Water content controlled instead of suction controlled strength tests

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Abstract: Most soils that concern geotechnical engineering are in the state of partial water saturation. Current practice tries to predict engineering properties of cohesionless soils using data from tests on saturated specimens, regardless of the saturation in the field. Due to complexity of test setups and high technical requirements, unsaturated soil tests are not among the common equipment of soil mechanics laboratory. One of these problems is the existence of suction, which is a function of water content and affects the strength behavior of unsaturated soils. Procedures to keep the water content of the partially saturated specimens constant and homogeneous in conventional soil tests are not well-established. The exception to this is unsaturated test setups, which are costly, complicated and found only in research institutions, hence prohibiting the industry from keeping up with the developments in this field. This study explores simple modifications to conventional methodologies of triaxial and direct shear tests, with the ultimate aim of preventing temporal and spatial variability of specimen water content throughout test duration. For different modifications, specimens of each test are dissected at the end of the test, and water content profiles of the specimens are obtained.
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1. Introduction

In most geotechnical problems, engineers encounter soils in partially saturated condition. And yet, unsaturated soil mechanics is a relatively new branch that has developed significantly during the past few decades. This is due to the complexity of the unsaturated soil behavior and complication of experimental setups required to study this behavior.

Unsaturated soil tests do not see widespread use in soil mechanics laboratories due to a few difficulties. One of these difficulties is the need for measurement and/or control of suction, which is the unsaturated counterpart to pore water pressure in classical (saturated) soil mechanics. Matric suction is one of the fundamental state variables that control the shear strength behavior of unsaturated soil specimens, which in turn is dependent on the initial water content and the method of specimen preparation (Vanapalli et al., 1996).

Geotechnical engineers resort to laboratory strength tests to measure the response of saturated soils to varying stress conditions. The most common strength tests are triaxial test, which is primarily employed for testing of saturated undisturbed specimens, and direct shear test, which is more commonly used for (dry or saturated) reconstituted specimens. Strength tests are also classified according to the control of drainage and pre-shear stress: consolidated drained (CD) consolidated undrained (CU) and unconsolidated undrained (UU). For unsaturated soils, tests can be run with controlled suction (Cunningham et al., 2003; Jotisankasa et al., 2007 &Teng1 and Ou, 2011) or constant water content (Bishop et al., 1960; Bishop and Donald, 1961; Rahardjo et al., 2004). In a constant water content (CW) test, air phase is drained, and the water phase is undrained. This test simulates the field condition at lower degrees of saturation, with continuous air phase, where excess pore-air pressure can dissipate instantaneously, and excess pore-water pressure dissipates with time. However, in such tests, uniformity of water content throughout the specimen may be questionable.

This study explores simple modifications to conventional testing methodologies with the ultimate aim of preventing temporal and spatial variability of specimen water content throughout strength tests. For this purpose, two series of laboratory tests (triaxial and direct shear) were done on sandy specimens under various water content and stress conditions. The only test results discussed here are water contents at sample preparation and end of test.

2. Equipment and Material Overview

2.1 Triaxial Setup

In this study, a GEOCOMP fully automated triaxial setup is employed to carry out the triaxial tests. The triaxial system consists of a load frame, a pressure volume actuator (PVA) for controlling cell pressure, a computer for test control and data acquisition. A second PVA for pore pressure and volume control and measurement is also a part of the setup, but this component is not used in unsaturated tests. Each PVA utilizes a high speed, precision micro stepper motor to regulate pressure and volume in the cell or specimen. The built-in microprocessor controls the micro stepper motor, which drives a piston in and out of a sealed cylinder. A pressure transducer on the end of the cylinder provides the feedback for control of pressure. Movement of the motor is used to compute volume change. The PVAs are capable of maintaining the desired pressure to within ±0.35 kPa (0.05 psi) while monitoring volume changes to within ±0.001 cc or ±1 mm^3 (Geocomp, 2010).

A water trap (sealed container of air and water with two inlets); and another container with an atmospheric air-water interface are added to the setup (Figure 1) in the later stages of this work, as described in section 3.

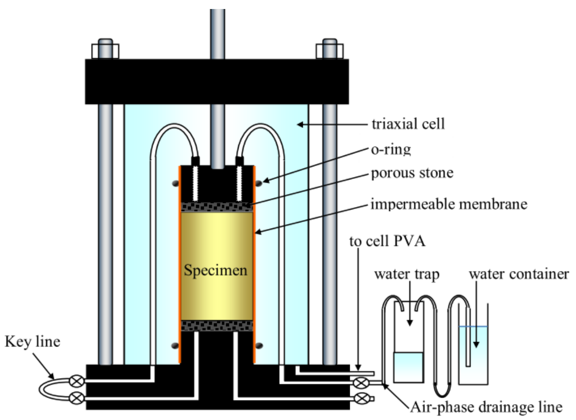


Figure 1. Schematic diagram of the triaxial cell with additions

number of individuals of most important species, Ns is the number of individuals of least important species and E is the evenness index.

2.2 Direct Shear Setup

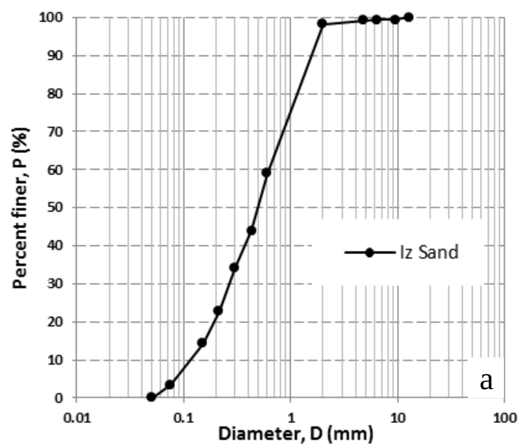
For direct shear tests (DST) a VJ automated DST machine used. This setup uses a 60 mm circular shear box. Its shearing motor rate is adjustable in 0.05mm/min increments. Added to the equipment are impermeable plexiglas discs with the same dimensions as the porous stones, and a wet towel.

2.3 Soil Properties

The soil used in this study is a sandy soil from Izmir area (shortened as Iz Sand), with no plastic fines. Table 1 and Figure 2 present its index properties, grain size distribution (GSD) and soil water characteristic curve (SWCC). The SWCC lays out three distinct drainage modes of soils: (i) saturated regime at suctions lower than the air entry value (about 7 kPa for this soil), (ii) bulk drainage or funicular regime where small variations of suction cause significant changes in water content (i.e. the steep portion of the curve between 8-22% water contents) and (iii) residual or pendular regime where all water is trapped around the particle-particle contacts.

Table 1. Material properties

Index properties	Gs	2.68
	USCS	SM
GSD indexes	D10 (mm)	0.11
	D30 (mm)	0.26
	D50 (mm)	0.49
	D60 (mm)	0.6
Atterberg limits	LL %	N.P.
	PL %	N.P.
	PI %	N.P.



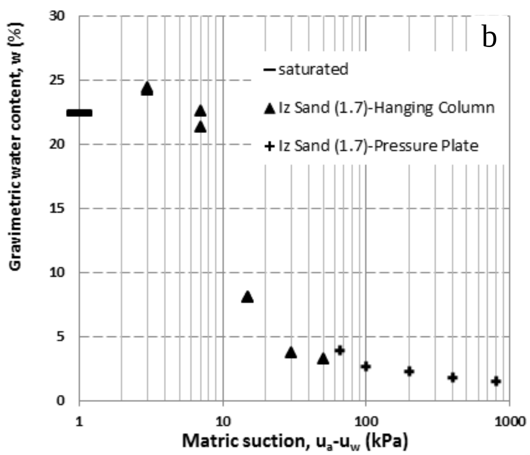


Figure 2. a) Particle size distribution, b) Soil Water Characteristic Curve of this soil at dry density of 1.7 g/cm3

3. Triaxial Tests

Triaxial specimens with 5 cm diameter and 10 cm height are prepared by the under-compaction method (Ladd, 1978) on the triaxial pedestal by controlling the density and water content. The preparation equipment consists of a conventional split mold and custom made hammer as shown in Figure 3. This hammer includes a steel rod for tamping and an adjustable collar for precise control of layer height.

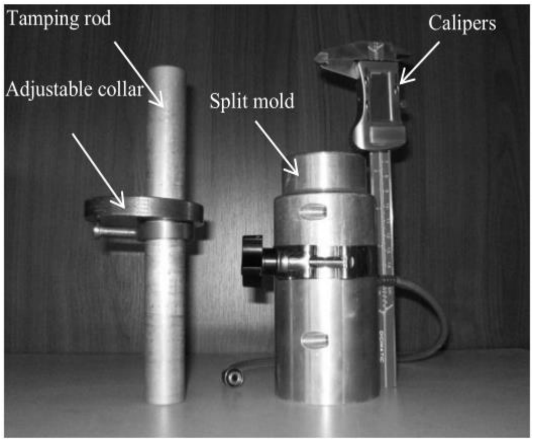


Figure 3. Equipment used for compaction

Specimens are arranged in five layers. Initially, the entire sample was mixed as a single batch, from which the soil was taken as small portions for each layer. However, this meant the lowermost layer, as it is placed first, had the highest water content, and as the soil of the following layers had waited longer, evaporating, they had gradually decreasing preparation water contents. To remove this error and to prepare uniform specimens, material is mixed in five different dishes, each with the desired water content (Figure 4a). A syringe is used for precise control of the amount of water added to the soil. Before placing each layer's material into the mold, its water content is measured prior to placement. Then each layer is placed and compacted to the desired density by controlling the thickness of the layer for a given mass of soil (Figure 5).

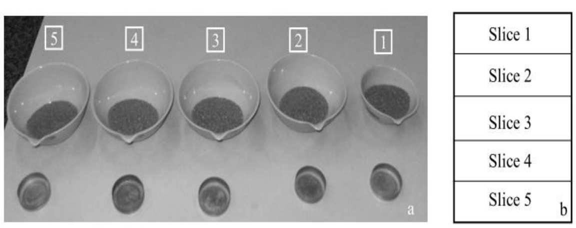


Figure 4. Specimen layers, a) soil prepared for each layer b) order of layers

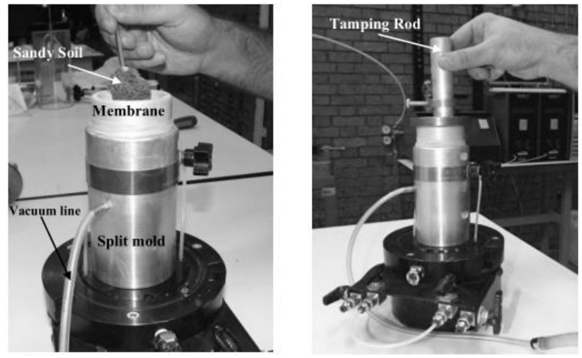


Figure 5. Preparing unsaturated specimen with desired water content

Then the triaxial cell is filled with distilled de-aired water. Next, the test conditions are specified and triaxial test is controlled by the computer from start to finish. In the CW tests, the air-phase line is kept open to atmospheric pressure throughout the test procedure. However, this air-drainage line is placed into a water container with atmospheric pressure, to avoid evaporation of water from the specimen. In order to prevent water flow between the phreatic water container and specimen (which was observed in earlier tests), a water trap was added on this line.

The specimen is then consolidated to desired isotropic stress, and then sheared at a constant rate of strain of 0.217 %/min. The same strain rate was used during shear in all triaxial tests presented here. The entire test takes 2-3 hours. At the end of test, air drainage valve is closed immediately and the specimen is removed as quickly as possible from the triaxial cell. Then, the specimen is divided into five slices and final moisture content of each slice is measured. The order of slices is shown in Figure 4b.

Nineteen triaxial tests were carried out at different confining pressures, initial water contents and drainage conditions. In these tests, specimens were prepared in both loose and dense condition, with dry density of 1.35 and 1.70 g/cm3, and initial water contents of 5, 10 and 15%. These are summarized in Table 2.

Two UU tests were done by initial water content of 5% under 40 and 80 kPa, sealing the specimen by placing wax paper at its boundaries. There was a little variation in water content of the layers (Figure 6), but the results are within the acceptable absolute error margin of water content measurements (0.5% according to ASTM D2216). However, due to inability of this system to keep air pressure constant, these types of tests were abandoned in favor of CW tests.

Table 2. Summary of triaxial test conditions

Drainage Conditions	Initial Water content (%)	Dry density (gr/cm^3)	Confining pressure (kPa)	Operator initials	Porous stone moisture
UU	5	1.7	40	RAN	-
UU	5	1.7	80	RAN	-
CW	10	1.7	30	RAN	10% wc
CW	10	1.7	70	RAN	10% wc
CW	10	1.7	140	RAN	10% wc
CW	15	1.7	30	RAN	15% wc
CW	15	1.7	140	RAN	15% wc
CW	5	1.7	30	RAN	5% wc
CW	5	1.7	70	RAN	5% wc
CW	5	1.7	140	RAN	5% wc
CW	5	1.35	30	MAA	5% wc
CW	5	1.35	70	RAN	5% wc
CW	5	1.35	140	MAA	5% wc
CW	5	1.7	140	MAA	5% wc
CW	5	1.7	140	RAN	Saturated
CW	5	1.7	140	MAA	dry
CW	5.5	1.7	70	RAN	dry
CW	5.5	1.7	30	RAN	dry
CW	5.5	1.35	140	RAN	dry

Afterwards, five CW tests were performed on specimens prepared at 10% and 15% water contents and sheared under 30, 70 and 140 kPa cell pressures. The water content values are found to increase from top of the specimen to bottom (Figure 7), indicating a trend of water migration within the specimen. The variation of water content is slightly more pronounced in the specimens with 15% percent preparation water content compared to the specimens with 10% water content. In specimens with high water content, the water phase permeability is also greater, while gravity becomes significant compared to suction. Both of these mechanisms contribute to water migration from top to down.

The tests were performed by two different operators. Comparing the results of the tests with preparation water content of 5%, there is an operator error in preparing specimens where the final water content of the specimens prepared by one of the operators are slightly lower and these of the other are slightly higher than 5%. However, this doesn't affect the uniformity of water content, as the difference between the water contents of layers of each test are within the acceptable absolute error margin of 0.5% (Figure 8).

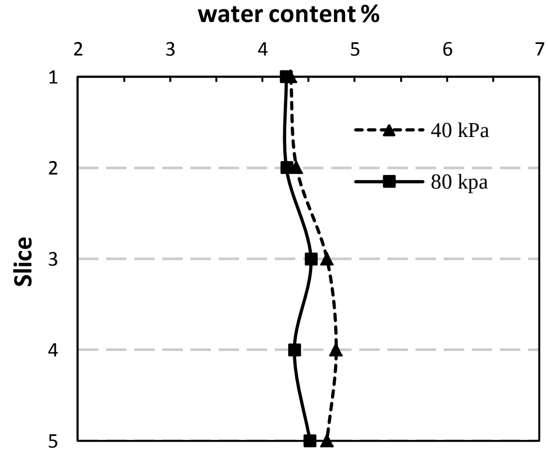


Figure 6. Water content variation at the end of the UU tests with preparation water content of 5%, at two different cell pressures

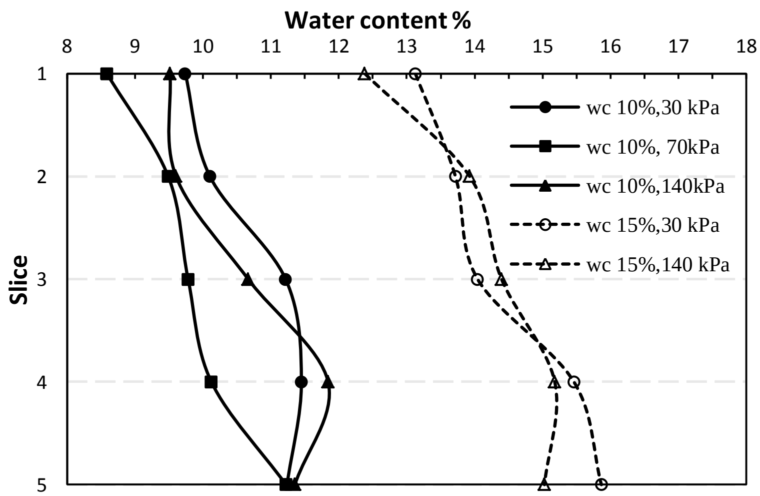


Figure 7. Variation of final water content, for specimens prepared at dry density of 1.7 g/cc, with 10 and 15% preparation water contents. The porous stones have 10 and 15% water content, respectively, at the start of test

To consider the effect of porous stone moisture on specimen water content, three CW triaxial tests were done. These tests were performed on specimens with 5% preparation water content, using dry, 5% moist and saturated porous stones. Results are shown in Figure 9.

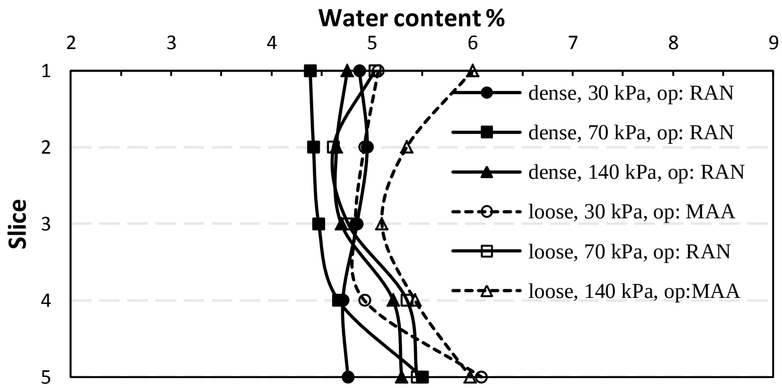


Figure 8. Effect of operator on variation of final water content in CW triaxial tests with 5% initial water content

The final water contents of the specimen with saturated porous stones are significantly higher than its preparation water content, and are maximum at the ends where the specimen is in contact with the porous stones. This indicates that some of the water was sucked into the soil from the fully saturated porous stone. When the porous stone is 5% moist, again a small amount of water is sucked by the top and bottom of the specimen. This is related to difference between the SMC curve of porous stone and soil sample. The test with dry porous stone gives most uniform water content values throughout the specimen. In addition, in all mentioned tests, specimens were observed to lose 0.5% water content at average, due to evaporation, during the specimen preparation. Therefore, performing the tests with dry porous stone and preparing the specimens with a preparation water content that is 0.5% higher than the desired value is the next step.

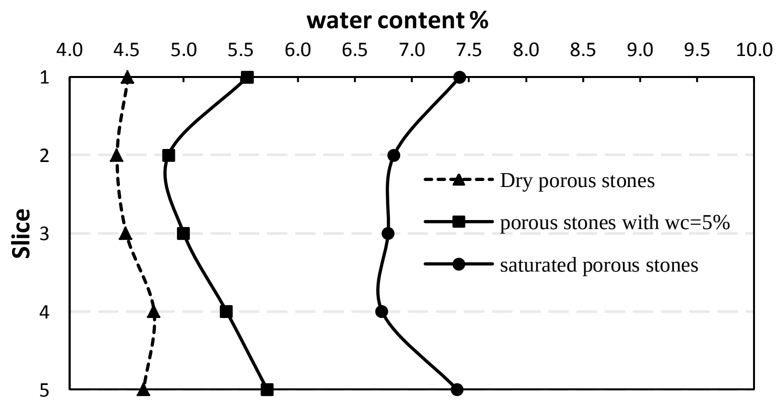


Figure 9. The effect of stone moisture on specimen water content. All of the three specimens have 5% preparation water content and 1.7 g/cc dry density

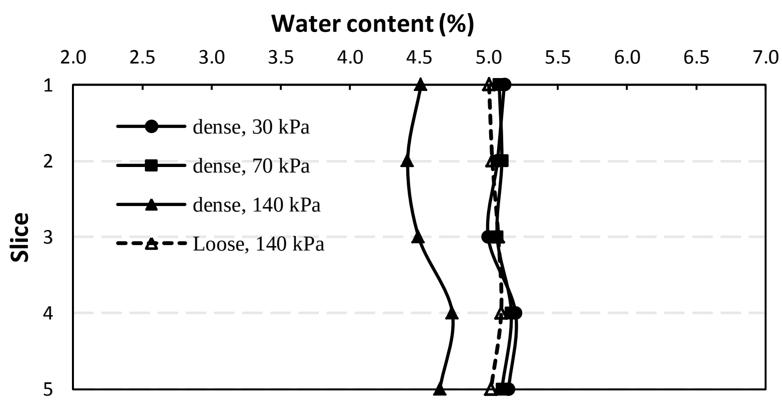


Figure 10. Variation of final water content with height, for tests with dry porous stones

Considering all of the previous tests, the least spatial variability of water content was observed in the test with dry porous stones. Therefore, three more triaxial tests with dry porous stones were performed to verify the repeatability of the procedure. To remedy the difference between the desired and measured water content (the "dry porous stone" curve in Figure 9 is about 4.5% whereas the desired water content was 5%), the preparation water content of the specimen was increased by the difference (0.5%). These test were done on both loose and dense specimens, and are presented alongside the initial dry porous stone test (labeled as 5%) in Figure 10. The results in Figure 10 show that there is no significant variation in water content from layer to layer. Moreover, confining pressure and density does not seem to noticeably affect water content homogeneity through the layers. All of the specimens with dry porous stones have lost 0.4 – 0.5% water content during preparation. For the three tests with 5.5% preparation water content, the mean difference between the measured and desired water content is 0.08% with a standard deviation of 0.06%, accounting for each layer's water content separately.

4. Direct Shear Tests

In order to do the direct shear tests, two significant modifications were made on the standard setup: replacing the porous stones with impermeable discs, and keeping the shear box humid.

In preliminary DST tests water content was found to have spatial variation at the end of the test. This variation in water content was observed in the form of dryness near the upper and lower porous stones. Soil water content changes due to the difference of suction between the specimen and the porous stones because of difference in SMC curve of the stone and soil sample. As a solution, in water controlled DSTs, the top and bottom boundaries are made impermeable, by replacing the porous stones with Plexiglas plates. The authors used two Plexiglas platens with the same thickness instead of the porous discs (Figure 11a). Note that the ribbed metal plates that provide the rough boundary surfaces above and below the specimen in conventional DST are not removed from the setup.

An additional observation during preliminary tests was reduced water content at the end of the test. This hints at evaporation during shearing, probably through the gap between two halves of the shear box, and possibly through the drainage ducts on the shearing box. In order to prevent evaporation, humidity around the shearing box was preserved by enveloping it within a wet cloth or towel (Figure 11b).

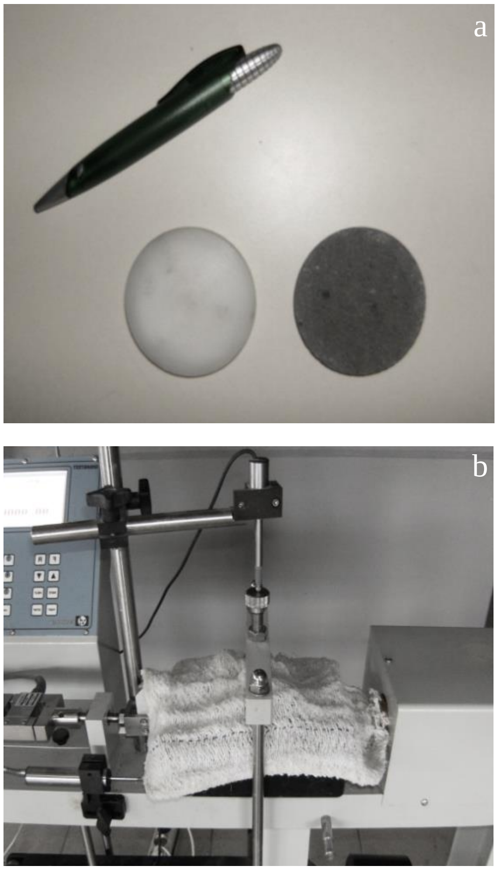


Figure 11. Modifications to DST. a) Plexiglas replacing porous stone, b) Shear box clothing

This moisture blanket covers the shear box loosely, in order not to introduce errors to the shear force measurements. However, it must be noted that this procedure was applicable only for the tests in cohesionless material since shearing rate was high enough to let the test finish before there is any significant transfer of humidity between the cloth and the specimen, or the cloth dries.

As the specimen of DST is relatively thin, the entire specimen is prepared at the desired initial water content and placed at intended dry density at once, as a single layer. Shearing rate is selected as in conventional DSTs (ASTM D3080), which in this case is horizontal displacement rate of 0.1 mm/min.

In order to study the water content changes in specimen through the tests multiple samples obtained for water content measurement from each of upper and lower (in some tests, only middle) parts of the specimen at the end of tests and compared with water content before the tests. Combinations of three preparation water contents (approximately 5, 10 and 15% – the preparation water contents were not precisely controlled as single-layer specimens are initially assumed as homogeneous), two initial dry densities (1.35 & 1.8 gr/cm3) and four normal stresses (20, 40, 80 & 150 kPa) were tested (24 tests in total).

Mostly two samples from each of upper and lower parts are taken for water content determination (W_{up} and W_{bot}). Investigating each test or set of tests shows that; as a general rule, water contents in the samples with lower initial moisture (5 for both densities and 10% for dense specimen) tend to stay uniform. The variations of water content at the end of the test (W_f) from initial water content (W_i) are shown in Figure 12. Water content of specimens with 5% preparation moisture deviated at most 0.3% from the initial value.

Water contents of specimens with about 10% preparation moisture deviated by up to 0.5% from the initial value during the test (Figure 12), and the water content was detected to increase with depth. In the dense specimens, this increase is no greater than 0.2% from top to bottom of the specimen, while it can be as large as 1.7% in the loose specimens (Figure 13). This may be because the SWCC of a dense specimen is lower on the water content axis compared to a loose specimen of the same soil (for a given suction, dense specimen can hold more water). The boundary between bulk drainage regime and pendular regime being around 9.5% would also cause this difference between the two sets of tests, whose preparation water contents are around 9% and 10%.

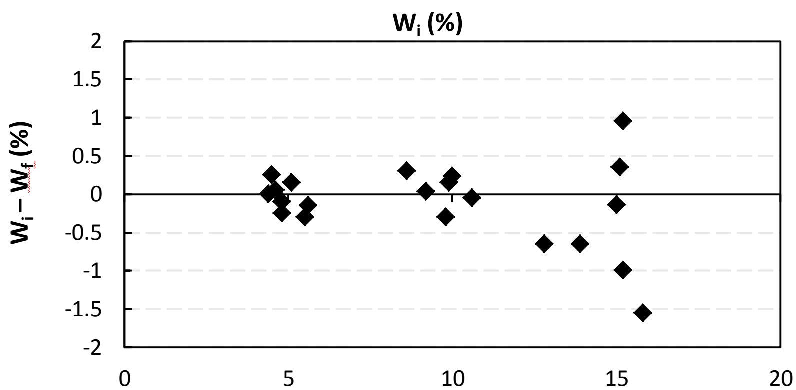


Figure 12. Variation of water content at the end of the test from initial value

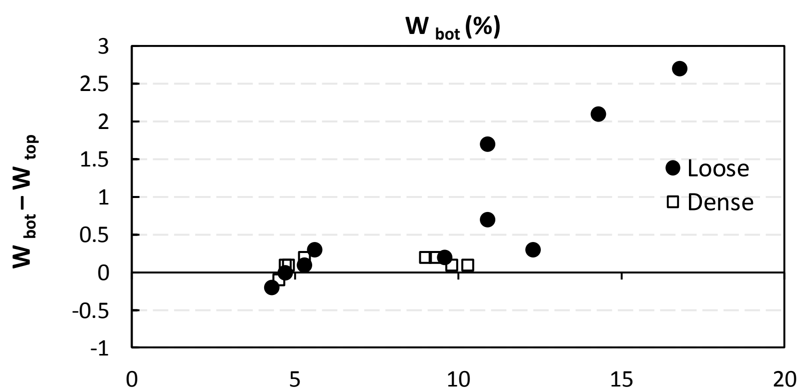


Figure 13. Variation of water content from top to bottom

In the specimens with high (15%) preparation water content, the range of differences between preparation and final water contents increase to ±1.6% (Figure 12), while downward transport of water (Figure 13) becomes more pronounced (up to 2.7% difference between top and bottom water contents at the end of test). The latter result (increased downward flow of water) is expected as the water phase permeability and relative effect of gravitational forces both increase with increasing water content. This result was also encountered in the triaxial tests where the preparation water content lies in the bulk drainage range.

4. Conclusion

For each laboratory tests type (triaxial and direct shear), a series of experiments were conducted on granular specimens, under various water-content and stress conditions. Based on the water content measurements before and after each test, the best procedure to keep the specimen moisture uniform and constant throughout each test type is devised, for test durations within the range of a few hours.

In order to carry out such a constant water content test in either test type, water content of the specimen must be within the pendular regime (high suction, low water content portion of SWCC). For larger water contents, the extra (bulk) water is significantly affected by gravity, causing in a downward moisture gradient within the specimen.

Differences of the final procedure to run a CW triaxial test, compared to a standard CD test (ASTM D 7181) are: (i) the pore pressure-volume measurement/control system is removed from the setup. (ii) The specimen is prepared at a water content that is 0.5% higher than the desired value, which must be within the pendular regime. (iii) The porous stones must be dry. (iv) The pore drainage line of the triaxial setup must be connected to the air phase of a sealed container of air and water, which in turn must be connected to a phreatic water reservoir. (v) If desired, specimen volume changes may be measured by calibrated measurements of cell fluid volume (Ahmadi-Naghadeh and Toker, 2012).

In order to perform CW tests, the following modifications were made to the direct shear setup and test procedure: (i) The specimen is prepared at the desired water content. (ii) Drainage through the top and bottom must be prevented by replacing the porous discs with two plexiglas platens of the same dimensions. (iii) In order to prevent evaporation, air surrounding the shear box has to be kept humid by loosely covering the shear box with a wet cloth or towel.

For both test types, the modifications outlined above result in the water content to be controlled throughout the specimen dimensions and testing duration, within the acceptable absolute error margin of water content measurements (0.5% according to ASTM D 2216).

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References

1. Ahmadi-Naghadeh, R. and Toker, N. K. (2012). Volume change measurement in triaxial testing of unsaturated soils, 3rd International Conference on New Developments in Soil Mechanics and Geotechnical Engineering, Nicosia, North Cyprus.
2. ASTM D2216 (2010). Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass, Annual Book of ASTM Standards, American Society for Testing and Materials, Easton, MD.
3. ASTM D3080 (2011). Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions, Annual Book of ASTM Standards, American Society for Testing and Materials, Easton, MD.
4. ASTM D7181 (2011). Method for Consolidated Drained Triaxial Compression Test for Soils, Annual Book of ASTM Standards, American Society for Testing and Materials, Easton, MD.
5. Bishop, A. W., Alpan, I., Blight, G. E., and Donald, I. B. (1960). Factors controlling the shear strength of partly saturated cohesive soil. ASCE Research Conference on Shear Strength of Cohesive Soils, pp. 503-532, Boulder, Colorado.
6. Bishop, A. W., and Donald, I. B. (1961). The experimental study of partly saturated soil in the triaxial apparatus. 5th International Conference on Soil Mechanics and Foundation Engineering, Vol. 1, pp. 13-21, Paris.
7. Cunningham, M. R., Ridley, A. M., Dineen, K., and Burland, J. J., (2003). The mechanical behavior of a reconstituted unsaturated silty clay. Geotechnique, Vol. 53, No. 2, pp. 183-194.
8. Geocomp Corp. (2010). TRIAXIAL Software Manual.
9. Jotisankasa, A., Coop, M., Ridley, A. (2007). The development of a suction control system for a triaxial apparatus, Geotechnical Testing Journal, Vol. 30, No. 1, pp. 69-75
10. Ladd, R.S., (1978). Preparing test specimens using under compaction. Geotechnical Testing Journal, Vol.1, No.1, pp.16-23.
11. Rahardjo, H., Heng, O. B., and Leong, E. C. (2004). Shear strength of a compacted residual soil from consolidated drained and constant water content triaxial tests. Canadian Geotechnical Journal, 41, pp.1-16.
12. Teng, F. and Ou, C., (2011). Application of a suction control system in the method of specimen saturation in triaxial tests. Geotechnical Testing Journal, Vol. 34, No. 6, pp.1-10.
13. Vanapalli, S. K., Fredlund, D. G., Pufahl, D. E. (1996). The relationship between the soil-water characteristic curve and the unsaturated shear strength of a compacted glacial till. Geotechnical Testing Journal, Vol. 19, No. 3, pp. 259-268.