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Reliability of Soil Water Characteristics Curve under Different Normal Stresses for Unsaturated Sand

Mustafa M. Abdalhusein[1*], *Mohammed* Shakir Mahmood[2], *Salah Mahdi Saleh*[3] ,*and Rusul* Almahmodi[4]

[1] Structures and Water Resources Eng. Dept., University of Kufa, Iraq
[2] Civil Eng. Dept., University of Kufa, Iraq
[3] Civil Eng. Dept., University of Kufa, Iraq
[4] Ph.D., Dept. of Building and Construction Technology Eng., Al-Furat Al-Awsat Technical University

Abstract. The soil water characteristics curve (SWCC) demonstrates a link between soil moisture content and suction. The SWCC is almost treated as an index parameter in unsaturated soil. The soil permeability and shear strength can be linked to SWCC. SWCC is established using filter paper for the wetting path. This paper compares SWCC for both cases stress-dependent and no stress (reference) in the wetting path. The samples of soil are brought from Al-Najaf City with a gypsum content of 29%, Iraq. The stress-SWCC is studied using a modified Oedometer cell with controlled water and air entrance to apply a specific matric suction. While the reference SWCC is estimated using the filter paper method. Matric suction is conducted at a range of pressures from 90 kPa to 0 kPa. The tests use three net normal stresses of 100, 200, and 400 kPa. The results show that there are decreasing values of the SWCC with increasing normal stresses. An interesting result is that this decrease is high and has zero matric suction. The water entry value (WEV) with the most significant value of the water entry change is represented by the matric suction of 50 kPa.

1 INTRODUCTION

Laboratory research has shown a correlation between the SWCC and the characteristics of unsaturated soil [1]. A basic relationship in unsaturated soil mechanics is the SWCC, which shows the connection between a soil's volumetric water content and matric suction [2]. Numerous studies have been conducted in this area, and this conceptual framework can be used to analyze the complex behavior of unsaturated soils [3]. The SWCC, which is connected to other soil characteristics including the unsaturated coefficient of permeability and shear strength [4], affects the behavior of unsaturated soils. There are direct and indirect methods for calculating SWCCs for a certain soil [2], [4]. Gypseous soil is collapsed soil when it is exposed to moisture [5], [6], [7], [8]. Many parameters can influence this collapse, including the wetting time [3], [5], [9], as do other factors such as increasing gypsum content and pores ratios, as well as permeability [10], [11], initial saturation levels [12] and soil time-based wetting before loading [12], [13], [14]. Many researchers proposed frameworks based on net stress (σ-ua) and matric suction (ua-uw) as two different stress factors [1], [13], [15]. For various gypsum compositions, the angles of internal frictions (Ø) have been shifted from roughly 35o to 28o as the matric suction decreases [16], [11]. Before shearing, the soil's shear strength can be improved by increasing the soaking period (over time) [13]. [18]. As the suction increased, the bearing capacity increased nonlinearly from 255% to 395% as an increasing percentage [19].

* Corresponding author: mustafam.alesawy@uokufa.edu.iq

ASTM D6836-16 has standardized the SWCC calculation. Methods A through E in the standard are used to calculate the SWCC for soils ranging from coarse to fine. METHOD D SHOULD BE PERFORMED when SWCC near saturation is not necessary [2]. In 1907, soil physicist Edgar Buckingham established the SWCC for six different soil types ranging from sand to clay. In contrast to some soils with a bimodal SWCC, most soils have a sigmoidal SWCC, also known as a unimodal SWCC [1]. Although the methods to estimate unsaturated soil properties are approximate, they are typically adequate for addressing unsaturated, saturated soil mechanical difficulties [20]. Stress path dependency is one of the essential properties of collapsing soil behavior, and a model capable of predicting such behavior is necessary [21]. The level of matric suction provided and the level of vertical net stress has a significant impact on the soil SWRCs [22]. The level of the net normal stress affects the unsaturated gypseous sand within the wetting progress [23], [24].
The current work investigates the effect of net normal stress level on the soil-water characteristics curve (SWCC) for the gypseous sand in Al-Najaf City, Iraq. Different matric suction variations using modified Oedometer experiments (wetting). This stress-dependent SWCC is compared to that investigated for the same soil sample in non-stressed conditions.

2 WORK METHODOLOGY

2.1 Soil Sampling and Identification

In the southwest of Iraq, in Al-Najaf, the disturbed samples were collected [3]. In this region, gypsum- and salt-containing problematic soils are a problem. Table 1 provides a summary of the soil characteristics of the examined specimens. Sand makes up more than 90% of the soil samples. The soil is characterized by the Barzanji classification as being extremely gypsiferous [25]. The natural soil is sparsely watered (5%). The gypsum concentration may account for the low specific gravity (Gs=2.38).

Table 1: Summarized soil properties [3].

Tests	Results
Sand, %	91
Soil Classification (USCS)	SP
Specific Gravity	2.38
Gypsum Content, %	29
Natural Water Content, %	5
Max. Dry Density, gm/cm3	1.825
Optimum Moisture Content, %	15

The particle size distribution has been done according to ASTM C136. The sample was taken from a depth of 0.5 m in Al-Najaf city, Iraq because at this depth may have organic materials. The grain size analysis results are shown in Figure 1.

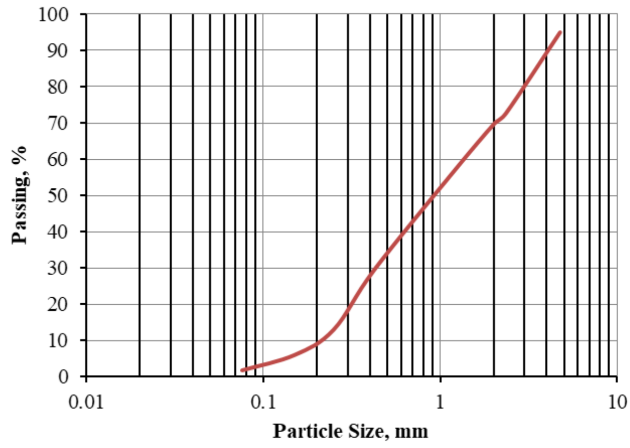


Fig. 1. Particle Size Distribution for the Tested Samples

3 Tools and Equipment

For reference, SWCC (no stress condition), the filter paper method for the wetting path is used in accordance with ASTM D5298-03. 35 soil samples were investigated in the wetting path, which was divided equally into seven groups of volumetric water contents (θ).
For the stress-dependent SWCC (Sd-SWCC), a modified Oedometer is used. Figure 2 shows the schematic of the modified Oedometer, and its accessories as defined by Fredlund and Rahardjo (1993) [1]. The pore water pressure is applied via a 1 bar high air entry (HAE) disc, as in Figure 3(a), while the air pressure is applied and controlled via the top cap. In the Oedometer test, the cell sample is 6 cm in diameter and 2 cm in height, as in Figure 3(b). The suggested control board for water volume adjustments and matric suction application is shown in Figure 4. To apply and maintain pressures, a compressor with an 11-bar pressure capacity and a regulator with a pressure range of up to 30 bar is utilized. Sensors connect a data logger to a computer and a control board to detect water and air pressure. During the test, a linear variable differential transformer (LVDT) with a precision of 0.01 mm was used to quantify the specimens' axial vertical displacement.

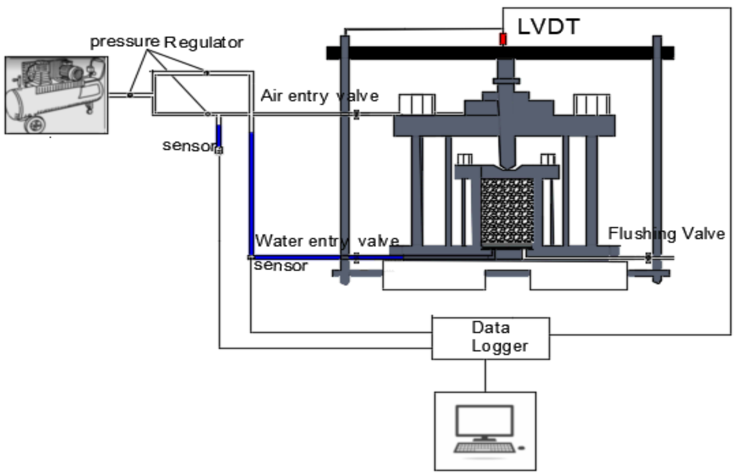
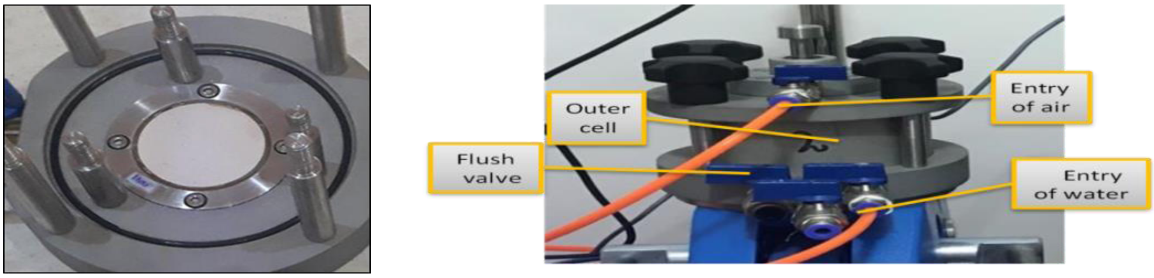


Fig. 2. The modified Oedometer cell.



(a) **(b)**

Fig. 3. The modified Oedometer cell, (a) high air entry (HAE) ceramic disc, (b) Setup of the Oedometer cell.

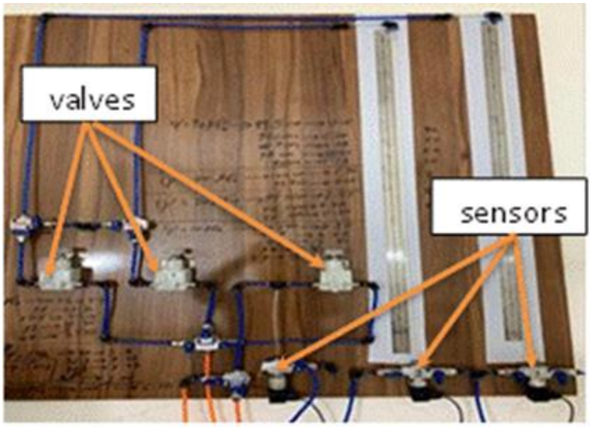


Fig. 4. Control board for applying pressures**.**

4 Tests Procedure

Filter paper was used to get the wetting path SWCC for non-stressed SWCC in accordance with ASTM D5298-03. The matric suction equivalent to the samples' natural (in situ) moisture content was determined to be 30 kPa (for all three samples) using the paper filter method.
In the Oedometer cell, the soil specimen had been treated and remolded. Three sets of tests represent a specific stress level, 100, 200 and 400 kPa. In each set, the specimen is gradually stressed to a specific stress level, and then the matric suction is decreased (wetting) (50, 20, 10, 7, 2, and 0 kPa). A matric suction was applied to the three specimens (ψ=90 kPa). Under this stress, the matric suction decreased.

5 RESULTS AND DISCUSSION

5.1 Reference SWCC

Figure 5 shows the SWCC from the filter paper method without the application of normal stress. The resulting SWCC is unimodal, like most SWCCs. The saturation volumetric water content is 0.3. this curve represents the fitting curve for the data using Fredlund and Xing (1994) [26] equation with fitted parameters, af=2.6, nf=1.8, and mf=1.1, as shown in Equation 1.

$$\theta = \theta_s \left[\frac{1}{ln\left[2.71828 + \left(\frac{\varphi}{2.6}\right)^{1.8}\right]} \right]^{1.1} \qquad (1)$$

Where: θ is the volumetric water content (VWC), θs is the saturated VWC and Ψ is the soil suction.

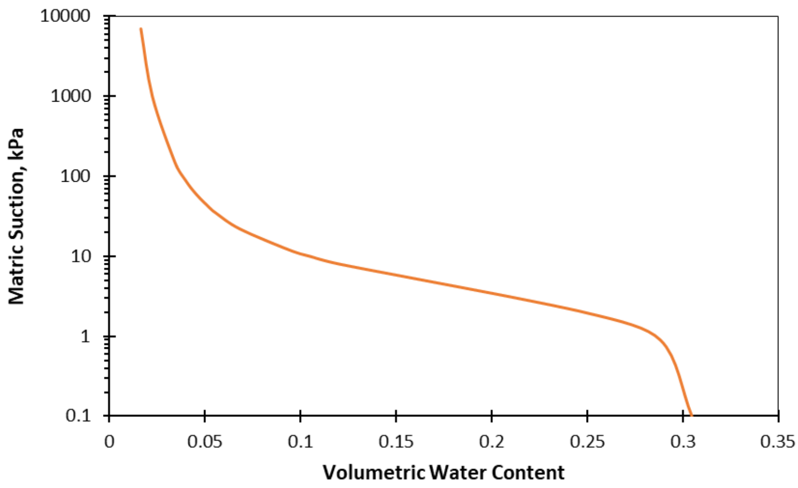


Fig. 5. The reference SWCC (non-stressed).

5.2 SWCC under 100kPa

Under the net normal stress (NNS) of 100 kPa, Figure 6 illustrates the comparison of the stress-dependent-SWCC with the reference one for different matric suctions (Ψ= 90, 50, 20, 10, 7, 2 and 0 kPa). Existence of the NNS is the reason for decreasing in the void ratio which led to decreasing in air volume and matric suction. While this state is approximately eliminated within the following decrease in matric suction starting from the 20kPa downward to the saturation state (zero matric suction), this may be related to the high initial decrease of the voids. Under the NNS of 100kPa, lower volumetric water content to achieve the saturation (θs=0.276) compared to the reference SWCC.

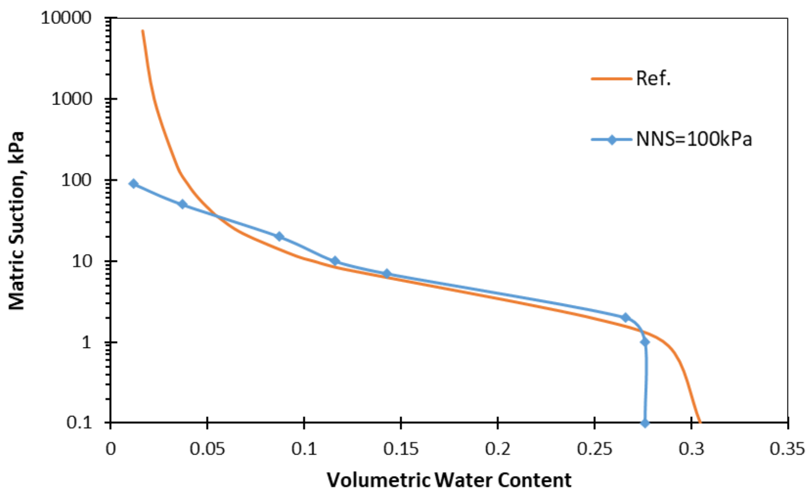


Fig. 6. SWCC comparison, reference and under net normal stress of 100 kPa.

5.3 SWCC under 200kPa

Continuously, the SD-SWCC shifts to the downward of the reference SWCC with increasing NNS up to 200 kPa, as in Figure 7. There is still a matching behavior within the matric suctions of 20 kPa downward to the saturation state for the same attribution of the pre-dominated void ratio. The θs is decreased to 0.269 and it is lower the value in the previous application of NNS (100 kPa).

5.4 SWCC under 400kPa

A distinguish behavior of the sd-SWCC under the NNS of 400 kPa, as in Figure 8. There is a splitting trend of the θ-Ψ relationship and below the reference SWCC. Higher NNS causes a higher decreasing in the void ratios and decreasing in the effect of matric suction. The θs is decreased to 0.259 and it is lower compared to the previous NNS (200 kPa).

5.5 Comparison

To estimate the fitting parameters (af, nf, and mf), Equation 1 is applied to the experimental data of volumetric water content (VWC, θ) versus matric suction (Ψ) under the NNS of 100, 200 and 400 kPa. Table 2 summarizes the fitting parameters and the correlation coefficients. Obviously, the significant parameter in Equation 1 is the "af", which changes with the estimate of the change of net normal stress (NNS) and is not related to the air entry, as stated by Fredlund and Xing, 1994 [26]. While the change in "af" is not constant, it is decreasing with the increase of the NNS. The correlation coefficients are reliable, with values close to unity. According to Fredlund and Xing, 1994, the point (af, θ(af)) represents the SWCC inflection point.
Figure 9 presents a comparison of the different SWCCs. It is obvious that there is a change in SWCC with increasing the net normal stress (NNS) level. The application of the NNS on the unsaturated sand specimens lowered the SWCC below the reference SWCC (no load). Table 3 shows the percentage change in volumetric water content (θ) for the different NNS. Generally, there are decreases in θ concerning the reference SWCC, except t some values due to the fitting process.

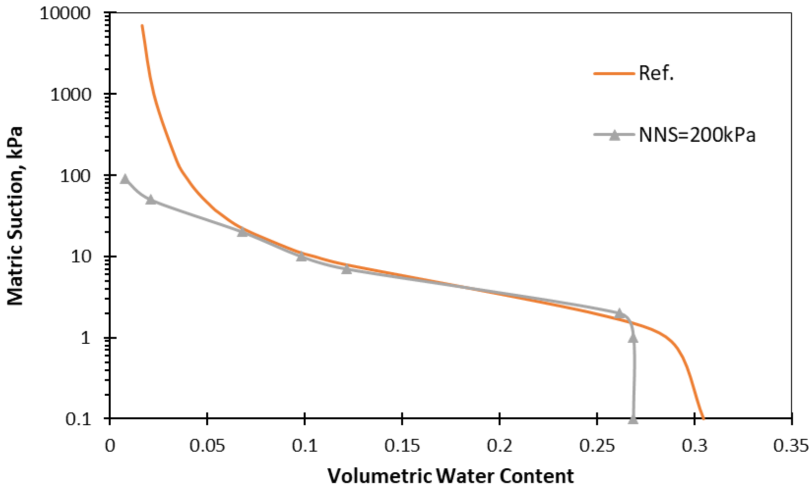


Fig. 7. SWCC comparison, reference and under net normal stress of 200 kPa.

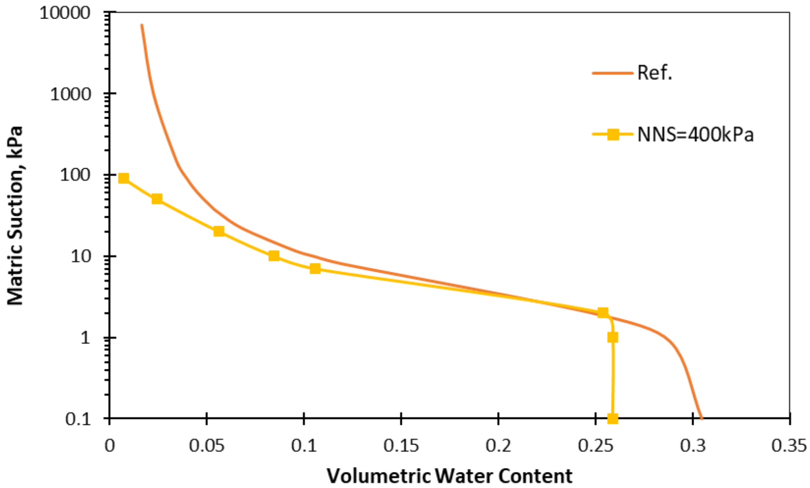


Fig. 8. SWCC comparison, reference and under net normal stress of 400 kPa.

Table 2. Summary of the fitting parameters and correlation coefficients.

Net normal stress, kPa	af	nf	mf	R^2
100	4	2	1.2	0.988
200	3.5	2	1.2	0.990
400	3.2	2	1.2	0.990

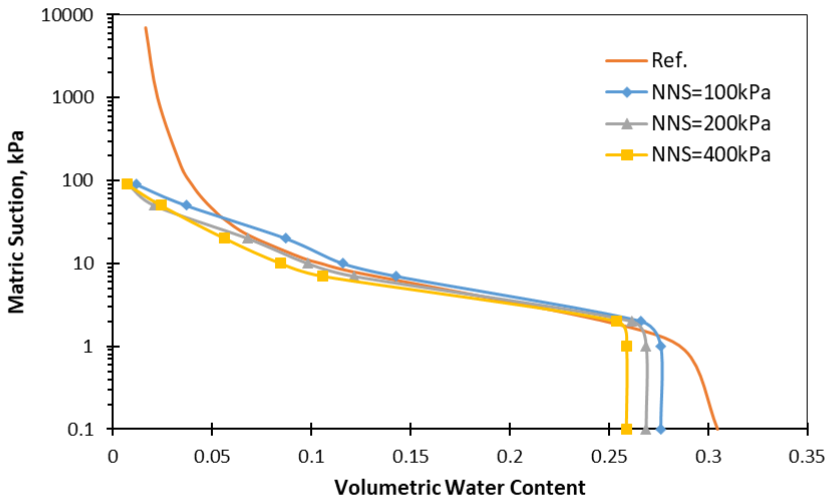


Fig. 9. Comparison of the SWCC for different investigated cases.

Table 3. Percentage changes in the volumetric water content concerning the non-stressed SWCC.

Matric suction, kPa	Change in volumetric water content (θ), %		
	under NNS=100kPa	under NNS=200kPa	under NNS=400kPa
90	-71	-81	-82
50	-24	-57	-50
20	22	-05	-21
10	10	-07	-20
7	09	-07	-19
2	07	05	02
1	-03	-06	-09
0.1	-09	-12	-15

6 CONCLUSIONS

A current paper examines the effect of normal stress level on the soil water characteristics curve (SWCC) in unsaturated gypseous sand soil using filter paper (as a reference) and a modified Oedometer cell. With increasing the stress, there is a shifting in the SWCC to the down, i.e., the higher net normal stress (NNS) leads to lower SWCC. This shifting is decreased with increasing the NNS and decreasing the matric suction (Ψ) and this situation is reflected by the combination of stress and wetting progress. The SWCC's equation is modified to represent the resulting data. Table 4 illustrates the fitting parameters (af, mf and nf) of Equation 1 for each investigated NNS with high R^2.
The comparison between the SWCCs frm triaxial.

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