Water Volume Change Due to Wetting of Unsaturated Gypseous Sand Using Modified Oedometer

Mustafa J. Abrahim\textsuperscript{1a}\textsuperscript{*} and Mohammed S. Mahmood\textsuperscript{1b}
\textsuperscript{1}Civil Engineering Department, University of Kufa, Al-Najaf, Iraq, \textsuperscript{a}mustafaj.alazawi@student.uokufa.edu.iq, \textsuperscript{b}mohammedsh.alshakarchi@uokufa.edu.iq
\textsuperscript{*}Corresponding author

Abstract. This paper investigates the water volume changes in gypseous sand soils within the change in matric suction and under different stress levels. The present research aims to examine water entry into the soil with different matric suction under different levels of constant net normal stress (221, 442, and 885 kPa). The soil sample is collected from Al-Najaf city, Iraq. The main soil of the city is sand with different percentages of gypsum at different locations and depths. These experiments revealed a clear relationship between decreasing the matric suction (wetting) and changing the gypseous soil structure, i.e., increasing the void ratio, and this behavior also depends on the net stress level. With the demolition of the voids under high-stress levels, there is a decrease in water volume change at zero matric suction (saturation). A comparison is made between the predicted soil water characteristics curve (SWCC) for the soil with the investigated values. The results show a shifting, which may be due to the accuracy of the curve fitting or/and the effect of the loading and gypsum content. This new understanding should help improve predictions of the impact of the load, gypsum content, and time.

Keywords: Unsaturated soils; unsaturated; gypseous soil; matric suction; modified oedometer; hydraulic characteristics.

1. Introduction
The relationship between the soil water suction (pressure) and water content (or degree of saturation) is described by SWCC for unsaturated soils [1,2]. A large and growing body of literature has investigated and estimated the soil water characteristics curve (SWCC). The general shape of the SWCC for various soils reflects the dominating influence of material properties, including particle and pore size distribution, density, organic material content, clay content, and mineralogy on the performance of the pore water retention [3]. The most widely used constitutive relations in unsaturated soil mechanics uses matric soil suction as a state condition [4]. Different researchers have proposed various forms of equations to describe the SWCC [2]. Mathematical models analyzed by Fredlund and Xing (1994), Van Genuchten (1980), and Fredlund et al. (1993) give good agreement with experimental results; also, the empirical correlation developed by Zapata (1999) and Zapata et al. (2000) gives a good agreement with experimental results that plasticity properties have a great influence on the obtained SWCC [5]. The SWCC for the soil that is exposed to pre-compression pressure in the past shifted toward the behavior of the clay soil [6].

Bonds between soil particles may be formed by cementing fine materials (salts or clay) and/or by capillary forces (suction). Sudden collapse occurs when vertical pressures (wetting processes or loading) exceed those bonding materials’ yield strength [7,8]. The natural collapsible soils consist predominantly of silt, and fine sand particles with small quantities of clay are common [9]. Soil layers can be exposed to wetting from different water sources, naturally, such as rains and groundwater rise, or human activities (washing, irrigation, ... etc.), but human activities dominate collapsible soils [10]. The rains induced a
limited effect due to limited penetration distance [10-12]. Initial void ratio (e₀), initial moisture content (w), soaking pressure (σw), bonding, initial suction, applied vertical stress, and duration of the sustained load has a straight effect on the collapse behavior [13]. In addition to the increase of the collapse, the potential is related to higher gypseous soils (collapsible soils) [14]. The Cp increased with the increase of soil time-based wetting prior to loading [15-17].

The essential difference between unsaturated and saturated soil is the matric suction, which affects the behavior of the unsaturated soil [18]. Matric suction (ua−uw) is defined as the difference between the pore air pressure (ua) and the pore water pressure (uw) [19]. The volumetric strains are increased with reduced matric suction and increased gypsum content [20-22]. Richards’ equation is a nonlinear constitutive relation that described the water flow in an unsaturated porous medium [23]. The bearing capacity increased nonlinearly from 2.55 to 3.95 times as the suction increased [24]. The present paper investigated the water volume changes within the changes in the matric suction and applied them to load for gypseous sand soil.

2. Materials, tools, and methodology

2.1. Site selection and soil sampling
The tests are performed on a soil sample from Al-Najaf city, Iraq. The sample was disturbed collected in a plastic bag to maintain the natural water content. The sample was representative with respect to the particle size distribution of the city soil [25]. According to the unified soil classification system (USCS), the soil is mainly sand and classified as SW. The gypsum content of the soil sample is 29%, has a specific gravity (Gs) of 2.38. The soil is classified as having high gypsum content, according to Barazanji [21]. The natural water content (ω) is 3% according to ASTM D2216, the maximum dry density ρdry,max) is 1.825 gm/cm³ and optimum water content (OWC) of 14% according to the standard Proctor test. Table 1 summarizes the soil components and properties.

| Test name                     | Test specification | Value  |
|-------------------------------|-------------------|--------|
| Sand, %                       | ASTM D422         | 85.897 |
| Fine, %                       | ASTM D422         | 1.735  |
| D10, mm                       | ASTM D422         | 0.22   |
| D30, mm                       | ASTM D422         | 0.47   |
| D60, mm                       | ASTM D422         | 1.45   |
| Coefficient of uniformity (Cu)| ASTM D422         | 6.6    |
| Coefficient of curvature (Cc) | ASTM D422         | 0.703  |
| Soil classification (USCS)    | ASTM D422         | SP     |
| Specific gravity (Gs)         | ASTM D854         | 2.38   |
| Gypsum content, %             | ASTM C25-99       | 29     |
| Natural water content (ω)     | ASTM D2216        | 3      |
| Max. dry density (Proctor test), gm/cm³ | ASTM D698 | 1.825 |
| Optimum moisture content (Proctor test), % | ASTM D698 | 15    |

2.2. Modified oedometer
A modified Oedometer cell was adopted to apply the specific matric suction by application of air and water pressures [26]. Figure 1 shows the schematic of the equipment and tools that have been used in the tests. Figure 2 shows the oedometer cell. The modified oedometer consists of a top cap, a grooved base plate, a High Air Entry ceramic disc (HAE), an inner cell, and an outer cell. The 5 cm diameter HAE disc is installed on the base plate. The Oedometer specimen ring is 19.38 mm in height and 50.31 mm in diameter. Figure 3 demonstrates the control board of the water volume changes and application of the matric suction. A compressor with a pressure capacity of 11 bar, with a regulator that can regulate the pressure up to 30 bar which is used to apply and maintain the pressures in the control board.
2.3. Testing procedure
For the purpose of analysis, three soil specimens were prepared and remolded into an oedometer cell. The dry density is 95% of the maximum dry density from the Proctor test with 3% by weight water content. The same site's soil water characteristics curve (SWCC) is adopted from published paper [21]. The initial matric suction of 50 kPa is selected depending on the natural water content of the soil sample and using the soil water characteristics curve (SWCC) [21].

Three matric suction (Sm) were selected to perform the tests, initial (50 kPa), intermediate (20 kPa), and zero matric suction (saturated). The water volume changes (WVC) are recorded for intermediate and zero matric suction and under different stress levels (221, 442, and 885 kPa). The change in matric suction is performed by maintaining the pore air pressure (ua) and increase the pore water pressure (uw). Each of the three specimens was initially subjected to the initial matric suction (Sm = 50 kPa) then a gradual loading was applied (55, 111, 221, 442, and 885 kPa) until the specific stress level. Table 2 illustrates the tests program.
Table 2. Tests program.

| Test group No. | Matric suction, kPa | Stress level, kPa |
|----------------|---------------------|------------------|
| 1              | 50$^*$              | 55, 111, and 221 |
| 2              | 50$^*$              | 55, 111, 221, and 442 |
| 3              | 50$^*$              | 55, 111, 221, 442, and 885 |
| 4              | 20                  | 55, 111, and 221 |
| 5              | 20                  | 55, 111, 221, and 442 |
| 6              | 20                  | 55, 111, 221, 442, and 885 |
| 7              | 0$^{**}$            | 55, 111, and 221 |
| 8              | 0$^{**}$            | 55, 111, 221, and 442 |
| 9              | 0$^{**}$            | 55, 111, 221, 442, and 885 |

* applied before loading  
** saturated condition

3. Results and discussion

Water volume changes (WVC) and volumetric water content ($\omega$) with different matric suction (50, 20, and 0 kPa) were compared under different stress levels (221, 442, and 885 kPa) using modified oedometer shown in the following sections.

3.1. Initial matric suction

Figure 4 shows the results obtained from the first specimen. The water volume changes (WVC) are sustained to achieve the initial matric suction (50 kPa), then the specimen is loaded gradually to the stress level of 221 kPa. As seen in Figure 4, the curve starts at 2 cm, representing the initial conditions, but still, there are changes in the water to achieve the initial matric suction (50 kPa). The increase of water is (0.085 cm$^3$) and may be due to water evaporation during the process of specimen preparation. Similarly, the WVC in the second specimen increased above the initial volumetric water (2 cm$^3$) but less than the first specimen (0.057 cm$^3$), as shown in Figure 5 for the same condition. The WVC returns to increase in the third specimen and above the first specimen (0.141 cm$^3$), as shown in Figure 6. The average increase in the WVC is about 0.094 cm$^3$, with a standard deviation of 0.043. The time required to reach the initial matric suction is generally short and within almost 5 minutes.

3.2. Intermediate matric suction

After reaching the stress level of 221 kPa in the first specimen, a decrease in the matric suction (or increase in $u_w$ with constant $u_a$) is performed to achieve the intermediate matric suction of 20 kPa under the specified stress level, as shown in Figure 7. The curve is starting with the final data of the previous stage (WVC and time period). There are two trends in the results' behavior: first, relatively, a quick change in the water volume up to 2.254 cm$^3$, and second, slow change up to 3.131 cm$^3$ and this may be attributed to the soil heterogeneity (distribution of the voids). This heterogeneity of the soil is a result of the soil component, sand particles distribution, and gypsum content.

The WVC was observed to be increased (3.357 cm$^3$) with increasing the net normal stress up to 442 kPa as shown in Figure 8, and this may be related to the redistribution of the soil particles and/or increasing of dissolving of gypsum materials. This increase in gypsum dissolution depended on the wetting progress under high stress level and time period. In the same trend, the WVC was 3.951 cm$^3$ under stress level of 885 kPa, as shown in Figure 9. This result may be attributed to the interaction of gypsum dissolution and high stress level (under 885 kPa). There is an obvious increase in the time period to achieve the specific matric suction (20 kPa) under the different investigated stress levels for the first, second and third specimens.
Figure 4. The water volume changes for the first specimen.

Figure 5. The water volume changes for the second specimen.

Figure 6. The water volume changes for the third specimen.
Figure 7. The WVC for matric suction of 20 kPa and under a stress level of 221 kPa.

Figure 8. The WVC for matric suction of 20 kPa and under a stress level of 442 kPa.

Figure 9. The WVC for matric suction of 20 kPa and under a stress level of 885 kPa.
3.3. Zero matric suction (saturation)

In saturated condition (zero matric suction), the WVCs were increased to fill all voids of the soil specimens under different stress levels. Figure 10 shows the WVC to achieve saturation under a stress level of 221 kPa, and the WVC is 10.919 cm$^3$. The WVC sustained less period compared to the previous stage (matric suction of 20 kPa). Similarly, Figures 11 and 12 show the WVC under net normal stresses of 442 kPa and 885 kPa. The WVC under a stress of 442 kPa is decreased to 9.548 cm$^3$ while the WVC under the stress of 885 kPa is the lowest (9.152 cm$^3$). This stage of matric suction is quicker than the previous stage (Sm=20 kPa), and this may be due to the contribution of the gypsum dissolution and connecting the voids in the soil specimen.

Figure 10. The WVC for zero matric suction (saturation) under a stress level of 221 kPa.

Figure 11. The WVC for zero matric suction (saturation) under a stress level of 442 kPa.

Figure 12. The WVC for zero matric suction (saturation) under a stress level of 885 kPa.
3.4. Effect of matric suction and loading
To investigate the soil water retention under loading, the WVCs are transformed into a term of volumetric water content ($\theta$). The volumetric water content is equal to the ratio of WVC to total volume. Figure 11 shows the change of volumetric water content ($\theta$) under different stress levels and matric suctions. The investigated values are compared with the values from SWCC in the literature, which is predicted for the same soil (hatched line). For the initial matric suction 50 kPa, a little change is experienced due to the different loading levels with a linear trend. For matric suction ($S_m$) of 20 kPa, an increase in the value of up to 0.0847, 0.0913, and 0.1092 under the stress of 221, 442, and 885 kPa, respectively. Generally, the values $\theta$ are diverged from the selected SWCC, as shown in Figure 13 (the dashed line), and this is due to the change in the voids depending on the gypsum dissolution and normal stress levels. When the matric suction is decreased to zero (saturation), the $\theta$ values are changed from 0.2955 to 0.2541 under stresses of 221 kPa and 885 kPa, respectively. When the water enters the soil, the bonding material suffers from dissolution and is replaced by water to fill the voids. All values of $\theta$ are below the estimated value from selected SWCC ($\theta = 0.305$) due to the effect of increasing stress levels. Table 3 illustrates the changes in the volumetric water content ($\theta$) with respect to the change of stress level and matric suction.

![Figure 13. Comparison between predicted and experimented void ratio concerning volumetric water content.](image)

| Loading | Matric suction = 50 kPa | Matric suction = 20 kPa | Matric suction = 0 kPa |
|---------|------------------------|------------------------|------------------------|
| 221     | 7.4                    | 52                     | 249                    |
| 442     | 7                      | 64                     | 185                    |
| 885     | 13.4                   | 85                     | 133                    |

4. Conclusions
- The required time to achieve intermediate matric suction (20 kPa) increases as the normal stress level increase (9-11 hrs.).
- The time periods to achieve saturation (zero matric suction) increased as the normal stress level increased (2-9 hours).
- Higher normal stress shows a higher water volume change period due to the restriction of the net normal stress.
- There is a little water volume change (WVC) in the initial matric suction stage, and this may be due to water evaporation during the process of specimen preparation or/and maybe contributed by the fitting inaccuracy of the used SWCC.
- At matric suction of 20 kPa, a redistribution of the soil particles, due to net normal stress and/or gypsum dissolution, due to wetting lead to an increase in WVC.
- With the demolition of the voids under high-stress levels, there is a decrease in WVC at zero matric suction (saturation).

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