Measuring pile shaft and tip capacities of a single pile embedded in saturated and unsaturated expansive clayey soil

Shaimaa Hasan Fadhil¹, Raid R. Al-Omari² and Mohammed Y. Fattah³

¹ Civil Engineering Department, Faculty of Engineering, Al-Mustansiriya University, Baghdad, Iraq.
² Civil Engineering Department, College of Engineering, Al-Nahrain University, Baghdad, Iraq.
³ Civil Engineering Department, University of Technology, Baghdad, Iraq.

E- mail: shaimaaahasan@gmail.com

Abstract This research presents a series of compression load tests conducted on a single pile embedded in saturated and unsaturated expansive clayey soil. Soil water characteristics curve (SWCC) and initial soil suction (total and matric) are measured using the filter paper technique to study the influence of soil suction on the pile and tip capacities. Soil pressure gauge is used and embedded in the soil under the pile at a distance of 2D. The results showed that the ultimate pile capacity is increased when the initial degree of saturation decreases. In addition, the tip capacity is increased when the degree of saturation decreases. Then, the sharing ratios of the ultimate tip and shaft capacities to the ultimate pile capacity are calculated. The results have shown that the sharing ratio of the ultimate tip capacity to the ultimate pile capacity of a single pile is increased with the decrease in the degree of saturation while the ratio of the shaft capacity to the ultimate pile capacity is decreased.

1. Introduction
Expansive soils are highly plastic materials that contain a large amount of clays and very sensitive to the changes in the water content. The study of this type of soil can be enclosed within the concept of the unsaturated soils, whose mechanical behavior is mainly governed by the phenomenon of suction. The term “soil suction” was introduced by Schofield (1935) to explain the negative pore pressure that is subjected to some soils where these soils have the capacity to absorb the water if they come into the contact with water at atmospheric pressure. In some cases, this inflow of water may lead the soil to collapse (irrecoverable volumetric reduction), whereas in others, it may lead the soil to swell (increase in volume) [1].

Deep foundations are one of the solutions for swelling clay problems, which includes methods of making the structure behavior independent of the expansive layers. The typical features of these solutions are those of a ‘palaphite’, which is a structure resting on piles extending down into the soil until they reach deep and stable layers. A gap is provided between the structure and the swelling surface of the soil. Usually the piles are bored and cast in place, as the consistency of these clays leads to driving difficulties [2].

Construction on expansive soils can generally be resolved using piles. However, shallow foundations can be used in these materials, the swelling pressure should be determined where the
foundations are designed to provide a greater pressure to counteract the swelling effect. Clearly, it will also be necessary to determine the capacity of the ground to sustain this load [1].

In the fine grained soil, the initial water content has a considerable influence on the soil structure. Thus, the change in the soil strength with the soil initial water content is due to the difference in the internal structures of the soil caused by the difference in water content for the same texture, plasticity, mineralogy and method of preparation [3].

Al-Omari et al (2017) studied the pull out test conducted on a single pile embedded in expansive soil compacted individually at different initial degrees of saturation. It was observed that the ultimate shaft capacity (skin resistance) increased non-linearly with the decrease in the initial degree of saturation and the increase in the initial matric suction. This is due to the increase in the shear resistance as the matric suction increases. The ultimate skin resistance increased about 49% when the initial degree of saturation decreases from 90 to 70%. It was also noticed that the adhesion factor obtained from the experimental work increases as both unconsolidated, undrained cohesion and the initial matric suction were decreased. The adhesion factor reached a value of 1.3 when the undrained cohesion, initial degree of saturation and initial matric suction were 36, 100% and 10 kPa, respectively [4].

Fattah et al (2018) studied the sharing ratio of the ultimate shaft resistance to ultimate pile capacity when as both compression and pull out tests were conducted on a single pile embedded in expansive soil compacted individually at different initial degrees of saturation. It was found that the sharing ratio decreased with the decrease of the initial degree of saturation [5].

2. Experimental work and materials

2.1 The soil
Several trials have been carried out to determine suitable portions of a mix containing both bentonite and sand. A prepared mixture of 70% bentonite and 30% sand was employed in this research. This mixture provides more workability and less expansion compared to pure bentonite. Hence, saving more time for being in fully saturated and partially saturated states. Bentonite Ca-based and silica sand were brought by the State Company for Geological Survey from a site in the west part of Iraq. Standard tests were performed to determine the physical and chemical properties of the mixed soil; details are given in table 1 and figure 1.

2.2 Piles used in tests
All piles used in the model tests are made of Aluminum hollow bar with square cross sectional area brought from local markets. The Aluminum bar has a thickness of 2 mm and an external side cross sectional width of 20 mm. The length to diameter ratio (L/D) is 10. Tension test was performed on the Aluminum bar to determine its strength and elastic modulus. From the stress-elongation data shown in figure 2, the elastic modulus, (slope of the initial straight part of stress-strain curve) is found to be of 69.1 GPa and all other test data are listed in table 2. Piles used in all tests are closed at the tip using an Aluminum plate with appropriate dimensions. The embedded length of the piles is 200 mm and a distance of 20mm above soil surface is left free, then the pile cap with the specified dimensions is attached as shown in figure 3.

3. Model Design, Equipment and Manufacturing
To study the behavior of expansive soil and its effect on piles; an experimental setup was designed and manufactured to achieve this goal. The setup consists of:
1. Steel container, 2. Modeled pile, 3. Strain control loading machine, 4. Load cell with load indicator, 5. Soil pressure transducer, 6. Hand held data logger, 7. Dial gauges.

Table 1. Physical properties of the mixed soil.

| Property                        | Value  | Standard                   |
|---------------------------------|--------|----------------------------|
| Activity                        | 1.4    |                            |
| Sand content % (0.075 to 4.75 mm) | 30     | ASTM D422 [6]              |
| Silt content % (0.005 to 0.075 mm) | 18.4   | ASTM D422 [6]              |
| Clay content % (< 0.005 mm)     | 51.6   | ASTM D422 [6]              |
| Liquid limit                    | 110    | (BS 1377) [7]              |
| Plastic limit                   | 40     | ASTM D4318 [8]             |
| Plasticity index                | 70     |                            |
| Classification (USCS)           | CH     |                            |
| Specific gravity                | 2.805  | ASTM D854 [9]              |
| $\gamma_d$ max kN/m$^3$          | 13.6   | ASTM D1557 [10]            |
| Optimum moisture content OMC %  | 28.3   | ASTM D1557 [10]            |

Figure 1. Grain size distribution of the used mixture.

Figure 2. The stress-elongation relationship of the tested pile.
Table 2. Mechanical properties of the tested pile.

| Mechanical properties       | Unit  | Data   |
|----------------------------|-------|--------|
| Elastic modulus            | GPa   | 69.1   |
| Maximum elastic stress     | MPa   | 81.73  |
| Stress at failure          | MPa   | 339.03 |
| Maximum test elongation    | %     | 4.21   |

Figure 3. Pile and cup dimensions.

3.1 Soil containers
The soil container is manufactured with appropriate dimensions to satisfy the test purposes. The dimensions of the containers have been chosen to ensure that the stress bulb is not in contact with the sides of the container. The failure stress is considered to extend about 2-4D under the pile tip for a single pile as stated by Bowles (1996) (where D is the width of the pile cross section) [11]. The spread out load distribution from the sides of the single pile is taken as 2:1 at a depth of L/3 from the tip of the pile, [11]. The container is made of steel plates with a thickness of 4 mm and has dimensions of (220x220x350) mm.

3.2 Loading frame and axial loading system
The axial loading system used in this experimental work is a compression machine with strain controlled system to control the rate of loading on the single pile in order to study the load – settlement behavior as shown in plate 1. The applied pressure is measured by a load cell of 50 kN capacity connected to a digital load indicator. Both load cell and load readout were calibrated at the Central Organization for Standardization and Quality Control.

3.3 Soil pressure gauge
Soil pressure gauge provides a direct means of measuring total pressure in the soil. Plate 1 shows the soil pressure gauge model KDE-PA manufactured by Tokyo Sokki Kenkyujo Co., Ltd., TML Company in Japan, which was imported especially for this study. The KDE-PA soil pressure gauge has 50 mm outside diameter. It is small in size and has a dual diaphragm structure, thus; it is widely used to conduct model experiments. With the KDE-PA, the Input/Output cable is connected from the
side of the cell body. The KDE-PA soil pressure gauge is made of stainless steel with excellent corrosion resistance. Minute displacement of pressure-sensitive area is due to double diaphragm structure.

3.4 Data logger and switching box

TC-32K is a compact and handheld digital data logger. The splash-waterproof construction enables outdoor use. The sensor connection of the terminal board is a patented one-touch type to facilitate connection with lead wires and banana plug and speed up the preparation for measurement. Sensor mode, coefficient and initial values can be set and the use of the exclusive switching box CSW-5B-05 makes 5-channel automatic measurement possible. TC-32K has an interval timer, data memory, compact flash memory card slot and interfaces for computer control and data transfer. CSW-5B-05 is a switching box for enlargement of measurement points combined with hand-held data logger, TC-32K. It can measure strain gauge, DC voltage and thermocouple up to 5 points. Sensor mode is set by TC-32K. Plate 2 shows the hand held data logger TC-32K and switching box CSW-5B-05 manufactured by Tokyo Sokki Kenkyujo Co., Ltd., TML Company in Japan, which was imported especially for this study.

Plate 1. Soil pressure cell model KDE-PA.
Plate 2. Hand held data logger model TC-32K and switching box model CSW-5B-05 connected to it.

4. Preparation of Model Tests

4.1 Control test

Before the preparation stage for the soil bed, many trial tests were performed to control the efficiency of the preparation method. Control tests were carried out to check the main points regarding the preparation of the homogeneous bed of soil and determine the variation of shear strength, dry unit weight, swelling percent and swelling pressure with different initial water contents. Several trials were made where the soil was placed in ten layers inside CBR moulds. Each layer was pressed by a hydraulic jack. Then, the samples were covered with polythene sheet and left for 24 hours. The undrained cohesion was measured by a portable vane shear device. Five samples were taken from each mould to obtain the dry unit weight and the initial degree of saturation $S_r$, then measuring the swelling percent and swelling pressure for each sample using the oedometer device. Typical results are presented in figures 4, 5 and 6. Three soil samples were selected with different initial degrees of saturation viz. 70, 87 and 91% to carry out the one dimensional consolidation test, since the two others were so hard with low degree of saturation that required a lot of effort and time to be tested in the oedometer. This test was performed using the oedometer device up to the end of the swelling pressure test. The test was carried out according to the ASTM D 2435–96 [12]. The swelling pressure of each
sample is given in table 3. It is obvious that the soil with \( S_r \) of 70% and dry unit weight of 12.75 kN/m\(^3\) has the highest expansion while the soil with \( S_r \) of 87% and dry unit weight of 13.22 kN/m\(^3\) has the intermediate expansion and the soil with \( S_r \) of 91% and dry unit weight of 12.26 kN/m\(^3\) has the lowest expansion. The expansion change or swelling potential is a function of both initial water content and initial dry unit weight. A soil sample that has \( S_r \) of 70%, \( c_u \) of 99.5 kPa, \( \gamma_d \) of 12.75 kN/m\(^3\), the swelling percent of 66.5% and swelling pressure of 240 kPa is chosen for the preparation of bed of soil, since it is considered as very high swelling soil according to the criterion proposed by Chen (1975) [13] and Al-Rawas and Goosen (2006) [14].

4.2 The bed of soil
All the tests were carried out at a dry unit weight of 12.75 kN/m\(^3\). Different initial degrees of saturation viz., 100, 90, 80 and 70% were selected to study the load-settlement behavior of a single pile. The soil was mixed with enough quantity of water to get the desired consistency and degree of saturation. The mixing operation was conducted by hand using a sprinkle jar in a large pan.

After a thorough mixing, the wet soil was kept inside two tightened polythene bags for a period of not less than fourteen days to get uniform water content distribution. After that, the water content was checked again, then the soil was placed in the desired steel container in layers, each layer was compressed by the hydraulic jack. A thick plate of 20 mm with appropriate dimension according to soil container was used to distribute the load exerted from the hydraulic jack. This process continued for the layers till reaching the desired thickness of the soil in the steel container. The number of layers for a single pile was 10 layers each of 30 mm thickness. After completing the final layer, the top surface was covered with polythene sheet to prevent any loss of water content and the whole box was kept inside a large polythene bag.

4.3 Installation of piles
After carrying out the preparation of the soil bed, the installation of piles in the model soil, which was layered in the box was performed by making a borehole with a diameter and length less than that of pile. A borehole with a diameter of 15 mm and a length of 170 mm was drilled using a hand auger manufactured for this purpose. To maintain the verticality of the hole, a special cover with a vertical neck was welded vertically at the central top part of the cover to make the auger penetrate the bed of soil vertically as shown in Plate 3. After that, the pile is inserted in the hole using a hydraulic jack.

![Figure 4. Variation of the undrained shear strength with water content.](image)

![Figure 5. Dry unit weight - water content relationship from static compaction test by pressing through a hydraulic jack.](image)
Figure 6. Swelling - time relationship for samples prepared at different initial degrees of saturation.

Table 3. Swelling pressure for different samples prepared at different initial degrees of saturation.

| Sr (%) | 70  | 87  | 91  |
|--------|-----|-----|-----|
| Swelling pressure kPa | 240 | 210 | 200 |

Figure 7. Relationship between the water content and soil suction.

5. Soil suction measurement
Soil suction (total and matric) is measured using the filter paper method according to ASTM D5298-03 specification as an indirect method to measure the soil suction and draw the full SWCC curve (drying and wetting curves) [15] as shown in figures 7, 8 and 9. All soil specimens were prepared at the selected initial dry unit weight of 12.75 kN/m³ and initial degree of saturation of 70%. Initial values of suction at different initial water contents, initial degrees of saturation and initial void ratios
are also investigated and shown in figures 10 and 11. Moreover, the general shape of the obtained SWCC does not strictly follow the S-shape, this commonly appears in bentonite soil type. This behavior is also observed by Agus (2005) [16], Arifin (2008) [17] and Al-Badran (2011) [18]. The presence of montmorillonite in the B-S mixture gives the ability to retain larger quantity of water where the soil suction increases with the increase in the soil plasticity due to the surface electrical charges.

Figure 8. Relationship between the water content and soil suction (total and matric).

Figure 9. Relationship between the void ratio and soil suction (total and matric).
Figure 10. Relationship between the degree of saturation and soil suction (total and matric), SWCC curve.

Figure 11. Relationship between the initial water content and the initial suction (total and matric) measured by the filter paper technique.

Figure 12. Relationship between the initial degree of saturation and the initial suction (total and matric) measured by the filter paper technique.

Figure 13. Relationship between the initial void ratio and the initial matric suction measured by the filter paper technique.
6. Shear Strength Measurements

Series of unconsolidated undrained shear tests were carried out on B-S mixture samples having different initial degrees of saturation viz., 100, 90, 80 and 70%. The soil samples were extracted from the beds of soil compacted individually at the same dry unit weight of 12.75 kN/m$^3$ but at different initial water contents viz., 41.4, 37.2, 33.1 and 29.0%, respectively to give the specified degree of saturation. Values of cohesion and angle of internal friction are shown in table 4. It is obvious from these results that the value of the undrained cohesion $c_u$ increases with the decrease in the initial degree of saturation due to contribution of matric suction while the undrained angle of internal friction is not affected.

Table 4. Values of the undrained cohesion $c_u$ and the angle of internal friction $\phi_u$ for samples prepared at different initial degrees of saturation obtained from unconsolidated undrained triaxial test.

| Initial degree of saturation, S_r, % | Undrained cohesion, $c_u$, kPa | Undrained angle of internal friction, $\phi_u$, ° |
|-----------------------------------|--------------------------------|---------------------------------|
| 100                               | 36                             | 5.1                             |
| 90                                | 66                             | 5.4                             |
| 80                                | 85                             | 5.2                             |
| 70                                | 149                            | 5.5                             |

7. Load – settlement tests

Four compression load tests are carried out on a single pile embedded in soil compacted individually at the same dry unit weight of 12.75 kN/m$^3$ but at different initial degrees of saturation viz., 100, 90, 80, and 70% and hence, different initial matric suctions. The soil was placed in the specified container in layers in a manner as mentioned in section 4.2. Soil pressure gauge is embedded in soil at a distance of 2D under the pile tip (where D is the width of the pile cross section). Figure 13 and plate 4 show the set up used in the load – settlement tests. The rate of loading through the compression machine is set to 1 mm/min. Figure 14 shows the load settlement relationship obtained from these tests.

It is clearly shown that the general shear failure has taken place and the point of failure is easily diagnosed from the plot of load vs. settlement. The ultimate pile capacity, $P_u$, is defined as the maximum load on the load – settlement curve, which corresponds to an obvious settlement. The ultimate pile capacity obtained from each test with the corresponding initial degree of saturation and initial matric suction is shown in figures 15 and 16, respectively. It is clear from these two figures that there is a nonlinear increase in the ultimate pile capacity with the decrease in the initial degree of saturation; and increase in the initial matric suction. This is caused by increasing both the shear strength of soil and pile tip capacity (increasing the undrained cohesion) due to the contribution of matric suction with the decrease in the initial degree of saturation as discussed previously. The ultimate pile capacity increases by about 50% when the degree of saturation of the soil is decreased from 90 to 70%.
Figure 14. Set up for the load–displacement test with details.

Plate 4. Placing the soil container in the compression machine to start the loading test.

Figure 15. Load-settlement behavior of a single pile embedded in soil compacted individually at different initial degrees of saturation.
Soil pressure under the pile tip

Soil pressure is measured at a distance of 2D (40 mm) under the pile tip during the compression load test conducted on a single pile using soil pressure gauge embedded in the soil bed at the specified depth. Figure 17 shows the generated soil pressure under the pile tip due to the load applied on the pile head. It is obvious that the soil pressure under the pile tip increases as the degree of saturation decreases. This is due to the increase in the pile tip capacity caused by the increase in the undrained cohesion owing to the contribution of matric suction. The soil pressure at 2D under pile tip increases by about 550% when the degree of saturation of the soil decreases from 90 to 70%.

The measured soil pressure at a distance of 2D under the pile tip can be transferred to be the load directly at the pile tip using the 2:1 load distribution method as shown in figure 18. It is shown that the pile tip capacity increases as the degree of saturation decreases; this is due to the increase in the shear strength as the degree of saturation decreases and this is due to the increase in matric suction. The tip capacity increases by about 550% when the degree of saturation of the soil decreases from 90 to 70%.

The average skin resistance is then obtained by subtracting the tip resistance from the applied load as shown in figure 19. It is obvious that the average skin resistance increases as the degree of saturation decreases due to the increase in cohesion due to the contribution of matric suction. Al-Omari et al (2017) reported that the ultimate shaft capacity (skin resistance) increases as the initial degree of saturation decreases and the initial matric suction increases. This is due to the increase of shear resistance as the matric suction increases [4].

Figures 20 to 23 show the tip and skin resistance against the applied load for each different degree of saturation. The sharing ratios of the ultimate tip capacity to the ultimate pile capacity for different degrees of saturation are tabulated in table 5. The sharing ratio of the ultimate tip capacity increases non linearly as the degree of saturation decreases and matric suction increases as shown in figures 24 and 25. The sharing ratio is increased by about 500% when the degree of saturation decreases from 100 to 70%. Fattah et al (2018) observed that the sharing ratio of the ultimate shaft capacity decreases as the degree of saturation decreases and matric suction increases [5].
Figure 18. Soil pressure measured at a distance of 2D under the pile tip at different initial degrees of saturation.

Figure 19. Pile tip capacity measured at different initial degrees of saturation.

Figure 20. Average skin resistance measured at different initial degrees of saturation.

Figure 21. Tip and shaft capacities measured at initial degree of saturation of 70%.

Figure 22. Tip and shaft capacities measured at initial degree of saturation of 80%.

Figure 23. Tip and shaft capacities measured at initial degree of saturation of 90%.
Figure 24. Tip and shaft capacities measured at initial degree of saturation of 100%.

Table 5. Ultimate pile tip sharing capacity ratios of a single pile embedded in soil compacted individually at different initial degrees of saturation

| Degree of Saturation, $S_r$%, | Ultimate pile capacity, kN | Ultimate pile tip capacity, kN | Sharing ratio, S.R% |
|-------------------------------|-----------------------------|-------------------------------|--------------------|
| 100                           | 0.82                        | 0.02                          | 2.44               |
| 90                            | 0.93                        | 0.03                          | 3.23               |
| 80                            | 1.10                        | 0.15                          | 13.64              |
| 70                            | 1.50                        | 0.22                          | 14.67              |

Figure 25. Variation of the ultimate pile tip capacity sharing ratio with the initial degree of saturation.

Figure 26. Variation of the ultimate pile tip capacity sharing ratio with the initial matric suction.
9. Conclusions
Based on the experimental works conducted in this study, the following conclusions can be drawn -

a) There is a nonlinear increase in the ultimate capacity of a single pile with the decrease in the initial degree of saturation and increase in the initial matric suction. The ultimate capacity of a single pile increases by about 50% when the degree of saturation is decreases from 90 to 70%.

b) The ultimate tip capacity of a single pile during the load-settlement tests at different initial degrees of saturation increases by about 550% when the degree of saturation decreases from 90 to 70%.

c) The sharing ratio of the ultimate tip capacity to the ultimate pile capacity of a single pile increases when the degree of saturation decreases and matric suction increases.

d) The sharing ratio increases by about 500% when the degree of saturation decreases from 100 to 70%.

References
[1] Yenes M, Nespereira J, Blanco J A, Suárez M, Monterrubio S and Iglesias C 2012 “Shallow Foundations on Expansive Soils: A Case Study of the El Viso Geotechnical Unit, Salamanca, Spain”, Bulletin of Engineering Geology and the Environment, Vol. 71, No.1, pp 51-59, Springer-Verlag.

[2] Ng C W W and Menzies B 2007 Advanced Unsaturated Soil Mechanics and Engineering. Taylor and Francis, New York, USA

[3] Vanapalli S K, Fredlund D G and Pufahl D E 1999 “The Relationship between the Soil Water Characteristic Curve and the As-Compacted Water Content Versus Soil Suction for a Clay Till. Proceedings of the 11th Pan American Conference on Soil Mechanics and Geotechnical Engineering, pp 991-998

[4] Al-Omari R, Fattah M and Fadhil Sh 2017 Adhesion Factor of Piles Embedded in Unsaturated Swelling Soil. Proceedings of the 19th International Conference on Soil Mechanics and Geotechnical Engineering, Seoul 2017

[5] Fattah M Y, Al-Omari R R and Fadhil Sh. H 2018 Load sharing and behavior of single pile embedded in unsaturated swelling soil European Journal of Environmental and Civil engineering, Taylor and Francis Group

[6] ASTM D422-02: “Standard Test Method for Particle-Size Analysis of Soils”, Soil and Rock (I), Vol. 04.08.

[7] British Standard B.S.:1377 part 2 1990 Methods of Test for Soils for Civil Engineering Purposes General Requirements and Sample Preparation. British Standard Institution, London

[8] ASTM D4318-03: Standard Test Method for Liquid Limit, Plastic Limit, and Plasticity Index of Soils. Soil and Rock (I), Vol. 04.08.
[9] ASTM D854-03: Standard Test Method for Specific Gravity of Soil Solids by Water Pycnometer. *Soil and Rock* (I), Vol. 04.08.

[10] ASTM D1557-03: Standard Test Method for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft³ (2,700 kN·m/m³)). *Soil and Rock* (I), Vol. 04.08

[11] Bowles J E 1996 “Foundation Analysis and Design”, 5th Edition, McGraw-Hill Book Companies, Inc. New York

[12] ASTM D2435-96: “Standard Test Method for One-Dimensional Consolidation Properties of Soils”, Reprinted from the Annual Book of ASTM Standards. Copyright ASTM, Vol.4, No.8

[13] Chen F H 1975 Foundations on Expansive Soils Elsevier Scientific Publishing Company, Amsterdam

[14] Al-Rawas A A and Goosen M F A 2006 Expansive Soils: Recent Advances in Characterization and Treatment. Taylor & Francis Group, London, UK

[15] ASTM D5298-03: Standard Test Method for Measurements of Soil Potential (Suction) by Filter Paper Reprinted from the Annual Book of ASTM Standards. Copyright ASTM, Vol.4, No.8.

[16] Agus S S 2005 An Experimental Study on Hydro-Mechanical Characteristics of Compacted Bentonite-Sand Mixtures. PhD Thesis, Faculty of Civil Eng., Bauhaus-Universität Weimar, Germany

[17] Arifin Y F 2008 Thermo-Hydro-Mechanical Behavior of Compacted Bentonite-Sand Mixtures: An Experimental Study PhD Thesis, Faculty of Civil Eng., Bauhaus-Universität Weimar, Germany

[18] Al-Badran Y M H 2011 Volumetric Yielding Behavior of Unsaturated Fine-Grained Soils Ph.D. Thesis, Faculty of Civil and Environmental Engineering, University of Bochum, Germany