Shear strength of compacted residual soils via constant water content direct shear tests

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ABSTRACT: Compacted residual soils are used in many construction projects. However, the shear strength of such soils is seldom determined correctly due to their unsaturated state. Unsaturated soil mechanics offers a framework for characterizing the shear strength of soils from the unsaturated state to the saturated state. The deterrence in the application of unsaturated soil mechanics is attributed to the long test duration for unsaturated soils using the constant matric suction test. The use of constant water content test shortens the test duration but incurs the need to measure matric suction during the test. The objective of this paper was to examine the shear strength interpretation of compacted residual soils through constant water content direct shear tests. Constant water content direct shear tests were conducted on compacted residual soils at various water contents for both saturated and unsaturated conditions. The shear strength of the compacted residual soils was interpreted using the extended Mohr-Coulomb failure criterion for unsaturated soils. The results show that reasonable saturated-unsaturated shear strength parameters can be obtained for engineering practice.

1 INTRODUCTION

Compacted residual soils have been used in many construction projects all over the world. The effectiveness of compacted soils depends mainly on the method of compaction and the degree of saturation. Since it is impossible to compact soil at 100% degree of saturation (zero-air void line), compacted soils should be characterised using unsaturated soil mechanics. The application of unsaturated soil mechanics in practice faces many practical challenges: test equipment for unsaturated soils is expensive; test method is complex; longer times are required. Hence, there is a need for a simplified method of assessing the shear strength of unsaturated soil using conventional test equipment and within a practical testing duration.

The shear strength parameters of unsaturated soils have been investigated using modified triaxial and direct shear apparatuses by researchers (Ho & Fredlund 1982, Gan & Fredlund 1988, Escario et al. 1989, Rahardjo et al. 1995, Likos et al. 2010, Kato et al. 2011). The modification done to the equipment is to use either suction control or to measure suction during shearing. Results from Escario & Sáez, (1986) and Gan & Fredlund (1988) showed that suction cannot be effectively maintained during shearing with increase in the net normal stress. The test also requires relatively long time that renders it unfeasible and uneconomical for applications in engineering projects. Recent studies done by Zhang (2015) shows that the stress path of unsaturated soils cannot be controlled precisely during loading.

Bishop & Donald (1961), Satija (1978) and Rasool et al. (2016) showed that constant water content tests reduces the time for testing unsaturated soils. In the constant water content test, the pore-air pressure is allowed to equilibrate with atmospheric pressure to reflect the field conditions.

Notwithstanding the disadvantages of the direct shear test, large shear displacements can be obtained in two directions and thin specimen used reduces the drainage path and testing time for soils of low permeability as compared to the triaxial test. The use of constant water content condition for testing unsaturated soil in the conventional direct shear apparatus is still scarce.

The use of constant water content may mean that matric suction is not constant during the test. However, Heitor et al. (2013) found that there is self-equilibration and matric suction remain constant if the displacement to failure is small.

The interpretation of direct shear tests on unsaturated soils under constant water content test is still formative and further study is required.

This paper attempts to examine the shear strength assessment of compacted residual soils using conventional direct shear equipment under constant water content condition. Throughout the experiment, matric suction was not measured. Any change in matric suction could be determined by analysing the test results using the extended Mohr-Coulomb failure criterion for unsaturated soils.

2 MATERIALS AND METHODS

2.1 *Basic soil properties*

The soil used in this study was a residual soil from the Bukit Timah Granite of Singapore. The soils were air dried and passed through a sieve size of 2.18 mm prior to use. The physical properties of the soil used are shown in Table 1 together with the grain-size distribution curve shown in Figure 1.

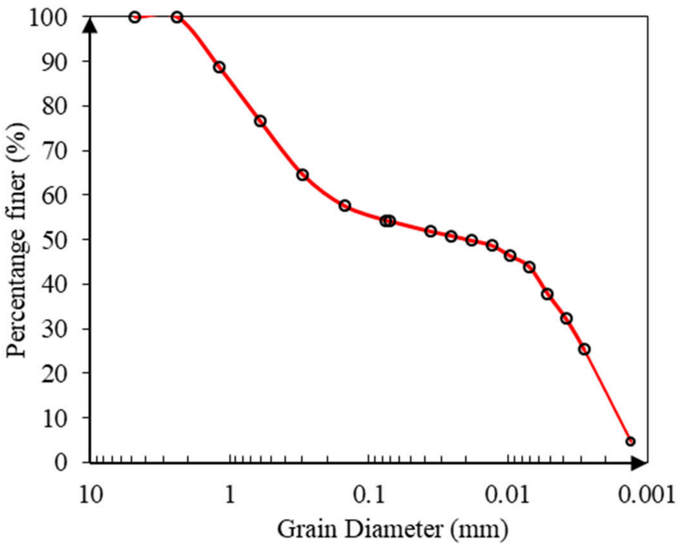

Figure 1. Grain size distribution of residual soil used for study.

Table 1. Summary of measured index properties

Index property	
Standard compaction tests	
Maximum dry density (kg/m^3)	1610
Optimum moisture content (%)	22.5
Grain size distribution	
Sand content (0.075 – 4.75 mm, %)	41
Fines content (≤ 0.075 mm, %)	59
Specific gravity	2.65
Atterberg limits	
Plastic limit (%)	36
Liquid limit (%)	56
Plasticity index (%)	20
Unified soil classification system (USCS)	MH

2.2 *Soil compaction*

Figure 2 shows the compaction curve for the soil obtained in accordance to ASTM D698-12e2 (Standard Proctor test). Five water contents were chosen on the compaction curve as shown in Table 2 to prepare the soil specimens. Point C is at the optimum water content, points A and B are on the dry side of the optimum whereas points D and E are on the wet side of optimum. Points B and D have the same dry density of 1.59 Mg/m^3 and points A and E have the same dry density of 1.54 Mg/m^3 but different water contents.

Soil specimens were statically compacted using a CBR machine. For each water content, the mass of the soil which will give the corresponding dry density on the compaction were calculated and divided into three equal portions. Each portion was statically compacted directly into a circular direct shear box of 63.5 mm diameter to give a final specimen height of 25 mm. To avoid over compaction of the bottom layers, the first layer of soil was compacted to about 10mm height, the second layer to 17.5mm and the last layer to 25mm. This procedure was developed by trial and error.

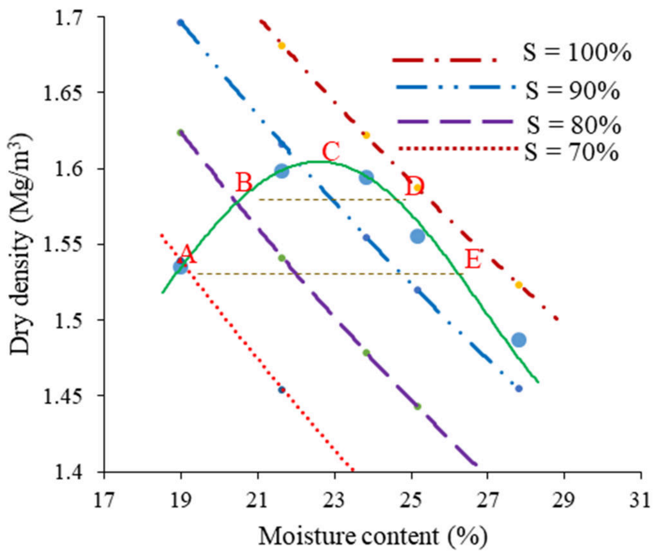

Figure 2: Selected points on the curve for the tests

Table 2. Water content, dry density and degree of saturation of the chosen points to prepare the soil specimens

Soil Sample	A	B	C	D	E
Water Content (%)	19.0	21.0	22.5	24.0	26.0
Dry Density (Mg/m^3)	1.54	1.59	1.61	1.59	1.54
Degree of Saturation (%)	70	84	93	95	96

3 TEST PROCEDURE

3.1 *Direct shear test*

The direct shear tests follow ASTM D 3080/3080M-11 as closely as possible. The compacted specimen in the direct shear box was weighed and then placed into the direct shear apparatus. A normal load was placed on the soil specimen and the vertical settlement was observed until strain equilibrium was achieved. The rate of shearing for the unsaturated soil specimen was set at 1 mm/min to minimise changes in water content during the shearing. For the saturated soil specimen, the rate of shearing was set at 0.00694 mm/min. Shearing was done at a slower rate for saturated soil specimens to ensure that the shearing was performed at fully drained condition. Shearing was conducted until maximum shear force was obtained or until a maximum displacement of 13 mm. For saturated soil test, the shear box containing the compacted soil specimen was inundated inside the direct shearing apparatus for at least 48 hours before application of the normal load. The above procedures were repeated for four different normal loads of 125N, 250N, 500N and 1000N as summarised in Table 2.

3.2 *Suction measurement*

The filter paper method (ASTM D5298 - 16) was used to measure the matric suction of the compacted soil specimens because it is a relatively cheap and simple technique for a wide range of suction. Statically compacted specimens were extruded from the compaction mould taking note of top and bottom sides of the specimen. Whatman No. 42 filter papers were placed on top and bottom of the specimen to measure matric suction of the soil specimen. However only one piece of filter paper was used instead of three pieces of filter paper as suggested in ASTM 5298-16 as Leong et al. (2007) found that more pieces of filter papers lead to overestimation of the matric suction. The dry weights of the filter paper before and after the test were measured to check that the filter paper was not contaminated by soil particles. Throughout the test, non-powder gloves were worn and a pair of clean tweezers was used to handle the filter papers to avoid contamination of the filter paper.

The soil specimen with the filter papers was wrapped with cling wrap, then aluminum foil and stored in a foam box in a temperature-controlled room for 21 days and the moisture content of the filter paper was determined. The calibration curve for Whatman No. 42 filter paper given in Leong et al. (2007) was used to determine the matric suction. Table 3 shows the initial matric suctions of the soil specimens statically compacted at the different moisture contents.

The extended Mohr-Coulomb equation proposed by Fredlund et al. (1978) as follows:

$$\tau = c' + (\sigma - u_a)_f \tan\varphi' + (u_a - u_w)_f \tan\varphi^b \qquad (1)$$

where τ= shear stress on the plane of failure, c' is the effective cohesion, ϕ' = effective friction angle with respect to the net normal stress, $(\sigma - u_a)_f$ = net normal stress, $(u_a - u_w)_f$ = matric suction on the failure plane at failure, ϕ^b = the rate of increase of shear strength due to matric suction, was used. When the soil becomes saturated, $u_a = u_w$ and Equation (1) becomes Equation (2), the shear strength equation for saturated soil:

$$\tau = c' + (\sigma - u_a)_f \tan\varphi' \qquad (2)$$

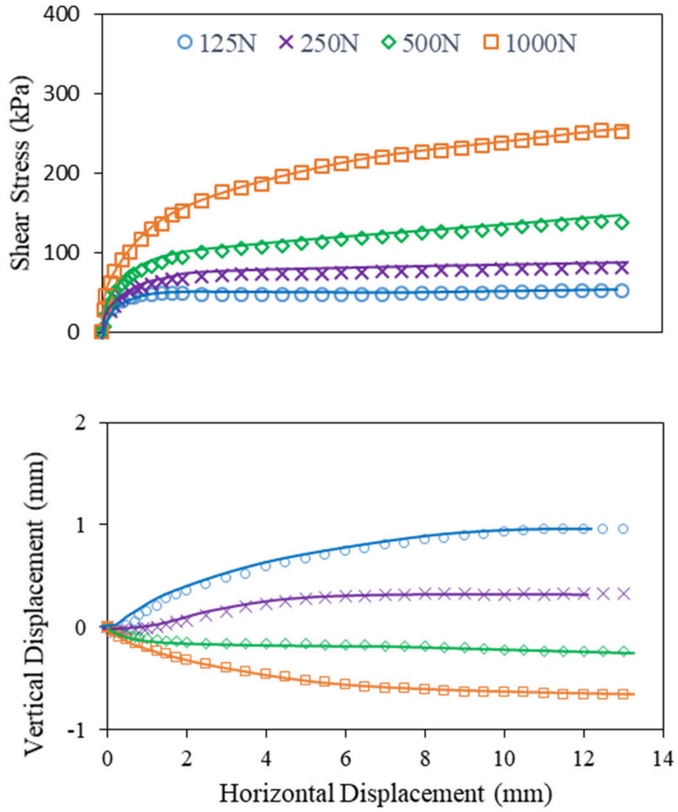

Figure 3 Shear stress; Vertical displacement and horizontal displacement (Unsaturated, 26%).

Table 3. Initial Soil suction

Water Content (%)	19.0	21.0	23.0	24.0	26.0
Suction (kPa)	620	345	200	150	40

4 RESULTS

4.1 *Direct shear test*

Due to space constraint, only test results for two points (A and E) are reported in greater details in this paper. Figures (3) and (4) show the shear stress versus horizontal displacement and vertical displacement versus horizontal displacement plots for soil specimens prepared at 26% moisture content (wet side of optimum) under as compacted (unsaturated) and inundated (saturated) conditions, respectively, while Figures (5) and (6) show the respective plots for soil specimens prepared at 19% moisture content (dry side of optimum). Results from direct shear tests on unsaturated soil specimens show that for all moisture contents, an increase in net normal stress causes an increase in shear stress. This generally agrees with the results obtained by Heitor et al. (2013). However, the results of direct shear tests on soil specimens compacted on the dry side of optimum do not show any distinct peak in the shear stress-horizontal displacement plot. This might be due to the difference in soil structure between the silty sand (SP-SC) used in Heitor (2013), and the residual soil (MH) used in this study.

Generally, the soil specimens experienced dilation at lower normal loads and contraction at higher normal loads during shearing for both unsaturated and saturated specimens. In addition, it can be observed that the shear stresses for soil specimens compacted on the dry of optimum are higher than those compacted on the wet side of optimum at comparable dry unit weight and at the same normal load.

The effective cohesion and effective friction angle for the saturated soil specimens are summarised in Table 4.

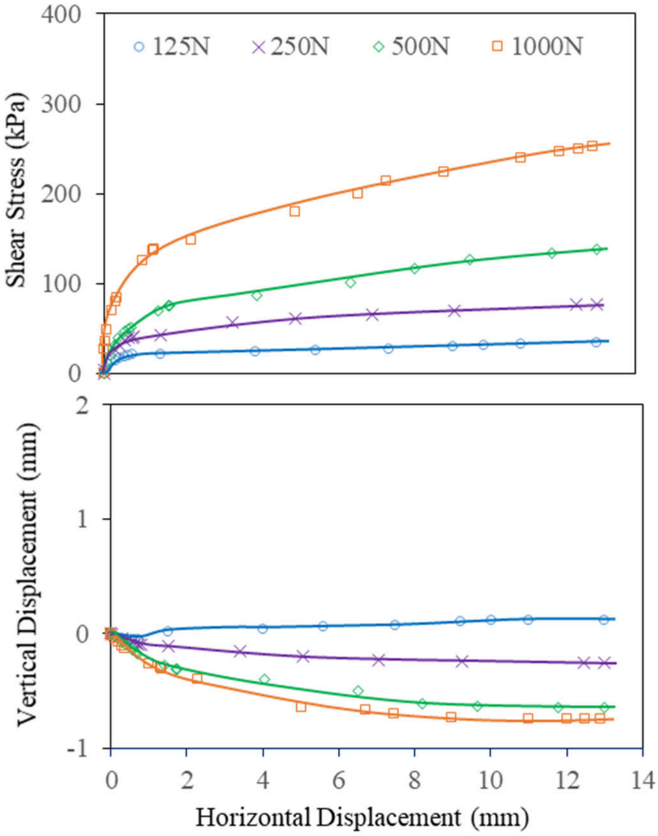

Figure 4. Shear stress; Vertical displacement and horizontal displacment (Saturated, 26%)

Table 4. Effective cohesion and friction angle for saturated compacted soils

Compaction water content of soil specimen	Dry Density (Mg/m^3)	Effective cohesion, c' (kPa)	Effective friction angle, ϕ'
19%	1.54	0.0	35.0°
21%	1.59	0.0	34.6°
22.5% (optimum)	1.61	0.0	34.1°
24 %	1.59	0.0	31.8°
26%	1.54	0.0	31.8°

It can be observed from Table 4 that ϕ’ is higher closer to the optimum water content reflecting the effect of dry unit weight or void ratio.

From Equation 1, the shear strength equation for unsaturated soils can be rewritten as

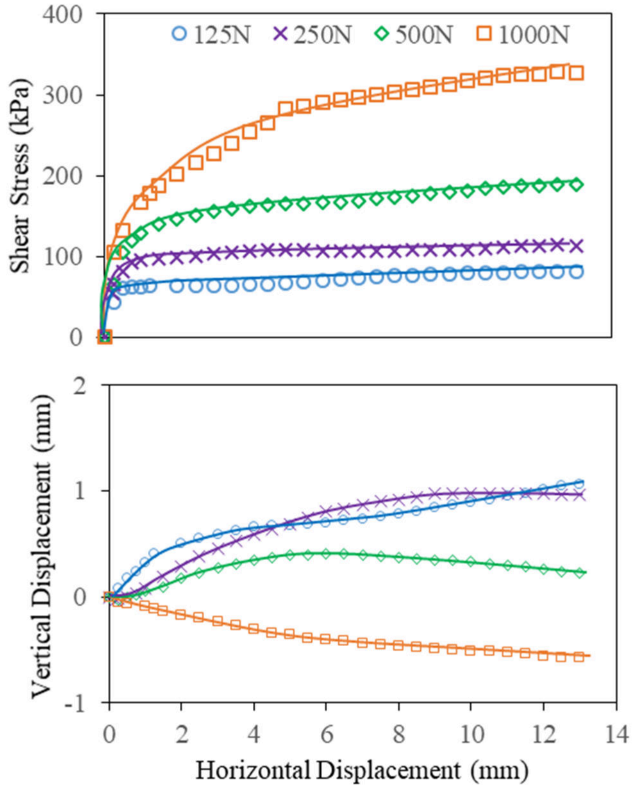

Figure 5. Shear stress; Vertical displacement and horizontal displacement (Unsaturated, 19%).

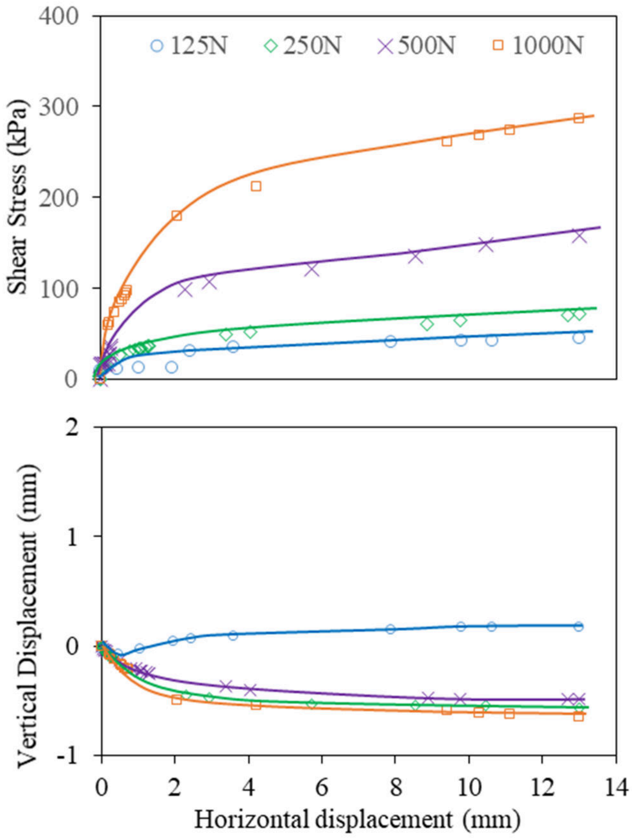

Figure 6. Shear stress; Vertical displacement and horizontal displacement (Saturated, 19%)

$$\tau = C + (\sigma - u_a)_f \tan\varphi' \quad (3)$$

where, C is total cohesion expressed as

$$C = c' + (u_a - u_w)_f \tan\varphi^b \quad (4)$$

Hence by plotting τ versus ($\sigma - u_a$), the intercept is given by C and the gradient of the line is given by tan ϕ'. This is illustrated in Figure 8 and Figure 9 for the soil specimens compacted at water contents of 19% and 26%, respectively. The saturated shear strength is also included in the figures as a solid line while the parallel dash lines are for the unsaturated shear strength.

The total cohesion, and (u_a - u_w) tan ϕ^b can be obtained from Figures 7 and 8 and are shown in Table 5 and Table 6 for soil specimens compacted at 19% and 26% moisture content, respectively.

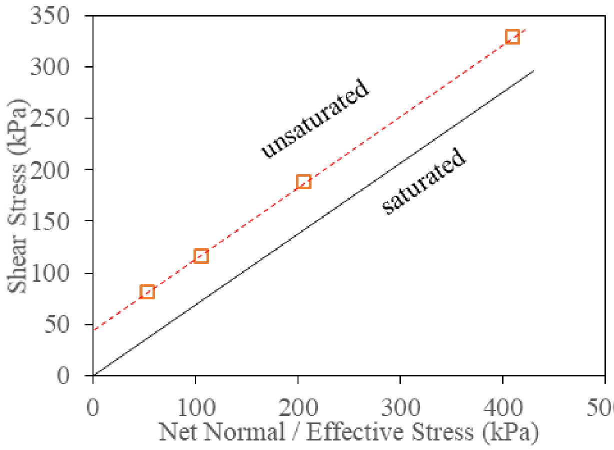

Figure 7. Maximum shear and normal stress for soil sample at 19% water content

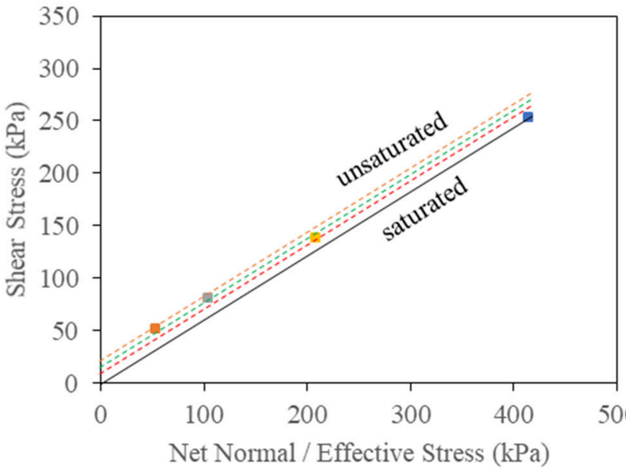

Figure 8. Maximum shear and normal stress for soil sample at 26% water content

In Figure 7, the dashed line passes through all the four points whereas in Figure 8, several dashed lines were drawn through each of the four points.

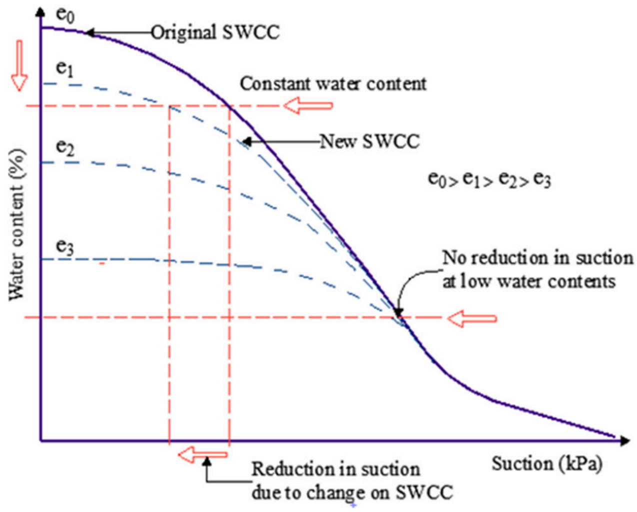

Figure 9. Systematic SWCC of a clayey silty sand (Modified from Wijaya & Leong. 2015)

The change in matric suction is more significant at low matric suction (high compaction water content) as indicated by the upper horizontal line in Figure 9. At high matric suction (low compaction water content), there is insignificant matric suction reduction as indicated by the lower horizontal line in Figure 9. For the soil specimen compacted at 26% moisture content, the shear stress at failure falls on the saturated soil test failure line indicating that the matric suction has reduced to zero during the shearing.

Table 5. Total cohesion and (u_a - u_w) tanϕ^b for soil specimens compacted at 19 % water content

Initial net normal stress (kPa)	Total cohesion, C (kPa)	(u_a - u_w) tan ϕ^b (kPa)
40 80 160 320	47	47

Table 6. Total cohesion and (u_a - u_w) tan ϕ^b for soil specimens compacted at 26 % water content

Initial net normal Stress (kPa)	Total cohesion, C (kPa)	(u_a - u_w) tan ϕ^b (kPa)
40	24	24
80	20	20
160	10	10
320	0	0

Table 7. Suction and ϕ^b computation for soil specimens compacted at 19 % water content

Initial suction (kPa)		620
tan (ϕ^b)	0.0758	ϕ^b = 4.3°
c'	0 (From saturated soil test)	
ϕ'	35° (From saturated soil test)	
(σ - u_a) (kPa)	C (kPa)	Suction (kPa)
40 80 160 320	47	620

Table 8. Suction and ϕ^b computation for soil specimens compacted at 26 % water content

Initial suction (kPa)		40
tan (ϕ^b)	0.525	ϕ^b = 31.0°
c'	0 (From saturated soil test)	
ϕ'	31.8° (From saturated soil test)	
(σ - u_a) (kPa)	C (kPa)	Suction (kPa)
40	24	40.00
80	20	33.33*
160	10	16.67*
320	0	0.00*

*Calculated based on a ϕ^b =31.0°

Table 7 and Table 8 show the suctions computed for the soil specimens compacted at 19% and 26%, respectively. The initial matric suction of the soil at the lowest normal stress is assumed to remain the same as that before the application of the normal stress and the angle ϕ^b is computed. With small changes in matric suction, ϕ^b is assumed to remain constant and the matric suction is calculated using Equation 4 for other net normal stresses.

It can be observed from Table 7 and Table 8 that ϕ^b/ ϕ' is high at high degree of saturation i.e. ϕ^b = 31.0° = 0.97ϕ' and ϕ^b =4.3° = 0.12 ϕ' for 26% and 19%, respectively. The ratio of which falls within the current assumed ranges of ϕ^b/ ϕ' (0.1 to 1.0) for Bukit Timah Granite residual soils observed by Rahardjo et al. (2004).

5 CONCLUSIONS

Constant water content direct shear tests were conducted and the shear strength of the compacted residual soils was interpreted using the extended Mohr-Coulomb failure criterion for unsaturated soils. The results show that reasonable saturated-unsaturated shear strength parameters can be obtained for engineering practice.

6 ACKNOWLEDGEMENTS

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