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Rate Effects in Constant Rate of Strain Compression Tests on Unsaturated Soils to High Pressures

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Abstract. This paper presents an investigation into the effect of strain rate on the results from constant rate of strain compression tests on unsaturated soils to isotropic pressures up to 110 MPa. Unsaturated conditions and high pressures lead to complex considerations on the testing methodology, as the strain rate required to maintain constant dissipation of pore water pressure depends on the effects of the degree of saturation and void ratio on the hydraulic conductivity. The rate of loading also has practical concerns in the duration of testing. Experimental results are presented from compression tests on unsaturated, compacted clay using a high pressure true triaxial cell under different rates of strain. Suction was controlled in the tests using the axis translation technique, which provides a constant head boundary condition. This approach also permits evaluation of water outflow during compression and the onset of pressurized saturation. The rate of strain effect was assessed by comparing the constant rate of strain tests having different rates with those from an incremental consolidation test, and it was found that the rates of strain in the constant rate of strain test recommended from empirical methods are too fast to ensure proper dissipation of excess pore water pressure in unsaturated soils at high stresses.

Keywords. Compression behavior, Experimental testing, Unsaturated soils

1. Introduction

During constant rate of strain (CRS) compression testing of soils, the transfer of total stresses applied to the external boundaries of the specimen to effective stresses within the soil skeleton depends on the rate of drainage of the excess pore water pressure. Ideally, the soil should be fully drained so that the applied total stress is equal to the effective stress, in which case the stress-strain curve would correspond to points of equilibrium on the compression curve for the soil. This requires the rate of strain to be sufficiently slow such that the pore water pressure is permitted to dissipate at a constant rate. Despite the widespread use of this type of testing, the rate of strain is typically identified on an empirical basis due to the complexities associated with changes in hydraulic conductivity and compressibility during testing. Although appropriate criteria

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for selecting a strain rate for a particular soil specimen have been discussed extensively in the literature, an investigation of the effects of strain rate on the results from CRS tests during compression of unsaturated clays to high stresses has not been performed. In this case, the volume change and rate of pore water pressure dissipation differs from those of saturated soils because the hydraulic conductivity depends on the degree of saturation (for low stresses below the point of pressurized saturation) and on the void ratio (for higher stresses). In an attempt to address the gap in the empirical studies, this paper involves an evaluation of the impact of strain rate using experimental testing results performed on unsaturated clay through comparison with the results of an incremental consolidation test.

2. Background

As the strain rate influences the shape of the compression curve and pore water pressure dissipation, it can affect the main parameters gained from a compression test, including the mean preconsolidation stress (p'_c), coefficient of consolidation c_v, and the coefficient of compression C_c (Vaid et al. 1979; Leroueil et al. 1983, 1985; Silvestri et al. 1986; Nash et al. 1992). The strain rate prescribed in the ASTM standard for constant rate of strain testing (ASTM D4186) has evolved over time. The rates were originally determined using solutions to the consolidation equation for a specimen with single-sided drainage developed by Wissa et al. (1971). Their solutions permit estimation of the average effective stress (σ'_v) by assuming that the soil has a constant coefficient of volume compressibility (m_v) and a linear distribution of excess pore water pressure during single-sided drainage. This average effective stress can be compared with the applied total stress to evaluate if the soil is drained. They also considered a nonlinear model that assumes that the soil has a constant compression index (C_c) and a parabolic distribution of excess pore water pressure to provide a secondary estimate of the rate of strain.

Table 1. Historically suggested rates of strain for CRS compression test by ASTM (1982)

Liquid limit	Rate of strain (%/min)
<40	0.04
40-60	0.01
60-80	0.004
80-100	0.001
100-120	0.0004
120-140	0.0001

The original version of ASTM D4186 (1982) prescribed rates of strain for different soil that depend on the liquid limit of the soil, as shown in Table 1. These rates should be used with caution as Crawford (1988) found that strain rate effect may not be influenced by the liquid limit. To address this, the most recent version of standard ASTM D4186 (2012) prescribes rates based on the Unified Soil Classification System (USCS), with 10%/hr for MH soil, 1%/hr for CL soil, and 0.1%/hr for CH soil.

Various approaches to determine the proper rate of strain have been proposed based on the ratio of excess pore pressure at the base of a specimen undergoing single-sided drainage to the applied vertical total stress (i.e., the pore water pressure ratio, u_b/σ_v) (Gorman et al. 1978; Larsson and Sallfors 1985; Sandbaekken et al. 1986; Sheahan and Watters 1997). In addition to providing insight on the strain rate, ASTM D4186-12 also states that u_b/σ_v should be between 3 and 15% during testing, although previous versions permitted maximum values of u_b/σ_v ranging from 3%-70%. Based on the approaches developed to determine the appropriate rate of strain based on drainage analyses (Smith and Wahls 1969; Armour and Drnevich 1986). Ozer et al. (2012)

proposed a semi-empirical model to predict the maximum allowable strain rate for different types of soils. Although their model involves the use of an incremental consolidation test as a baseline, their model predicts an upward shift in the compression curve with increasing rates. Instead, it is expected that a greater amount of change in void ratio will occur if the excess pore water pressures are allowed to fully dissipate during compression. Although many researchers attempted to determine the proper strain rate for CRS tests, the proposed solutions are valid only for the specific soils under saturated conditions. Wijaya et al. (2014) evaluated the pore water pressure response of unsaturated kaolin from CRS tests under different strain rates, their findings are only valid for the specific soil material since they focused on finding the appropriate strain rate to produce similar results for saturated kaolin.

3. Material

A low plasticity clay referred to as Boulder clay was used in this study. The clay was air-dried, crushed, and processed after collection to remove all particles larger than the #10 sieve (aperture of 2 mm). Relevant geotechnical properties of Boulder clay are summarized in Table 2. Based on these index properties, Boulder clay is classified as low plasticity clay (CL) according to USCS. The specimens tested in this study were compacted to a void ratio of 0.51 (dry density of. 17.5 kN/m^3) and a degree of saturation of 0.9, so the standard Proctor compaction curve is shown for reference in Figure 1(a). The Transient Water Release and Imbibition Method (TRIM) of Wayllace and Lu (2012) was used to infer the drying and wetting paths of the SWRC for a Boulder clay specimen having the same initial void ratio as that used in the compression tests (0.51), and is shown in in Figure 1(b). This approach permitted inverse estimation of the van Genuchten (1980) SWRC model parameters α and n for the drying and wetting paths, which are shown in the figure. The air entry suction for the drying path is approximately 40 kPa. The initial suction-saturation points for the specimens evaluated using the tensiometer are also shown in this figure, which correspond well with the drying path of the SWRC.

Table 2. Geotechnical properties of Boulder clay

Property	Value
D_{10}	< 1.7×10^{-4} mm
D_{30}	< 0.001 mm
D_{50}	0.001 mm
Percent fines	100 %
G_s	2.70
LL	41
PL	18
PI	23
A	0.75

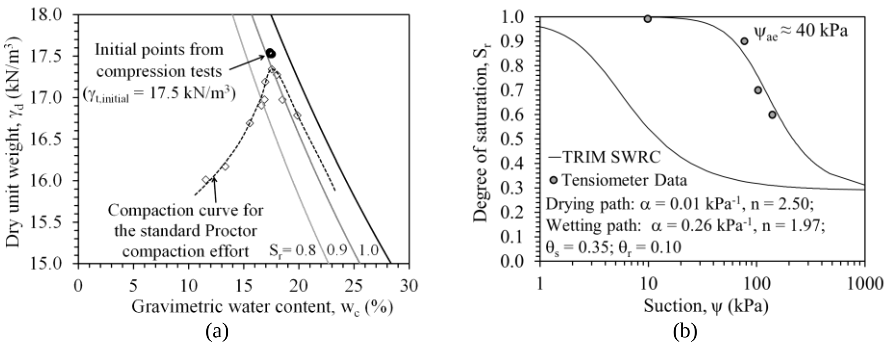


Figure 1. (a) Standard Proctor compaction curve for Boulder clay; (b) SWRC for Boulder clay

4. High pressure true triaxial setup

The true-triaxial cell used in this study was developed by Mun and McCartney (2014), who used it to evaluate the compression of compacted clay up to a pressure of 0.2 MPa. A schematic of the true-triaxial cell and associated pressure control system along with the photo of bottom platen of the cell is shown in Figure 2. A 101.6 mm cubical soil specimen is placed in the center of a cubical space frame, and is then enclosed by five flexible walls and a rigid-bottom base. Reaction walls are then connected to the space frame behind the bladders so that pressurization of the bladders transmits uniform principal stresses to each side of the specimen. Isotropic pressures are applied to the specimen by applying the same fluid pressure to each bladder. A high pressure syringe pump is used to apply pressures to the different faces of the specimen, and is also used to infer the deformation of the specimen by tracking the flow of fluid into or out of the bladders. Pressures are delivered from the pump to the test cell via brake fluid that passes through steel tubing having a yield stress of 240 MPa.

The bottom face of the soil specimen rests on a rigid plate that contains porous discs to independently apply pore air pressure (u_a) and pore water pressures (u_w) so that the suction can be controlled using the axis translation technique. The water pressures are applied through a porous ceramic disc that has an air-entry suction of 500 kPa. A pore water pressure transducer (PPT) is used to monitor the water pressure behind the ceramic disc and a differential pressure transducer (DPT) is used to track the outflow of fluid from the specimen, which can be used to estimate the change of degree of saturation of the soil specimen during compression.

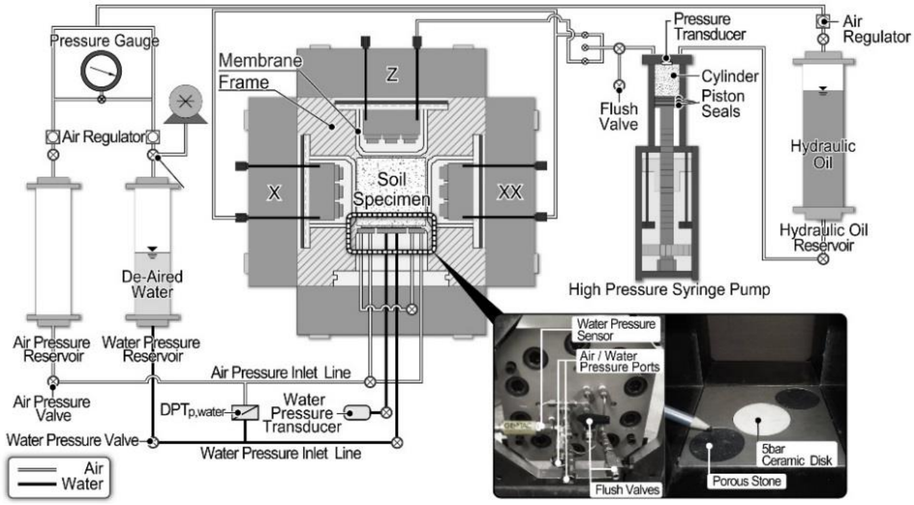


Figure 2. Schematic of the overall experimental setup for the true-triaxial loading cell

Before testing of the soil specimens, the machine deflections were characterized by measuring the deflection response of an aluminum block with known elastic properties (Young’s modulus of 69 GPa and Poisson’s ratio of 0.33). Using the syringe pump, isotropic loading was applied under a rate of strain of 2 %/hr up to a cell pressure of 110 MPa. The pressure effect can be seen from the subtraction of the measured data with the displacement of the aluminum specimen, as shown in Figure 3(a). Since the nonlinear machine deflection curve reflects the accommodation of the bladders on each face, the initial part of the curve was not used for data interpretation as similar effects will happen with the soil specimen. The actual deformations of the soil were defined by subtracting the machine deflections from the measured displacements during the test. An example of the plot of pressure applied versus volume change for a soil specimen tested up to an isotropic stress of 110 MPa is shown in Figure 3(b).

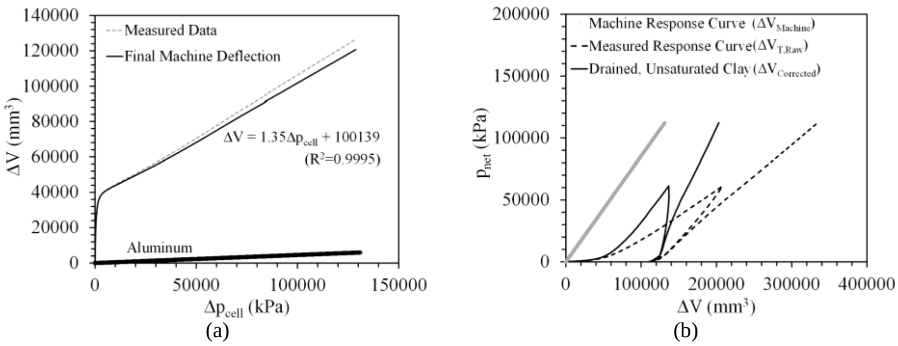


Figure 3. (a) Machine response curve of the isotropic cell; (b) Net pressure vs. volume change curve for the specimen along with the machine deflection curve ($\Delta\varepsilon_{axial}$ = 0.1%/hr)

5. Experimental procedures

Two quasi-drained compression tests were performed on identical, compacted Boulder clay specimens under constant suction. To ensure the uniformity, compacted cubical specimens of Boulder clay were prepared in 5 lifts using static compaction with a mechanical press. Then, a suction of 40 kPa was applied to the specimens using the axis translation technique (Hilf, 1956). In this case, positive air and water pressures are applied independently to the base of the specimen, with a difference $u_a - u_w$ being equal to the targeted matric suction in the specimen. Although sufficient testing time is necessary to get the initial suction stress state in this study as water should flow from the bottom face of the specimen to the upper corners of the specimen through capillarity, the test results improves the understanding of the relationship between drainage and testing time. After establishing the initial suction stress state, the net pressure was increased isotropically to the specimens at a constant rate using the syringe pump, up to a pressure of 110 MPa. The tests were conducted with rates of axial strain of $\Delta\varepsilon_{axial}$ = 1.0 and 0.1 %/hr to evaluate the effects of strain rate. The faster strain rate was prescribed by ASTM D4186-12 for this type of soil, without consideration of unsaturated conditions, while the slower strain rate is recommended for CH clays with lower hydraulic conductivity. The scheme of suction application during testing is shown in Figure 4.

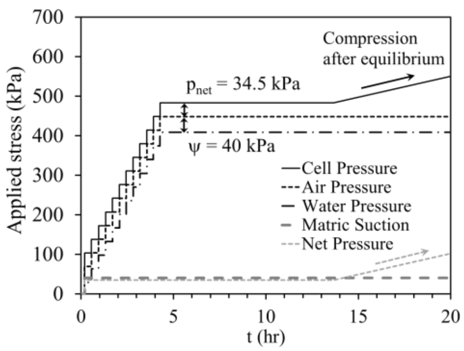
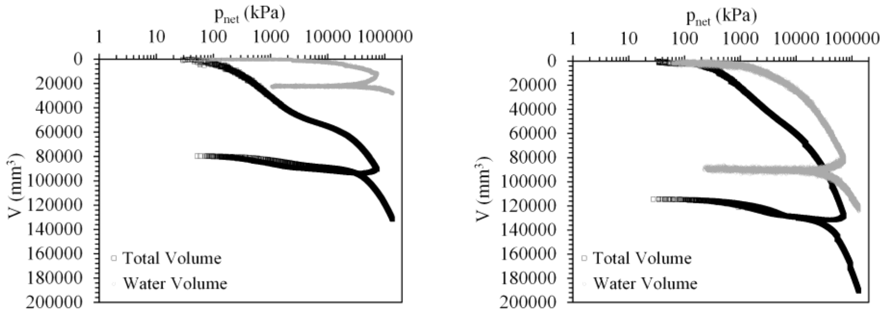


Figure 4. Approach for applying cell and air pressures during drained compression for constant suction tests

6. Test results

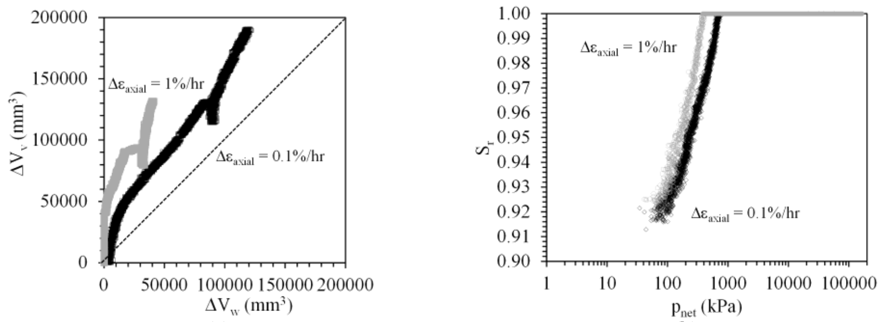
Although the initial compression of unsaturated soils is primarily due to collapse of air-filled voids, it is expected that remaining air bubbles will either be forced out of the voids or will be dissolved into the water at the point of pressurized saturation (Mun and McCartney 2014, 2015). At isotropic stresses greater than the point of pressurized saturation, the change in volume of the soil specimen is expected to be the same as the water outflow, as the voids will be filled with water at this point. However, the results in Figure 5(a) and 5(b) indicate that there may be a significant difference between these two values, with a greater difference noted for the fast strain rate.



(a) (b)

Figure 5. Volume change versus net stress during drained compression of Boulder clay specimens under different rates of axial strain: (a) 1 %/hr; (b) 0.1 %/hr

Following the same line of thought, a 1:1 trend between ΔV_w and ΔV_v is expected after the point of pressurized saturation. The change in volume as a function of water outflow for the fast strain rate shown in Figure 6(a) does not show a slope that is similar to the 1:1 line for either test, along it is closer for the slower strain rate. The change of degree of saturation with net stress for different strain rate shown in Figure 6(b) indicates that the point of pressurized saturation occurred at a net mean stress of about 800 kPa. Unfortunately, the pore water pressure ratio after the point of pressure saturation was not monitored in the tests because the test was drained (i.e., a constant suction was applied through the high air entry porous disc).



(a) (b)

Figure 6. (a) Comparison of water outflow and volume change; (b) Degree of saturation with net mean stress

The compression curves from the two true triaxial tests performed at rates of strain of 1 %/hour (gray line) and 0.1 %/hour (black line) are shown in Figure 7 in terms of the mean effective stress. The mean effective stress was calculated using the degree of saturation as the effective stress parameter in the definition of Bishop (1959). The contribution of suction (40 kPa) to the effective stress is relatively small due to the wide range of net stresses applied. The results from an incremental consolidation test performed in an oedometer are also shown in Figure 7 (dashed line). This specimen has the same initial suction and compaction condition as those tested in the true-triaxial test, and the values of vertical stress in the oedometer were converted to the mean stress by assuming K_0 conditions.

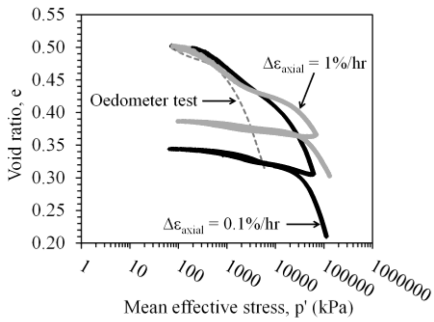


Figure 7. Comparison of the constant rate of strain test with an incremental consolidation test

Although the three compression curves are similar until reaching a mean effective stress of 800 kPa, the true-triaxial compression curves deviate at this point and show less volume change for a given change in stress. The point of deviation of the true-triaxial compression curves coincides with the points of pressurized saturation observed in Figure 6. The difference between the oedometer and true-triaxial compression curves is due to the different drainage conditions and stress paths. In the case of the true-triaxial test, the suction is maintained constant, while the suction was not controlled within the oedometer test. The isotropic stress path may have caused the stiffer response in the true triaxial cell because the cubical specimen was compacted in horizontal lifts. Further, a stiffer response may have been initiated when the soil specimens became pressure saturated. Nonetheless, comparing the slopes of the compression lines at high stresses, the slower true triaxial test is similar to the incremental consolidation test (λ=0.02). This indicates that the slower test is likely closer to drained conditions than the specimen with a greater rate of strain, which exhibits a void ratio that is nearly 50% greater and a shallower compression curve at high stresses. Although there is not a significant amount of data to confirm that the slower true triaxial test is fully drained, the results confirm that the axial strain rate prescribed by the ASTM standard used for this soil (1 %/hour) is too fast to ensure drained conditions, especially at high stresses. The unloading-reloading curves had a similar slope regardless of the rate of axial strain.

7. Conclusion

This paper investigated the effect of axial strain rate on the compression curves of unsaturated compacted clay specimens under mean effective stresses up to 110 MPa. The compression curves from the constant rate of strain tests corresponded well with the results from an incremental compression test to stresses up to 800 kPa. However, the results indicate that the strain rate effects become more pronounced at high stresses due to the reduction in hydraulic conductivity. Although faster axial strain rates may be needed for practical reasons, use of the prescribed rate of strain from the ASTM standard will lead to inconsistent results when testing unsaturated soils to high stresses.

The insight gained from the measured changes in degree of saturation and the outflow data along with the shapes of the compression curves provides useful information for verifying predictions of the required rate of loading for unsaturated soils considering the changes in hydraulic conductivity with both the degree of saturation and void ratio.

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