Variation of shear strength of an unsaturated silica sand during drying

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ABSTRACT: This paper presents shear strength results obtained from a modified suction-controlled triaxial test device of an unsaturated silica sand. A novel method was developed which has the ability of conducting unsaturated tests at low net stresses. The equipment is comprised of a flow pump for implementing matric suction based on the axis translation technique, pressure panel for applying the net stress and calculating volume change of the specimen during the test and the axial load system for controlling the deviator load. The results of this study reveal that sandy soils are unlike silty soils, with the increase of the matric suction the shear strength increasing to a peak value and then displaying a dramatic decrease in values with a further increase in matric suction. Such observations can be attributed to the material properties and inter-particle forces peculiar to sand. Results obtained from this study also indicate a curved shear strength envelope. Specifically, at low levels of mean net stress, the soil failure envelope was observed diverge from Mohr-Coulomb criteria and this finding should be considered when determining the suction stress characteristic curve for sandy materials.

1 INTRODUCTION

Shear strength of soils is a fundamental parameter for safety analysis and stability of geotechnical structures such as dams, excavations, pavements, retaining walls, evaluation of bearing capacity of foundations, etc. As in most of the geotechnical problems such as construction and operation of the earth dams, the unsaturated condition prevails, considering the unsaturated shear strength of unsaturated soils is of paramount importance. In the unsaturated condition with the introduction of the air as the third phase of the soil, the capillary forces arisen between soil particles will create internal forces that hold soil particles together like a glue. This phenomenon leads to greater values of shear strength by increasing the apparent cohesion and bringing about tensile strength.

Over the past two decades, there has been quite extensive research on the strength behavior of unsaturated soils, all indicating the significant effects of the type of materials, the state of stress (matric suction and net stress), and the soil's degree of saturation on the strength characteristics of the materials. For example, the shear strength of silt and clay has been observed to increase as a result of any increase in soil's state of stress (matric suction or mean net stress) or a decrease in the degree of saturation (Bishop 1960, Blight 1967, Escario 1980, Krahn 1989, Ho and Fredlund 1989). However, in contrast to silt and clay in which a clear and specified trend for the shear strength change with matric suction increase was reported, the shear strength of sands was observed to behave differently with suction increase. Shear strength of sand with a uniform grain size distribution varied mostly in an up-and-down manner with suction increase with a maximum value at some suctions ranging between the air entry and residual suctions. Results of studies on well-graded sands or sand with considerable fine content, on the other hand, showed that the tested soil in this case may vary in degree of saturation over a wider range of suction, resulting in a shear strength behavior similar to the well-known continuously-increasing trend for the shear strength of silt and clay (Lu and Wu 2006, Nam et al. 2011).

While the results of former studies allowed for identifying the trends of shear strength for unsaturated sand during drying, the experiments in these studies were mostly performed on specimens of sand prepared at different initial water contents which is different from the situation in the field where the water content of the soil is routinely fluctuated with seasonal weather changes. Consequently, a dilemma may exist as what error is introduced in the results due to the method of unsaturated sand testing.

This paper aims to gain a better understanding of the shear behavior of sandy soils under different hydraulic and mechanical loading conditions. In this regard, a series of drained triaxial shear tests were carried out in a modified triaxial apparatus with suction-saturation control ability. This new apparatus allows precise control of the net stress and matric suction, two key components of the shear strength of unsaturated soils to magnitudes as low as 0.4 and 0.1 kPa, respectively. Results of this study were also used to define the constitutive relationship between suction stress and matric suction for an unsaturated sand following the procedure proposed by Lu and Likos (2006).

2 MATERIAL AND SPECIMEN PREPARATION

The material used in this study was a poorly graded silica sand with rounded and sub-rounded particles and a uniform grain-size distribution curve as plotted in the Fig. 1. Typical geotechnical properties of the tested material are summarized in Table 1. The tested specimens were cylindrical specimens with the height of 76 mm and the diameter of 38 mm which were prepared using aerial pluviation (sand raining) technique. In this regard, specific amount of oven-dried sand was pluviated through a series of holes in a guide tube from a height of 70 cm into a membrane expanded over a two-part split vacuum mold, placed atop the pedestal of the testing setup. Studies have revealed that for the tubes with heights above 50 cm, with further increase of the falling height, the deposition intensity does not change (Vaid and Negussey 1984). In this study, the falling height was kept constant at 70 cm, while the area of the openings was changed to obtain soil specimens with an initial void ratio, *e*, of 0.71.

Table 1. Geotechnical properties of tested material

Soil property	Description
Chemical composition	99% SiO_2
G_s	2.65
e_{max}	0.9
e_{min}	0.62
D_{50} (mm)	0.19
C_u	1.29
D_r (%)	67
$e_{Initial}$	0.71

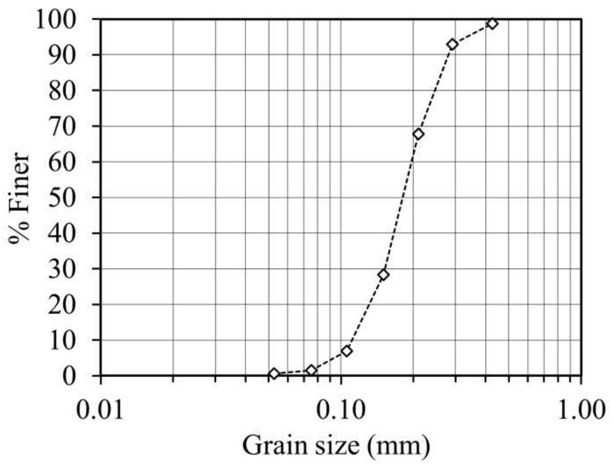

Figure 1. Grain-size distribution curve for the tested material

3 TESTING DEVICE AND PROCEDURE

A modified triaxial apparatus for unsaturated soil testing was developed for conducting shear strength tests under varying matric suction and stress state conditions. Fig. 2 outlines the schematic sketch of this apparatus. In this device, a pneumatic pressure panel with accuracy of 0.1 kPa was designed and utilized to control and adjust air and water pressures during testing. The pneumatic system was also used to measure changes in the volume of specimen through the use of a set of graded burettes connected to the cell and the bottom of the specimen, respectively. Matric suction and saturation degrees of the specimen during different processes of testing were controlled with a flow pump system. The flow pump system that was used in this study consists of a cylinder with cross-sectional area of 1134 mm^2 and its performance is based on a suction feedback control loop providing the target suction when reaching equilibrium. More details about the flow pump is provided by Khosravi and McCartney (2011), Khosravi et al. (2016a), and Khosravi et al. (2016b). The use of flow pump provided the opportunity to control the matric suction and the degree of saturation independently which is not possible in a conventional burette system. The axis translation technique was employed to separately control the air and water pressure for unsaturated testing. In this regard, a HAE (High Air Entry) ceramic disk with air entry suction of 80 kPa was embedded in the pedestal. In this study, net stress at low stresses was provided and adjusted using the gravitational water pressure head. This method provided the opportunity to perform unsaturated shear tests under stress levels as low as 0.4 kPa.

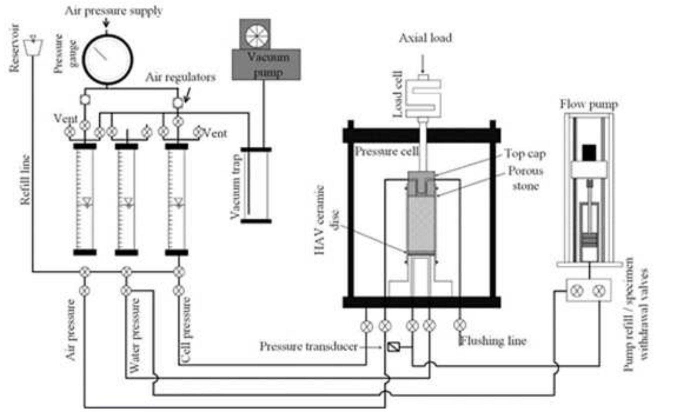

Figure 2. Schematic sketch of the modified triaxial apparatus

After preparing the specimen on top of the pedestal, the specimen was saturated by applying vacuum to the top of the specimen, while allowing de-aired water to flow through the specimen from the bottom. After saturation, vacuum was removed and then the specimen was subjected to the desired mean net stress. After reaching an equilibrium condition, the unsaturation process was initiated by an approach suggested by Khosravi and McCartney (2011) to reach desired equilibrium suction values. During the tests, the degree of saturation during the test was recorded with operating the pump and locating the rotational movements of the stud caused by the step motor, and the suction values were measured by a pressure transducer attached to the drainage line connected to the bottom of the specimen. After reaching equilibrium in each of the desired suctions, 0 kPa (saturation state), 4 kPa (around the air entry value), 6 kPa (suction in the transition zone of the SWRC), 8 kPa (around the residual suction) and 12 kPa (suction in the residual zone of the SWRC), a drained triaxial shear test was performed under constant net stress conditions. Loading conditions for the tested material are summarized in Table 2.

Table. 2. Shear tests carried the tested material

Net Stress (kPa)	Matric suction (kPa)				
0.4	0	4	6	8	12
2	0	4	6	8	12
24	0	4	6	8	12
70	0	4	6	8	12

4 RESULTS

4.1 *SWRC results of the unsaturated sand*

The SWRC results obtained from the tested material under different net stresses of 0.4, 2, 24, and 70 kPa are shown in Fig. 3. The SWRCs denote initial drying from saturated condition up to a suction of 13 kPa. As presented in this figure, there is shift to the right in the SWRCs as the net stress increases from the net stress of the 0.4 kPa to 70 kPa which indicates the dependency of the water retention ability of the soil on magnitude of the net stress. As a result of this shift, the air entry suction value changes from the suction of 2.8 kPa at the lowest net stress to 4 kPa at higher stresses.

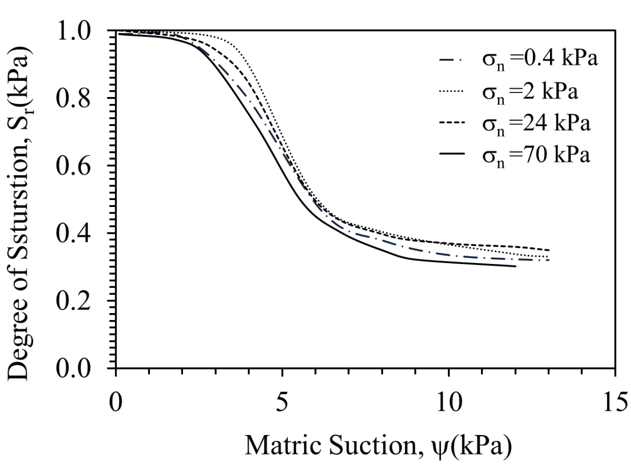

Figure 3. The SWRCs of the tested material under different net stresses

Such observation can be attributed to the rearrangement of soil particles and the pore space volume change with increase of the net stress. Similar results on different types of soils were reported by Khosravi and McCartney (2011) and Khosravi et. al (2016c).

4.2 *Shear strength results of the unsaturated sand*

Shear strength values of the tested materials obtained from the unsaturated drained triaxial shear tests under different net stresses are presented in Fig 4. As presented in this figure, regardless of the magnitude of the net stress applied to the specimen, an up-and-down trend for the shear strength of unsaturated sand is observed when plotted as a function of matric suction. However, the rate of changes in shear strength may change depending on the level of net stress and matric suction considered for testing.

For the specimen of sand under an initial net stress values of 0.4, 2, 24 and 70kPa, an initial increase in the shear strength was noted at low values of suction as the specimen was dried from an initially saturated condition. After reaching a maximum value at a suction of 4 kPa, which is close to the air entry, the shear strength decreased in a significant rate toward its minimum value at a suction, corresponding to the residual condition. Similar observations were reported by Milatz and Grabe (2015). This observation is different from silt and clay where the shear strength results indicated an increase in magnitude with matric suction stress increase. Such a difference in the strength behavior for sand can be attributed to the nature of the interparticle forces between the particles in different soils. As suction increases, the drying process results in the formation of water menisci between the particles, creating some forms of interparticle forces that increase stability of the particles against slippage or rolling. At great values of suction, however, these water menisci collapse and as a result, the shear strength of soils decreases. The value corresponding to the maximum shear strength in sand is believed to be dependent on different terms, most notably, the grain size distribution of the particles, as well as the fine content of the material (Khosravi et al. 2016c, Khosravi et al. 2018). Results also indicate a significant increase in the strength of soil as a result of net stress increase.

4.3 *Suction stress*

Lu and Likos (2006) introduced the concept of suction stress as a macroscopic variable to incorporate the effects of capillarity, soil- and pore fluid-specific forces such as van der Waals forces, electrical double-layer repulsion forces, and net attraction forces arising from chemical cementation at the grain contacts into the definition of effective stress. An experimental approach was proposed by Lu and Likos (2006) to characterize trends between the suction stress and the matric suction, defined as SSCC as presented in Fig. 5. This approach uses the shear strength failure envelopes of the unsaturated soil obtained for predetermined values of matric suction. Interpolation of the failure envelop intercept which is called the apparent cohesion, to the normal stress axis defines the suction stress as follows:

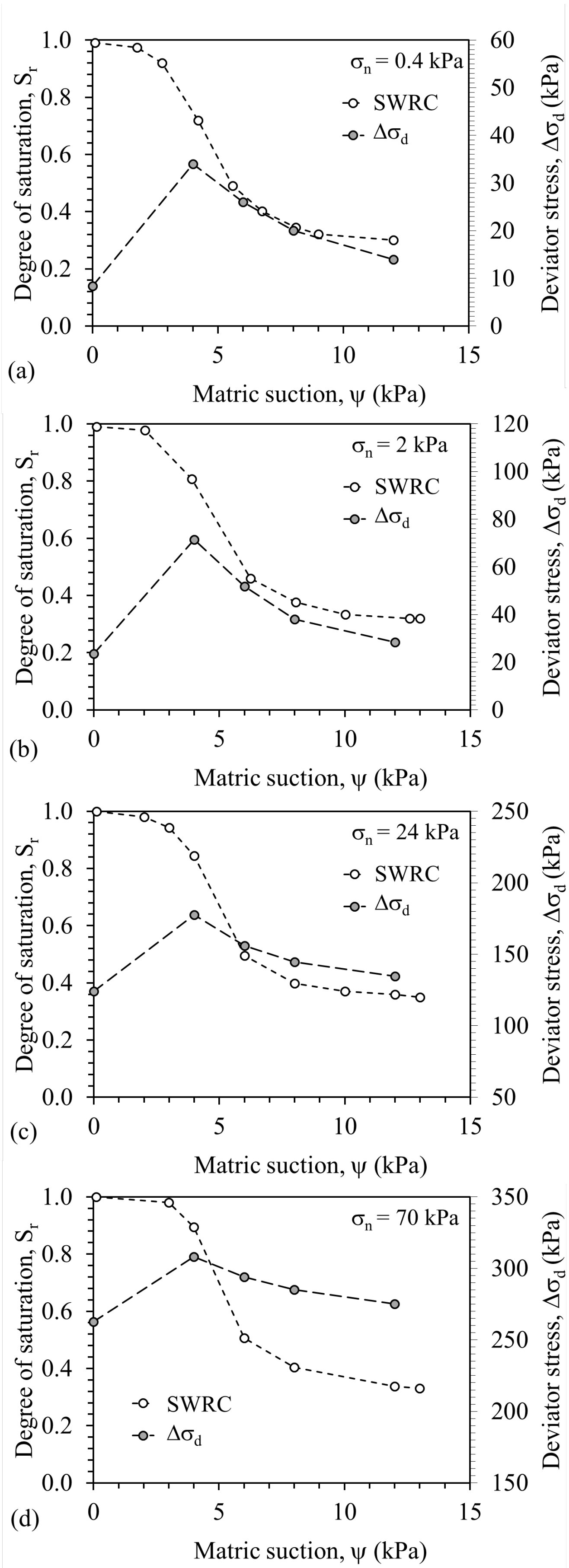

Figure 4. Results of shear strength Vs. matric suction together with corresponding SWRCs for specimens at various values of mean net stress: (a) $\sigma_n = 0.4$ kPa; (b) $\sigma_n = 2$ kPa; (c) $\sigma_n = 24$ kPa; (d) $\sigma_n = 70$ kPa

$$\sigma_s = \frac{c'}{\tan(\phi')} \tag{1}$$

A schematic highlighting the procedure for determining the SSCC from shear strength failure envelopes conducted on different matric suction values is shown in Figure 5. While determining the suction stress, the apparent cohesion of the saturated condition is considered to be as zero. In this method, failure envelops are assumed to be linear for the applied range of net stresses and the friction angle for different matric suctions values is considered to be a constant value. The validity of the last assumption has been proven only for the case of soils with rigid particles (soil particles that do not change in volume during changes in matric suction (*e.g.*, sands, silts, and clays of low plasticity). The validity of using the same friction angle for both saturated and unsaturated soils was also investigated by Vanapalli et al. (1996). As the suction stress concept is the extension of Bishop's approach, similar to the χ factor, the SSCC shown in Fig. 5 is path dependent.

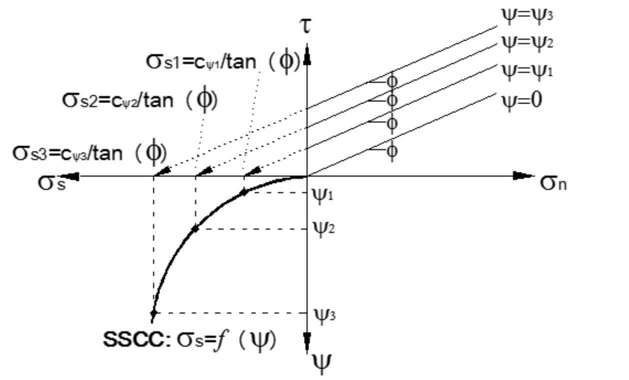

Figure. 5. Schematic for evaluation of the SSCC from shear strength data (after Lu and Likos 2006 and Khosravi and McCartney 2009).

The approach proposed by Lu and Likos (2006) for determining the SSCC from shear strength failure envelopes was found to be a useful approach for silt and clay. However, for sandy soils the story is a bit different. In this case, depending on the soil's initial conditions and the magnitude of applied stresses, the soil specimen may show different failure behaviors. For stresses in the order of tens to hundreds of kPa, the failure behavior of sand has patterns very similar to silt and clay, while for stresses lower than this range, particularly in the tensile stress regime, the strength behavior of sand may not follow Mohr-Coulomb (M-C) frictional behavior (Lu et al. (2007, Maksimovic, 1989, Kim, 2001). In these low stress regimes, the ratio of shear stress to normal stress may increase significantly and instead of a linear M-C failure envelope, a non-linear trend would be a good description of relationship between shear strength and normal stress. Kim (2001) reported a friction angle of 23° within the range of normal stress from 0.5 kPa to 1.0 kPa, 28° within the range of normal stress from 0.25 kPa to 0.5 kPa, and 47° for normal stresses from 0.1 kPa to 0.25 kPa when testing dry clean Ottawa sand

(F-75). This nonlinear behavior of sand under small compression regimes or under undergoing tensile failure is an important factor when characterizing the SSCC, as it defines the friction angle of soil at or near zero normal stress. The friction angle value of soil at this normal stress condition can then be used for the linear portion in the tensile regime.

The experimental setup which was developed in this study allowed performing tests at net stresses as low as 0.4 kPa, results of which were used to first, investigate the nonlinear nature of sand's shear failure behavior, also to properly obtain the suction stress characteristic curve of sand. The failure envelops of specimens of sand tested under different matric suctions of 0, 4, 6, 8 and 12 kPa are presented in Fig 6. As presented in this figure, also stated earlier, for matric suctions up to the air entry value, there was an increase in shear strength of the specimen with matric suction increase, and therefore, the Mohr-Coulomb envelope associated with the matric suction of 4 kPa was located on top of the other envelops while for suctions beyond the air entry suction, the values of shear strength experienced a dramatic drop, reaching their minimum at some suction representing the residual condition. Results also clearly show the nonlinearity of the Failure envelops for unsaturated sand at different values of suction which can be of paramount importance when determining the SSCC of the unsaturated sand.

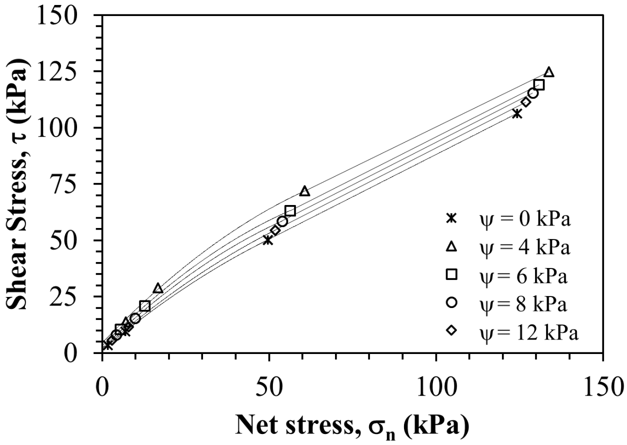

Figure 6. Shear strength failure envelops for the matric suctions of 0, 4, 6, 8 and 12kPa

The failure envelops presented in Fig. 6 were used to determine the SSCC of the tested material, results of which are presented in Fig. 7. Based on the results presented in this figure, variations in suction stress, σ_s, during drying showed an up-and-down trend when plotted as a function of ψ. As presented in Fig. 7, the impact of ψ on σ_s during drying can be categorized into three different zones. The first zone is the saturation zone, ranging from zero to the air entry suction, in which the soil specimen experienced negligible change in S_r. In this zone, ψ increase led to a relatively linear increase in σ_s. Through the second (or transition) zone, ranging from the air entry suction to the residual suction, the SWRC showed significant reduction in S_r with ψ increase (Fig. 3). In this zone, σ_s initially increased to a peak value at a suction value of 4 kPa (a value between the air entry and residual suctions), after which a sudden drop in its magnitude was observed with suction increase. For suctions greater than the residual suction value, the rate of change in S_r was negligible, and σ_s experienced a slight decrease in magnitude with suction increase.

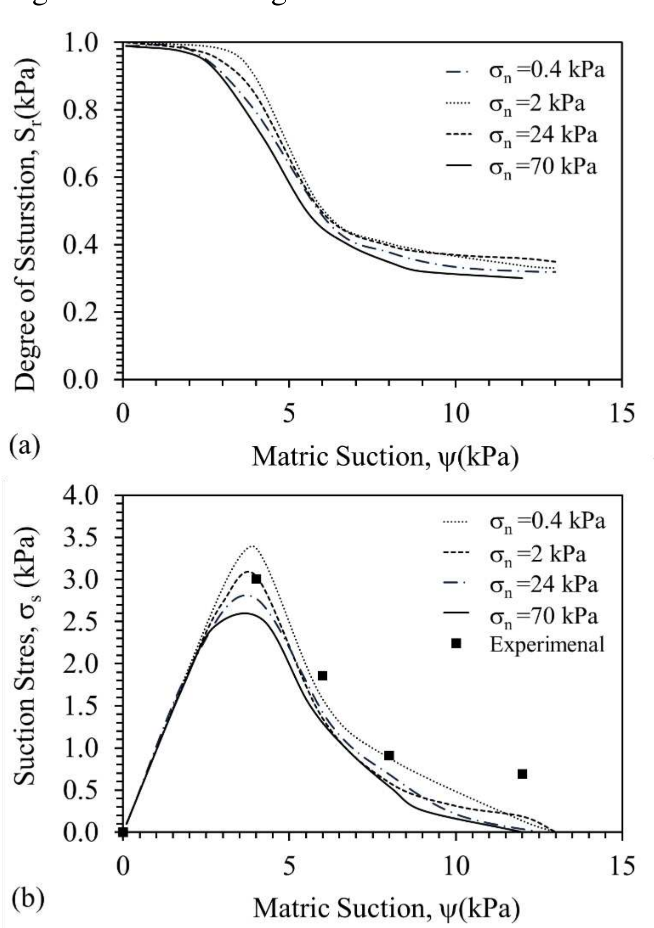

Figure 7. Comparison of the experimental values of SSCC and values obtained from the equation: (a) SWRCs and (b) SSCCs Under different net stresses

The measured suction stress values presented in Fig. 7 were also used to assess the applicability of an approach proposed by Lu et al. (2010) to estimate the suction stress characteristic curve of unsaturated sand. Lu et al. (2010) used a working hypothesis formed on the basis of experimental observations and thermodynamic justifications and proposed a closed-form equation for suction stress as follows:

$$\sigma_s = \psi \times S_e \tag{2}$$

where S_e is the effective degree of saturation defined as:

$$S_e = \frac{S_r - S_{r,res}}{S_{r,sat} - S_{r,res}} \tag{3}$$

where $S_{r,sat}$ and $S_{r,res}$ are the degrees of saturation corresponding to the saturation and residual condition, respectively, and S_r is the current degree of saturation which were obtained from the SWRC curves presented in Fig. 3. Fig. 7 provides a comparison between the measured SSCC (data points) and those predicted using Eq. 2 under different net stresses. Based on the results presented in this figure, the predicted curves of the suction stress under different net stresses show trends very similar to the experimentally measured SSCC during drying. The value of σ_s was observed to have an initial increase in magnitude with ψ at suction values below or near the point of air entry, after which a sudden decrease in suction stress was observed with matric suction increase. However, the results of this study may indicate an uncertainty in the uniqueness of the SSCC for unsaturated sand under different levels of net stress. As presented in Fig. 7, the predicted SSCC curves show different paths under changing net stress conditions with higher values in high net stress testing. This observation is likely due to the differences in the water retention ability of sand specimens under different net stresses which resulted in the measurements of the SWRCs with different shapes and slopes (Fig. 3).

5 CONCLUSIONS

This paper describes details of a modified suction-controlled triaxial shear test device for testing unsaturated sand. This device has the capability of applying matric suction values with an accuracy of 0.1 kPa and net stresses as low as 0.4 kPa. Shear strength test results for silica sand specimens also presented, and unlike the case for silt and clay, the plot of shear strength vs. matric suction of the silica sand was observed to follow an up-and-down trend, with a maximum value at a degree of saturation close to air entry suction (a matric suction approximately 4 kPa), and its minimum at a matric suction close to the residual suction (approximately 8kPa). Results of this study also indicate the efficiency of an approach proposed by Lu and Likos (2006) in predicting the suction stress of unsaturated sand during drying, even though in contrast to the experimental measurements, the suction stress-matric suction curves were observed to be net stress dependent.

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