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Compression Behavior of Unsaturated Clay under High Stresses

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ABSTRACT: This paper focuses on preliminary characterization of the compression behavior of unsaturated compacted clay under high stresses (up to 55 MPa) and different drainage conditions. The motivation for this work is to provide calibration data to define parameters needed to simulate the reaction of compacted soil to a buried explosive. The impact of suction on the shape of the compression curve (i.e., the preconsolidation stress and the slope of the virgin compression curve) was investigated through a series of small-diameter drained oedometer tests. Suction values at the beginning of oedometer testing ranged from 39 kPa to 164 MPa, and were applied using the vapor equilibrium technique. Application of suction caused a reduction in the initial void ratio from 0.51 to 0.37, and suction was observed to affect the apparent preconsolidation stress (suction-induced hardening). The impact of drainage conditions on the compression behavior of the same unsaturated soil under stresses up to 55 MPa was also investigated using a high-pressure true triaxial device. As expected, the compacted clay was much stiffer during undrained loading, although deformations were noted due to compression of the air-filled voids until reaching pressure saturation.

INTRODUCTION

Detonation of shallow-buried explosives can produce high blast pressures on overlying vehicles or pedestrians. The magnitude of the upward blast pressure is sensitive to the reaction provided by the underlying soil, which depends on the depth of burial, the soil type, density, degree of saturation, etc. (Akers 2001). In the case of buried explosives encountered in the field, the near surface soil is typically partially saturated and is often compacted. Ground loading imposed by the overburden pressure can be anticipated in an element of soil at some distance from the blast, as shown in FIG. 1(a). The compression of unsaturated soils can occur due to rearrangement of the soil skeleton, compression of the pore fluids, or compression and crushing of the particles themselves (Akers 2001; Wang & Lu 2003). The initial deformation of an unsaturated soil is complex, as rearrangement of the soil skeleton will be resisted by capillary forces (matric suction). The mechanisms of compression will change at different stage during a loading process, which can be expressed schematically as shown in FIG. 1(b). The deformation characteristics of unsaturated soils depend on the drainage conditions, which are typically considered sensitive to the rate of loading. For example, fast loading is typically considered to lead to undrained conditions, as time is not available for water to drain from the soil pores. Most predictions of blast loading use the drained compression

curve in their analyses, primarily because dry soil conditions are typically considered (Moral et al. 2010). Blast loading leads to complex fluid flow processes as well, so it is important to characterize both undrained and drained conditions for comparisons in numerical simulations.

FIG. 1. (a) Buried explosion in unsaturated soil; (b) Compression behavior of unsaturated soils during isotropic loading under different drainage conditions

There are several important transition points on the compression curves for unsaturated soils noted in the schematic in FIG. 1(b). The initial void ratio of the specimen may depend on the magnitude of suction in the soil, as application of high suctions may cause contraction of the soil structure (Matyas & Radakrishna 1968; Wheeler & Sivakumar 1992). Initial compression of an unsaturated soil in undrained conditions will occur due to compression of the air-filled voids until reaching the point of pressure saturation where the air dissolves into the pore water. Beyond this point, deformation of the undrained soil may only occur due to elastic compression of the water and soil skeleton. Initial compression of an unsaturated soil in drained conditions near the ground surface will typically follow an unloading-reloading curve with slope κ until reaching the mean apparent preconsolidation stress p_c that depends on suction. For example, Maatouk et al. (1995) performed isotropic and anisotropic compression tests on a collapsible unsaturated silty soil under various suctions and found that the apparent preconsolidation stress increases with suction. This is a common feature in most elasto-plastic constitutive models for unsaturated soils (Alonso et al. 1990; Wheeler et al. 2003). Although Maatouk et al. (1995) found that the slope of the normal compression line (λ_s) depends on suction, Uchaipichat (2010) performed a series of suction-controlled shear tests on both dried and wetted specimens using a modified triaxial device and found that the slope of the normal compression lines the recompression lines were independent of matric suction. Nonetheless, compression of an unsaturated soil to higher stresses will eventually lead to a single normal compression line at the point of pressure saturation. If water is still permitted to drain from the soil, the particles will begin to crush and rearrange until reaching the point of void closure.

The long-term goal of this study is to characterize the compression behavior of unsaturated soils having different initial suction values over a wide range of isotropic stresses in order to identify the transition points and slopes of the different portions of the curves shown in FIG. 1(b). This paper includes the results from different components of a preliminary characterization of the properties of a low plasticity clay

being investigated in blast loading experiments. First, the volume change behavior of unsaturated soils under various suction magnitudes is characterized in an oedometer up to axial stresses of 3.5 MPa to evaluate the role of suction in the initial void ratio, the slope of the recompression line, the apparent preconsolidation stress, and the slope of the normal compression line. Second, a high-pressure true triaxial device is used to characterize the undrained compression of an unsaturated specimen of the soil up to a pressure of 55 MPa. Finally, the results from a drained compression test on a specimen with suction control in the true triaxial cell are presented, but only to a pressure of 0.2 MPa. Modifications underway for the high-pressure true triaxial cell to measure/apply suctions and measure deformations during high stresses are described.

TEST MATERIAL

A low plasticity clay obtained from Boulder, Colorado was selected a test material for this study, and is referred to as Boulder clay. The clay was air-dried, crushed, and processed after collection to remove all particles greater than the #10 sieve. The liquid and plasticity index of Boulder clay are 43 and 22, and the percentage of fines is 76, so Boulder clay is classified as low plasticity clay (CL) according to the Unified Soil Classification System (USCS). The specific gravity G_s was measured to be 2.70. Results from a standard Proctor compaction test indicate that the optimal water content is 17.5% and the maximum dry unit weight is 17.1 kN/m^3 [FIG. 2(a)]. The axis translation technique and the vapor equilibrium technique were used to define points on the soil water retention curve (SWRC) for Boulder clay, which is shown in FIG. 2(b). The van Genuchten Model (1980) was fitted to the points, and the air entry value for this soil was estimated to be 111 kPa.

FIG. 2. (a) Standard Proctor compaction curve for Boulder clay (b) SWRC for Boulder clay

TEST PROCEDURES

Compacted specimens of Boulder clay were prepared for the oedometer test using static compaction in a mechanical press to an initial void ratio of approximately 0.51 and a degree of saturation of 88%. Soil was first mixed with water to reach the target

gravimetric water content. The specimens were compacted in three lifts into the oedometer ring having an inside diameter of 38 mm and a height of 30 mm. The vapor equilibrium technique (VET) was then used to change the initial suction of the different specimens. This technique involves the use of saturated salt solutions to control the relative humidity of the air within a closed chamber (Delage et al. 2008; Alsherif & McCartney 2012). Saturated salt solutions were prepared in desiccators by dissolving the salt in distilled water until precipitated salt remained visible [FIG. 3(a)]. The specimens were suspended above the different types of salt solution to allow a water exchange between the liquid and vapor phases in the headroom of desiccators. The desiccator was placed in a chamber in order to maintain a constant temperature. The relative humidity was measured every hour using a combined sensor-data logger from Lascar Electronics that can measure relative humidity values ranging from 0 to 100% with an accuracy of $\pm 3\%$. The range in gravimetric water content of the soil specimen with increasing soil suction was estimated by weighing the specimen every three days until it reached a constant mass. The step for measuring water content was performed with short enough so that water evaporation during the weighing process was negligible. The 5 different suction values, which are corresponding to the 5 different relative humidity values, were estimated using Kelvin's equation (Fredlund & Rahardjo 1993), given as follows:

$$\psi' = \frac{\rho_w RT}{M_w} \ln \left(\frac{R_h}{100} \right) \quad (1)$$

where ψ is the total suction in kPa, ρ_w is the density of water (kg/m^3), R is the universal (molar) gas constant, T is the absolute temperature in Kelvin, M_w is the molecular mass of water vapor equal to 18.02 g/mol, and R_h is the relative humidity in percent. Similar relative humidities for each salt solution were obtained with previously published values [FIG. 3(b)].

FIG. 3. (a) Apparatus for VET in desiccator chamber; (b) Relative humidity values corresponding to different saturated salt solutions at T=22°C

After the mass and dimensions of the specimens reached a constant value within the desiccator cabinet, small-diameter oedometer tests were performed on the unsaturated

specimens to characterize the volume change behavior under various high suction magnitudes and axial stresses up to 3.5 MPa. During oedometer testing, the specimen is loaded under drained conditions from both ends, being sandwiched between two porous stones. The radial strains are assumed to be zero throughout the test due to the relatively large oedometer wall thickness of 19 mm. A pneumatic loading piston was used to apply axial stresses in stages of 51, 102, 205, 410, 512, 1024, 2048, and 3584 kPa to the specimen. At each loading stage, time was permitted for the specimen to reach 90% consolidation using a root-time consolidation plot, or until settlement stopped. After this point, the final height of the specimen was recorded and the gravimetric water content was measured using oven-drying. This is a preliminary testing program as the suction was not controlled within the oedometer setup itself. However, the degree of saturation is relatively low after suction equilibration (less than 0.5), so it is expected that the amount of outflow will be negligible.

In addition to the drained oedometer tests, undrained and drained isotropic compression tests were performed on initially unsaturated, compacted Boulder clay with the true-triaxial cell developed by Sture (1973). The original cell only permits undrained loading as it was designed for evaluation of rocks and concrete under stresses up to 200 MPa. This study presents results from undrained tests up to a pressure of 55 MPa, drained tests performed under low stresses, as well as details of the modification to evaluate drained compression behavior of unsaturated soils with suction/saturation control up to high stresses. A test with both suction control and application of high stresses has not yet been performed, but these systems have been evaluated separately. Specifically, an isotropic compression tests was performed on a compacted specimen without drainage of air or water in order to characterize the undrained compression response under isotropic stress of 55 MPa. A drained compression test was performed on an unsaturated specimen up to an isotropic stress of 0.2 MPa. For a true triaxial test, a cubical specimen was prepared in a mold having a side length of 101.6 mm by static compaction using a loading press in five lifts.

FIG. 4. Experimental setups: (a) Oedometer; (b) High-pressure true triaxial cell

TEST RESULTS

Oedometer Tests

The impact of suction on the apparent preconsolidation stress as well as the slope of the normal compression line was investigated using the results from the oedometer tests on compacted soils. Drained compression curves for each unsaturated specimen with neglecting pore water pressure are shown in FIG. 5(a). The apparent preconsolidation stress of the compacted clay was estimated using the method of Casagrande. Results indicate that the matric suction has a significant effect on the behavior of the specimen, especially on the initial void ratio before loading. During loading the slope of the void ratio against log of the vertical stress increased slightly as the suction increased, although the stresses applied were not significant enough to reach the normal compression portion of the curves for the higher suction tests. The apparent preconsolidation stress was observed to increase with increasing suction as expected as indicated by the dark vertical arrows in FIG. 5 (a). The variation of preconsolidation stress with different suction values is shown in FIG. 5 (b), along with the results from other studies. In the framework of elasto-plasticity, the apparent preconsolidation stress can be interpreted as a point on the yield surface. The shortcomings of this approach are that the suction is not controlled within the testing setup during compression, and the volume of water escaping from the specimen (if any) could not be tracked. Finally addition, the range of loading system for current oedometer setup is limited up to 3.5 MPa, which was insufficient to define the preconsolidation stress of specimens having an initial suction greater than 1000 kPa.

The experimental yield points measured from the isotropic compression tests and corresponding loading-collapse (LC) curves for different kind of soil types are shown in FIG. 5(b) for comparison. The yield stresses observed from Boulder clay are higher than those stresses of the other soils, with exception to the silty clay tested by Jotisankasa (2005). This is attributed to both the higher initial densities and suctions of the compacted specimen compared to the other soils.

FIG. 5. (a) Compression curves under various suction values for Boulder clay; (b) Experimental yielding stresses for low plasticity clays from the literature

True-Triaxial Tests

An undrained compression test was performed with the true triaxial setup in the original configuration developed by Sture (1973). In this device, stresses are applied to the soil specimen through pressurized bladders, and the displacement of each of the six faces of the soil specimen is measured using proximitors. Before testing of the soil specimen, it was necessary to evaluate the machine deflections by evaluating the deflection response of an aluminum block with known elastic properties. The actual deformations of the soil were defined by subtracting the machine deflections from the measured displacements during the test. During the undrained compression test, the isotropic pressure was applied up to 55 MPa for this test. The plot of pressure applied versus axial displacement for the test is shown in FIG. 6(a). This curve is nearly linear as expected, although a slight bend in the curve likely corresponds to the point at which pressure saturation occurs. For stresses above this point the slope of the curve is related to the compressibility of the water and soil skeleton.

The undrained compression curve of the compacted specimen is shown in FIG. 6(b). A comparison of the results from the oedometer and undrained true triaxial test are shown in Table 1. As expected, a much smaller change in void ratio was noted in the undrained true triaxial test compared to the drained oedometer test. This table also summarizes the slopes λ and κ of the normal compression and recompression lines from the oedometer tests and the slope κ_u from the undrained test. The slopes from the oedometer tests were calculated from the measurements in the one-dimensional e - $\ln \sigma_v'$ plane, so they were converted to slopes representative of isotropic conditions using the equations in Table 1.

FIG. 6. (a) Pressure vs. displacement curve for the specimen along with the machine deflection characteristic curve; (b) Undrained compression curve obtained from true-triaxial test

Table 1. Synthesis of compression behavior of Boulder clay

Suction, ψ (MPa)	λ ($C_s/\ln 10$)	κ ($C_s/\ln 10$)	Preconsolidation stress, p_c' (kPa)	Water content, w (%)	
				Initial	Final
0 (Sat.)	0.083	0.014	600	17.2	-

0.04 (Drained)	0.105	0.006	1400	17.1	14.4
22	0.111	0.003	1700	7.6	4.9
65	-	0.003	-	5.8	4.4
74	-	0.002	-	6.6	5.1
84	-	0.003	-	6.2	5.4
164	-	0.003	-	4.0	3.9
0.04 (Undrained)	-	0.001	-	17.9	-

HIGH PRESSURE TRUE TRIAXIAL SETUP FOR DRAINED CONDITIONS

An issue with the high-pressure true triaxial cell system developed by Sture (1973) is that it can only evaluate undrained loading. Another issue is that the proximitors used in the system cannot measure axial displacement larger than 10 mm. The true triaxial cell has been adapted to measure and control the pore air and water pressures on one face of the true triaxial cell using the approach developed by Hoyos and Macari (2000) so that drained conditions can be considered. Further, the external hydraulic pressure system has been changed from hand pumps to a stepper motor-controlled flow pump (model 65HP from Teledyne Isco) that permits both stress-controlled and strain-controlled testing schemes. The flow pump is capable of both controlling the stresses applied to the different faces of the specimen as well as tracking the deformation of the specimen through the flow of fluid into or out of the bladders.

A drawing of the modified true-triaxial device is shown in FIG. 7. The bottom face of the specimen is replaced with a rigid plate that contains porous stones to apply pore air pressure (u_a) or water pressures (u_w). The water pressures are applied through a high air-entry porous ceramic that only allows water to pass. Matric suction in the specimens can be either be measured or controlled with this approach. To measure the matric suction, the air pressure is maintained at atmospheric conditions and the pressure in the water reservoir behind the high air entry ceramic is measured in the same manner as a tensiometer. If a compacted soil is placed atop the ceramic, there will be a tendency to draw water from the stone into the specimen due to the initial suction in the specimen. The axis translation technique can be used to control the suction (Hilf 1956). In this case, positive air and water pressures can be applied independently to the base of the specimen, with a difference $u_a - u_w$ being equal to the matric suction in the specimen. Although possible, suction control using this approach is not optimal because water must flow from the bottom face of the specimen to the upper corners of the specimen through capillarity. However, it is possible to measure the suction in the specimen using the tensiometer approach, and then subsequently apply this suction using the axis translation technique, which avoids the need to wait for complicated water flow processes.

FIG. 7. Schematic of the pore-air/water pressure control/monitoring system for high pressure true triaxial cell

A preliminary drained test using the approach of measuring the suction then applying it to the specimen with the axis translation technique was performed for low mean stresses up to 0.2 MPa. The change in pore water pressure (equal to the negative of the change in suction) measured using the tensiometer approach as a function of time is shown in FIG. 8(a). An initial suction of 39 kPa was measured in the specimen. After this point, the cell pressure, air pressure, and water pressure were increased in stages to apply an initial net stress of 1 kPa, and an initial suction of 39 kPa to the bottom of the specimen. Because the same suction that was measured in the specimen was applied, no flow of water or air was expected from the specimen. Next, the specimen was loaded in drained conditions up to 0.2 MPa to define the isotropic compression curve. A comparison of the measured compression curve with the compression curve from the oedometer under same conditions is shown in FIG. 8(b). The curves from the two testing approaches correspond well.

FIG. 8. (a) Negative pore water pressure during suction measurement in the true-triaxial cell; (b) Drained compression of compacted Boulder clay

A series of suction-controlled isotropic compression tests under axial stresses up to 160 MPa are planned for both drained and undrained conditions. This stress range is suitable for evaluation of the point at which the normally consolidated lines for different suction values converge as the air voids are compressed, and potentially the point of void closure. Different drained tests are planned. First, a loading test will then be performed where the air is permitted to drain and changes in matric suction are measured using the tensiometer approach (constant water content compression test). This test will only permit characterization of the behavior of the soil up to the point of pressure saturation. Second, the initial matric suction in the compacted specimen will be measured using the tensiometer approach, after which this same matric suction will be applied using the axis translation technique. A compression test similar to that shown in FIG. 8 will be performed (constant suction test at the initial suction). Finally, a test in which matric suction will be controlled using the axis translation test will be performed in drained conditions (constant suction test at a controlled suction).

CONCLUSIONS

The compression behavior of unsaturated clay under pressures up to 55 MPa was evaluated in this paper. Although useful parameters to describe transition points on the isotropic compression curve for both drained and undrained conditions were defined using small-diameter oedometer and high-pressure true triaxial tests, additional research is necessary to fully describe the compression behavior. Details on the modification of a true triaxial cell to control or measure matric suction in the specimen, as well as a new flow pump incorporated to perform compression stresses up to isotropic stresses of 160 MPa were presented to provide a pathway forward in future research on this subject.

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