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Loading unsaturated soil

*Mohamed Abdellatif Ali Albarqawy[1)]

[1)] *Faculty of Petroleum and Mining Engineering, Suez Canal University, Suez, Egypt*
[1)] *albarqawy@gmail.com*

ABSTRACT

Loading unsaturated soil is very important issue as it effects on the behavior of foundations founded above such soils. The behavior of foundation was monitored by the settlement related to the loading from the foundation. An experimental model for simulation of the behavior of unsaturated soil underneath isolated footings at different values of load was set in the laboratory. An artificial soil which is a mix from sand, silt and clay was used. Also, The moisture content had changed to affect the degree of saturation of used soil test. The soil settlement related to the loading process had accurately measured. The change of water content of soil showed considerable effect in unsaturated soil behavior.

1. INTODUCTION

The soil phases are mainly three, these are solid soil particles as a solid, liquid, usually water, and gas, usually, air. All types of soil should be formed from two or three of the soil phases, consequently, soil could be dry, saturated or unsaturated based on the phases within the soil mass. Most researchers use the term partially saturated soil which has the same meaning of the term unsaturated soil or partially saturated soil (Ali Mahmoud M. A. 2003).

Dry soil and saturated soils are two phasess, which are the soil particles and air in the case of the dry soils and soil particles and water in

[1)] Ph.D.

the case of saturated soil. However, unsaturated soils are formed of all three phases, i.e., soil particles, water, and air (Fredlund and Rahardjo, 1993).

In dry soils the voids are fully filled with air, the degree of saturation is zero. In saturated soils the voids are completely filled with water, (Sr = 100%). In unsaturated soils, the degree of saturation is between zero and 100%. Figure 1 shows the phase diagram of unsaturated soils.

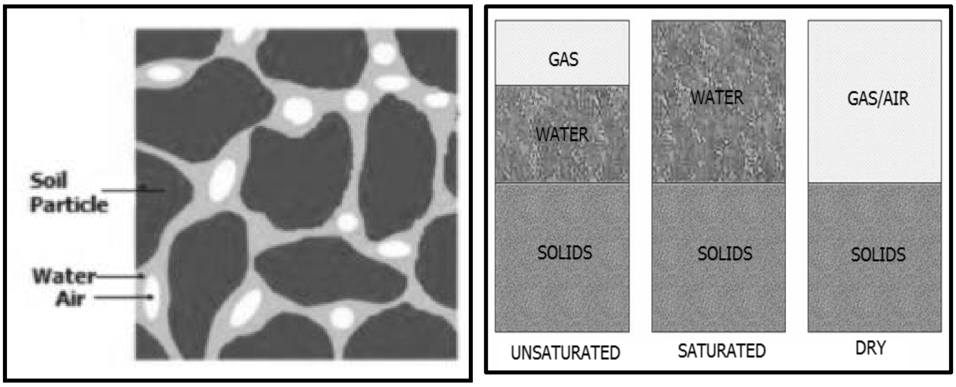

Fig 1. Phase diagram of unsaturated soil

Loading unsaturated/partially saturated soils is very important issue as it effects on the behavior of foundations founded above such soils.

In the current paper, the behavior of foundation is monitored by the settlement related to the loading acting from foundation above such soils. An experimental model for simulation of the behavior of unsaturated soil underneath isolated footing at different values of loads had set in the laboratory. An artificial soil which is a mix of sand, silt and clay had used. Also, loading frame with some particular modifications had used for loading process. The loading frame was based on California Bearing Ratio (CBR) test frame with some particular modifications to meet the requirements of loading process.

The moisture content had changed consequently the degree of saturation of used soil. The soil settlement had accurately measured

2. LITERATURE REVIEW

Traditional soil mechanics (dry and saturated soil mechanics) practice has experienced significant changes during the past few decades. Some of these changes are related to increased attention being given to the unsaturated soil zone above the ground water table (Fredlund and Rahardjo, 1993).

Soil mechanics researches have been focused on providing solutions of the geotechnical problems which are related to the behavior of saturated and dry soils. So, there is a shortage or weaknesses in understanding the behavior of unsaturated soils, (Fredlund and Rahardjo, 1993, Fredlund, 1995).

While most research has mainly focused on the matric suction, volume change, permeability, and shear strength of unsaturated soils, investigations of load – settlements relationships of unsaturated soil especially granular materials have not taken same attention except for cemented and clayey materials (Kim , T. and Hwang, C. 2003).

In unsaturated soil, the soil suction has a great effect based on high degree of saturation. In unsaturated soil, there are pore air pressure (u_a) which is resulted from the presence of air in the soil mass and pore water pressure (u_w) which is resulted from the presence of water in the soil mass. The difference between pore air pressure and pore water pressure is called the soil suction (s), (Smith and Smith, 1998).

$$s = u_a - u_w \quad \text{......} Eq.(1)$$

where:

u_a = *Pore air pressure*
u_w = *Pore water pressure*.

Fredlund & Rahardajo in their book in 1993 suggested the following equation for the effective stress of unsaturated soils

$$\sigma` = \sigma - u_a + \chi_m (s - u_a) + \chi_s (\pi - u_a) \quad \text{......} Eq.(2)$$

where:

χ_m = effective stress parameter for matrix suction
s = matrix suction
χ_s = effective stress parameter for osmotic (solute) suction
π = osmotic suction

Fredlund defined his model as in equation 3 combines the net normal stress, and suction using ` and b.

$$\tau = c^{`} + (\sigma - u_a)\tan\phi^{`} + (u_a - u_w)\tan\phi^{b} \text{..........} Eq.(3)$$

where:

$(\sigma - u_a)$ = net normal stress on the failure plane at failure
u_a = pore-air pressure on the failure plane at failure
$\phi^{`}$ = Angle of internal friction associated with the net normal stress state variable.
$(u_a - u_w)$ = matrix suction on the failure plane at failure
ϕ^{b} = angle indicating the rate of increase in shear strength relative to the matrix suction.

A quasi-theoretical soil compaction model was presented by R.A. McBride (1989) which gives good estimation of the complete density-stress compression line for soils of variable initial moisture content under static loads from 0 to 1.0 MPa. The 3 unknown parameter coefficients of the generalized model equation are shown to be highly correlated to several soil properties such as moisture content, pre-compression (initial) void ratio, texture, organic matter content and the Atterberg consistency limits. A 3-tier classification for partition consistency limits. A-tier classification for portioning soils into groupings of response to compressive stress is proposed for soil compaction modeling. This categorization was based on soil plasticity and the existence of a “compaction threshold “sensitivity threshold” in most soils.

Rampino, C. et al, 2000, reported experimental study and modeling of the mechanical response of a silty sand used in the core of the Metramo dam, Italy. Specimens were prepared by compacting the soil at optimum water content conditions using the modified Proctor technique. Tests were performed under suction-controlled conditions by a stress path in triaxial cell and an oedometer. The findings indicate the strong influence of suction on compressibility, stiffness, and shear strength. The mechanical properties of the soil improve with suction following an exponential law with decreasing gradient. Furthermore, the soil exhibited collapsible behavior upon wetting even at low stress levels. Interesting results were also achieved in elasto-plastic modeling as well. The results led to characterization of soil behavior with reference to widely accepted modeling criteria for unsaturated soils, providing noteworthy suggestions about their applicability for granular materials with a non-negligible fine component.

Richard, et al (2001) mentioned that tillage and traffic modify soil porosity and pore size distribution, leading to changes in the unsaturated hydraulic properties of the tilled layer. These changes are still difficult to characterize. The have investigated the effect of compaction on the change in the soil porosity and its consequences for water retention and hydraulic conductivity. A freshly tilled layer and a soil layer compacted by wheel tracks were created in a silty soil to obtain contrasting bulk densities (1.17 and 1.63 g/Cm^3, respectively). Soil porosity was analyzed by mercury porosimetry, and scanning electron microscopy was used to distinguish between the textural pore space and the structural pore space. The laboratory method of Wind (direct evaporation) was used to measure the hydraulic properties in the tensiometric range.
They also stated that: for water potentials < -20 kPa, the compacted layer retained more water than did the un-compacted layer, but the relation between the hydraulic conductivity and the water ratio (the volume of water per unit volume of solid phase) was not affected by the change in bulk density. Compaction did not affect the textural porosity (i.e. matrix porosity), but it created relict structural pores accessible only through the micropores of the matrix. These relict structural pores could be the reason for the change in the hydraulic properties due to

compaction. They can be used as an indicator of the consequences of compaction on unsaturated hydraulic properties. The modification of the pore geometry during compaction results not only from a decrease in the volume of structural pores but also from a change in the relation between the textural pores and the remaining structural pores.

3. EXPERIMENTAL WORK

To study the relationships of water content/degree of saturation, loading and settlement, an experimental model had set in the laboratory. The model is mainly steel mold filled with compacted soil specimens at different moisture content. Then, concrete cube had been used to represent the isolated footing. A frame was used for loading process and dial gauges with accuracy of 10 m (0.01 mm) were used for measuring of the related settlement. Figure 2 shows schematic diagram for the used experimental model.

3.1 The experimental model

The experimental model is based on the California Bearing Ratio (CBR) apparatus with some modifications to suit the required experimental work for current paper as follow:

- The experimental model is mainly based on CBR apparatus frame for loading and measuring of displacement.
- A thick wooden plate had been fixed with the load ram to be used in bearing the loading weight to act vertically on the footing, consequently on unsaturated soils.
- A steel mold had been used to be filled with compacted unsaturated soil specimens at specific moisture content.

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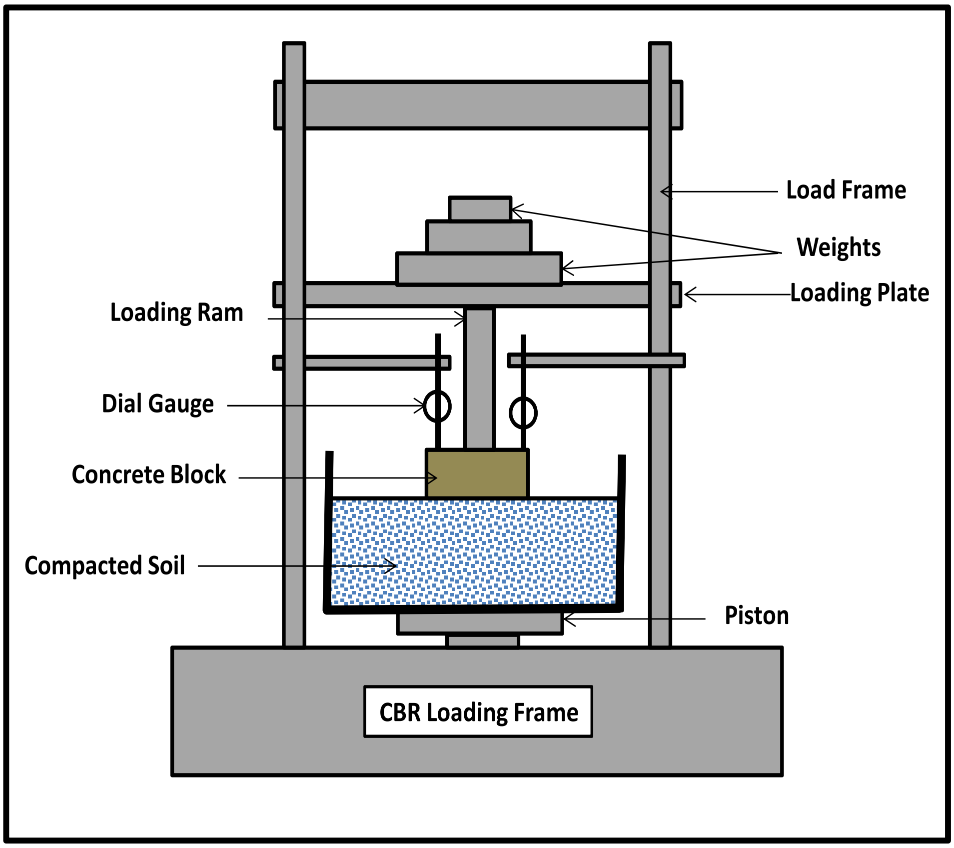

Fig. 2 The experimental model used for testing

- Two dial gauges with accuracy of 0.01 mm (10 m) and capacity of 25 mm had been used for measuring the vertical displacement or settlement.
- Concrete block had been used to simulate the isolated footing as a foundation on an unsaturated soil.
- During all stages of testing the CBR apparatus was switched off as the loading is static and no noise was around the experimental model.

3.2 Technical considerations for the experimental model

All technical consideration for accurate and reliable measurements had been considered as follow:

- Both dial gauges had been calibrated prior to measuring of displacement.
- The weight has been calibrated to accuracy of ± 0.1% from the original weight of each single piece.
- Lubricating silicon grease had been used to reduce the friction between the wooden bearing plate and the rods of CBR loading frame.
- Paraffin wax had been used over the compacted soil to keep same moisture content during all time of each single test.
- To make sure the rig is working properly; several runs of testing had been carried out under same conditions to check the liability and repeatability of test results and the rig gave mostly same results.

After considering the previous technical notations, the experimental model was working efficiently for testing program.

3.3 Testing Program

The aim of testing program is to study the behavior of isolated footing, particularly, settlement under different loads and different soil moisture content. Sand (siliceous Sand) soil specimen with traces of silt and clay had been used as a soil test media. The sieve analysis and compaction test results of the test soil are shown in figure 3 and figure 4 respectively. Also, the specific gravity had been measured. All Tests had carried out according Egyptian Code of Practice of Soil Mechanics and Foundation Design (ECP 202 – 2001) Also, according American Society of Testing and Materials (ASTM). Some test soil parameters are shown in table 1.
After carrying out the compaction test, the relationship between dry density and soil moisture content had been plotted. Different 10 values of moisture content had selected for loading the soil test at these values. These values cover the range of moisture content before and after the maximum dry density and optimum moisture content.

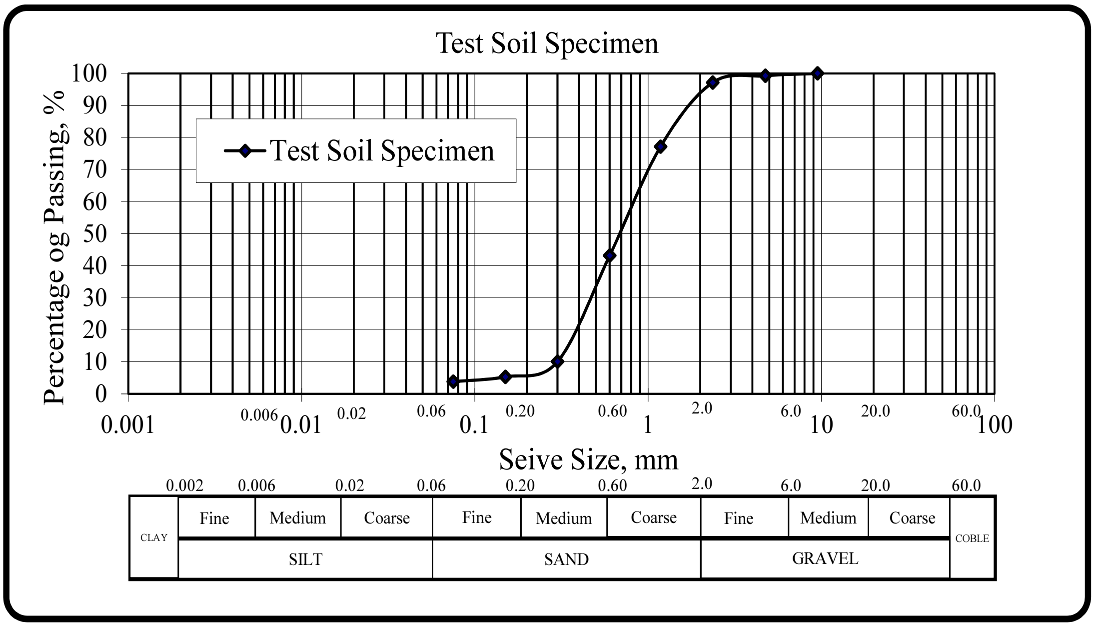

Fig. 3 Mechanical/Sieve analysis for test specimen

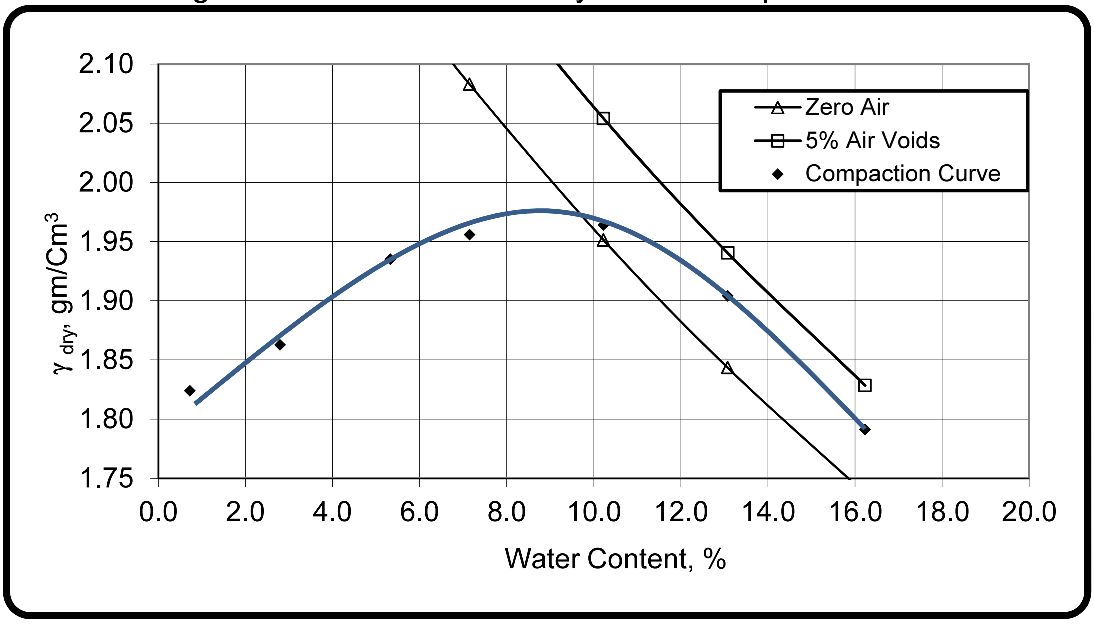

Fig. 4 Compaction/Proctor test of soil test specimen

Table 1 Some properties of soil test material

Specific Gravity	Compaction Test: Maximum Dry Density, gm/Cm^3	Compaction Test: Optimum Moisture Content, %	Percentage of fine materials %	Consistency Limits: LL, %	Consistency Limits: PL, %	Free Swelling, %
2.56	1.97	10.00	3.81	0.00	0.00	0.00

Table 2 presents for tests at different values of moisture content. The moisture content values range from 0.60% as a minimum value and 16.13% as a maximum based on the compaction test results mentioned previously.

Table 2 The value of moisture content at each single test

Test No	1	2	3	4	5	6	7	8	9	10
W_c, %	0.60	1.04	2.88	3.69	4.95	5.93	7.38	10.33	14.15	16.13
Stage	1st Stage							2nd Stage	3rd Stage	

3.3.1 Testing at values less than optimum moisture content

Seven tests had carried at moisture content values below the optimum moisture content. The relationships between the stress values and settlement are shown in figure 5 for values from 0.64% to 3.69% and figure 6 for values from 4.95% to 7.38%.

3.3.2 Testing at values of optimum moisture content

Fig. 7 shows the eighth (8th) test for relationship at value of moisture content (nearly the optimum values that give the maximum dry density) of the soil test. The moisture content for that test is mostly the optimum value.

3.3.3 Testing at values more than optimum moisture content

The relationships between the stress values and settlement are shown in figure 8 for values of moisture content of 14.15 % and 16.13%. The values are above optimum moisture content level.

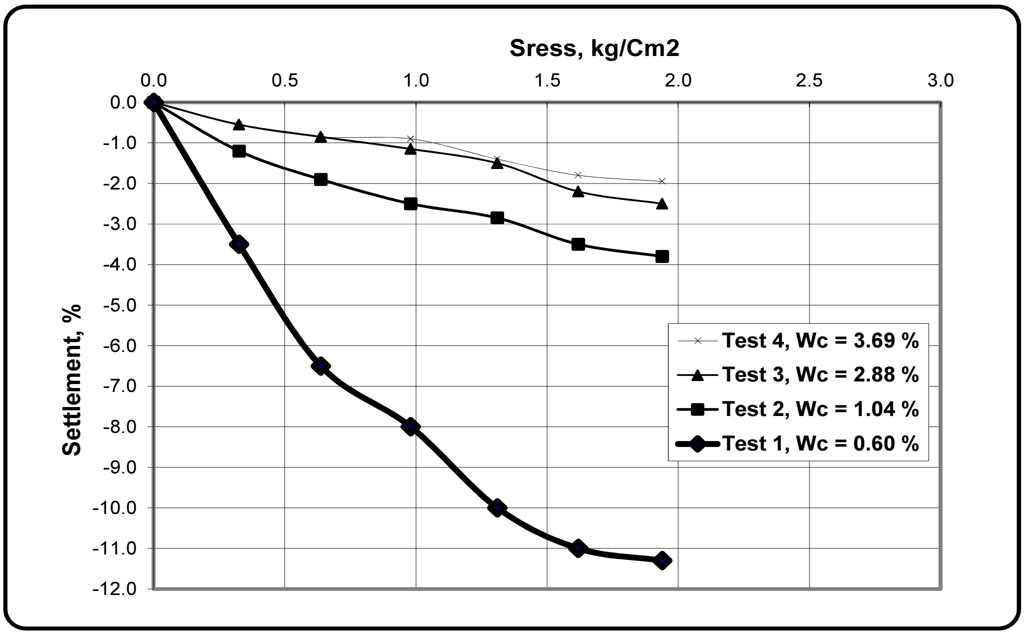

Fig. 5 Load-Settlement relationships for Wc 0.6 to 3.69%

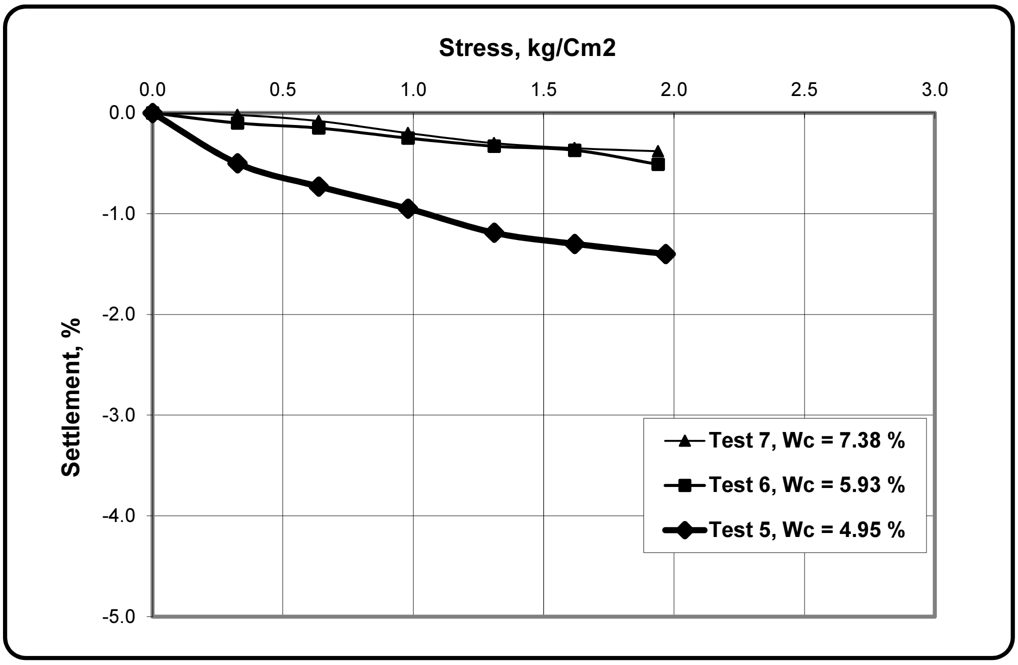

Fig. 6 Load-Settlement relationships for Wc 4.95 to 7.38

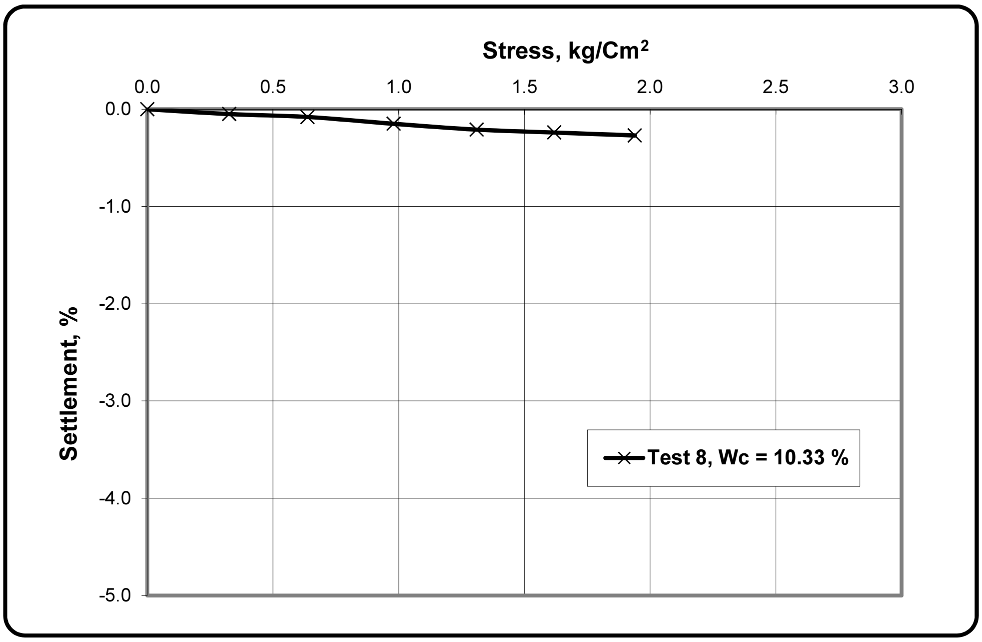

Fig. 7 Load-Settlement relationships for Wc 10.33 (~optimum)

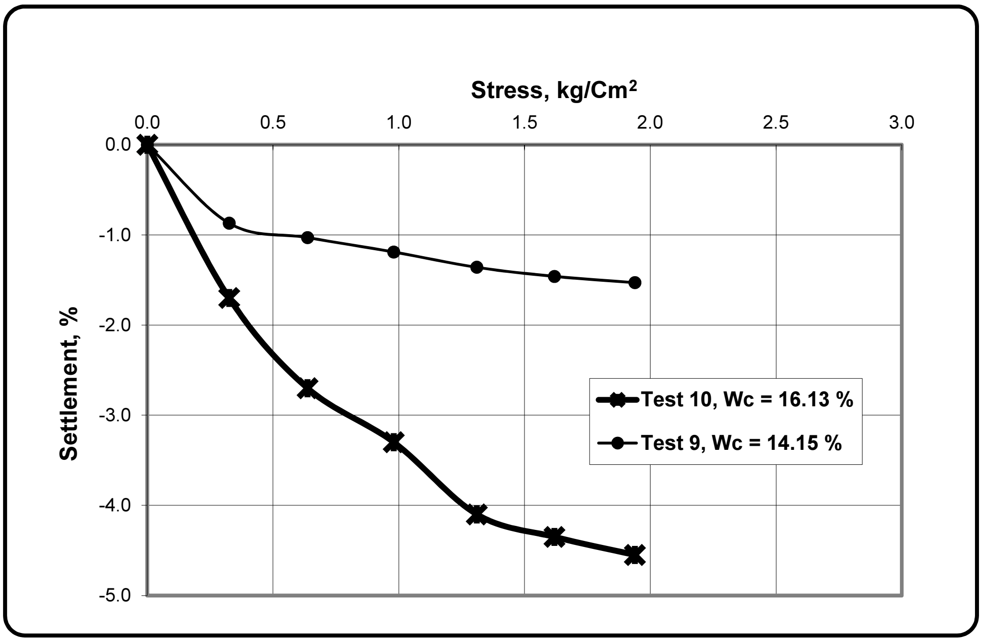

Fig. 8 Load-Settlement relationships for Wc 14.15 and 16.13%

3.4 RESULTS AND DISCUSSIONS

As mentioned in previous sections, the soil mass phases are mainly three, these are solid soil particles as a solid, liquid, usually water, and gas, usually, air. As the soil mass in the current paper is not saturated as in most cases of soil media. The test soil in our case is partially saturated soil or unsaturated soil. When loading unsaturated soils, the soil passes throw three main stages, as follow:

First; unsaturated soil has low moisture content or low degree of saturation, that means that the presence of water phase is discontinuous, consequently the soil suction has no great effect in the soil bearing capacity.

Second; unsaturated soil has moisture content around the optimum value or high degree of saturation, that means that the present of water phase is continuous, consequently the soil suction has great effect in the soil bearing capacity, the higher soil suction the higher value of bearing capacity.

Third; soil has moisture content above the optimum value or high degree of saturation (nearly saturated) and that case is well studied in saturated soil mechanics and out of the scope of current paper. Herein is the discussion in some details.

4.1 Soil has low moisture content

Referring to figure 5 and figure 6 that illustrate the first stage of soil behavior at low moisture content or low degree of saturation. The soil introduces high value of settlement. The soil suction at this stage has no much effect as the water within the soil mass is discontinuous and the air within the voids is highly compressible, consequently, the soil mass has the chance to be compressed.

4.2 Soil has optimum moisture content

Referring to figure 7 which illustrates the second stage of soil behavior at higher moisture content or high degree of saturation. The soil introduces lower value of settlement. The soil suction at this stage has much effect as the water within the soil mass is in continuous and the percentage of air within the voids is very small, consequently, the soil settlement is very small at different values of stresses.

4.3 Soil has high moisture content

Referring to figure 8 which illustrates the third stage of soil behavior at higher moisture content or nearly saturated soil as in test 9 and test 10. The soil introduces value of settlement. The soil is this stage is nearly saturated as the voids is filled with water. The water expels out of soil masses causes much amount of settlement at the same values of stress. Figure 9 shows the assembly of three stages in one figure to show how is the degree of saturation effects on settlement values.

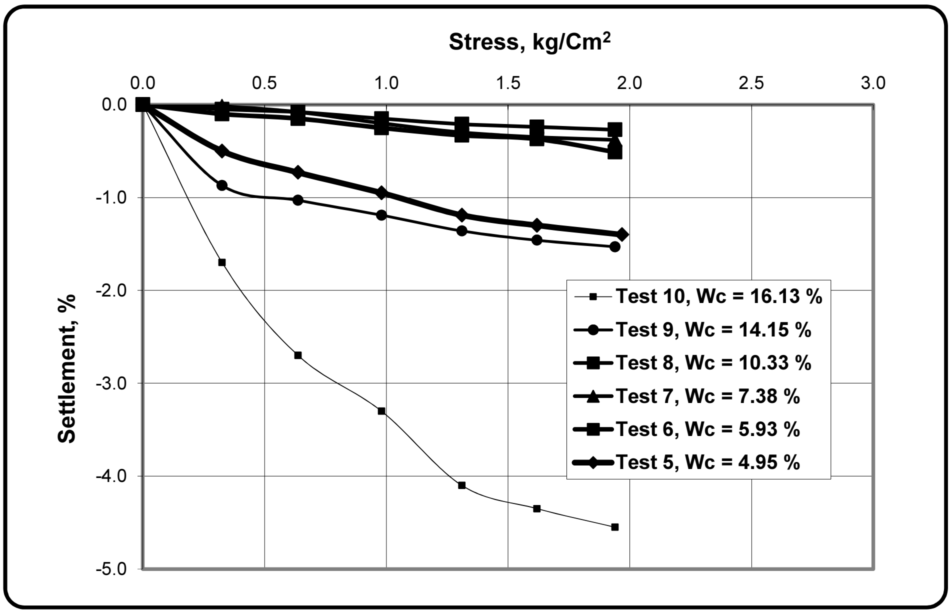

Fig. 9 Load-Settlement relationships for W_c 14.15 and 16.13%

4.4 Stress and moisture content

Fig. 10 represents for the relation between the soil moisture content or degree of saturation with the settlement at two different stress values which are 0.98 kg/Cm^2 (~1.0 kg/Cm^2) 1.94 kg/Cm^2 (~1.0 kg/Cm^2). It can be noticed that:

At values of low moisture content (low degree of saturation) and high values of moisture content (nearly saturated), the settlement resulted from loading is high, but at values of high degree of saturation around the optimum moisture content, the settlement resulted from stresses is very low.

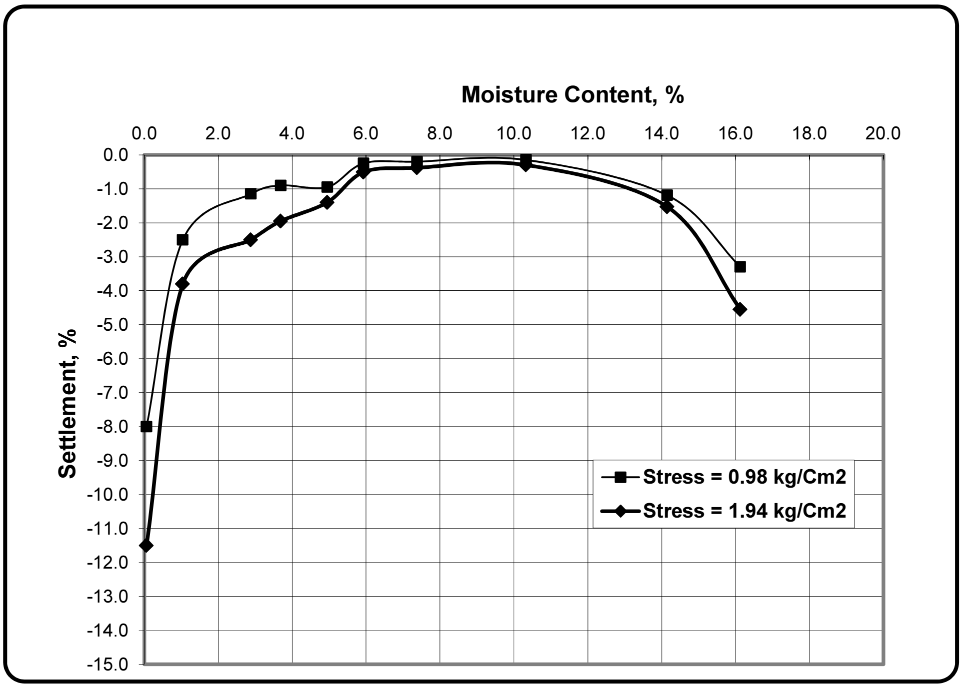

Fig. 10 Water content-settlement relationship at specific applied stress

CONCLUSIONS

Unsaturated soils in the most category of soil types and need much studying of its behavior under loading conditions. From the study in the current paper we conclude that:

1. The moisture content/degree of saturation has much effect of the behavior of soil under loading conditions.
2. The best performance of soils under loading conditions is resulted when the moisture content value is around the optimum moisture content values resulted from compaction.
3. Soil suction increase the soil bearing capacity at the values of degree

of saturation at optimum moisture content as in that stage the water within the soil mass is continuous phase.

4. At low moisture content or low degree of saturation, the water within the soil mass is discontinuous phase and occurs like water balls, and the air content is high, consequently introduces low bearing capacity and higher value of settlement.
5. At high moisture content or high degree of saturation (the stage above the optimum value, the soil mass is saturated and loading causes water to flow out of the soils and cause higher settlement.

It is recommended that the principle of dry and saturated soils to be revised from the point of view of unsaturated soil behavior as it forms the most soil category around the world.

In Egypt, particularly, the compaction process is need to be investigated according the principles of unsaturated soil as the degree of compaction or relative compaction to be at lower percentage. It is suggested to consider the value is between 90 and 95% particularly for silty sand.

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