0	1.5574
11.917	1240.0	1.5512
12.033	1225.7	1.5333
12.200	1221.0	1.5274
12.400	1224.0	1.5312

Table 10: Saturated hydraulic conductivity (Ks) of samples from the weathering profile over porphyritic biotite granite.

Sample	Depth (m)	Sub-zone	Ks (cm/hr)	Comments
A	3.70 m	I C	0.2420	Clayey sand
B	16.11 m	II B	0.7464	Silty sand
C	22.71 m	II C	4.1131	Silty sand (pegmatite pod)
D	37.26 m	II D	1.9585	Silty sand
E	42.77 m	III D	1.5313	Silty sand

values of dry unit weight (15.99 KN/m^3) and density (1,630 kg/m^3) (Tables 3, 4 and 10). The low saturated hydraulic conductivity would therefore, indicate the presence of a very limited volume of connected pores in saprolite.

Sample C (from sub-zone II C) is a silty sand with the largest values of hydraulic conductivity (4.1131 cm/hr), porosity (55.8%) and void ratio (1.26), but the lowest values of dry unit weight (11.27 KN/m^3) and density (1,149 kg/m^3) (Tables 3, 4 and 10). The large hydraulic conductivity therefore, indicates the presence of a large volume of connected pores. It must be noted, that this particular sample is a site specific sample, having been collected at a weathered pegmatite pod (Table 10).

Sample B (from sub-zone II B) is a silty sand with the second lowest value of hydraulic conductivity (0.7464 cm/hr) and intermediate values of dry unit weight (13.50 KN/m^3), dry density (1,376 kg/m^3), porosity (47.0%) and void ratio (0.89) (Tables 3, 4 and 10). The fairly low saturated hydraulic conductivity can thus be considered to reflect the presence of a limited volume of connected pores.

Sample D (from sub-zone II D) is a silty sand with the second highest hydraulic conductivity (1.985 cm/hr) and intermediate values of dry unit weight (13.23 KN/m^3), dry density (1,398 kg/m^3), porosity (48.7%) and void ratio (0.95) (Tables 3, 4 and 10). Sample E (from sub-zone II D) is a silty sand that has similar properties as sample D with intermediate values of hydraulic conductivity (1.5313 cm/hr), dry unit weight (13.79 KN/m^3), dry density (1,406 kg/m^3), porosity (45.3%) and void ratio (0.82) (Tables 3, 4 and 10). The relatively large values of the saturated hydraulic conductivity of samples D and E are thus considered to reflect the large volume of connected pores present in sub-zone II D.

Regression analyses furthermore, show variable trends with low to moderate correlation coefficients (R^2) when saturated hydraulic conductivity values are plotted against index properties. Plots of hydraulic conductivity versus clay contents for instance, show a negative trend with a very low correlation coefficient (R^2=0.2546), whilst plots of hydraulic conductivity versus silt contents show a positive trend with a moderate correlation coefficient (R^2=0.5167).

Regression analyses also show variable trends with low to large, correlation coefficients (R^2) when saturated hydraulic conductivity values are plotted against physical properties.

Plots of hydraulic conductivity versus porosity for instance, show a positive trend with a low correlation coefficient (R^2=0.3512) (Figure 5). Plots of hydraulic conductivity versus dry unit weight, however, show a negative trend with a large correlation coefficient (R^2=0.8249) (Figure 6). Plots of hydraulic conductivity versus void ratio furthermore, show a positive trend with a large correlation coefficient (R^2=0.8839) (Figure 7).

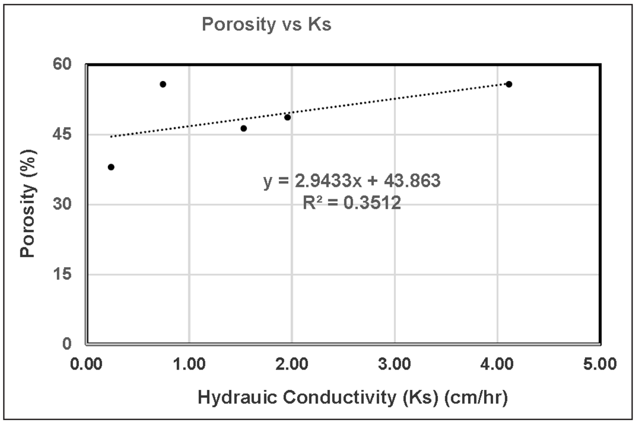

Figure 5: Plots of porosity versus saturated hydraulic conductivity.

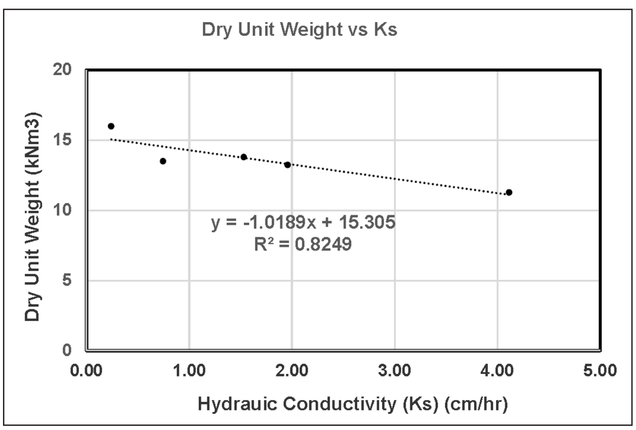

Figure 6: Plots of dry unit weight versus saturated hydraulic conductivity.

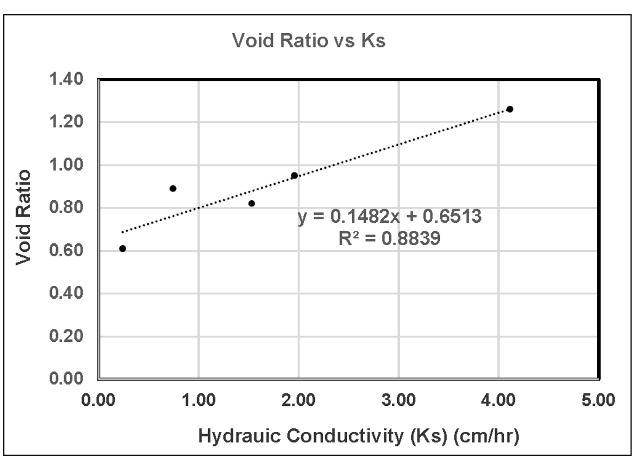

Figure 7: Plots of void ratio versus saturated hydraulic conductivity.

Published data for purposes of comparison is seen in the coefficients of permeability of 0.36 to 3.60 cm/hr of moderately weathered granite (Grade III), 1.62 to 32.40 cm/hr of highly weathered granite (Grades IV and V), and 1.01 to 9.36 cm/hr of completely weathered granite (Grade VI) reported from field and laboratory tests for the Cameron Highlands Hydro-electric Scheme (Dickinson & Gerrard, 1963). The coefficients of permeability for moderately weathered granite (Grade III) are comparable with the hydraulic conductivity of samples C, D and E of this study though the coefficients for moderately (sample B), and completely (sample A), weathered granite are slightly larger.

The saturated hydraulic conductivity of 0.2420 cm/hr for sample A (saprolite) in the present study is also much lower than the conductivity of 6.50 cm/hr for granite saprolite reported by Hamdan *et al.* (2006). It must be noted, however, that the granite saprolite of Hamdan *et al.* (2006) is much coarser grained than sample A, with 64% sand, 25% silt, and 11% clay, sized particles.

The hydraulic conductivity values of the present study are also much larger than those reported for the weathering profile over the Bukit Timah granite in Singapore where Grade VI granite (saprolite), Grade V (saprock), and Grade IV (saprock), are said to have coefficients of permeability of 0.00144, 0.00212, and 0.00262, cm/hr, respectively (Rahardjo *et al.*, 2004).

Differences in saturated hydraulic conductivity with depth and texture will furthermore, have implications on surface runoff during rainfall events. In areas of undisturbed natural ground surfaces, there can be expected limited percolation of rainwater following its infiltration in view of the clayey sand saprolite (soil horizon I C) with its relatively low hydraulic conductivity. At slope cuts and areas where excavations have been carried out, however, there can be expected rapid percolation of rainwater following its infiltration in view of the exposed, silty sands of Zone II (saprock) which have relatively large values of hydraulic conductivity. Rapid percolation can therefore, give rise to a quick increase in unconfined groundwater levels.

CONCLUSIONS

It is concluded that the saturated hydraulic conductivity (Ks) of earth materials within the weathering profile over porphyritic biotite granite varies with depth as a result of textural differences. Clayey sand from the I C soil horizon (saprolite) has a conductivity of 0.2420 cm/hr, whilst silty sand from sub-zone II B has a value of 0.7464 cm/hr. Silty sands from sub-zone II D have saturated conductivity values of 1.5313, and 1.9585, cm/hr, whilst a silty sand from sub-zone II C has a conductivity value of 4.1131 cm/hr due to it being collected at a relict pegmatite pod.

Regression analyses show variable trends with low to moderate correlation coefficients (R^2 <0.600) for hydraulic conductivity versus index properties as clay and sand contents, but large correlation coefficients (R^2 >0.820) for hydraulic conductivity versus physical properties as dry unit weight and void ratio.

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