Loading rate effect on mechanical properties of an unsaturated silty sand

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Abstract. This paper presents the results of an experimental study on the effects of testing rate on stress-strain behavior and volumetric changes of soil. A series of suction-controlled triaxial tests has been performed on reconstituted specimens of a silty sand (SM), at different stress-rates and strain-rates, respectively. The stress-strain paths were applied by using a modified version of a Bishop and Wesley device (USPv2), capable of applying independently pore-water and air pressure at both ends of the soil sample. During the isotropic compression stages loading rates of 2 and 32 kPa/h have been applied under constant suction values of 15 and 45 kPa. The drained deviator stages were conducted at the same suction levels under strain rates of 0.25 and 2.50 %/h. Results are presented in terms of applied loading rates as a function of the specimens specific volume, preconsolidation pressure, soil compressibility and deviatoric stress against strain rate. A comparison of results was made to a former study, under similar testing conditions of suction and loading rates at University of Napoli Federico II. The effect of loading rate on the soil behavior seems to have an insignificant effect on the specific volume variations, for the imposed values during the testing campaign.

1 Introduction

Triaxial testing of soils under unsaturated conditions, unlike saturated soils, allows the study of a broader range of possible geotechnical field conditions under different stress paths. Between the two components of suction, Fredlund & Rahardjo (1993) [1] presented the importance of matric suction in the mechanical behavior of unsaturated soils. On the contrary of osmotic suction, which has a negligible effect on the soil shear strength (Katte & Blight 2012) [2]. The matric suction triaxial control on the soil specimen is generally performed by means of the axis translation technique using separate pore air and pore water pressure control systems.

Classic saturated soil mechanics describes consolidation as the dissipation of pore water pressure in the soil and corresponding deformation at constant loading conditions only depending on compressibility and permeability parameters. Theory commonly does not take loading velocity into an account. Therefore, the following implementation of continuous loading tests at different rates allowed the study of further testing procedures and applications. Continuous loading of unsaturated soils during triaxial tests are generally implemented during the compression stage (CRL) at constant(controlled) suction conditions. Likewise, the constant rate of strain (CRS) is used during the shearing (deviatoric) stage. On the other hand, incremental loading approach (IL) consists of sudden loading and rapid volume deformations in undrained conditions quickly compressing the air trapped in the soil voids.

Literature regarding triaxial testing of unsaturated soils and rate of strain has been reviewed showing that medium dense and highly dense unsaturated sandy soils have a propensity to display stress-induced dilatancy during the test, followed by a peak in the shear vs strain graph and a post-peak softening phase when it approaches to the critical state. Alternatively, loose sandy soils have a volumetric compression during monotonic loading and a strain-hardening behavior in the deviatoric phase. Patil et al. (2015) [3] performed several triaxial tests with the purpose of determining suitable shearing rates on concluding that velocities of 0.054%/hr were appropriate for high suction studies on silty sands.

Rojas & Mancuso (2009) [4] conducted a series of triaxial tests with different isotropic loading rates and shearing strain velocities concluding that consolidation loading rates effects on reconstituted pyroclastic sand specimens seem to be insignificant on the shear behavior during the deviatoric stage of the triaxial tests.

Further work by Huat & Choong (2016) [5], has shown that volume change behavior is greatly affected by the rate of loading at constant imposed suction on the soil specimen showing a smaller void ratio of samples under fast loading rates rather than slow loading specimens.
Patil et al. (2014) [6] displayed that slow (0.174%/hr) and medium (0.516%/hr) on a compacted silt sand shearing rates produced almost identical volumetric strains and

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deviatoric stresses on the samples. However, the fastest shearing rate (0.84%/hr) caused greater volumetric strains and shear peak strengths indicating that such strain rate is insufficient to adequately dissipate pore air and pore water pressures in drained conditions at constant suction tests. In the current research, adequate constant shearing rates (CRS) for triaxial testing of an intermediate unsaturated soil (silty sand) of 2.5%/hr and 0.5%/hr were selected.

2 Triaxial device and procedures

2.1 Description of the used Triaxial device

For this study, an experimental triaxial device capable of measuring and controlling matric suction in the samples was used. The apparatus described by Rojas (2008) [7], is a modified device of Rampino (1997) [8], to include a double drainage system to shorten the drainage path significantly reducing testing time in comparison to a one-way drainage triaxial device as a result of the inclusion of two 5 bar HAEV (High Air Entry Value) porous ceramic disks of 7mm thick 24mm diameter and peripheral steel porous disks positioned at both ends of the sample. The used device is capable of measuring and controlling independently pore water and pore air pressures during each test, allowing to impose a matric suction value with the axis translation technique. On the other hand, volume and water variations are recorded with the use of two separate measuring systems. Figure 2 describes the general layout of the triaxial apparatus used in this study.

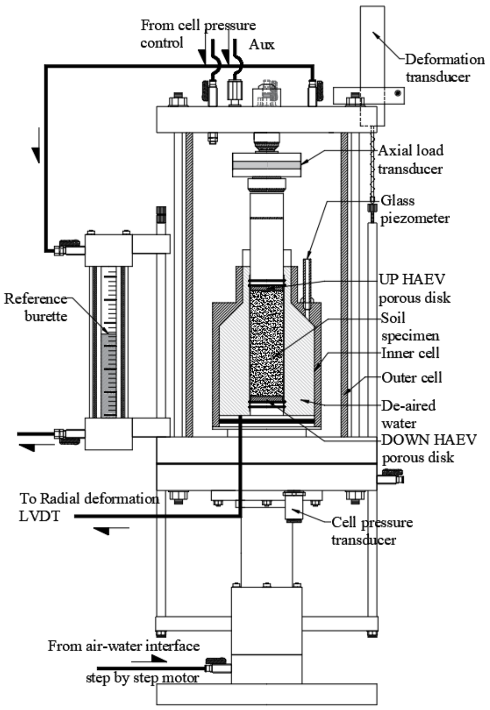

Fig. 2. Triaxial apparatus and components.

2.2 Selected material and test plan

A laboratory testing program was developed in order to study the effect of loading rate during the isotropic compression stage and the effect of the shearing stress rate during the deviatoric stage of the triaxial test in the shear resistance of each sample. The layout of the testing program is shown in Table 1.

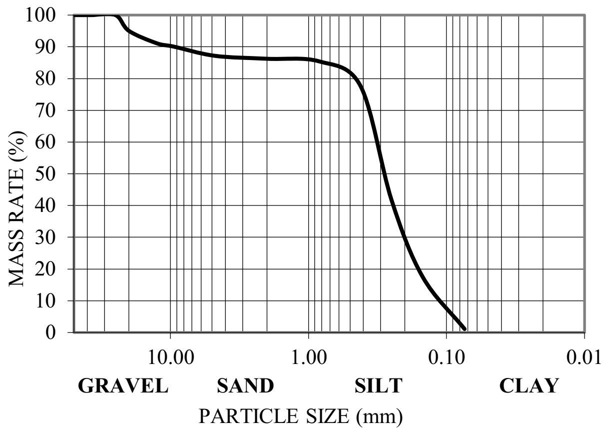

Fig. 1. Particle size distribution graph.

Table 1. Tested soil properties

USCS Classification symbol	SM
Specific gravity, G_s	2.67
Water percentage, %w	8.00%
Void ratio, e	0.52
Saturation, S	40.80%
Density, γ_w	19.44 kN/m^3
Dry Density, γ_D	18.00 kN/m^3
Optimum wet percentage, %w	7.70 kN/m^3

The tested soil is classified as silty sand (SM) according to the Unified Soil Classification System (USCS) from the region of Sucre, Bolivia. Figure 1 describes its particle size distribution. The laboratory testing on the selected material specified in this research involved unsaturated triaxial compression tests under different values of controlled matric suction.

Table 2. Summary of testing plan

	Matric Suction (kPa)	**Mean net stress (kPa)**	**Loading rate (kPa/h)**	**Strain rate (%/h)**
Isotropic compression stage	15	200	32	---
			128	
	45	200	32	---
			128	
Deviatoric stage	15	200	32	0.5
				2.50
	45	200	32	0.5
				2.50

2.3 Sample preparation

The triaxial tests were performed on reconstituted compacted samples. Attempts were made in order to prepare identical soil specimens for each test with the purpose of evaluating and comparing volume variations and stress-strain relationships at different loading rates.

The undercompacting procedure for specimens was selected according to Ladd (1978) [9], in order to minimize the number of uncertainties and to benefit from more consistent test results and repeatability from each compacted sample.

The specimen has dimensions of 38m of diameter and 76mm of height, was compacted in five layers on a stainless-steel mold, by means of a 25mm diameter plunger and a drop height of 15cm. For each layer, 25 blows were considered. Careful inspections were made to the specimens after to identify any possible interfaces between each layer of compaction. A target wet content of 8% was used for the tests.

2.4 Equalization stage

Once the sample has been completely compacted and removed from the steel mold. Then the specimen is mounted on the base of the triaxial device on top of the presaturated HAEV ceramic disk. The procedure for saturation of the disks is described by Fredlund et al. (2012) [10]. Afterwards the sample is properly sealed and attached to the top HAEV disk like is shown in the Figure 2. Finally, degassed water is poured into the inner cell to measure volume variations of the sample during the test with the use of a LVDT and a reference to record any fluid variations.

The target matric suction is then imposed by means of the axis-traslation technique (15 and 45kPa). The saturated attached water pressure lines and the base of the pedestal are regularly flushed using a peristaltic pump to dissipate air diffused bubbles from the bottom HAEV disk. Equalization is considered to be completed when the total volume of flowing water through the sample is lower than 0.04% per day. Thanks to the double drainage system of the triaxial device, equalization was achieved in 3-4 days.

2.5 Isotropic consolidation

Once constant matric suction conditions have been obtained, the sample is then isotropically consolidated from its initial value of mean net stress (50kPa) to the desired final target stress (200kPa) at constant loading rates of 32 and 128kPa. Constant deviatoric stress of 5 kPa is applied to avoid collapsing or irreversible volume changing of the specimen. In order to ensure a complete dissipation of pore water and pore air pressure, each specimen is consolidated for at least 24-48hr. Suction is kept constant during the duration of the stage.

2.6 Shearing stage

Shearing was performed by axially loading the samples at constant rate of strain, similar to a conventional consolidated drained triaxial test. The applied strain rates of 0.5%/hr (slow) and 2.5%/hr (fast) were selected according to previous studies by Rojas (2009). Axial load was monotonically applied to each sample by means of a step-by-step motor. Axial deformation was monitored using a LVDT (Linear Variable Differential Transducer) with a maximum displacement of 25mm. Volume changes during the shearing stage are recorded with a LVDT as the inner water volume is displaced when the sample starts to deform.

3 Test results and interpretation

3.1 Consolidation loading rate effect results interpretation

The experimental data regarding the isotropic consolidation stage of samples and the variations of specific volume can be seen on the Figure 3. The loading rate effect of 32kPa/hr seems to have a slight influence on the specific volume of the 15kPa and 45kPa suction samples. A similar behavior is observed with the loading rate of 128kPa/hr as the variation of specific volume appears negligible on both of the suction values of the specimens. The insignificant effect of loading rate on low suction samples confirms the results obtained by Rojas & Mancuso (2009) [4] under the same suction values and consolidation loading rate on a pyroclastic sand with pumice classified as a non-plastic silty sand (SM).

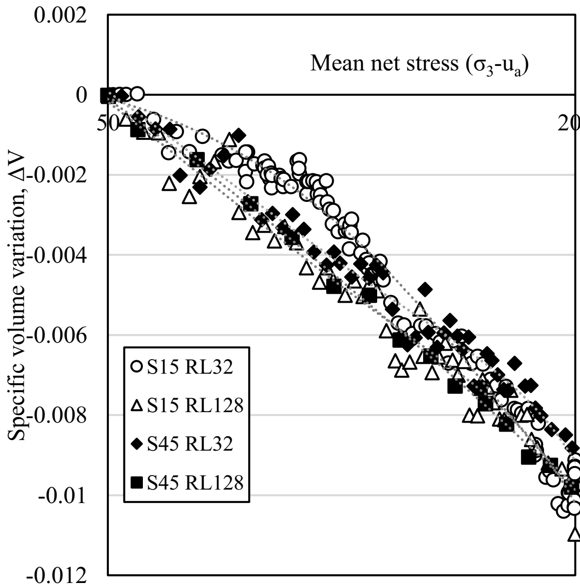

Fig. 3. Specific volume variations at different consolidation loading rates.

Compressibility and preconsolidation parameters of the isotropic compression stages are presented in the Table 3. It is shown that compressibility isn't significantly affected by loading rate, having little difference between the samples of 32kPa/hr and 128kPa/hr. On the contrary, a greater difference is observed when the matric suction is 45kPa instead of 15kPa. Figure 4 displays the difference of specific volume between each suction level and loading rate applied to the samples.

Table 3. Calculated properties from compression stages.

Sample	Preconsolidation pressure p_0 (kPa)	Compressibility $\lambda_{(s)}$
S15 RL32	106	0.0107
S15 RL128	109	0.0105
S45 RL32	118	0.0095
S45 RL128	120	0.0094

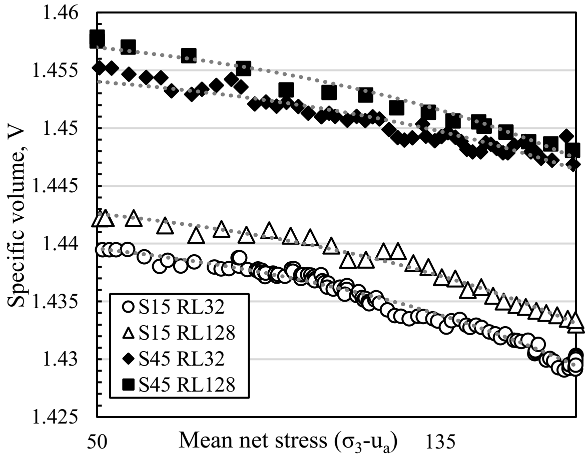

Fig. 4. Specific volume at different consolidation loading rates.

3.2 Stress-strain results interpretation

The Figure 5 presents the deviatoric stress (q) vs the axial strain (ε_a) for reconstituted compacted silty sand specimens during consolidated drained triaxial tests (CD), at constant suctions of 15 kPa and 45kPa. Different values of constant axial strain in the shearing stage of each test, 0.5%/hr and 2.5%/hr, were also considered. The plotted stress-strain curves indicate that strain velocity significantly affects the peak strength, showing a greater increase in shear strength in the samples with a suction of 45kPa (13.3%). The samples with a suction of 15kPa present a variation of 9.5% in peak strength in both strain rates.

On the contrary, results presented by Rojas & Mancuso (2009) [4] from experimental tests at similar suction values and shearing velocities showed a minimal increase in shear strength which could be described by the Author as normal experimental variations. In contrast to the results observed by Patil et al (2014) [6], which showed increased peak shear strengths under faster loading rates of 0.014%/min compared to slower rates of 0.0029%/min. A brittle behavior is observed in the shear-strain graphs as the shear strength suddenly decreases after the rupture of the samples under monotonically axial loading. Generally, the value of axial strain at which the specimens tend to fail is 2-3.5%.

Moreover, larger shear strength variations due to the suction level on the samples under the same values of net confining stress (200kPa) are observed to show an increase up to 97%, comparing the 15kPa and 45kPa suction samples. It can be noted that the samples reached the critical state condition at similar values of axial strain (7-12%).

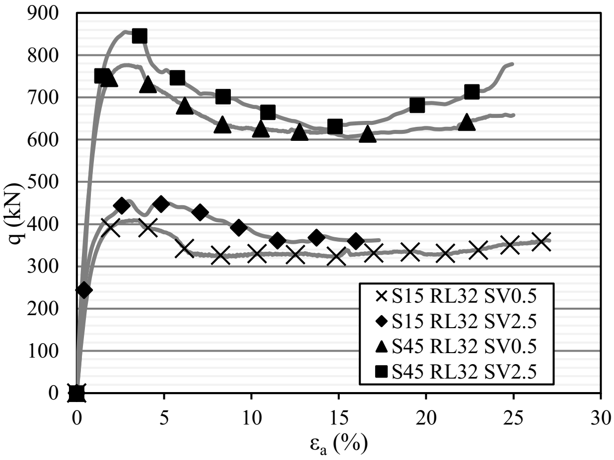

Fig. 5. Shear stress at different axial strain velocities and suction values.

3.3 Volumetric-axial strain results interpretation

As it is observed in the Figure 5, the volumetric-axial strain behavior displays a sudden increase in volume change, indicating the rupture of each specimen during the shearing phase. Volumetric strain jumps are observed at the same axial strain values where the peak shear strength occurs on the tested samples. This volumetric behavior is different to the studies presented by Patil et al. (2014) [6]; Cattoni et al. (2007) [11]; Rojas & Mancuso (2009) [4], indicating a brittle response of the tested soil. The specimens loaded with the fastest strain velocity of 2.5%/hr show greater volumetric changes throughout shearing failure rather than the samples with lower strain velocities (0.5%/hr).

On the other hand, samples with 45kPa of suction show low volumetric strain (ε_v) variations before reaching the shear failure and consequently the sudden increase in volumetric deformation. Volumetric strain behavior shows a slight tendency to dilate during the initial shearing stage of the samples with 15kPa of suction before the peak rupture.

Dilatancy response affected by the shearing rate seem to be higher in the samples with velocities of 2.5%/hr, representing an incomplete pore air and pore water dissipation.

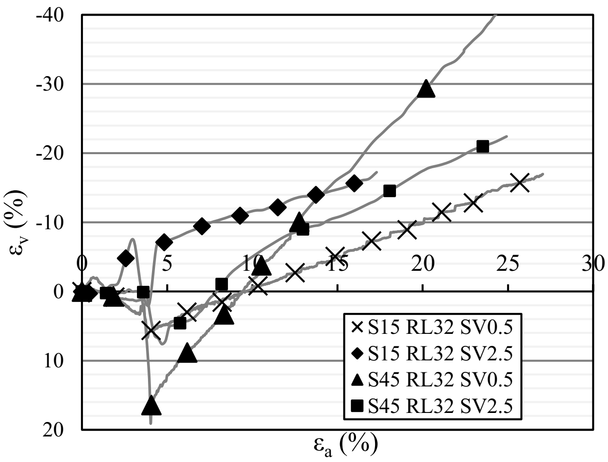

Fig. 6. Volumetric strain under different strain rates during the deviatoric stage.

4 Conclusions

A study of a partially saturated soil from the region of Sucre (Bolivia) is presented and discussed. Triaxial CD tests were carried on reconstituted specimens under constant suctions of 15kPa and 45kPa. Appropriate isotropic loading rates of 32kPa/hr and 128kPa/hr were selected according to previous work by Rojas & Mancuso (2009) [4], under similar suction testing values. Volume changes were measured during each triaxial stage. Results obtained from shearing under different strain velocities of 0.5%/hr and 2.5%/hr made possible the study of the stress-strain behavior of the selected reconstituted material. It is observed that under low suction values of 15 and 45kPa, specific volume variations and compressibility (λ_s) are considered negligible for different loading rates as stated also by former studies by Rojas & Mancuso (2009) [4]. However, the suction level seems to have an increasing effect on the preconsolidation pressure (p_0) and a decrease in $\lambda_{(s)}$ with higher matric suction. This compressibility behavior is consistent with the BBM formulation proposed by Alonso et al. (1990) [12].

Based on the results obtained from the deviatoric stages for the reconstituted material, initial stiffness and peak shear strength are higher on the samples with 45kPa of suction. Comparison between both of the shearing velocities (0.5%/hr and 2.5%/hr) stress-strain graphs showed a significant effect of shearing rate on peak deviatoric shear stress on the samples under constant suctions of 15 and 45kPa. The peak deviatoric stress at 2.5%/hr strain rate is higher than the 0.5%/hr rate. On the other hand, volumetric-axial strain behavior displays a great volumetric change in the same axial strain value as the peak shear strength due to the shear failure, indicating a brittle behavior of each soil sample. The critical state was observed to reach at higher values of axial strain on the specimens with 45kPa of suction compared to the 15kPa samples.

Differences of experimental results under similar constant suction conditions, loading rate and strain rate between former studies by Rojas & Mancuso (2009) [4] can be explained by the properties of the selected tested material, such as the initial void ratio (e), the particle size distribution and mineralogy, as well as the different techniques of sampling preparation.

Acknowledgments

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