Collapsibility of gypseous soil under suction control

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Abstract Many geotechnical problems and foundation failures in engineering structures were recorded due to the presence of unsaturated gypseous soils. One of the main reasons, which introduced large volume change and collapse behaviour is the variation of suction pressure and water potential within the gypseous soil mass. In this study, Sandy gypseous soil from Al-Ramadi city (west of Iraq) with gypsum content of more than 70 % is used. In order to investigate the collapse deformation of gypseous soil under suction control by multi-steps wetting procedure, also the effect of sensors positions and applied vertical stress, a special soil-model device is designed and manufactured. In this device, high accurate and sensitive Tensiometers and Time Domain Reflectometry (TDR) sensors with an assistance of high quality Data logger are used for measuring and monitoring of matric suction and gravimetric water content of the soil sample during the deformation processes. The test results indicated that a large volume change and collapse deformation occurred upon reduction of matric suction. The void ratio dramatically reduced stepwise with reducing of matric suction by multi-steps wetting irrespective the value of applied vertical stress.

Keywords
Gypseous soil, Unsaturated soil, Matric suction, Collapse, Tensiometer

1. Introduction
1.1 Unsaturated soil and concept of suction
It is very important to know the behaviour of the soils located above groundwater level and the extent of its effect on the geotechnical properties of unsaturated zone. Since most of the design equations in soil foundation and geotechnical engineering assumed firstly that the soil is fully saturated and this issue may not be accurate. Therefore, it is the time to consider the effect of capillary forces and suction pressure for the soil located above the level of groundwater and especially near it. At this zone, the soil is at unsaturated condition and not completely dry. An unsaturated soil has commonly been referred to that soil has a three phase’s system. Recently, the realization of the important role of the air-water interface (i.e. the contractile skin) has warranted its inclusion as an additional phase when considering the physical mechanisms of unsaturated soil. When the air phase is continuous, the contractile skin interacts with the soil particles and provides an influence on the mechanical behaviour of the soil. The mass and volume of each phase can be schematically represented by a phase diagram shown in figure 1 (a), which represents a rigorous four-phase diagram for unsaturated soil. The thickness of the contractile skin is in the order of only a few molecular layers. Therefore, the physical subdivision of the contractile skin is unnecessary when establishing volume-mass relations for unsaturated soil. The contractile skin is considered as part of the water phase without significant error. A simplified three-phase diagram, depicted in figure 1 (b) can be used in writing the volume mass relationships (Fredlund and Rahardjo, 1993). The behaviour of unsaturated soils is decisively conditioned by the soil suction (ψ), which is a general term that can be used when referring to matric suction, osmotic suction or total suction (Aitchison, 1964; Fredlund and Rahardjo, 1993).
Figure 1. Phase diagrams for an unsaturated soil: (a) Rigorous four phase unsaturated soil system; (b) simplified three-phase diagram (Fredlund and Rahardjo, 1993).

Soil suction can be defined as the free energy state of soil water. Suction is a major factor affecting the behaviour of unsaturated soils. Total suction has two components, namely matric suction, and osmotic suction. This can be expressed as:

$$\psi = (u_a - u_w) + \varphi_s$$  \hspace{1cm} (1)

Where: $\psi$ = total suction, $(u_a - u_w)$= matric suction and $\varphi_s$ = osmotic suction. In geotechnical engineering applications, the osmotic suction is usually ignored. Matric suction is defined as the difference between pore air pressure ($u_a$) and pore water pressure ($u_w$).

In soil mechanics, pore air pressure can be considered equal to atmospheric pressure and therefore, it can be ignored ($u_a=0$). Determination of matric suction and its distribution in unsaturated zone represents a major and necessary step for further geotechnical applications regarding specific unsaturated soil behaviour. Furthermore, Matric suction is necessary for determination of shear strength, permeability and effective stress state in unsaturated soil condition (Agus, 2005; Fredlund and Rahardjo, 1993; Fredlund et al., 2012).

1.2 Collapsible soils in unsaturated soil framework

Collapsibility of the soil could be investigated through direct response to wetting/loading tests using laboratory and field methods. The volume change and the degree of wetting that will take place are considered as major challenges facing collapsible soils (Jefferson & Rogers, 2012).

Under normal circumstances, naturally occurring of collapsible soils are not wetted to significant depth by precipitation. Rainfall (particularly in arid regions) either runs off or only infiltrates the water to a short distance and then evaporates from the surface. Problems of collapsible soils are almost associated with man-induced changes in the surface water and groundwater regime. This is often coupled with a failure to identify the collapse condition before construction and/or to a lack in knowledge of potential wetting sources. Collapse, triggered by increased water content or decreased of suction can typically be linked to engineering modifications and alteration of natural flow patterns. In some cases, the overburden stresses alone are sufficient to drive the collapse process when wetting occurs. When cementation is very strong or the collapsible soils are very shallow, additional stress due to a structure or foundation may be necessary for collapse to happen (Ng, 2007).
Al-Obaidi (2014) concluded that the final volume change of gypseous soil resulted from single or multi-step wetting is denoted as collapse deformation, which is a function of net vertical stress, initial void ratio, initial degree of saturation and range of applied suction. Moreover, three main distinct phases for collapse mechanism over suction range are observed, namely: pre-collapse phase, main collapse phase, and post-collapse phase.

The main objectives of this study are to demonstrate the geotechnical behaviour of unsaturated gypseous soil under suction control and monitoring the variation of matric suction for different collapse zone under different vertical stresses.

2. Basic characteristics of the investigated soil
The disturbed soil samples were brought from a site of high gypsum content located in a semiarid to arid region nearby Al-Anbar University within Al-Ramadi city in western Iraq. The soil can be described as dense to very dense reddish brown fine to medium SAND with high amount of gypsum content in the form of white salts and crystalline particles. The main physical and chemical properties of the investigated soil are shown in tables 1:

| Property                              | Value          |
|---------------------------------------|----------------|
| Natural water content [%]             | 1              |
| Atterberg's limits [%]                | No plasticity |
| Specific gravity:                     |                |
| by Water [-]                          | 2.37           |
| by Kerosene [-]                       | 2.35           |
| In place dry density [g/cm³]          | 1.3            |
| Relative density [%]                  | 82             |
| Natural void ratio [-]                | 0.81           |
| Standard compaction test:             |                |
| Maximum dry density [g/cm³]           | 1.57           |
| Optimum moisture content [%]          | 15.5           |
| Particle size analysis:-              |                |
| Cu [-]                                | 4.5            |
| Cc [-]                                | 1.4            |
| Passing sieve (0.075mm),              | 4.7,17.6, 3.3  |
| by (dry, water, kerosene) [%]         |                |
| Soil classification                   | SP             |
| TSS [%]                               | 11.5           |
| SO₃ (acid) [%]                        | 34.5           |
| Gypsum content [%],(Al-Mufty and Nashat 2000) | 70 |

3. Soil-Model Device
In order to investigate the volume change, matric suction, and critical collapse zone; special soil-model device was designed and manufactured as shown in figures 2 and 3. The soil-model device has the following technical details: rigid steel material of 1.5 cm (thickness), inner dimensions are 30.2 cm (length), 30.2 cm (width), 31.0 cm (sample height) and 2.0 cm (thickness of rigid plate cover). The soil-
model device is provided with graded gravel filter layer of 0.5-1.0 cm (particle diameter range) and 2.0 cm (filter height). The filter layer includes two opposite valves used as a water inlet and flashing of air bubbles. In addition, many valves have been provided in the horizontal and vertical directions of the model in order to mobilize the sensors to the desired level of soil.

The first sensor is highly sensitive Tensiometer sensor type (EQ3 equitensiometer) to measure the matric suction of the soil as shown in figure 4a, and second sensor is Time Domain Reflectometry sensor (TDR) type (ML3 Theta Probe) to measure the volumetric water content of the soil as shown in figure 4b. These two sensors are connected to the data logger type (GP1 Data Logger) as shown in figure 4c.

The applied axial loading was controlled by using an automatically rigid loading frame with a loading capacity of 200 kN. The soil settlement was monitored by using two sensitive dial gauges with an accuracy of 0.002 mm.

![Figure 2. Sketch of the Soil-Model device](image-url)
**Figure 3.** Soil-Model device with loading and measuring system (all dimensions in mm)

**Figure 4.** Sensors and Data logger used for measurement the matric suction and volumetric water content manufactured by Delta-T Devices Ltd company, UK. (a) Tensiometer type EQ3, (b) TDR type ML3 and (c) Data logger type GP1

4. Results and Discussion

In this section, the results of volume change under constant vertical stress and suction control test using the soil-model device will be presented. The properties of the soil sample in all tests were according to table 1. The effect of sensor position (i.e. measuring depth: top, mid and bottom) within the soil mass under constant vertical stress of 25 kPa are shown in figures 5 to 8, while the effect of applied vertical stress of values 12.5, 25 and 50 kPa at mid position of the sensors are shown in figures 9 to 12. In general, the results of sensor position shows that there is a dramatical reduction in matric suction that has occurs with the increase in gravimetric water content of the soil mass as shown in figure 5. This behaviour can be attributed to the action of water potential, which destroys the capillary forces between the soil particles at unsaturated state. Moreover, it can be clearly observed that the soil can be achieved at the same suction level by different water content based on the sensor position. This behaviour can be
related to that of the capillary forces at the bottom level near the water reservoir (i.e. filter layer) that are weaker and lower resistance than those at the top position.

![Figure 5. Variation of suction with gravimetric water content, (Sensor position effect)](image1)

![Figure 6. Variation of suction with the volume change, (Sensor position effect)](image2)

![Figure 7. Variation of suction with void ratio, (Sensor position effect)](image3)

![Figure 8. Variation of suction with collapse percentage, (Sensor position effect)](image4)

Therefore, the lower zone of the gypseous soil, which is already in contact with the water reservoir is consider as a critical collapse zone due to high action of the water potential and vanishing of suction pressure.

Figures 6 to 8 shows that there is a considerable volume change as a collapse deformation are a notice during multi-steps wetting processes. In gypseous soils, the most common reason for collapse deformation is almost related to the destruction of cementing bonds between the soil particles as a result of gypsum dissolution by the soaking and/or leaching processes (Nashat 1990, Al-Mufy 1997, Al-Obaidi et al., 2012 and others). The accumulative collapse percentage increase with a large reduction in void ratio upon multi-step wetting, especially at a low range of soil suction as shown in figures 7 and 8. These results confirm the results obtained by Fredlund and Gan 1995 and Al-Obaidi 2014.

The results of the effect of applied vertical stress on the behaviour of gypseous soil under suction control are shown in figures 9 to 12. According to the results of the test, it can be noticed that there is no effect of the applied vertical stress on the general trend of the matric suction and water potential. The gravimetric water content (figure 9) and volume change (figures 10 to 12) showed a significant reduction in their values simultaneously with the reduction in suction values toward the saturated soil state. Figure 9 shows that under the same suction, the gravimetric water content will increase with the increase of vertical stress value. In other words, at the same water content value, at the higher applied vertical stress the higher suction will be achieved. Furthermore, the collapse potential will be increased with the
decrease in matric suction toward the saturation state of the soil mass. Also, at the same suction value, with higher applied vertical stress the higher collapse percentage will be obtained (Figure 12). These results can be attributed to the increase in the applied vertical stress, which leads to damage more cementing bonds and reduce more voids between the soil particles and keeps and/or generates more capillary forces resulting in increase in the matric suction (Figures 10 and 11). In other words, the suction pressure is more restricted under high applied vertical stress, especially at the top layer within the stress distribution zone.

5. Conclusions

1. The soil suction dramatically decreases from its high initial value at unsaturated state to the zero value when the water content and degree of saturation gradually increases irrespective of the measuring depth and applied vertical stress.
2. The reduction in soil suction leads to considerable deformation and collapse behaviour of gypseous soil, especially at the low range of matric suction.
3. Collapse deformation increases with the large reduction in void ratio upon multi-step wetting, especially at high applied vertical stress when water potential increases irrespective of the collapse zone depth.
4. The lower zone of the gypseous soil, which is already exposed to moisture is considered as a critical collapse zone due to high action of the water potential and vanishing of suction pressure.
5. At the same suction value, higher applied vertical stress causes higher collapse deformation of gypseous soil.
6. The suction pressure will be more restricted under high applied vertical stress, especially within the stress distribution zone.

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