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ESTIMATION OF SHEAR STRENGTH OF GRAVELLY AND SANDY SOILS FROM SHALLOW LANDSLIDES

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ABSTRACT: This study seeks to investigate the unsaturated shear strength of six gravelly and sandy soils collected from shallow landslides in New South Wales, Australia. Results from a series of shear box tests on unsaturated soil specimens revealed that changes in water content (from 0% to 30%) could significantly reduce the shear strength of soil (by 34% to 43%). The observed increases in soil's apparent cohesion and friction angle were attributed to more pronounced effects of suction at low values of water content. The obtained laboratory data were compared with the shear strength estimates obtained by two published models for estimating shear strength. One of the methods was refined to provide a more simplified approach to obtain the air entry value (AEV) using the soil basic parameters. In addition, a new simplified method was proposed to predict the shear strength of unsaturated gravelly and sandy soils using the soil gradation characteristics. Comparisons made between the laboratory data and numerical methods showed a good agreement between the predicted and experimental values across a large range of matric suction which was within 35%.

Keywords: Apparent cohesion, Friction angle, Suction, Shear strength, Prediction

1. INTRODUCTION

It is already well-known that the shear strength of soil can be affected by changes in moisture content. Guan et al [1], Farooq et al [2], Cogan et al [3] reported that during rainfall, as moisture content increases, the matric suction decreases, reducing the shear strength of soil. Thus, the knowledge of shear strength of unsaturated soil provides vital information for slope stability analysis, especially shallow landslides [4,5]. Laboratory studies conducted in the past several years have revealed that although the shear strength generally decreases with increasing moisture, the response patterns may be somewhat different. For example, Hossain and Yin [6], Gallage and Uchimura [7], Patil et al [8] showed that a decrease in water content can significantly increase the apparent cohesion of soil, however, the friction angle may remain almost the same. On the contrary, Kong and Tan [9], Tilgen [10] reported that the apparent cohesion may first increase with increasing moisture content and then significantly decrease as the amount of moisture in soil keeps increasing. In addition, the friction angle decreases as well [11]. Such difference may be attributed to the different structure, plasticity and origin of soil samples used in the aforementioned studies. It was also recognized that such laboratory studies can be extremely costly and time-consuming, which makes the available up-to-date experimental data rather limited. In addition, special equipment is typically required to perform suction-controlled tests, which may continue for a long period of time [8]. This can be seen as an obstacle in engineering practice where such special testing equipment is often not available, and the time allotted for laboratory investigation is generally constrained by project deadlines.

Another approach that can minimize the use of experimental data is related to numerical studies. Several methods including Fredlund et al [12], Vanapalli et al [13], Khalili and Khabbaz [14], Vilar [15], Naghadeh and Toker [16] have been proposed to predict shear strength of unsaturated soils using soil-water characteristic curves (SWCC). However, these methods generally work well only for the soils for which they were developed, while they tend to yield relatively large errors (about 20% or even more) when applied to different soil conditions [14]. There is a lack of prediction models for gravelly and sandy soils from landslide-prone areas.

It is clear that more experimental data is needed to better understand the properties of unsaturated soils while a proven alternative technique for shear strength prediction that does not require special laboratory equipment would be of great benefit to engineers. This study seeks to investigate the unsaturated shear strength of six gravelly and sandy soils collected from shallow landslides in New South Wales (NSW), Australia

[17], and proposes a simplified procedure to estimate the shear strength of such soils using the soil basic properties. This paper briefly introduces the theoretical considerations utilized to estimate the soil-water interaction and shear strength of unsaturated soil and discusses a new simplified procedure to obtain the air entry value. It continues with the discussion of the laboratory data in respect to the effect of suction on shear strength of soil. Finally, it compares the measured shear strength with its estimates using the already existing methods as well as the newly-proposed technique.

2. THEORETICAL CONSIDERATIONS

2.1 Soil-Water Characteristic Curves

Soil-water characteristic curves (SWCC) show the relationship between suction and water content, and they are commonly used to estimate the effect of suction on soil properties, including shear strength and permeability. Fredlund and Xing [14] suggested Equation (1) to describe the entire SWCC using volumetric water content (θ) and suction (ψ).

$$\theta = \theta_s \left[1 - \frac{\ln\left(1+\frac{\psi}{\psi_r}\right)}{\ln\left(1+\frac{1000000}{\psi_r}\right)}\right] \left\{\frac{1}{\ln\left[e+\left(\frac{\psi}{a}\right)^n\right]}\right\}^m \quad (1)$$

where, θ_s is the saturated volumetric water content, ψ_r is the suction value corresponding to the residual volumetric water content θ_r. The fitting parameters (a, n and m values) can be determined using a nonlinear regression procedure as outlined by Fredlund and Xing [14]. As suction depends on soil moisture content, the normalized volumetric water content Θ is frequently used to define the amount of water contained in the pores of soil in Equation (2).

$$\Theta = \frac{\theta}{\theta_s} = \left[1 - \frac{\ln\left(1+\frac{\psi}{\psi_r}\right)}{\ln\left(1+\frac{1000000}{\psi_r}\right)}\right] \left\{\frac{1}{\ln\left[e+\left(\frac{\psi}{a}\right)^n\right]}\right\}^m \quad (2)$$

2.2 Shear Strength of Unsaturated Soils

Kim and Borden [14] discussed the most commonly used methods of shear strength prediction, including Fredlund et al; Vanapalli et al and Khalili and Khabbaz, and concluded that the Khalili and Khabbaz's method tends to provide more accurate estimates of shear strength of unsaturated coarse-grained soils. As the tested soils in this study are coarse-grained material, this method will be discussed in detail. In addition, a recent model proposed by Naghadeh and Toker [16] will be reviewed and discussed for comparisons.

2.2.1 Khalili and Khabbaz's (1998) method

According to Khalili and Khabbaz's method, the shear strength of unsaturated soil is estimated as shown in Equations (3) to (5):

$$\tau_f = c' + (\sigma_n - u_a)\tan\phi' + (u_a - u_w)_f[\chi(\tan\phi')] \quad (3)$$

where,

$$\chi = \left[\frac{(u_a - u_w)_f}{(u_a - u_w)_b}\right]^{0.55}, \text{ when } (u_a - u_w) > (u_a - u_w)_b \quad (4)$$

$$\text{where, } \chi = 1, \text{ when } (u_a - u_w) < (u_a - u_w)_b \quad (5)$$

where, $(u_a - u_w)_f$ is the matric suction of specimen at failure condition; $(u_a - u_w)_b$ is the air entry value (AEV, in kPa). It is commonly assumed that $(u_a - u_w)$ is 100,000 kPa when the moisture content is zero as the total suction is the same as the matric suction for any type of soil [12].

When there is no sufficient lab data, it may be rather difficult to accurately obtain AEV values for SWCC. Zapata [18] analysed SWCC of 120 non-plastic soils and suggested that D_{60} can be a key parameter to represent coarse-grained soils. Drawing on Zapata's findings, this study proposes Equation (6) to estimate the AEV value using D_{60}.

$$AEV = R \cdot \gamma \cdot D_{60} \quad (6)$$

where, R is the model parameter; γ is the unit weight of water (9.81kN/m^3), and D_{60} is the 60% particles are finer than this size (in m). In this study, Eq. (4) to Eq. (6) will be used to estimate the shear strength of the studied soils using the Khalili and Khabbaz's method.

2.2.2 Naghadeh and Toker (2019) method

Naghadeh and Toker [16] proposed a relatively new approach that considers changes in the apparent cohesion of soil with different moisture content using the transition suction (ψ_t). Equations (7) and (8) describe the mathematical relationships used to estimate the unsaturated shear strength:

$$\tau = c' + (\sigma - u_a) \text{ x } \tan\phi' + [1 - e^{\left(-\frac{\psi}{\psi_t}\right)}] \text{ x } \psi_t \text{ x } tan\phi' \quad (7)$$

where, c' is the effective cohesion; ϕ' is the effective angle of internal friction; σ is the normal stress; u_a is the pore air pressure; ψ is the matric suction; ψ_t is the matric suction at transition. To estimate the transition suction (ψ_t), Naghadeh and Toker [16] suggested Eq. (8) which involves the maximum capillary cohesion (c''_{max}).

$$c''_{max} = (\tan\phi' \times \psi_t) \quad (8)$$

Naghadeh and Toker [16] also reported the relationship between the apparent cohesion, c_a effective cohesion (c') of saturated soil, and capillary cohesion (c") as shown in Equation (9):

$$c'' = c_a - c' \quad (9)$$

According to Lu and Likos [19], the capillary cohesion is proportional to matric suction, and the value of matric suction becomes very high when the moisture content is close to zero [20]. Thus, it can be assumed that the maximum capillary cohesion (c''_{max}) occurs when the moisture content is close to zero. Eq. (9) was proposed by Naghadeh and Toker [16] for all types of soil, including plastic soils with the effective cohesion. When applied to coarse-grained soils, it can be simplified using the assumption that the effective cohesion (c') of fully saturated coarse-grained soil is 0.

2.2.3 A new model to estimate the shear strength of unsaturated

This study proposes a new approach as shown in Equation (10) to estimate the shear strength of coarse-grained soil under low normal stress conditions using soil basic parameters such as the coefficient of uniformity (C_u) and shear box and suction test results.

$$\tau = c' + (\sigma_n - u_a) \text{ x } tan\phi' + \psi \text{ x } (\frac{1}{C_u})^M \text{ x } tan\phi' \quad (10)$$

where, c' is apparent cohesion at a particular moisture content; σ_n is normal stress which is 28.5 kPa at shear box tests which reflects low normal stress or shallow depth conditions; u_a is pore air pressure which is assumed to be zero; ϕ' is friction angle at a particular moisture content; ψ is the matric suction at a particular moisture content; M is the model parameter**.**

Eq. (10) was developed using measured shear strength at a normal stress of 28.5 kPa at various moisture contents from shear box tests. The matric suctions at the corresponding moisture contents were obtained from the best fit curve of SWCC. The model parameter M was calculated by applying optimization technique by minimizing the squared sum of normalized residuals between measured shear strength and estimated shear strength using Eq. (10).

As suction is related to soil porosity [20] which is a reflection of soil grading, C_u can be selected as a key parameter to predict the matric suction of coarse-grained soils [21], Eq. (10) will be tested in this work to estimate the shear strength of six gravelly and sandy soils, and the obtained results will be compared with the laboratory data and estimates of shear strength using the Khalili and Khabbaz's and Naghadeh and Toker's methods.

3. EXPERIMENTAL PROGRAM

For this study, six soil samples of gravelly and sandy soils were collected in the northern New South Wales (NSW) from landslide-prone areas [17], Table 1 provides the particle size distribution, coefficients of uniformity (C_u) and curvature (C_c) as well as USCS classification for each soil. It is evident from this table that all soils were non-plastic coarse-grained soils, varying from gravel to sand with different degree of gradation. A series of laboratory tests including direct shear and suction tests were conducted on each soil in Griffith University, Gold Coast, Australia. The following section details the experimental procedures.

Table 1. Particle size distribution and classification of tested soils

Soil No.	%Passing 4.75 mm sieve	Fines (%)	Cu	Cc	USCS
1	89.4	2.4	8.6	1.2	SW
2	70.5	5.6	13.2	1.7	SW
3	78.9	3.7	15.7	1.1	SW
4	94.4	3.8	2.7	1.2	SP
5	70.7	3.0	13.1	1.4	SW
6	40.0	3.8	43.2	2.9	GW

3.1 Direct Shear Tests

Direct shear tests (the size of the shear box was 60 mm x 60 mm) were performed according to the AS1289.6.2.2 - 1998 procedure. Soil samples were oven-dried at 105^0C for 24 hours, and then passed through the 4.75 mm sieve. For each soil type, shear box tests were performed on specimens at various moisture contents, ranging from 0 to 40%. To allow comparisons of the obtained results, all specimens for each soil sample were prepared to the same dry density. The moist specimens were prepared by mixing the oven-dried soil with certain amount of water. They were allowed to rest in a sealed bag for 24 hours for more even saturation. Then, the soil specimen was compacted in the shear box in six layers to achieve the desirable value of dry density. The soil specimens were sheared under the effective vertical stress of either 28.5, 55.8 or 83.0 kPa. The peak shear stress was recorded and used to determine the strength characteristics of each soil specimen.

3.2 Suction Test Using Filter Paper Technique

Suction tests were performed using the standard Whatman No. 42 filter paper, following the ASTM D5298 – 2016 procedure. The soil specimens were prepared with at least four different moisture contents, after which the individual SWCC could be obtained. For suction tests, material passing through a 2.36 mm sieve from the oven-dried samples was used. The suction tests were carried out using an O-ring, air-tight glass container and cling wrap. Special hand gloves and forceps were used to prepare the specimen to avoid any oil transferring from the hand to the filter paper. The wet samples were prepared by adding 10%, 20%, 30% and 40% of distilled water by weight. A set of four larger size filter papers and a smaller size filter paper were dried for 16 hours in the oven prior to use.

The plastic O-ring (a hollow tube of 51 mm diameter and 25 mm height) was placed on top of the cling wrap and the sample was hand-compacted up to the middle of O-ring. Two large filter papers with one small filter paper in between were then placed at the middle of O-ring. The purpose of the small filter paper was to measure matric suction. Then the sample was hand-compacted up to the top and a wire separator and another two large filter papers were placed at the top. The total suction was measured using the top two filter papers.

The soil sample with the O-ring was placed in a small glass bottle (of 62 mm opening diameter and 88 mm height) with the top two filter papers exposed within the bottle. Then, the bottle was tightly closed with a lid and placed in a cooler box for at least a week. After 7 days, the weight of the wet filter papers (the top two filter papers for total suction and the small filter paper for matric suction) were measured using a sensitive balance with four decimal points. Immediately, they were placed in the oven at 105^{0}C for 2 hours. After this drying, the weight of the filter papers was measured at once. This process was completed as quickly as possible to avoid any change due to the moisture in the air. The total suction and matric suction were calculated using Whatman No.42 calibration curves.

4. RESULTS OF LABORATORY TESTS

This section presents the lab data from shear box and suction tests. It also discusses the data on the apparent cohesion, friction angle, best fit models of SWCC, and AEV values.

4.1 Shear Strength of Unsaturated Soils

The shear strength at various moisture contents were obtained for each soil through a series of shear box tests and presented as the shear strength vs. displacement plots. To demonstrate typical behaviour of soil under shear, Figure 1 presents the lab data for Soil 1 at different normal stresses (28.52 kPa, 55.77 kPa, and 83.02 kPa). Figures 2 and 3 provide the apparent cohesion and friction angles of the tested soils plotted against the volumetric moisture content.

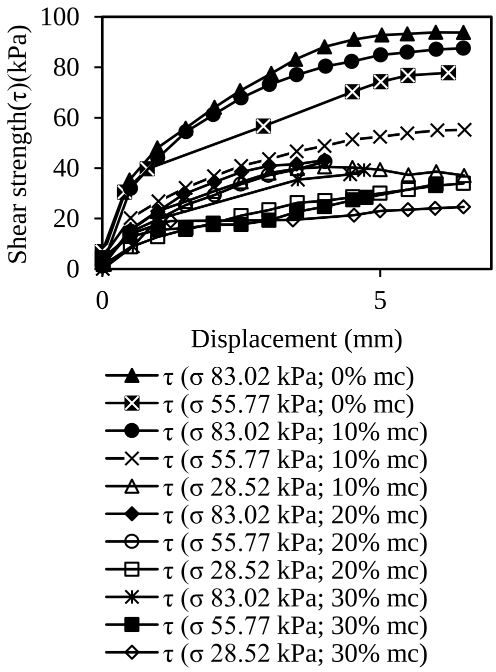


Fig. 1 Shear stress vs. shear displacement at different normal stresses and moisture content (mc, in %).

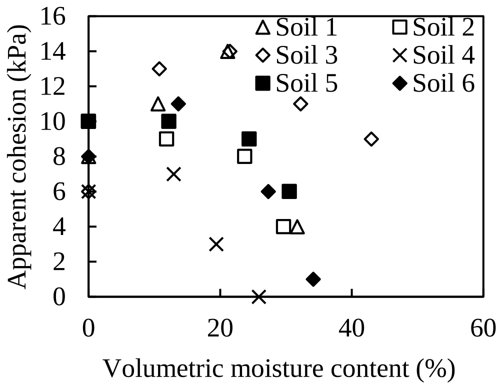


Fig. 2 Test results from shear box tests plotted as the apparent cohesion vs. volumetric moisture content.

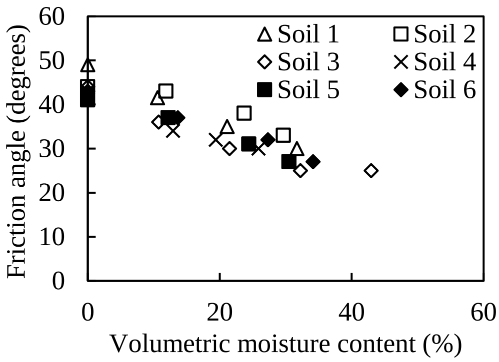


Fig. 3 Test results from shear box tests plotted as the friction angle vs. volumetric moisture content.

From Fig. 2, it can be noted that for four soils (Soil 1, 3, 4 and 6) the apparent cohesion increases up to a certain extent and then decreases with increasing amount of moisture. However, for all tested soils, the friction angle tends to decrease with increasing moisture content, as shown in Fig. 3.

Based on the shear test results, Equations (11) and (12) can be obtained. These equations show the relationship for the cohesion ratio (c/c_0) and the friction angle ratio (ϕ/ϕ_0) with the moisture content, respectively, using an optimization technique by minimising the squared sum of the normalized residuals (SSNR):

$$c/c_o = 1 - 7.23\,\theta^2 \tag{11}$$

where, c is the cohesion at any volumetric moisture content; c_0 is the cohesion at zero volumetric moisture content; and θ is the volumetric moisture content.

$$\phi/\phi_0 = e^{-1.38\theta} \tag{12}$$

where, ϕ is the angle of internal friction at any volumetric moisture content; ϕ_0 is the angle of internal friction at zero volumetric moisture content.

Eq. (11) and Eq. (12) provide the relationship between the shear strength parameters of gravelly and sandy soils and moisture content that can be used to estimate the change of shear strength for similar types of gravelly and sandy soil.

4.2 SWCC of Tested Soils

The suction tests produced a series of data plotted as the volumetric moisture content against matric suction, as shown in Figure 4.

To build SWCC for a wider range of moisture content, the lab data from Fig. 4 and Eq. 1 were used. According to Vanapalli et al [13], the suction value at the residual water content (ψ_r) can be assumed to be around 3000 kPa as it produced good estimates of shear strength. The saturated volumetric water content θ_s was obtained from the SWCC plot (Fig. 4). The fitting parameters (a, n, and m) from Eq (1) were estimated by applying the optimization technique. To estimate the range of these parameters, the data on 30 coarse-grained soils provided by Chin et al [22] was considered. The following ranges were assumed: a (from 0.1 to 5), n (from 0.1 to 15), and m (from 0.1 to 2). The estimated fitting parameters are reported in Table 2.

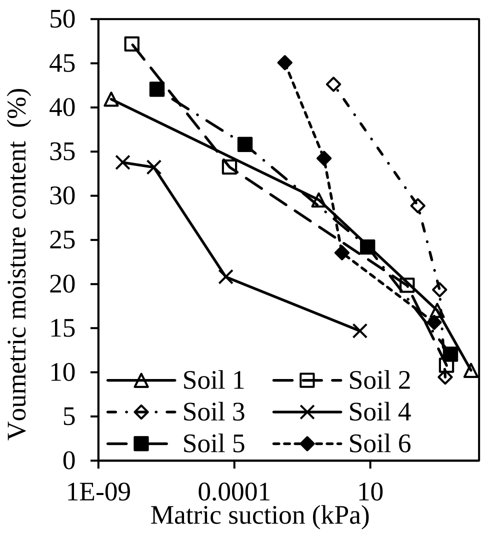


Fig. 4 Volumetric moisture content vs. matric suction (measured SWCC)

Table 2. Model parameters used to estimate shear strength

Soil No.	SWCC fitting parameters			D_{60} (m)	AEV (kPa)	M
	a	n	m			
1	0.1	0.1	1.2	1.9E-03	6.5E-09	5.9
2	0.2	0.1	2.0	3.3E-03	1.1E-08	5.6
3	5.0	0.5	0.9	5.8E-04	2.0E-09	4.7
4	0.6	9.6	0.3	2.7E-04	9.3E-10	7.0
5	2.2	8.4	0.2	3.4E-03	1.2E-08	7.0
6	0.2	15.0	0.2	2.8E-03	9.6E-09	3.9

Figures 5a-c show an example of comparisons between the laboratory data and the best fit SWCC models for Soils 1, 2 and 6, respectively, which will be used later for shear strength prediction.

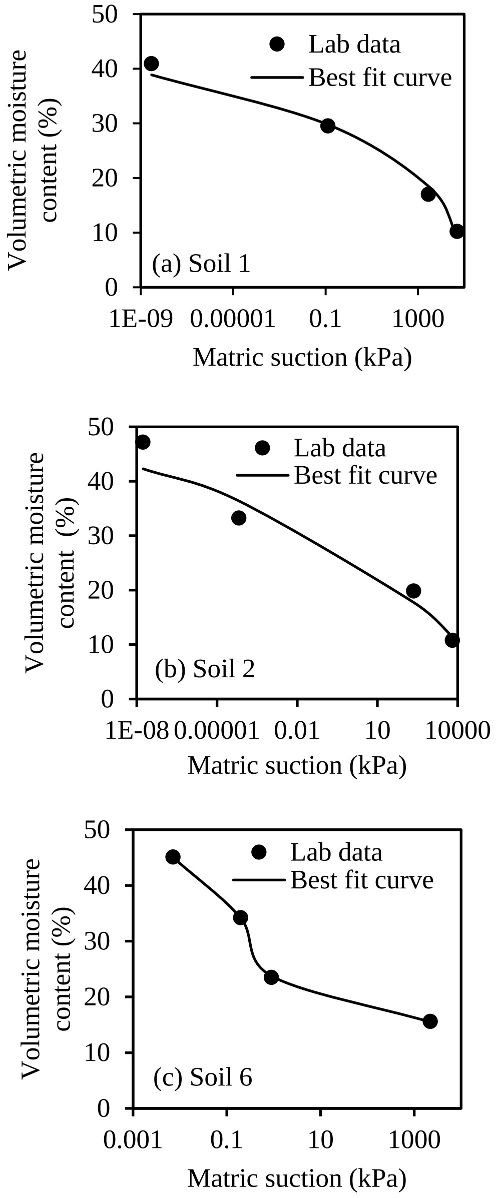


Fig. 5 Comparisons of the best fit SWCC models with the measured lab data.

5. ESTIMATION OF SHEAR STRENGTH

Vanapalli et al [23] and Kim et al [24] noted that the effect of vertical stress on the SWCC is negligible under relatively low confining pressures. Therefore, it can be assumed that the SWCC obtained using the filter paper technique can represent the SWCC of soils that are subjected to low vertical stresses. For this reason, only the shear box data obtained for the lowest normal stress of 28.5 kPa was used to for comparisons.

The suction value (u_a - u_w) for each moisture content was obtained from the relevant best fit SWCC models using the data from Table 2. The model parameter R used in Eq. (6) was calculated using the Excel Solver option by applying the optimization technique. In this study, R was estimated for all six soils as 0.35 x 10^{-6}. The estimated values of AEV for each soil were obtained using Eq. 6 and summarized in Table 2.

The shear strength for six soils was estimated using the Khalili and Khabbaz's method in Eq. (3) to Eq. (5) and the AEV value from Table 2. Eq. (7) to Eq. (9) were used to estimate the shear strength by the Naghadeh and Toker's method. For the newly-proposed method, the parameter M from Eq. (10) was calculated using the Excel Solver by applying the optimization technique. The range for parameter M was assumed to be between 1 and 7. The obtained values of M for each soil are presented in Table 2. Figure 6 provides comparisons of the predicted shear strength using three models with the measured shear strength from the shear box tests.

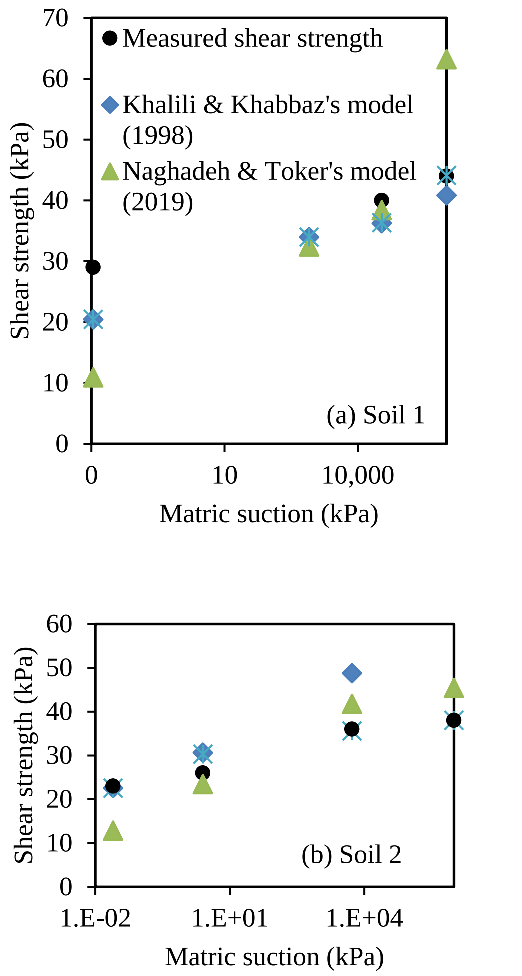
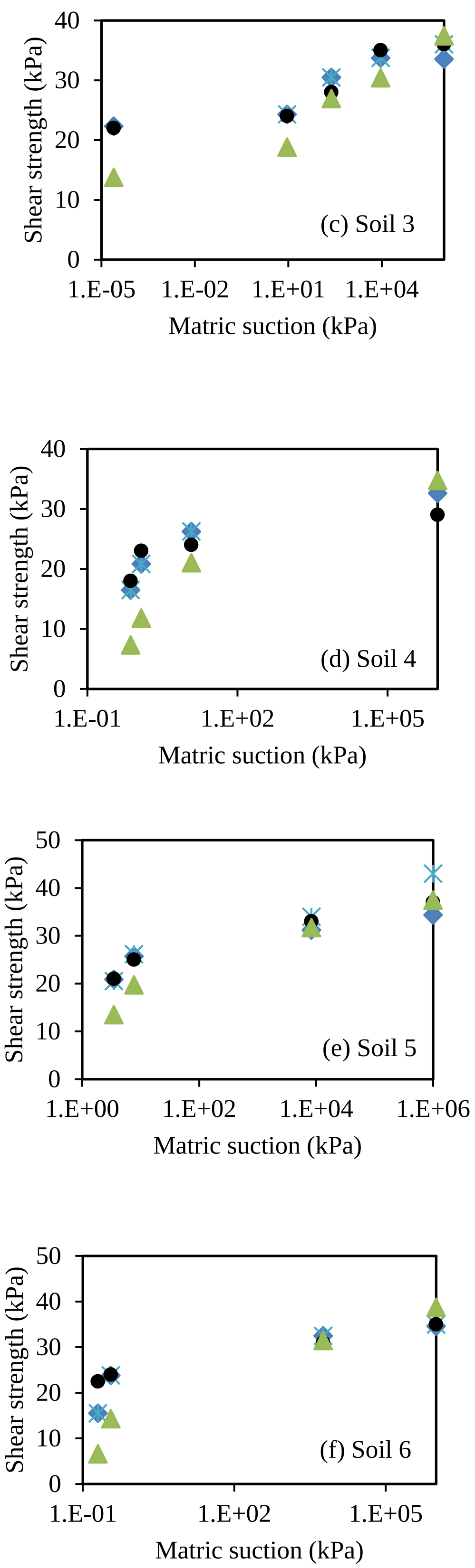


Fig. 6a and b Comparison of predicted shear strength with measured shear strength of Soils 1 and 2



Figs. 6c-f Comparison of predicted shear strength with measured shear strength of Soils 3 to 6

It is evident from Fig. 6 that the three models predict the shear strengths of unsaturated soils within reasonable limits. However, both the Khalili and Khabbaz's model and the newly-proposed model provide closer values to the measured shear strength in the lab. The Khalili and Khabbaz's model predicts within 35% of the measured shear strength, while the Naghadeh and Toker's method tends to overestimate (44 - 71%). The proposed method predicts within 31% of the measured shear strength. The overestimation obtained for the Naghadeh and Toker's method can be attributed to the fact that this approach was developed using fine-grained plastic soils.

6. CONCLUSION

A series of shear box and suction test were performed on six coarse-grained soils at different water content and based on the obtained results the following major conclusions can be drawn:

- The shear strength of the studied soils decreased from 34% to 43% when the water content increased from 0% to 30%.
- It was found that the apparent cohesion slightly increased up to a certain extent and then significantly decreased with increasing water content. On the other hand, the friction angle continuously decreased with increasing water content.

The Khalili and Khabbaz's model predicts within 35% of the measured shear strength, while the Naghadeh and Toker's method overestimate within 71%. The proposed method predicts using the soil gradation characteristics within 31% of the measured shear strength. Although being limited to gravelly and sandy soils, the proposed method can predict the shear strength of soil at low normal stress conditions in respect to changes in moisture content with reasonable accuracy.

7. ACKNOWLEDGEMENTS

The comments and views expressed in this paper are those of the authors and not necessarily of others. It is acknowledged that soil samples were obtained from public authorities.

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