# Effect of loading rate on the behaviour of unsaturated soils

## L'effet de charger rate un le comportement de sols non saturés

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ABSTRACT

The aim of this paper is to analyze the influence of loading rate on the observed soil behaviour. To this aim, a series of suction-controlled triaxial tests has been performed on reconstituted specimens of pyroclastic silty sand, including isotropic compression stages and deviator stages performed at different stress-rate and strain-rate, respectively. During the isotropic compression stages the loading rates of 2, 8, 32, 128 kPa/h have been applied under several suction values (i.e. 15, 45 and 300 kPa). The drained deviator stages have been carried out at the same suctions levels under strain rates of 0.25 and 2.50 %/h. No effect of loading rate was registered during isotropic compression stage at low suction values (i.e. 15 and 45 kPa). At higher suction (i.e. 300 kPa), as the loading rate is increased the stiffness of the soil also increases, however, a loading rate value was identified from which an opposite trend was observed. For the strain rates studied on deviator stage, no effect was observed on the soil behaviour.

RÉSUMÉ

L'objectif de cet article est d'analyser l'influence de la vitesse de test sur le comportement observé des sols. Dans ce but, une série de test triaxial a succion contrôlée ont été effectués sur des échantillon reconstituée de sable limoneux pyroclastiques, y compris les stage de compression isotrope et déviante effectuées en utilisant différents vitesse de tension et deformation, respectivement. Au cours des stage de compression isotrope le vitesse de chargement de 2, 8, 32, 128 kPa/h ont été appliquées sous plusieurs succion constante (c'est-à-dire 15, 45 et 300 kPa). Le stage déviatoric drainé ont été réalisées à la même succion à la vitesse de deformation de 0.25 et 2.50%/h. Aucun effet de la vitesse de chargement a été enregistré au cours de phase de compression isotrope à faible niveau de succion (c'est-à-dire 15 et 45 kPa). A la plus haute succion (300 kPa), selon la vitesse de chargement est augmenté la rigidité du sol augmentent également, toutefois, une vitesse de charge a été identifié à partir de laquelle une tendance inverse a été observée. Pour les vitesses de déformation analyse pendant le stage deviatoric, pas d' effet on è été observé sur le comportement des sols.

Keywords : unsaturated soils, suction controlled triaxial test, loading rate

## 1 INTRODUCTION

In recent years the literature papers on unsaturated soil mechanics have hugely increased. However, a gap between theoretical developments and engineering practice still exists. One of the causes of this drawback may be partially ascribed to the long time required for the laboratory measurements of unsaturated soil properties. As a matter of fact, in constant suction tests relative low loading rates are required in order to keep the pore-water pressure increments within acceptable limits. Nevertheless, in unsaturated soils mechanics no recommendations exist on the appropriate loading rate to be adopted, and the selection of the optimal loading or straining rate remains open questions. To contribute to the solution of this unresolved aspect of soil testing, a research program was undertaken at University of Napoli Federico II (Italy) aimed at the experimental analysis of loading rate effect on the mechanical behaviour of unsaturated soils.

## 2 LITERATURE REVIEW

In unsaturated soil testing, continuous loading procedures are the only suitable method for constant suction testing. Constant rate of loading (CRL) and constant rate of strain (CRS) are generally used on compression and shearing, respectively.

One of the most used recommendations in unsaturated soil testing is that from Sivakumar (1993), who suggested to increase the load at a rate such that the excess pore-water pressure in the sample is kept within acceptable limits. Further contributions were given by Cui & Delage (1996), who compared the results of isotropic compression tests on unsaturated soils performed under incremental loading (IL) and continuous loading (CRL). In the IL method the sudden loading induces drastic instantaneous (undrained) decrease of the soil volume due to the compression of the air present in the soil voids. The Authors argued that, due to the mechanical coupling between the pore fluids and the soil skeleton, the undrained loading induced unacceptable increment in pore-water pressure and the test results cannot be associated to the suction level prescribed at the specimen-boundary. Conversely, analysing the data from the CRL tests, Cui & Delage (1996) argued that a better suction control was achieved provided that the selected loading rate was slow enough. The Authors also noticed that the effect of loading procedure is smaller when saturation is approached (i.e. low suction values). Recently, Huat et al. (2006) performed a study to analyze the effect of loading rate on the volume change behaviour of an unsaturated granitic residual soil. The Authors conclude that the loading rate has a pronounced effect on the volume change behaviour of the soil subjected to a given boundary suction. All the above indicate that slow enough loadings have to be selected in order to avoid pore-water pressure built-up causing suction reduction and loss of specimen stiffness. Conversely, reduced loading rates will causes long duration of loading, giving rise to significant creep phenomena, provided that constant net stress strains occur not only after the dissipation of pore-water pressure but during the whole loading process. Thus, additional strain could be observed in the loading stage, making difficult the estimation of proper compressibility soil parameters.

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Some information is available in literature also with reference to CRS shearing of unsaturated soils. The few publications covering this topic, state that inappropriate strain rates have pronounced effect on matric suction and may cause loss of suction effects on the soil skeleton and deviation of the observed behaviour from that expected in constant suction conditions. To select appropriate strain rate avoiding menisci disturbance, Porras Ortiz (2004) conducted deviatoric compression tests at different strain rates. This author performed tests on a silt at low confinement and a relatively high suction in order to generate particularly favourable condition for menisci disturbance. The results show that slower strain rates cause smaller strains. Similar results were obtained by Macari & Hoyos (2001) during drained true triaxial tests performed at different shearing rates on specimens of reconstituted silty sand. The Authors concluded that the higher adopted loading rates are inappropriate since causing menisci break down and loss of matric suction effect on soil skeleton.

Matsushita et al. (1999) studied the dependency of the stress and strain behaviour on strain rate performing saturated drained plane strain compression tests on sands. The Authors observed that for saturated soils the stress–strain relationships were independent of the strain rate even when the rate of straining differs by a factor of 500. Yamamuro & Lade (1993) conducted saturated drained triaxial compression tests on a uniform Cambria Sand. The deviator stresses showed very small increases with increasing strain rate.

Summarizing, in unsaturated soils a fast loading rate may cause menisci rearrangement and, consequently, suction variation. However, as suction decreases the loading rate effect diminishes and becomes negligible in saturated condition.

## 3 TESTING DEVICE

To study the effect of loading rate on the mechanical behaviour of soils, the tests were conducted in the USPv2 (Unsaturated Stress Path, 2nd version) triaxial apparatuses developed at the University of Napoli Federico II by Rojas et al. (2008). This device is a double walled triaxial device capable of testing samples under suction controlled condition and equipped with a double drainage system to reduce the drainage path. The suction is controlled by the axis translation technique. The base platen and the top-cap incorporate a combination of two different porous disks: a peripheral annular porous stone and an internal HAEV ceramic disk (5 bar) connected to the pore-air and pore-water pressure lines, respectively (Figure 1). This configuration allows the air and water drainage from both top and bottom ends and is symmetric about the mid-plane (point A in Figure 1), the flow of water and air being upwards above it and downwards below it. As reported in Rojas et al. (2008), this double drainage system reduced the equilibration time by a factor of 4.4 compared with the previous version of the device developed by Rampino et al. 1997 (having a single water drainage). As a consequence of the double drainage system, the USPv2 allows higher loading rates also during the compression and deviatoric stage with respect to the USP triaxial device.

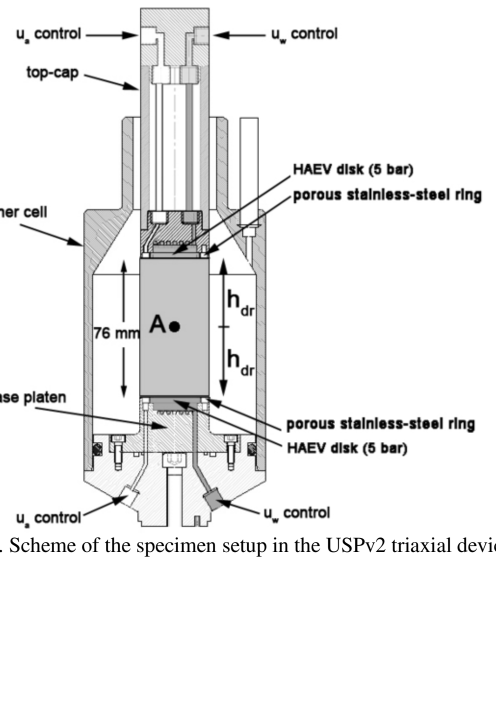

Figure 1. Scheme of the specimen setup in the USPv2 triaxial device.

## 4 TESTED MATERIAL

The soil used for the tests presented in this paper comes from a flow slide in Cava dei Tirreni (Italy). It is a pyroclastic sand with pumice, and corresponds to a non plastic silty sand (SM) in the Unified Soil Classification System. It consists of 60% sand, 30% silt, and 10% clay.

Reconstituted samples have been selected in order to minimize the samples heterogeneity and potentially obtain a more consistent set of data. The main purpose was to produce reconstituted samples of low density as in the case of the undisturbed volcanic soil, which in the Campania region (Italy), are characterized by void ratio ranging from 0.7 to 2.3 (Pellegrino 1967). According to these values, a high void ratio (e) of 1.67 has been selected.

In the tests results discussed in this paper, all the specimens were prepared using the moist tamping (MT) method. The MT method produces very loose unsaturated samples and is suitable to avoid the segregation of fines. The appropriate value of water content was selected after preliminary compaction tests and was selected equal to 28.5%. The moist-tamped specimens were compacted in five layers having identical thickness. The resulting samples (i.e. mold internal dimensions) were 38 mm in diameter and 76 mm in height.

## 5 EXPERIMENTAL PROGRAM

The experimental program includes isotropic compression and deviatoric stages performed at suction levels ranging from 0 to 300 kPa. Testing program is summarized in Table 1.

Isotropic compression tests consist of a total of 10 constant-suction fully drained tests. The tests were conducted in the triaxial device by increasing the net confining stress ($\sigma_3$ – $u_a$) under different constant loading rates. Four loading rates were selected by using a geometric progression with a common ratio of 4 and a scale factor of 2 kPa/h. Then, the generated series was: 2, 8, 32 and 128 kPa/h. The study of unloading paths is beyond the scope of this work.

Table 1. Summary of the testing program

| Test | Suction | Isotropic compression | | Shearing |
|---|---|---|---|---|
| | | Net confining stress [kPa] | Stress rate [kPa/h] | Strain rate [%/h] |
| s15$\sigma_3$660(8) | 15 | 660 | 8 | --- |
| s15$\sigma_3$660(32) | 15 | 660 | 32 | --- |
| s15$\sigma_3$660(128) | 15 | 660 | 128 | --- |
| s45$\sigma_3$600(8) | 45 | 600 | 8 | --- |
| s45$\sigma_3$600(32) | 45 | 600 | 32 | --- |
| s45$\sigma_3$600(128) | 45 | 600 | 128 | --- |
| s300$\sigma_3$375(2) | 300 | 375 | 2 | --- |
| s300$\sigma_3$375(8) | 300 | 375 | 8 | --- |
| s300$\sigma_3$375(32) | 300 | 375 | 32 | --- |
| s300$\sigma_3$375(128) | 300 | 375 | 128 | --- |
| s0$\sigma_3$50S | 0 | 50 | 32 | 0.25 |
| s0$\sigma_3$50F | 0 | 50 | 32 | 2.50 |
| s15$\sigma_3$50S | 15 | 50 | 32 | 0.25 |
| s15$\sigma_3$50F | 15 | 50 | 32 | 2.50 |
| s15$\sigma_3$200S | 15 | 200 | 32 | 0.25 |
| s15$\sigma_3$200F | 15 | 200 | 32 | 2.50 |
| s45$\sigma_3$200S | 45 | 200 | 32 | 0.25 |
| s45$\sigma_3$200F | 45 | 200 | 32 | 2.50 |
| s300$\sigma_3$50S | 300 | 50 | 32 | 0.25 |
| s300$\sigma_3$50F | 300 | 50 | 32 | 2.50 |

To study the loading rate influence on the soil behaviour during deviator stage, 10 drained triaxial compression tests were performed at two different strain rates, 5 for each loading rate.

Based on previous test conducted on similar soils, a constant strain rate of 0.25 %/h was selected as the baseline. Since significant behaviour changes typically arose over logarithmic cycles, a loading rate of 2.5 %/h was selected as representative of high straining rates. These strain rates allows to reach 25 % of axial strain in 100 and 10 h for the slower and higher rate, respectively.

## 6 EXPERIMENTAL RESULTS

### 6.1 *Equalization*

The purpose of the equalization stage was to enable the pore water pressure within the sample to equal the selected back pressure value. All the equalization stages were run under a constant net confining stress ($\sigma_3 - u_a$) of 20 kPa and a deviator stress (q) of about 5 kPa. Such values were selected in order to prevent collapse (i.e. irreversible volume decreases on wetting) and to allow the identification of even low yield stresses in the subsequent compression stages.

The results shown that after compaction the suction is around 45 kPa. As a matter of fact, for suction values less than this value (i.e. 5 and 15 kPa) a flow of water towards the soil occurs (i.e. the water content of the tested specimens increase) while for suction values higher than 45 kPa (i.e. 300 kPa) the water flows in the opposite direction (i.e. the specimen water content decrease).

### 6.2 *Isotropic compression*

Once the specimens were equalized at the specified initial suction (i.e. 15, 45 and 300 kPa), isotropic compression stages were performed up to the required maximum net confining stress ($\sigma_3 - u_a$) while maintaining suction constant at the sample ends. The loading rates applied in the tests were 8, 32 and 128 kPa/h. For the 300 kPa suction series an additional test at a loading rate of 2 kPa/h was also performed.

Figures 2 and 3 shown the experimental data pertaining to the isotropic compression tests on 15 kPa and 45 kPa suction specimens, respectively. As expected in the low suction range, the applied loading rates seem to have an insignificant effect on the variation of the specimen specific volume. The non-effect of loading rate at low suction ranges for the analyzed pyroclastic soil confirms the results obtained for the aeolian silt (Cui & Delage 1996) and granitic residual soil (Huat et al. 2006), respectively. The compressibility indexes obtained for these tests are summarized in Table 2.

Figure 4 shows the data from the isotropic compression tests on 300 kPa suction samples. In contrast with the observations reported in Huat et al. (2006), for the loading rates 2, 8 and 32 kPa/h, the higher is the loading rate the lower is the sample compressibility. The observed behaviour is similar to the data reported by Crawford (1964), where different time intervals were left during incremental loading (IL) oedometer tests performed on saturated Leda clay. The reason for such variation is that as testing time is increased the amount of creep of the specimen is also increased. As a matter of fact, if the presence of a too high rate of loading is postulated, a pore water pressure increases, hence a suction decrease, should be expected during the "high" rate of loading compression tests. If this were the case, an increase of soil compressibility with loading rate must be expected in opposition to what has been observed during the tests. Since creep strains should have developed during all the tests duration, it is quite obvious that for the sample s300$\sigma_3$375(2) compression effects occurred during all the 185 h required to reach the final net confining stress (i.e. ($\sigma_3$ - $u_a$) = 375 kPa). In samples s300$\sigma_3$375 (8) and s300$\sigma_3$375(32), on the contrary, creep deformations are less pronounced due to the significantly smaller time (46 h and 12 h) respectively required to reach the maximum applied isotropic compression stress. However, when the loading rate as fast as 128 kPa/h is applied (test s300$\sigma_3$375(128)), the compressibility increases, showing a soil behaviour opposite to than individuated by the general trend highlighted above. In this case it may be postulated that the excess in pore-water pressure generated during the loading process has significantly reduced the suction value and, due to the relative short time required (3 h) to reach the target net confining stress (375), the creep phenomena are less evident.

As Cui & Delage (1996) suggested, the yield points for the pyroclastic silty sand were determined by the intersection of the initial straight portion and the final straight section of the compression curves (in a net confining stress logarithmic

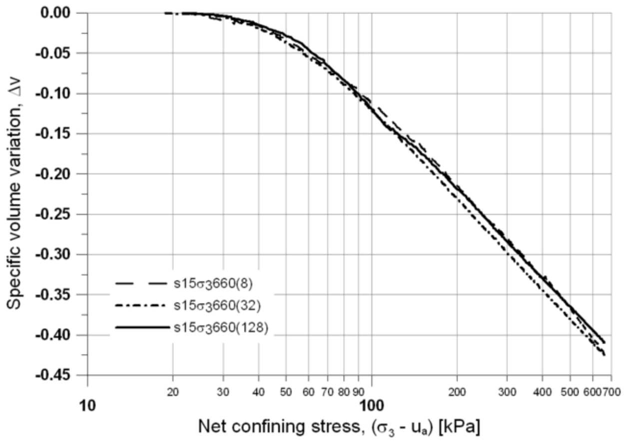


Figure 2. Isotropic compression tests at a constant suction of 15 kPa and at different loading rate (8, 32 and 128 kPa/h).

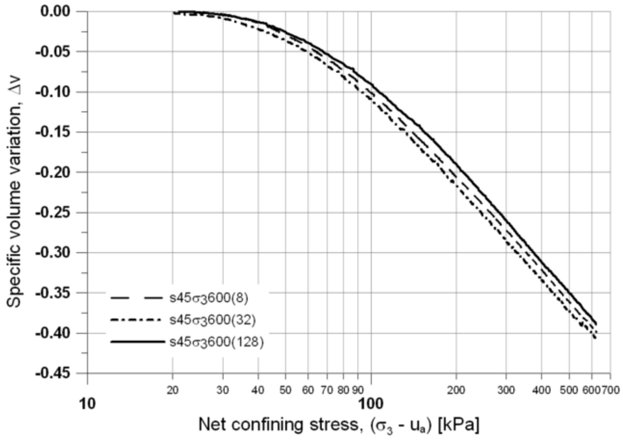


Figure 3. Isotropic compression tests at a constant suction of 45 kPa and at different loading rate (8, 32 and 128 kPa/h).

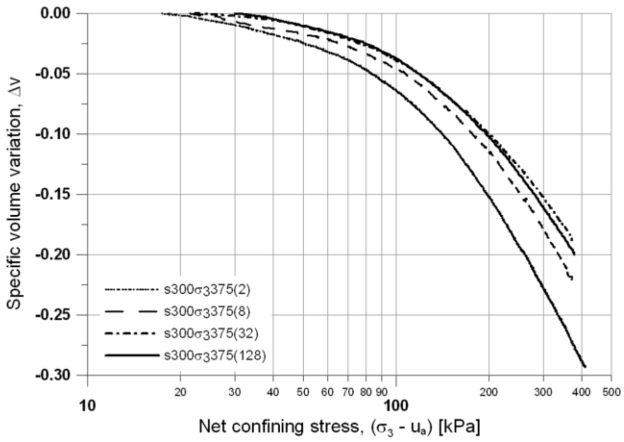


Figure 4. Isotropic compression tests at a constant suction of 300 kPa and at different loading rate (2, 8, 32 and 128 kPa/h).

representation). Table 2 summarizes the obtained yield points (i.e. preconsolidation pressures). The results shows that it is possible to obtain slightly different values of preconsolidation pressure ($p_0$) depending upon the selected strain rate.

Isotropic consolidation tests on unsaturated soils give information on the variation of the compressibility with suction. A summary of the compressibility is presented in Table 2. For suction ranging from 15 to 45 kPa, the compressibility of the tested soil shows relatively little variation with loading rate. However, a significant effect in the value of $\lambda$ is observed when the imposed suction is 300 kPa.

Table 2. Main parameters obtained from the isotropic compression tests.

| Test | Preconsolidation pressure $p_0$ [kPa] | Compressibility $\lambda(s)$ |
|---|---|---|
| $s15\sigma_3 660(8)$ | 58 | 0.168 |
| $s15\sigma_3 660(32)$ | 51 | 0.163 |
| $s15\sigma_3 660(128)$ | 58 | 0.161 |
| $s45\sigma_3 600(8)$ | 70 | 0.170 |
| $s45\sigma_3 600(32)$ | 60 | 0.169 |
| $s45\sigma_3 600(128)$ | 73 | 0.175 |
| $s300\sigma_3 375(2)$ | 107 | 0.206 |
| $s300\sigma_3 375(8)$ | 118 | 0.190 |
| $s300\sigma_3 375(32)$ | 110 | 0.153 |
| $s300\sigma_3 375(128)$ | 113 | 0.160 |

### 6.3 *Deviatoric stage*

To bring the soil specimens at the desired stress states, suction equalization and isotropic compression stages were carried out prior to shearing. In particular, the specimens were initially equalized at the specified initial suction imposed at the ends of sample and then isotropically loaded at 32 kPa/h. The following deviatoric stages were conducted at constant net confining stress. Details on the initial stress state of the specimens and the adopted straining rates are again summarized in Table 1.

As indicated in Figure 5, the tests at low net confining stress (50 kPa) and slower loading rate (i.e. 0.25 %/h), show slightly lower ($s0\sigma_3 50S$ and $s15\sigma_3 50S$) or similar ($s15\sigma_3 50Sa$ and $s300\sigma_3 50S$) deviatoric stress compared to the higher loading rate (i.e. 2.5 %/h). The test $s45\sigma_3$ 200S carried out at high net confining stress (200 kPa) and slow loading rate, shows a slightly higher peak deviatoric stress than test $s45\sigma_3 200F$ (Figure 10). The variations in the quantities obtained for the drained triaxial tests at different loading rate, however, are very small and may be ascribed to a normal experimental scatter. In contrast to the data reported by Macari & Hoyos (2001) and Porras Ortiz (2004), which observe that fast loading rate cause suction variation (i.e. stress-strain response variation), the effect of loading rate during drained triaxial tests conducted on the pyroclastic silty sand appears to be negligible.

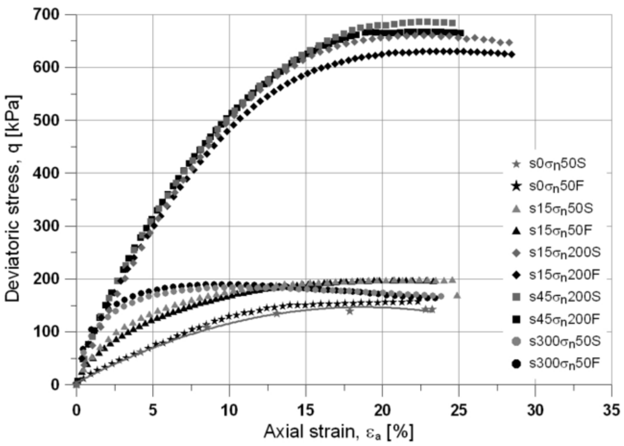


Figure 5. Drained shearing tests at different constant suction (0, 15, 45 and 300 kPa), at diverse effective confining pressure (50 and 200 kPa) and different loading rate (slow = 0.25 %/h and fast = 2.5 %/h).

## 7 CONCLUSIONS

The study of loading rate effect on partly saturated soils is important to determine a proper rate of loading allowing "true" constant-suction tests. A total of 20 tests (isotropic compression and deviatoric compression) were performed on a Pyroclastic non plastic silty sand, to analyze the loading rate effect.

The applied loading rates at low suction values (15 and 45 kPa) seem to have an insignificant effect on the specific volume variations. The effect on preconsolidation pressures is not negligible, but relatively small. When suction value is increased to 300 kPa, the tested pyroclastic soil showed rate of loading dependent behaviour. For loading rates of 2, 8 and 32 kPa/h, the higher is the rate of loading the lower is the sample compressibility. The reason of such variation is ascribed to the reduction of creep deformations induced by the testing time decrease with respect to the increase of the pore-water pressure (i.e., suction reduction) caused by the higher stress rates. On the opposite, when the rate of loading is increased to 128 kPa/h, the excess of pore-water pressure generated during loading process reduces the suction value acting inside the specimen making the soil softening phenomena prevailing on the creep ones. The above observations also induce slightly different values of over-consolidation pressures observed during the tests performed at different loading rate. In conclusion, the determination of an appropriate loading rate that ensures constant suction condition throughout the entire test by testing different loading rates is hinder by the coupled effect of suction reduction and creep phenomena. The results clearly point to the need for further studies where pore-water pressure changes are monitor at the middle point of sample (point A in Figure 1) to determine an appropriately loading rate that ensures non menisci disruption.

Finally, the effect of loading rate on the soil behaviour during unsaturated drained deviatoric stages appears to be negligible for the tested material. This conclusion is based on the strain rates applied and the suctions imposed.

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