Constant void ratio vs. constant confining pressure tests on partially saturated silty soil

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Abstract. The presence of soil solids, water, and air complicates understanding unsaturated soil dynamics. A thorough understanding of unsaturated soil behavior is essential for the fruitful design of slopes, embankments, and retaining structures. A series of constant void ratio and constant confining pressure triaxial compression tests were carried out under constant water content conditions (pore air pressure drained and pore water pressure undrained) to study the shear strength and deformation characteristics of a partially saturated silty soil. Test specimens were prepared with a water content of 15%, 20% (Optimum water content), and 25%, with the corresponding degree of saturation of 37, 49, and 62.5%. The degree of compaction of all specimens was kept at 83% while the dry density was 1.29 g/cm3, and the void ratio was around 1.045. All the samples were isotropically consolidated under 500kPa by keeping deviatoric stress at 0kPa. The constant void ratio test results showed that the deviatoric stress reached a peak value followed by a sudden decrease within the axial strain of 0-1.5%. In contrast, the deviatoric stress increased continuously until reaching the critical state without depicting any peak for constant confining pressure tests. However, in both cases, the lower the water content at the time of specimen preparation, the higher the shear resistance.

1 Introduction

Triaxial tests on unsaturated soils are typically performed under various conditions, i.e., unconfined, constant suction, constant mean net stress, etc. [1-3]. The constant void ratio tests on unsaturated soil have received little attention. Undrained triaxial testing satisfies the criteria for constant volume tests for saturated soils [4-5]. Water movement (the volume of fluid entering or leaving the soil specimen) and sample volume change are directly related in saturated soils. In the case of unsaturated soils, it is challenging to estimate the volume change of the total sample and the air and water volumes [6]. Shimizu and Terakata (2010) [7] conducted triaxial compression tests with the constant volume on slurry-prepared, unsaturated soil. During shear, the volume was maintained constant by altering the air pressure supply to the sample. It was determined that a unique failure envelope was obtained despite differences in stress history and the void ratio. In another study, samples were sheared using different stress paths. One method involved using a computerized control system to increase u_a and u_w by equal amounts to maintain a constant volume during shearing (maintaining constant suction). The axial strain to failure was discovered to vary according to the test type, ranging from 10% for constant volume shear to over 30% for entirely drained shear. The deviator stress-axial strain curve climbed monotonically to an asymptotic value for most tests, with no indication that the curve had a peak. A unique state boundary hypersurface seemed to be traversed by each test path [8].

In view of the above, constant void ratio and constant confining pressure triaxial compression tests are carried out in this study with the aim of achieving the following objectives:

- To explore the mechanical behavior of unsaturated compacted soils.
- To compare the response of unsaturated compacted soil samples when sheared with a constant void ratio and constant confining pressure.

Tests are performed under constant water content conditions that simulate sudden field failure conditions. [9]. The constant void ratio test can give contour-like lines that will help define the state boundary surface for unsaturated soil [10].

2 Material, Apparatus, and Procedures

The physical characteristics of the studied soil, sample preparation, test apparatus, and procedures will be discussed in the following subsections.

2.1 Material Properties and Sample Preparation

DL-Clay is the name of the soil material used in this study. It is a commercially available silty soil initially produced as a carrier of agricultural chemicals, and it is made by mechanically crushing or grinding kaolinite material. According to chemical analysis, 95.2% of DL-clay is Silica (SiO_2), with 2.1% Alumina (Al_2O_3). DL clay is non-plastic and homogeneous. It is made up of 90% silt and 10% clay and has a uniform grain size

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distribution with a mean grain size D50 of about 0.03 mm. It has a maximum dry density of 1.55g/cm3 and optimum water content of 20%. The index properties of the soil are $G_s = 2.635$ g/cm^3, I_p = Non-Plastic, and L_L = Non-Plastic. From the soil water characteristic curve (SWCC) of the studied soil, the maximum matric suction is 50 kPa, while its air entry suction is around 11 kPa [11].

Water was added to dry DL-clay before compaction to prepare samples containing 15%, 20%, and 25% water content, i.e., from the dry to the wet side of optimum water. The soil was compacted in five layers, each 2 cm thick, in a cylindrical mold with a diameter of 5 cm using a static compaction machine equipped with a hydraulic jack [12]. The specimens were compacted to 83% density and had a dry density of 1.29g/cm3. The properties of the soil samples prepared for this study are shown in Table 1.

Table 1. Properties of the prepared specimen

Properties	Unit	Value		
D_c	(%)	83	83	83
ρ_d	(g/cm^3)	1.29	1.29	1.29
w	(%)	15	20	25
S_r	(%)	36.9	49.3	62.5
e	-	1.04	1.045	1.048
Compaction Pressure ≈	(kPa)	600	325	200

The pressure exerted on the soil during sample preparation is less than the confining pressure during the test consolidation phase for specimens compacted with 20% and 25% water content. As a result, the samples are considered to be normally consolidated. Similarly, for the sample prepared with 15% water content, the pressure applied during sample preparation is greater than the applied stress during the test consolidation phase, indicating that the sample is slightly over-consolidated. All the prepared samples measured 5 cm in diameter and 10 cm in height.

2.2 Test Apparatus

The general layout of the test device utilized in this study is depicted in Fig. 1.

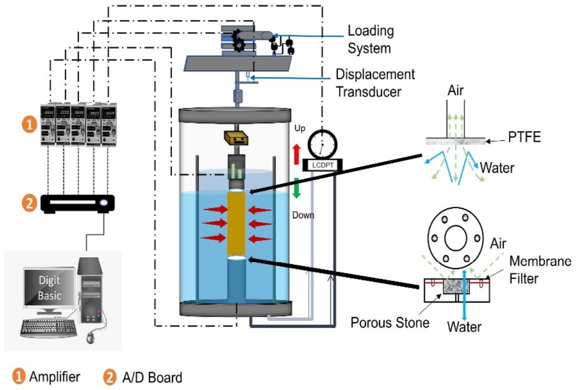

Fig. 1. Schematic of the triaxial apparatus

The main experimental works were conducted using a modified version of a conventional triaxial apparatus that allows a sample's water pressure, air pressure, overall volume change, and water volume change to be measured or controlled independently. The device consists of three major components: a double-chamber triaxial cell, a loading system, and a measuring system.

The cell pressure and pore water pressure were measured using pressure transducers with a maximum capacity of 1 MPa. In contrast, the pore air pressure transducer had a maximum capacity of 200 kPa. The confining pressure was applied and maintained to the top of the double cell chamber filled with water by regulating the air pressure with a 'Supre Precision Regulator' (RS/RR series) by Fujikura Inc. Japan. Since the inner cell is open-ended, the pressure on its inner and outer sides is the same, negating the requirement for volumetric correction. The water level in the internal compartment is kept higher than the outer cell before the test begins, and the water level in the outer cell is kept constant and used as a reference. When the specimen contracts, the water level in the inner cell falls, and the water level rises when the soil specimen dilates. The volume change in the soil sample as a function of the water level fluctuation in the inner cell was measured using a Low Capacity Differential Pressure Transducer (LCDPT) manufactured by Fuji Electric in Japan. The vertical deformation of the sample was measured using an external Linear Variable Displacement Transducer (LVDT). A balance with an outer load cell was linked to the triaxial apparatus to measure the amount of water drained in or out of the specimen. The triaxial device could measure pore air and pore water pressures at the same time. To separate the paths for pore air and pore water pressure monitoring, a thin membrane and polytetrafluoroethylene (PTFE) sheet layers were used. The PTFE sheet was fixed to the top cap to stop the water flow. A thin membrane, "Supor 450" from Pall Corporation, with a membrane thickness of 140 µm, a pore size of 0.45 µm, and an air entry value (AEV) of 250 kPa, was set on the pedestal to stop the airflow.

2.3 Test Procedure

The bottom pedestal was fully saturated before each test to ensure that there were no air bubbles entrapped inside the porous stone of the pedestal. The water in the external lower and upper tanks was de-aired for at least one day using negative pressure.

The shearing phase was carried out under a regular shear rate of 0.05 mm/min and was automatically terminated when the axial strain reached 15%, following Japan Geotechnical Society standards "JGS 0527-2020" [13]. The stepwise procedure for the constant void ratio and constant confining pressure triaxial compression tests carried out in this study under constant water content conditions are as follows:

First, the sample was wrapped in a rubber membrane and placed over a pedestal with a membrane to record the initial suction value. The axis translation technique (ATT) was used after determining the initial suction value. The primary purpose of ATT is to prevent the formation of any cavities in the pedestal drainage system that would interfere with the measurement of pore-water pressure and to keep pore-water pressure above atmospheric. During ATT, the pore air and confining pressures were simultaneously increased to achieve zero pore water pressure while maintaining the original specimen volume to keep the volumetric strain equal to zero [14]. To achieve the desired state before shearing, the specimen was isotropically consolidated after ATT using the required net confining pressure of 500kPa. The drain valve was left open throughout the consolidation phase to relieve excess pore water pressure. The axial stress was automatically adjusted by the load management system to keep the deviatoric stress (q) at zero. Following isotropic consolidation, the samples were subjected to shear with a constant void ratio under constant water content conditions (pore water pressure undrained and measured, pore air pressure drained and controlled). The sample volume was kept constant by carefully varying the confining pressure in response to the volume change of the specimen (i.e., reading of the LCDPT value) [10, 15]. Fig. 2 shows the various phases of the constant void ratio test.

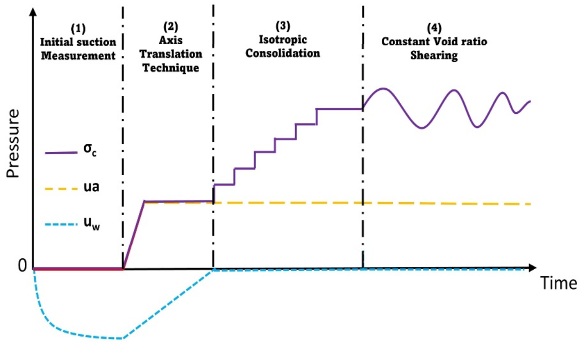

Fig. 2. Stages for the constant void ratio test

The initial suction, ATT, and consolidation stages of constant confining pressure tests are carried out the same way as for the constant void ratio test. The samples are isotropically consolidated under 500kpa confining pressure. The pore water valve is closed, while the pore air pressure valve is kept open and controlled during the shearing phase to maintain constant water content conditions. The matric suction changes slightly with increasing axial strain during the shear process, whereas samples have a stable net confining pressure. The pore-water pressure would increase or decrease during shear depending on the volume change of the soil specimen. The stages of the constant confining pressure triaxial test are depicted in Fig. 3.

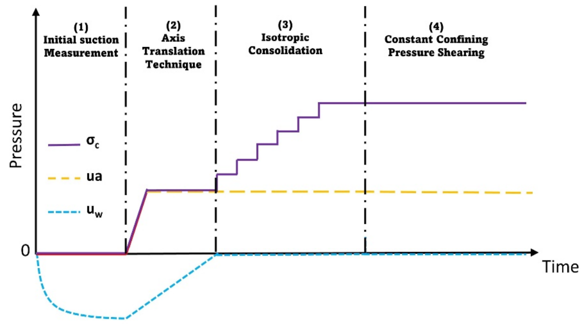

Fig. 3. Stages for the constant confining pressure test

3 Test Results

Table 2 shows the test ids and the initial matric suction value for the specimen tested in this study. All samples for both series of tests were subjected to 500kPa confining pressure during the consolidation phase. The initial matric suction is almost the same for the specimen prepared with identical moisture content, and the slight difference can be due to the preparation procedure.

Table 2. Test Id and initial matric suction values of specimen

Test ID	D_c (%)	*w* (%)	Initial Suction Value ≈ (kPa)	Remarks
CV-w15	83	15	27	Constant Void Ratio Test
CV-w20	83	20	20.9	
CV-w25	83	25	14.8	
CC-w15	83	15	27.2	Constant Confining Pressure Test
CC-w20	83	20	20.5	
CC-w25	83	25	13.5	

The initial matric suction greatly influences unsaturated soils' mechanical behavior. When the water content of a sample is low, the initial matric suction value is high and takes longer to stabilize than when the water content is high. Similar behavior was observed by Ahmad et al. (2023) [10].

The tests were carried out under constant water content conditions, which meant that the water drain valve was closed and the air drain valve was open. For the series of constant void ratio tests, the samples had to be sheared with zero volumetric strain; the cell pressure was manually adjusted using the regulator following the change in the LCDPT value. Fig. 4 depicts the constant volumetric strain of samples maintained during the shearing phase for the constant void ratio test series.

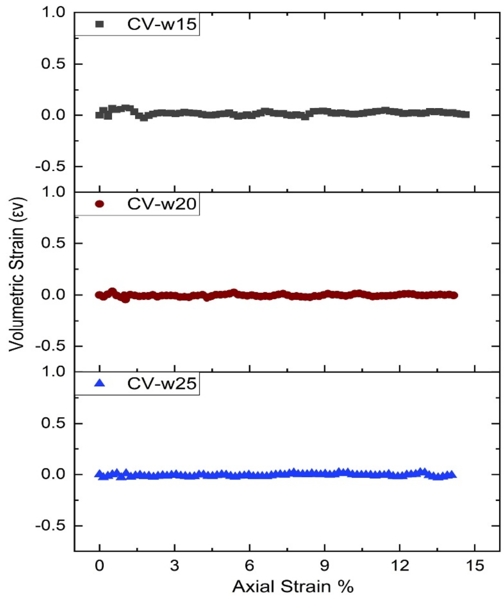

Fig. 4. Volumetric strain for constant void ratio tests

For the series of constant confining pressure tests, all the samples exhibited compressive behavior during shearing, meaning the void ratio decreased. Fig. 5 shows the volumetric strain of samples during constant confining pressure tests. Positive volumetric strain indicates compression in general soil mechanics [16].

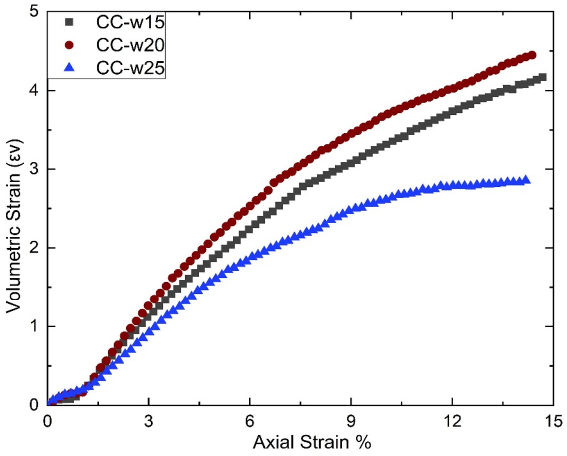

Fig. 5. Volumetric strain for constant confining pressure tests

The relationship between deviatoric stress and axial strain when sheared with a constant void ratio is depicted in Fig. 6. It can be seen that the deviatoric stress peaks within the axial strain range of 0-1.5% and then decreases. Notably, the deviatoric stress curve for CV-w25 exhibits dilative behavior after 13% of axial strain. [5]. Also, the shear strength is more significant in specimens prepared on the dry side of the optimum and decreases toward the wet side.

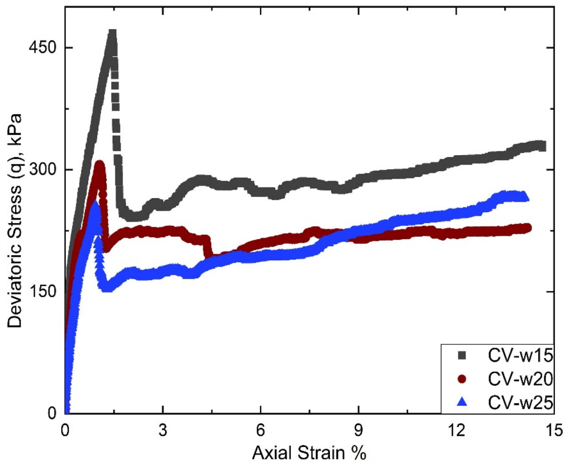

Fig. 6. Shear strength of samples during constant void ratio tests

For the constant confining pressure tests, the deviatoric stress increased monotonically without any evidence of a peak until it reached the critical state. It can be seen from Fig. 7 that the higher the sample's water content, the lower the shear strength and stiffness of the sample, the same trend as for the shear strength of samples tested with a constant void ratio. It is interesting to note that the overall strength of samples is more when tested with constant confining pressure than with a constant void ratio. The reason can be the high pressure of 500kPa maintained during the shearing phase for CC tests compared to the CV tests in which the confining pressure is altered corresponding to the sample volume.

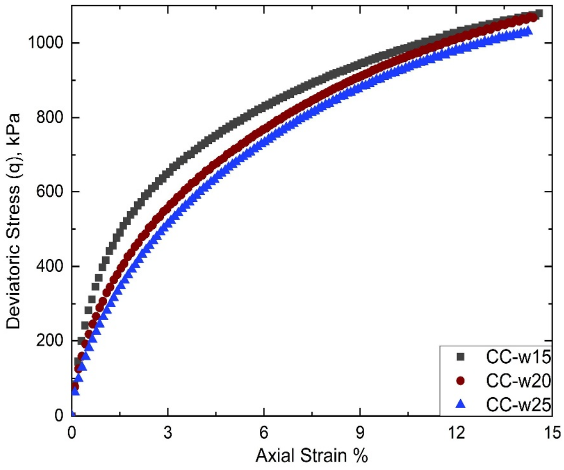

Fig. 7. Shear strength of samples during constant confining pressure tests

Figure 8 shows the stress paths of samples tested with a constant void ratio. It exhibits some unusual behavior in the beginning. The abrupt loading impact could cause this phenomenon at the start of the shearing phase, which could cause the suction-held soil particles to collapse and quickly reorient [15]. The unusual behavior in effective stress within the axial strain range of 0-1.5% is due to the increase or decrease in cell pressure. It is interesting to observe that the unusual behavior is reduced with an increase in the water content of the samples. There is no such unusual behavior for the constant confining pressure tests, as shown in Fig. 9. The deviatoric stress and the effective stress increase gradually with the axial strain. It should be noted that samples with a water content of 20% and 25% are normally consolidated because the confining pressure is greater than the pressure exerted during sample preparation. In comparison, because the confining pressure is less than the sample preparation pressure, the sample prepared with 15% water content is lightly over-consolidated.

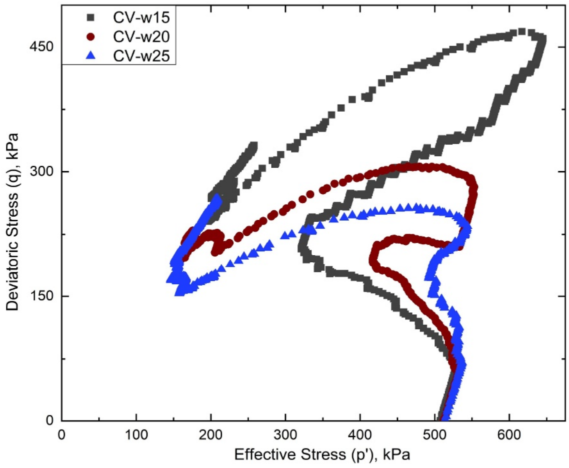

Fig. 8. Stress paths of samples during constant void ratio tests

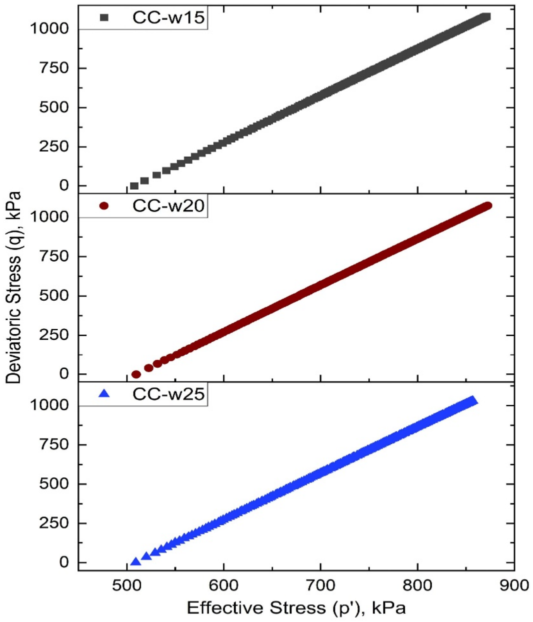

Fig. 9. Stress paths of samples during constant confining pressure tests

Figure 10 represents the matric suction of samples tested with a constant void ratio. For samples with 15% and 20% water content, the matric suction initially decreased slightly, followed by a sudden increase and a continuous slight decrease until it reached the critical state. However, the matric suction slightly increased for samples containing 25% water until it reached the failure criteria. The matric suction of samples under constant confining pressure initially decreased somewhat, followed by a continuous slight increase until it reached the critical state, as shown in Fig. 11. It is due to the decrease in the pore water pressure of samples. In contrast, the pore air pressure remained nearly constant throughout. For constant void ratio tests, the degree of saturation did not change during shearing because the samples maintained constant volume. In contrast, the degree of saturation increased for constant confining pressure tests due to a decrease in the void ratio of the soil specimen.

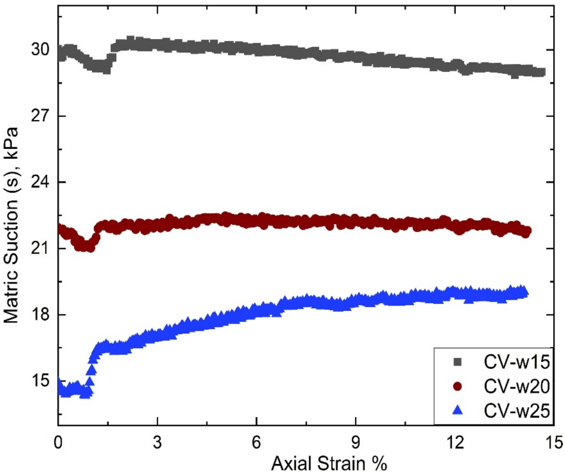

Fig. 10. Matric suction of samples during constant void ratio tests

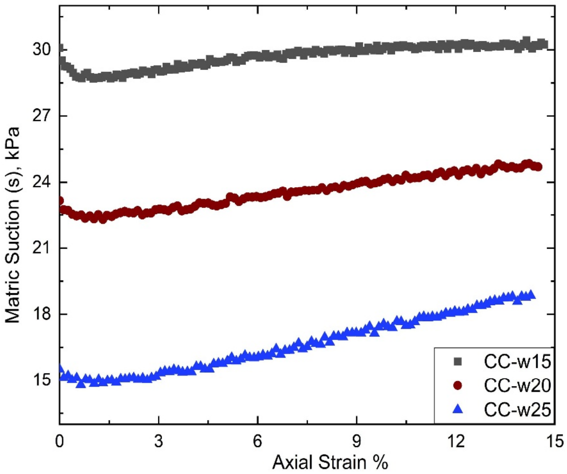

Fig. 11. Matric suction of samples during constant confining pressure tests

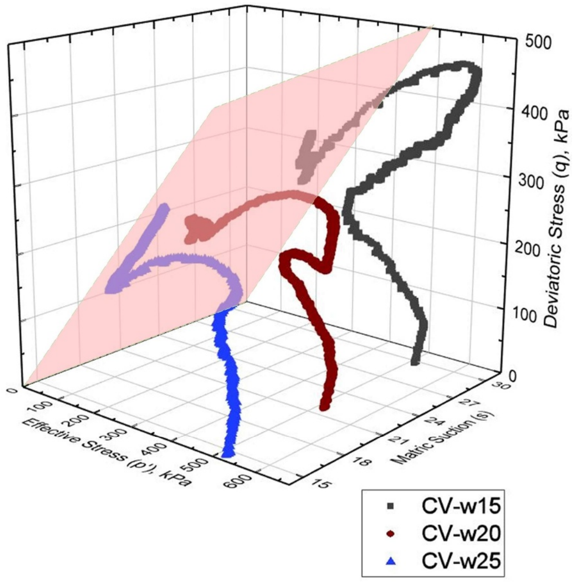

Fig. 12. Stress paths followed in p’sq space under constant void ratio tests

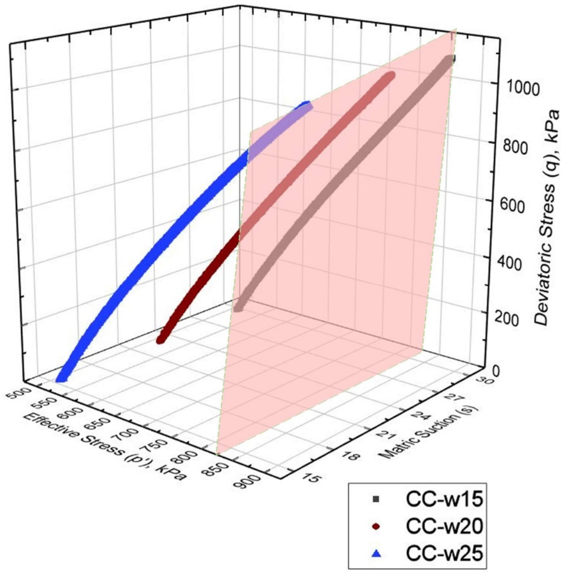

Fig. 13. Stress paths followed in p’sq space under constant confining pressure tests

The relationship between mean effective stress (p'), matric suction (s), and deviatoric stress (q) at failure for constant void ratio tests and constant confining pressure tests are plotted in 3D space in Fig. 12 and Fig. 13, respectively. The stress paths from constant void ratio tests represent contour lines that provide insight into the state boundary surface (SBS) for unsaturated soil. An envelope surface of all potential states or pathways in the constant void ratio plane makes up the SBS, and no state of soil can reach beyond the SBS under any circumstances. It can be seen from the stress paths of constant void ratio tests that as the matric suction increases, so does the unusual behavior. All final points are located on the same failure surface, demonstrating that a failure surface is a distinct plane unaffected by matric suction variations. A similar response was perceived by Rasool and Kuwano (2022) [11].

4 Conclusions

A series of laboratory element tests were performed to examine the mechanical behavior of unsaturated compacted soil and compare unsaturated soil response when tested under constant void ratio and constant confining pressure conditions during shearing. The findings from this study are as follows:

- The initial matric suction value is more remarkable for samples prepared on the dry side of the optimum water content and decreases with an increase in the sample's water content.
- For the constant void ratio tests, the cell pressure was manually adjusted in response to the volume change indicated by LCDPT. All samples tested with constant confining pressure showed compressive behavior.
- The deviatoric stress manifested a peak followed by a decrease for samples tested with a constant void ratio. In contrast, the deviatoric stress for samples tested with constant confining pressure showed a gradual increase without any peak. However, samples tested with constant confining pressure possessed a higher shear strength overall.
- The stress paths of samples tested with a constant void ratio exhibited unusual behavior at the start, possibly due to a sudden temporary collapse of soil particles held together by suction.

Acknowledgements

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