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Residual shear strength of a weathered graphitic-quartz-mica schist in humid tropical Peninsular Malaysia

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Abstract: *In situ* weathered bands of graphitic-quartz-mica schist some 0.5 to 1.0 m thick intercalated with 0.3 m thick layers and lenses of quartz-mica schist are found at the site of a compound slide at Km 25.4 of the Kuala Lumpur - Seremban Highway. These schists, mapped as the Kajang Schist of Silurian age, are seen in thin-section to consist of thin (<0.5 mm) layers of fine grained quartz in parallel alignment with thicker layers (up to 5 mm) of aligned sericite, muscovite and clay minerals; the graphitic variety also containing aligned graphite flakes. The weathered graphitic-quartz-mica schist shows variability in index properties with mean dry, and saturated, densities of 1,355 kg/m^3, and 1,845 kg/m^3, respectively, and a porosity of 49.5%. The weathered schist comprises on average 12.4% sand-sized, 62.6% silt-sized, and 25.0% clay-sized, particles. Three samples of the mortar ground weathered schist were tested with the Bromhead ring shear apparatus to determine residual strength using the pre-shearing procedure with multi-stage loading. Sample A comprised particles <0.18 mm in size, Sample B particles <1.00 mm in size, and Sample C was the original unsieved sample. Plots of effective shear stress at maximum displacement against effective normal stress yield "complete failure envelopes" that can be differentiated into two distinct linear segments. Linear segments for effective normal stresses below 150 kPa yield residual friction angles (Φ_r) of 24.7^o, 25.5^o, and 25.8^o, for Samples A, B, and C, respectively, or an average residual friction angle of 25.3^o. These residual friction angles are comparable with the residual friction angle of 26.5^o determined in soil shear box tests along a pre-cut surface in similar weathered schist but under low normal stresses (<10 kPa) and limited displacements. Linear segments for effective normal stresses exceeding 150 kPa yield unwarranted cohesion intercepts due to increased friction as a result of sample extrusion and settlement of the top platen into the specimen container. It is concluded that the pre-shearing test procedure with multi-stage loading is only applicable to determining the residual strength of weathered graphitic-quartz-mica schist under effective normal stresses below 150 kPa.

Keywords: weathered graphitic-quartz-mica schist, residual friction angle

INTRODUCTION

In the case of most landslides, the formation of a shear zone or shear surface involves disruption of an existing fabric and its replacement by a fabric dominated by the effects of shear (Bromhead, 1986). This alteration of the fabric results in a decrease in the strength properties of earth materials; the strength with the original fabric known as the "peak strength", and the strength under large deformation conditions known as the "residual strength" (or also sometimes called the ultimate or large deformation strength) (Bromhead, 1986).

The shear box has been widely used to obtain the peak shear strength parameters of soil and has in more recent years been modified to determine the residual strength by continual forward and reverse shearing of a sample (Bromhead, 1986). The ring shear apparatus developed by Bishop *et al.* (1971) allows continuous shearing of a sample in one direction as does the less sophisticated Bromhead ring shear apparatus which has become more widespread in use as it is relatively cheap and easy to operate (Bromhead, 1979; 1986). Results obtained with the Bromhead apparatus, however, have been treated with some reservation by practicing engineers on the grounds that the determined residual friction angles are under-estimates of the true values (Hawkins & Privett, 1985). Careful testing furthermore, has shown that in the case of remoulded samples, similar results can be obtained using the Bromhead apparatus and the conventional reversal shear box (Hawkins & Privett, 1986).

In a comprehensive literature review, Rigo *et al.* (2006) have stated that the residual strength of transported soils and soils resulting from weathering of sedimentary rocks is extensively described in the geotechnical literature with well-known examples being the over-consolidated clays, clays and clay shales of northern Europe and North America. Rigo *et al.* (2006) furthermore, noted that there is significantly less published data on the residual strength of soils in tropical areas. The soils of tropical areas also often indistinctly to distinctly preserve the minerals, textures and structures of the original bedrock, giving rise to anisotropic weathered materials, especially when developed over inherently anisotropic bedrock as metamorphic rocks (Deere & Patton, 1971). Several authors as St. John *et al.* (1969), Ayetey (1985), and Raj (1988) have thus shown that the laboratory determined shear strength parameters of such

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weathered materials are influenced by the orientation of samples relative to the relict textures and structures present.

In Peninsular Malaysia, deep weathering profiles are found over different bedrock as a result of prolonged and pervasive weathering throughout most of the Cenozoic Era (Raj, 2009). Some of these profiles are developed over metamorphic bedrock, though there is little published literature on their shear strength apart from Raj (1988). Komoo & Morgana (1988) have also pointed out that the IAEG (1981) weathering classification of rock mass requires modification when applied to sedimentary and meta-sedimentary bedrock in tropical areas in view of their continuous weathering to form residual soils. In this paper are discussed the results of laboratory tests with the Bromhead ring shear apparatus to determine the residual shear strength of a weathered graphitic-quartz-mica schist at a slope cut where a compound slide had occurred.

GEOLOGICAL SETTING OF SAMPLING SITE

The slope cut, where failure occurred, was excavated in the mid 1970s and is located on the eastern side of the Kuala Lumpur - Seremban Highway at Km 25.4. The Highway here cuts the col between two low hills and extends in a general northwest-southeast direction across an undulating terrain (some 40 to 60 m above mean sea-leve) developed over the Kajang Schist (Figure 1). At the time of the slope failure in 1981, the cut was of an approximately symmetrical shape with a length of some 80 m along its base and a maximum vertical height of 10 m at its center. The cut with an overall slope angle of 36^o was benched; the benches of 3.05 m vertical height and face angles of 45^o to 50^o, separated by 1.83 m wide horizontal berms. Along the base of the cut, and separated from it by a 1.5 m wide berm, was located an unlined, shallow ditch of about 0.5 m deep and 0.8 m wide. Earthworks associated with widening of the highway in the 1990s have resulted in substantial modification to the slope cut.

At the foot of the cut were exposed thick bands (0.5 to 1 m thick) of *in situ* weathered, dark grey to black, graphitic-quartz-mica schists intercalated with thin bands (<0.3 m thick) and lenses of orange to pale brown, quartz-mica schists. These schists, which contain many thin quartz veins and pods, have been mapped as the Kajang Schist which is reported to be strongly folded with variable strikes and dips, and is of a probable Silurian age (Yin, 1976). At the cut, the weathered materials indistinctly to distinctly preserve all the minerals, textures and structures of the original bedrock; the foliation, though variable, generally striking north-south with a westward dip of about 30^o. Several sets of indistinct to distinct, closely spaced, relict joint planes are also seen and developed perpendicular to the foliation. These joint planes are also often occupied by thin quartz veins (Raj, 1988).

In thin-section, the graphitic-quartz-mica schists are seen to consist of thin layers (about 0.5 mm thick) of fine grained quartz crystals in parallel alignment with thicker layers (up to 5 mm thick) of aligned graphite, sericite, muscovite, and clay minerals. The quartz-mica schists also show a similar appearance in thin-section, though graphite is absent, or only present in minor amounts, in the thicker layers. In the thin-sections, secondary iron oxide and hydroxide stains and grains are also seen, while thin quartz veins and fissures are sometimes seen perpendicular to foliation. Binocular microscope observations of the weathered graphitic-quartz-mica schist show its' sand-sized particles to comprise angular quartz grains and a few, sub-rounded lateritic concretions, whilst its' silt-sized particles are overwhelmingly of flaky sericite.

Consolidated drained, shear box tests on samples of the weathered graphitic-quartz-mica schist under very low effective normal stresses (<10 kPa) show the shear strength to be dependent upon the orientation of samples relative to the inherent relict textures and structures (Raj, 1988). It was also then concluded that variations in the peak and residual shear strengths resulted mainly from differences in the planarity of shearing surfaces caused by variations in the orientations of mineral grains relative to the direction of shearing (Raj, 1988).

METHODOLOGY

Small blocks (measuring some 0.03 m^3 in volume) of *in situ* weathered, dark grey to black graphitic-quartz-mica schist were first collected at the base of the cut from undisturbed, saturated, slope material adjacent to the compound slide. Two constant volume samples were also collected using brass tubes of 4 cm length and 7.6 cm internal diameter to determine index properties of the weathered material. The small blocks were split by hand and then air-dried before being gently ground with a mortar and pestle; the ground materials separated into several portions using a mechanical sample splitter.

In order to see the influence of particle size on the residual shear strength, three samples were prepared for testing; Sample A being the total sample sieved though a 0.18 mm woven wire mesh sieve, Sample B being the total sample sieved through a 1.00 mm woven wire mesh sieve, and Sample C being the total unsieved sample. Particle size distributions of these samples were then determined using the sieving, and sedimentation, methods for the coarse (>0.063 mm diameter), and fine (<0.063 mm diameter) fractions respectively (GBRRL, 1959). The plastic and liquid limits of the fine fractions (<0.42 mm size) of the three samples were also determined according to standard methods (GBRRL, 1959).

The Bromhead ring shear apparatus allows testing of an annular sample, some 5 mm thick with inner and outer diameters of 70 and 100 mm, respectively that is confined radially between concentric rings. The sample is compressed vertically between porous bronze loading platens by means of a counter balanced 10:1 ratio lever loading system. A rotation is then imparted to the base plate and lower platen by means of a variable speed motor and gearbox driving

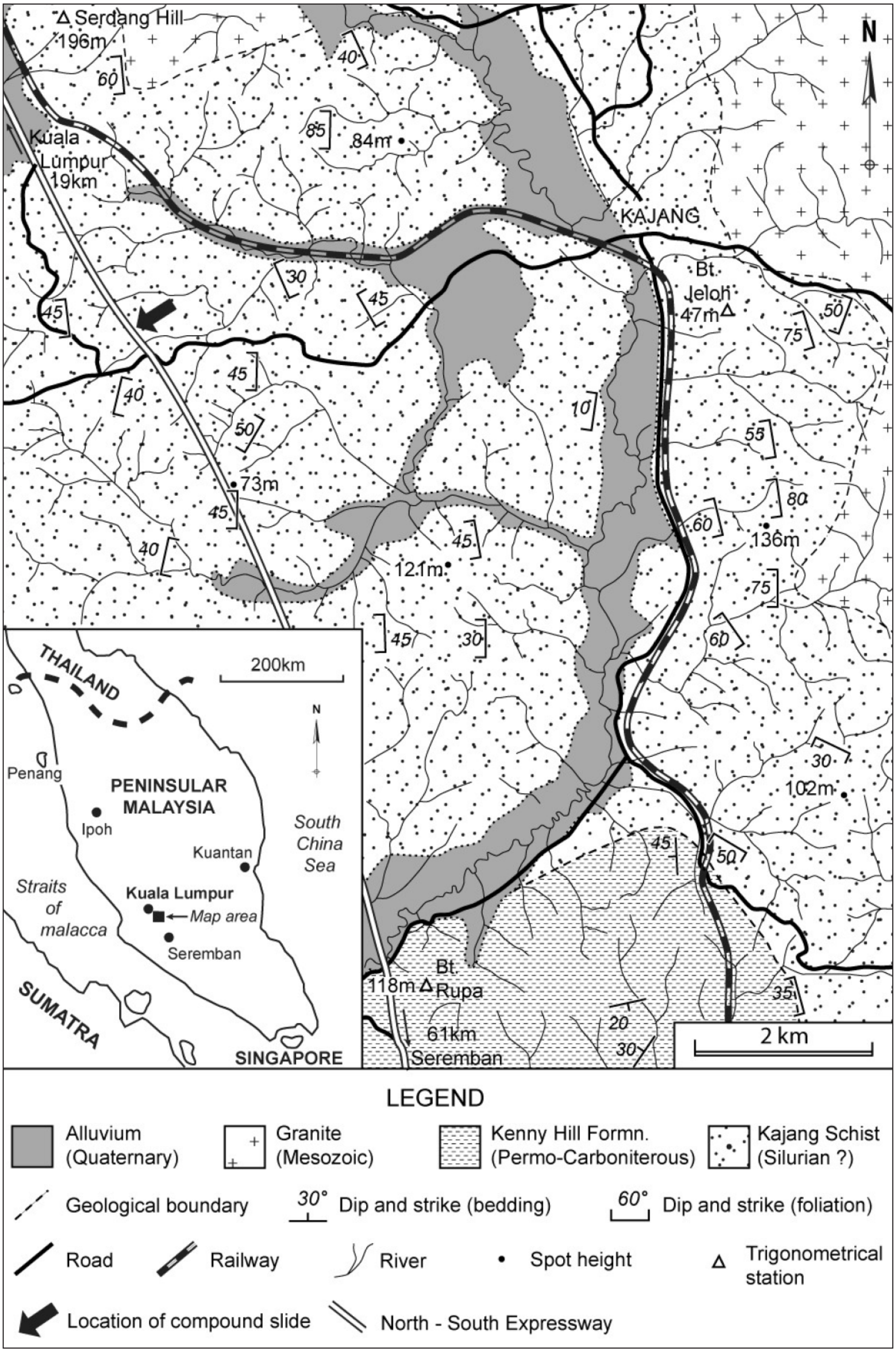

Figure 1: Geological sketch map of the Kajang area, Peninsular Malaysia. Main roads in 1985. (After Yin, 1976)

through a worm drive. This causes the sample to shear close to the upper platen which is artificially roughened to prevent slip at the platen/soil interface (Wykeham Farrance, 1988). Settlement of the upper platen during consolidation or shear can be monitored by means of a sensitive dial gauge bearing on top of the load hanger.

Several test procedures have been proposed for use with the Bromhead ring shear apparatus, including the single stage procedure which provides a good estimate of the residual strength at effective normal stresses below 200 KPa, though settlement of the upper platen into the specimen container at higher stresses results in larger values of residual strength (Stark & Vettel, 1992). The pre-shearing procedure facilitates creation of a shear plane and reduces the length of horizontal displacement needed to reach the residual condition, though there is often extrusion of a substantial amount of soil during the shearing (Wykeham Farrance, 1988; Anayi *et al.*, 1988). In the multi-stage procedure, an additional strength often develops during consolidation and shearing, probably due to wall friction as the top platen settles into the specimen container (Stark & Vettel, 1992). The flush procedure has also been proposed where increasing the thickness of the specimen prior to shear reduces the wall friction and is thus said to give more trustworthy measured values (Stark & Vettel, 1992).

The pre-sheared test procedure with multi-stage loading was adopted in the present study as this was the recommended procedure in the manual provided by the manufacturer of the Bromhead ring shear apparatus (Model WF36859) used in the tests (Wykeham Farrance, 1988). A displacement rate of 0.048 mm/min was adopted for the ring shear tests as this was recommended in the manual. The average effective shear stress acting on the pre-formed slip surface was calculated from the recorded values of two load gauges and this plotted against the corrected average linear displacement calculated from the recorded values of angular displacement. The effective shear stress at maximum corrected linear displacement plotted against the effective normal stress then defined the “complete failure envelope” (Hawkins & Privett, 1985).

RESULTS

Index properties of weathered graphitic-quartz-mica schist samples

The constant volume samples show the weathered graphitic-quartz-mica schist to have mean dry, and saturated, densities of 1,355 kg/m^3, and 1,845 kg/m^3, respectively, and a porosity of 49.5% (Table 1). The constant volume samples furthermore, show the weathered graphitic-quartz-mica schist to have mean dry, and saturated, unit weights of 13.287 kN/m^3, and 18.094 kN/m^3, respectively (Table 1).

Particle size distributions show the three samples to consist overwhelmingly of silt-sized particles with some minor differences in their medium to coarse sand-sized (0.18 to 2.00 mm) fractions. Sample A (sieved through a 0.18 mm mesh sieve) represents the sample that is typically

Table 1: Index properties of weathered graphitic-quartz-mica schist Samples A, B and C.

Property	Sample A (<0.18 mm)	Sample B (<1.0 mm)	Sample C (Total Sample)
1. Dry Density	1,355 kg/m^3		
2. Saturated Density	1,845 kg/m^3		
3. Dry Unit Weight	13.287 kN/m^3		
4. Saturated Unit Weight	18.094 kN/m^3		
5. Moisture Content	33%		
6. Porosity	49.5%		
Particle Sizes (mm)			
1. % particles >1.0 mm)	0.0 %	0.0 %	2.1 %
2. % particles (0.18-1.0 mm)	0.0 %	3.2 %	5.7 %
3. % particles (0.063-0.18 mm)	5.0%	4.9 %	4.6 %
4. % Silt (<0.0039-0.063 mm)	73.0 %	71.9 %	62.6 %
5. % Clay (<0.0039 mm)	22.0 %	20.0 %	25.0 %
Consistency Limits			
6. Plastic Limit	37.9 %	31.2 %	31.2 %
7. Liquid Limit	48.1 %	43.5 %	43.5 %
8. Plasticity Index	10.2 %	12.3 %	12.3 %

used for determination of residual shear strength (Wykeham Farrance, 1988) and consists of 73% silt-sized particles, 22% clay-sized particles and 5% fine sand-sized particles. Sample B (sieved through a 1.0 mm sieve) contains 72% silt-sized particles, 20% clay-sized particles and 8% fine to medium sand-sized particles, while Sample C (total unsieved sample) consists of 63% silt-sized particles, 25% clay sized particles and 12% fine to coarse sand-sized particles (Table 1).

Consistency limits of the fine fractions (<0.42 mm size) of the three samples show some variability with Samples B and C having similar values of Plastic, and Liquid Limits, of 31.2%, and 43.5%, respectively (Table 1). Sample A with its relatively larger content of silt and clay particles, however, shows Plastic, and Liquid Limits, of 37.9%, and 48.1%, respectively (Table 1).

Linear displacement versus effective shear stress

Plots of the effective shear stress versus cumulative corrected linear displacement for all samples are seen to be generally planar at low to moderate effective normal stresses (<150 kPa) (Figures 2, 3 and 4). These planar plots indicate the presence of smooth sliding surfaces with little resistance to displacement and are unexpected given the parallel alignment of the predominantly platy, silt sized particles during shearing. This feature is similar to that reported by Vaughan (1988) for sedimentary soils with clay contents exceeding 40%, where there is increasing orientation of the low-friction, platy shaped clay particles along slip surfaces with increasing shear displacement.

At larger effective normal stresses (>200 kPa), however, the plots are often not planar, but curved and indicate variations in resistance to shearing along the slip surface. Observations during testing furthermore, show that there was sometimes extrusion of sample from the specimen container during consolidation under large effective normal stresses (>200 kPa). This feature represents a limitation of the multi-stage loading test procedure as settlement of the upper platen into the specimen container results in an

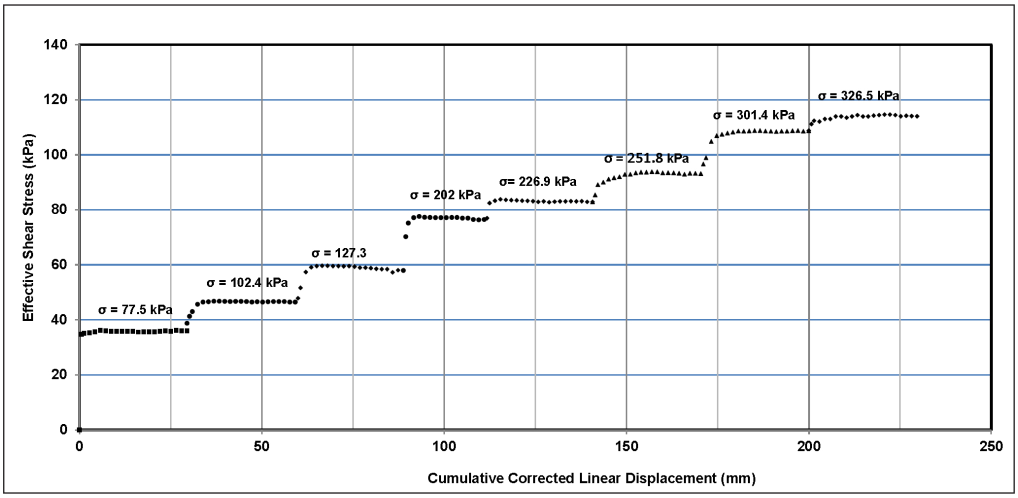

Figure 2: Effective shear stress versus cumulative corrected linear displacement - Sample A (particles <0.18 mm size).

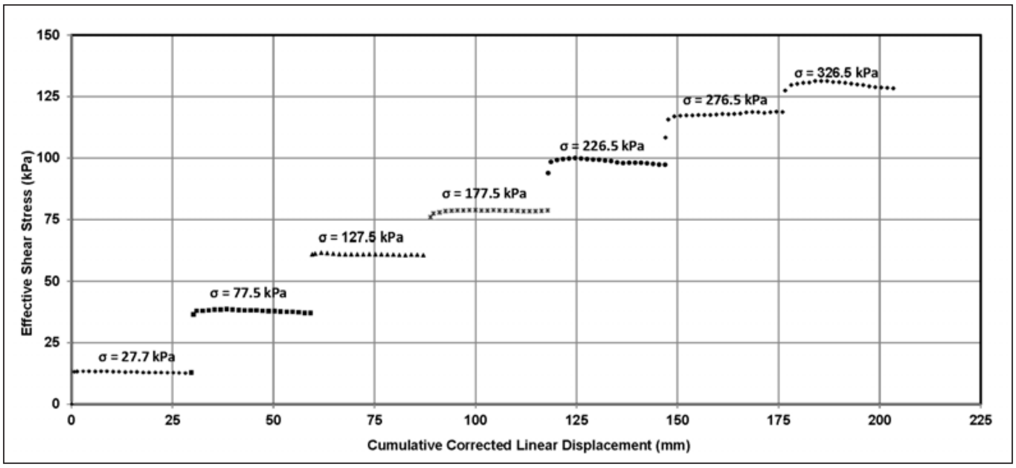

Figure 3: Effective shear stress versus cumulative corrected linear displacement - Sample B (particles <1.00 mm size).

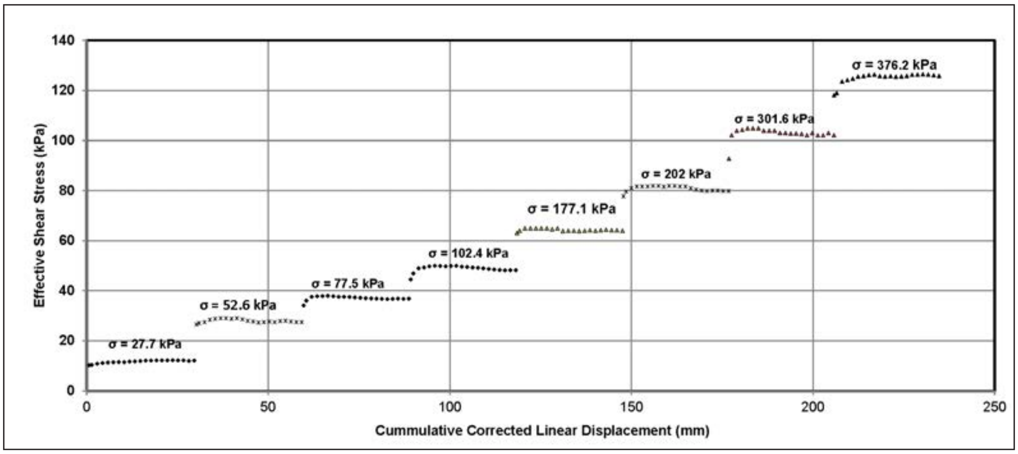

Figure 4: Effective shear stress versus cumulative corrected linear displacement - Sample C (Total Sample).

additional strength due to increased wall friction (Stark & Vettel, 1992). It has also been reported that there is also often extrusion of a substantial amount of soil during the pre-shearing process (Wykeham Farrance, 1988; Anayi *et al.*, 1988).

Failure envelope

The residual friction angle in Bromhead ring shear tests is determined by measuring the gradient of the linear relationship between the average effective shear stress and effective normal stress; the plots defining what is termed the "complete failure envelope" (Hawkins & Privett, 1985). This relationship has been shown to be a "curved" one in many Bromhead ring shear tests and implies that the residual friction angle is dependent upon the effective normal stresses acting along the sliding plane (Hawkins & Privett, 1985).

In the case of the three samples tested, however, plots of effective shear stress against effective normal stress yield "complete failure envelopes" that can be differentiated into two distinct linear segments below, and beyond, some 150 kPa effective normal stress (Figures 5, 6 and 7). Linear segments of the failure envelopes below 150 kPa normal stress yield residual friction angles (Φ_r) of 24.8^o, 25.5^o, and 25.5^o, for Samples A, B and C, respectively, or an overall residual friction angle of 25.2^o (Figure 8) (Table 2).

For effective normal stresses above 150 kPa, however, assumed linear relationships with effective shear stress yield "cohesion" intercepts of 13.4, 21.3, and 14.1 kPa, and residual friction angles of 17.9^o, 18.2^o, and 17.6^o, for Samples A, B and C, respectively (Table 2). As remoulded samples are involved, the "cohesion" intercepts are unwarranted and can only result from the additional friction that developed when the upper platen settled into the specimen container due to sample extrusion during consolidation under high effective normal stresses. This additional but variable friction thus gives rise to the wide scatter of plots when effective shear stresses are plotted against effective normal stresses of all tested samples for normal stresses exceeding 150 kPa (Figure 8). Stark & Vettel (1992) have thus stated that the main factor affecting the residual strength measured in the Bromhead ring shear apparatus is the magnitude of wall friction that is developed along the inner and outer circumferences. The farther the top porous stone settles into the specimen container, the more wall friction that is developed on the shear plane and the higher the measured residual strength.

DISCUSSION

From the above results, it is clear that the pre-shearing test procedure with multi-stage loading is only useful for determining the residual shear strength of the weathered graphitic-quartz-mica schist under low to moderate effective normal stresses (<150 kPa). Under high effective normal stresses (>200 kPa), there is extrusion of sample during consolidation and this results in increased friction as the upper platen settles into the specimen container. This limitation in terms of the maximum applied effective normal stress, however, is not really a problems as slope cut failures in the weathered schist have all occurred at depths of less than 10 m (Raj, 1983; Tan, 1990).

The results also show that under low to moderate effective normal stresses (<150 kPa), there are only slight variations in the residual friction angle (φ_r) with differences in the content of sand sized particles. The total sample (Sample C) yields a residual friction angle of 25.8^o, whilst samples passed through 0.18 mm (Sample A), and 1.0 mm (Sample B), mesh sieves, yield residual friction angles (Φ_r) of 24.7^o and 25.5^o, respectively. Published data with which these results can be compared is the earlier study by Raj (1988) involving consolidated drained soil shear box tests on exactly similar weathered graphitic-quartz-mica schist (Table 3). Two cycles of displacement along a pre-cut surface in the weathered quartz-mica-schist (cut parallel to the inherent relict foliation) yielded a residual friction angle of 26.5^o; though this was determined under very low effective normal stresses (<10 kPa) and limited displacements. This residual friction angle of 26.5^o; is definitely very close to the residual friction angle of 25.5^o determined for the total

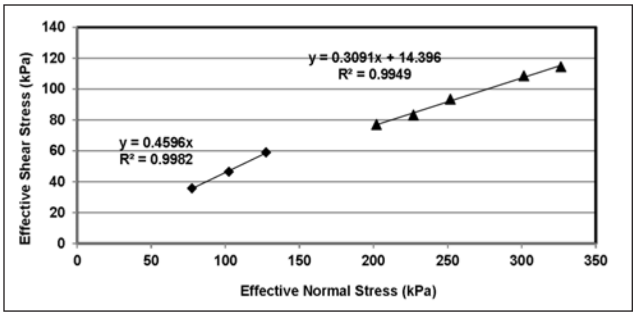

Figure 5: Effective shear stress versus effective normal stress (complete failure envelope) - Sample A (<0.18 mm particle size).

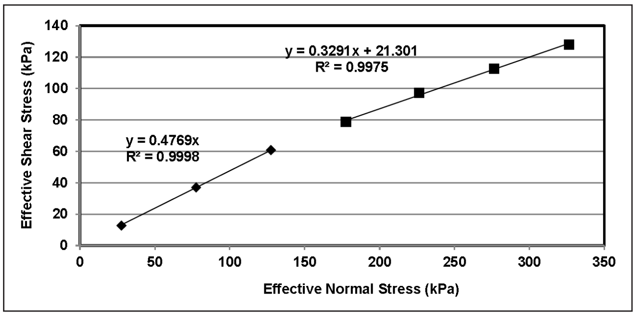

Figure 6: Effective shear stress versus effective normal stress (complete failure envelope) - Sample B (<1.00 mm particle size).

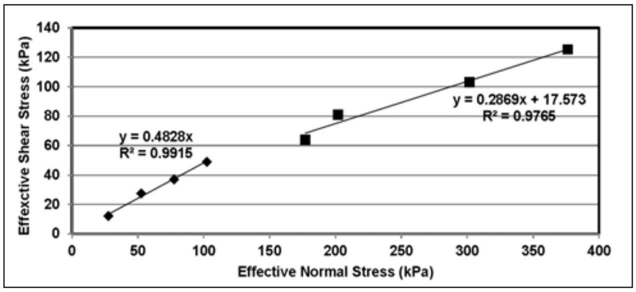

Figure 7: Effective shear stress versus effective normal stress (complete failure envelope) - Sample C (total sample).

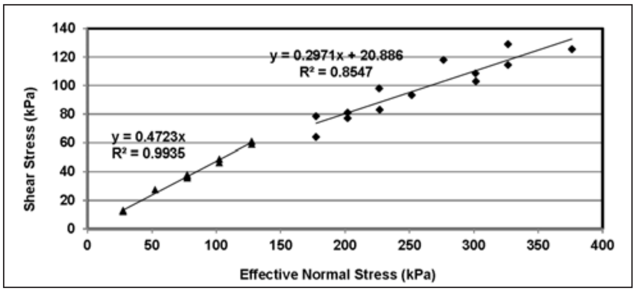

Figure 8: Effective shear stress versus effective normal stress (complete failure envelope) - Samples A, B and C.

Table 2: Summary of results of Bromhead ring shear tests.

Linear Equation (y in kPa)	Normal stress range	Intercept y-axis (‘c’) (kPa)	Angle Internal friction (φ°)	R^2
Sample A (<0.18 mm size)				
1. y = 0.4596x	<150 kPa	0.0	24.7	0.9982
2. y = 0.3091x + 14.4	200-350 kPa	14.4	17.3	0.9949
Sample B (<1 mm size)				
1. y = 0.4769x	<150 kPa	0	25.5	0.9998
2. y = 0.3291x + 21.3	150-350 kPa	21.3	18.2	0.9975
Sample C (Total Sample)				
1. y = 0.4828x	<150 kPa	0	25.8	0.9915
2. y = 0.2869x + 17.6	150-400 kPa	17.6	16.0	0.9765
All Samples Combined				
1. y = 0.4723x	<150 kPa	0.0	25.3	0.9935
2. y = 0.2971x + 20.9	150-400 kPa	20.9	16.6	0.8547
3. y = 0.3808x	0-400 kPa	0.0	20.9	0.9381

sample (Sample C), as well as the overall residual friction angle of 25.2° for normal effective stresses less than 150 kPa.

There is also limited published data from other tropical areas with which the present results can be compared; a limitation pointed out by Rigo *et al.* (2006). Bucher & Kyulue (1980) for instance, have from ring shear tests, determined residual friction angles of 29.2°, 22.2°, and 29.5°, for a micaceous soil from Ghana, a weathered mudstone from Tanzania, and a lateritic soil from Tanzania, respectively (Table 4). Bucher & Kyulue (1980) have also reported that ring shear tests on silty lateritic soils over dolerite and quartzite in Zimbabwe and Tanzania yielded residual friction angles of between 29.5° and 38.3°, whilst similar tests on volcanic ash in Tanzania yielded residual friction angles of between 31.0° and 35.6° (Table 4). Ring shear tests on volcanic ash derived soils in Java and New Zealand have yielded residual friction angles of between 25° and 35°; these values being attributed to the presence of halloysite which does not likely experience particle orientation with increasing displacement (Wesley, 1977; 1992).

CONCLUSION

It is concluded that the pre-shearing test procedure involving the Bromhead ring shear apparatus with multi-stage loading is only useful for determining the residual shear strength of weathered graphitic-quartz-mica schist at low to moderate effective normal stresses (<150 kPa). Under these normal stresses, the weathered graphitic-quartz-mica schist has an overall residual friction angle of 25.2°. Variations in sand content have also little influence on the residual friction angle, with the total sample, sample <1.00 mm size, and sample <0.18 mm size, yielding friction angles (Φ_r) of 24.7°, 25.5°, and 25.8°, respectively.

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Table 3: Results of consolidated drained shear box tests on weathered graphitic-quartz-mica schist (Raj, 1988).

No.	Test Description	Range Normal Stress	Peak Strength	Residual Strength
1	Sheared along (parallel to) relict foliation	1 - 5 kPa	Φp = 33°	Φr = 29°
2	Sheared along plane cut parallel to foliation	1 - 5 kPa	No Peak	Φr = 29°
3	Sheared across gently dipping relict foliation	1 - 5 kPa	Φp = 36°	Φr = 31°
4	Sheared perpendicular to relict foliation	1 - 5 kPa	Φp = 43°	Φr = 32°
5	Sheared twice parallel to relict foliation	1 - 5 kPa	No Peak	Φr = 26.5°

Table 4: Published values of residual friction angles of weathered schists in (humid) tropical areas - determined from ring shear tests.

No.	Sample Description	Angle $\Phi_r{}^o$	Reference
1	Micaceous soil, Kumasi, Ghana	29.2°	Bucher & Kyulue (1980)
2	Weathered mudstone, Ilima, Tanzania	22.2°	Bucher & Kyulue (1980)
3	Shale, Accra, Ghana	21.8°	Bucher & Kyulue (1980)
4	Residual soil of migmatite (micaceous), Sao Paulo, Brazil	17° to 30°	Sousa Pinto & Nader (1991)
5	Residual soil of migmatite (lateritic), Cambai, Alvorada, Brazil	20.8° to 21.6°	Rigo *et al.* (2006)
6	Saprolite (Sample A) over gneiss, Porto Alegre, Brazil	17.4° to 18.9°	Rigo *et al.* (2006)
7	Saprolite (Sample B) over gneiss, Porto Alegre, Brazil	18.5° to 20.3°	Rigo *et al.* (2006)

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