Influence of saturation degree on soil liquefaction behavior

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ABSTRACT
Among damages potentially caused by an earthquake, liquefaction is one of the most dangerous. Many authors have already studied soil liquefaction. However, many damages are still caused by this phenomenon, showing that some parameters are not fully controlled nor understood yet. For instance, according to the normative acts, if the soil is not fully saturated, the risk of liquefaction should not be considered. Some studies have already shown that a soil could liquefy, even when its saturation degree is below 100%. However, those studies are few, and most of them only take into account the pore fluid compressibility of the unsaturated soil. Effects of suction are most of the time neglected. The aim of the present experimental work is to study mechanical behavior of sand under cyclic loading, considering variation of initial saturation state. What are the factors involved in those complex mechanism? Influence of initial suction value and distribution pattern of the air phase is of interest. Cyclic triaxial tests have been performed on Fontainebleau sand samples, under various initial state of saturation. A special equipment was developed in the laboratory to study unsaturated soil behavior. A high air entry porous stone and a water column device were added to the classical Bishop and Wesley cell. These experimental devices enable suction's control and measurement. The soil-water characteristic curve was obtained in the laboratory using the filter paper method. It was then used to connect suction to saturation degree. Local LVDT sensors allow a complete volumetric strain monitoring during cyclic loading. The first results confirm that liquefaction can arise even when the soil is not fully saturated. Although the presence of air enhances the material's mechanical properties, it does not prevent the liquefaction to occur.

1 INTRODUCTION

1.1 State of the art

Liquefaction phenomenon has been of a primary interest for many authors among the geotechnical engineering community within last few decades. Events such as the 2011 off the Pacific Coast of Tohoku Earthquake (Tsukamoto et al., 2013) reinforced the strong concern of scientists to study those complex mechanisms.

In spite of the theoretical and experimental advances realized on the understanding of liquefaction, dramatic damages are still regularly observed on various seismic areas (Yasuda et al., 2012 ; Unjoh et al., 2012 ; Adalier et al., 2000 ; Ramakrishnan et al., 2006) highlighting the fact that some features are not fully understood yet.

Liquefaction can be triggered under any dynamics excitation, such as earthquakes, and results in the buildup of pore-water pressure within the granular material (Seed and Idriss, 1982 ; Michallet et al., 2009). In practice, the potential of liquefaction of any soil layer is evaluated only if some conditions are filled, among which the complete soil saturation. As a result, and according to normative regulation, soils above the water table are never considered as liquefiable.

However, most of the shallow soils, meaning exposed to liquefaction risks, are unsaturated. It is proved by Fredlund and Rahardjo (1993) that in most of geotechnical engineering applications, we are dealing with unsaturated soils, through negative pore pressure field measurements using tensiometers. Moreover, occluded air bubbles can be found within soil layers up to 5 meters below groundwater table (Tsukamoto et al., 2014).

Two major features strongly differentiate unsaturated and saturated soils behavior; the suction enhances mechanical properties by developing intergranular forces within the material. Air as a pore fluid tends to absorb excess of pore pressures.

Several authors worked on liquefaction instability of partially saturated sands. Okamura and Soga (2006) performed undrained triaxial tests on Toyoura sand, using a classical triaxial apparatus. The experimental device did not benefit of any adaptation regarding unsaturated soils specificities. They showed that decreasing the saturation degree (Sr) leads to better liquefaction resistance. However, they focused their study of the pore fluid compressibility, systematically neglecting effects of suction.

Kamata et al. (2007) presented triaxial tests on unsaturated Toyoura sand, using the axis translation technique to impose initial suction conditions. During the cyclic shearing, the water was kept undrained, while the air valve was left open. They tested a large range of saturation degree, from 12% to 67%. In these conditions, they showed that liquefaction of unsaturated Toyoura sand was unlikely to occur.

Kazama and Unno (2007) performed triaxial tests on a volcanic sand, using the axis translation technique. The samples were submitted to a cyclic shearing, under total undrained conditions (water and air). They also explored a wide range of initial unsaturated conditions, from Sr = 43% to Sr = 100%. They define the liquefaction state for unsaturated conditions with the same concept that for saturated soils, meaning when the effective stress as defined by Terzaghi becomes zero. They observed liquefaction for every tested samples, regardless the initial saturation degree. However volumetric behavior, potentially strongly affected by the presence of air was not under interest in this study.

Tsukamoto et al. (2014) examined the cyclic behavior of unsaturated silty sand, through suction-controlled triaxial tests using the axis translation technique. The cyclic loading was applied under strain-controlled conditions. They showed that liquefaction was unlikely to occur under a range of initial saturation degree from 40% to 70%.

Unno et al. (2006) investigated the role of suction on the cyclic behavior of unsaturated volcanic sandy soils, through strain-controlled triaxial tests associated to axis translation method for imposing initial suction conditions. An indirect measurement of pore air pressure was conducted during the cyclic shearing. Their results gave birth to a very interesting and original conclusion: the air entry value of the material would be a key parameter in the liquefaction mechanism of unsaturated soils. For the samples with initial suction below the air entry value, liquefaction was observed. While for samples initially submitted to suction higher than air entry value, no liquefaction was observed. However, as far as we know, those results have not been confirmed by any other author.

1.2 Objectives of the study

Through the state of the art, it first appeared that investigation of cyclic behavior under various saturation conditions is complex. Many studies focused on the effect of pore fluid compressibility, but neglecting suction, which is a key parameter in unsaturated soils behavior. Other studies investigated the role of suction, but without a real interest on volumetric behavior.

It appeared that very low degree of saturation is unlikely to give rise to liquefaction occurrence within granular materials, and various studies have already proved it. However, few experimental laboratory studies have been published on the region close to saturation, and it seems to be of major interest. It seems that the distribution pattern of the air and water phases are of a major importance regarding liquefaction behavior of granular materials.

Finally, considering the complex theoretical frame of unsaturated soils mechanics, definition of liquefaction state for partially saturated conditions can be discussed.

The objectives of this study is to explore cyclic behavior of fine sand, under various initial conditions of saturation. Considering the previous studies listed above, we centered our interest on a narrow range of initial saturation conditions. Three state of saturation are defined and investigated: (1) Totally saturated state: only one pore fluid, water. (2) Nearly-saturated zone: suction is negligible, but pore fluid is compressible. Air phase consists of dissolved/occluded air bubbles. (3) Unsaturated zone: suction is positive, air phase is continuous.

The influence of air entry value on liquefaction potential will be examined. In this study, thanks to specific devices, both suction and volumetric behavior are under interest.

2 EXPERIMENTAL DEVICES AND TESTING PARAMETERS

2.1 Experimental device

Specific adjustments of the classical triaxial cell were developed in the laboratory, in order to study mechanical behavior of unsaturated sand samples.

2.1.1 Negative Water Column device

Buckingman (1907) is one of the pioneers in the use of negative water column technique to measure the relationship between capillary potential and water content, meaning the Soil Water Retention Curve (SWRC). Then Richards (1928) or Haines (1930) improved the experimental device, and extended its field of application (Vanapalli et al., 2008). In this study, a negative water column device was developed and adapted in order to impose initial suction condition to the samples. It consists of a double cylinder, as shown on Figure 1. The outer cylinder is filled with water and connected to the lower base of the sample, while the inner cylinder permits the measurement of the water volume going out of the sample during equilibration phase.

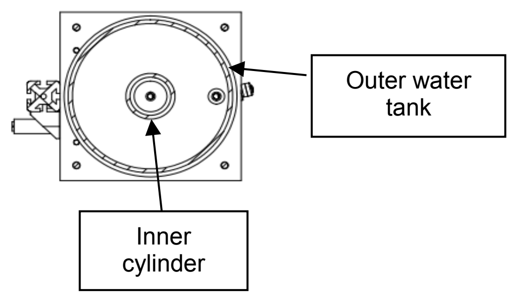

Figure 1 : Top view of the Negative Water Column device

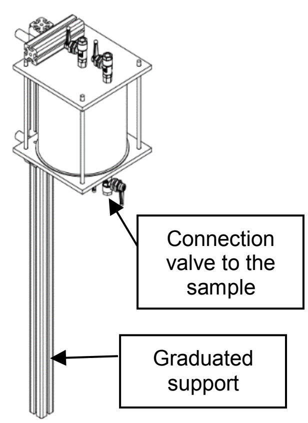

Figure 2 : Side view of the Negative Water Column device

The suction, $s=u_a-u_w$ is applied by varying the height of the tank. The upper valve of the sample is left open during equilibration phase, so the pore air pressure is considered atmospheric.

2.1.2 Local displacement measurement

The volumetric behavior of the samples is studied thanks to local LVDT sensors, directly glued on the membrane (Figure 3). Two axial and one radial sensors permits the calculation of volumetric strains all along the saturation and loading phases.

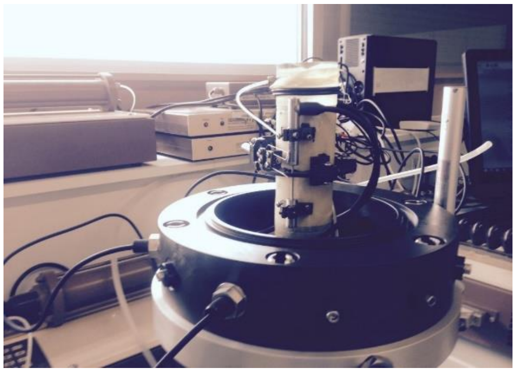

Figure 3 : Triaxial sample equipped with local sensors, before testing

2.2 Testing parameters

2.2.1 Tested material and initial state conditions

The tested material is a fine clean sand, known as Fontainebleau sand. Samples are reconstituted in laboratory with the wet tamping method, in order to satisfy low-density criteria (e=0.85). Minimum and maximum void ratio are e_{min} = 0.54 and e_{max} = 0.94. Initial effective confining pressure is the same for every sample, and equals σ'_c = 100kPa.

The SWRC (Figure *4*) was obtained in the laboratory using the filter paper method (ASTM Standards; Bicalho et al. 2007). The model curve arises from Brooks and Corey equation (Brooks et al., 1964).

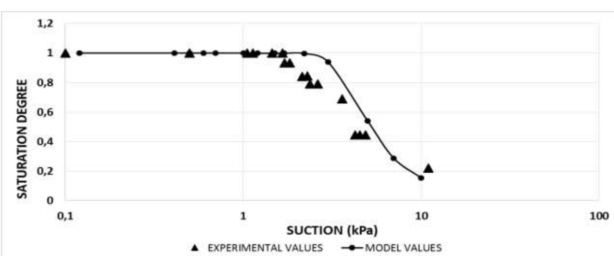

Figure 4 : Soil Water Retention Curve of Fontainebleau sand, experimental values and Brooks and Corey's equation values

The range of initial saturation state tested is narrow, chosen as to be centered on the air entry suction value s_e of Fontainebleau sand (s_e = 2kPa).

Table *1* summarizes samples initial conditions.

Table 1: Tested samples characteristics

Test name	Id	Saturation Degree (%)	Initial suction (kPa)
Test_Sat1	0.22	1	0
Test_Sat2	0.22	1	0
Test_Unsat1	0.10	95	-
Test_Unsat2	0.22	86	3

2.2.2 Loading parameters

The loading is applied with a 0.017Hz frequency. This frequency was chosen slow enough to allow the measurement of pore pressure during the loading. The cyclic loading is stress-controlled and purely compressional, with a deviatoric stress lying from 50kPa to 300kPa. The level of applied stress was calculated according to Seed and Idriss recommendations (Seed et al., 1971), to fit with real seismic conditions.

The drainage conditions are of major importance when studying liquefaction instability. It is usually considered that during an earthquake, the loading frequency is so high that water drainage cannot be fully ensured. That is why when studying liquefaction instability in laboratory, saturated samples are usually submitted to undrained triaxial loading.

There are two different ways in performing triaxial tests on unsaturated soil samples. The first way is to perform pore-water undrained and pore-air drained tests. The second way is to prohibit any drainage, for water and air. The first type of tests was already explored by different authors like Kamata et al. (2007). During an earthquake, as written before, it is considered that water cannot be drained. It is related to soils permeability. Assuming that soils air permeability is unlikely to be much higher than soils water permeability, we considered that if water cannot be drained, air cannot either. As a result, we chose to perform both pore-water and pore-air undrained tests. The evolution of pore-pressure is measured from the bottom and top of the sample.

3 RESULTS

3.1 Highlighting the triggering of instability and liquefaction state for totally saturated sample

Liquefaction instability can be qualified by studying various key parameters.

Figure 5 shows evolution of deviatoric stress with number of loading cycles. Instability is detected after 5 cycles, when the shear stress starts to decrease. After 12 cycles, the sample has lost almost entirely its shear strength.

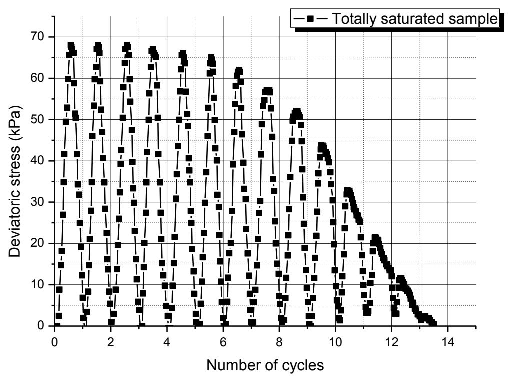

Figure 5 : Evolution of deviatoric stress with number of cycles - Totally saturated sample (Test_Sat1)

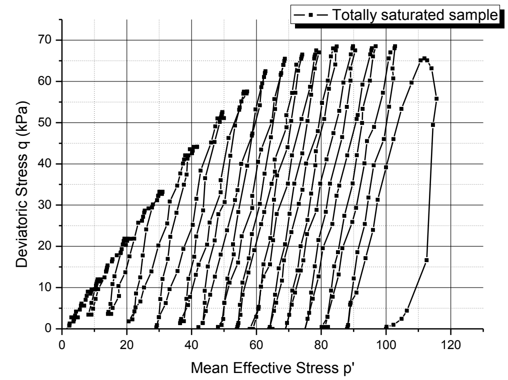

Figure 7 : Stress path - Totally saturated sample (Test_Sat1)

Figure 6 shows evolution of axial strain of the sample under cyclic loading. For the first 5 cycles, the axial strain remains very small, under 0.5%. Suddenly after 5 cycles, at the same moment of the loss of shear strength, the axial strain quickly develops, and finally reaches 5.5%, when the sample entirely liquefied.

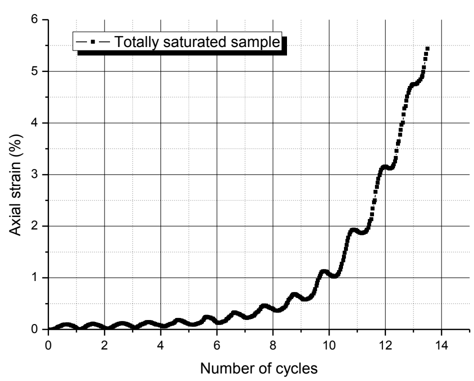

Figure 6 : Evolution of axial strain with number of cycles - Totally saturated sample (Test_Sat1)

Stress path (Figure 7) highlight typical liquefaction instability behavior, meaning: after 5 cycles under constant deviatoric stress, and decreasing mean effective stress, due to increase of pore water pressure, the effective stresses decrease dramatically, until reaching origin of the axes. The sample has liquefied.

Finally, liquefaction can be qualified as the annulment of effective stress, as defined by Terzaghi (Terzaghi, 1943) under the assumption of a totally saturated soil:

$$\sigma' = \sigma - u \qquad [1]$$

with σ' effective stress, σ total stress and u pore water pressure.

Under cyclic loading, pore water pressure u increases, as it is shown on Figure 8. When pore water pressure equals confining pressure, the liquefaction state has been reached.

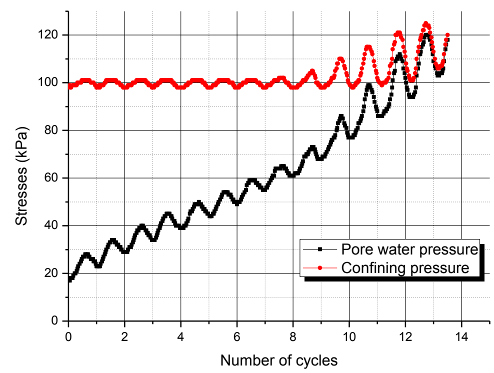

Figure 8 : Evolution of pore water and confining pressure with number of cycles - Totally saturated sample (Test_Sat1)

Through this paragraph, we presented typical cyclic undrained triaxial tests results on sand samples. Liquefaction instability can be detected through the loss of shear strength of the sample, quantified by deviatoric stress, and strong development of axial stain. Liquefaction state is presented here as the annulment of effective stress. This concept, introduced in Soils Mechanics by Terzaghi is very well adapted for saturated soil, but not relevant when considering unsaturated sample. It is then interesting to consider liquefaction instability not only in terms of pore pressure increase, but also in terms of strain rate as presented in next section.

3.2 Influence of pore fluid compressibility

Second part of this experimental work focuses on the comparison between totally saturated sample and nearly-saturated sample. In this latter phase, it is assumed that air phase consists of dissolve or occluded air bubble. Meaning that suction is negligible.

In this paragraph, two samples are compared: one is totally saturated (Sr = 1), and the other is initially nearly saturated (Sr = 0.95). According to the SWRC, the initial suction corresponding to this saturation degree is almost 0kPa. As a result, we considered that under those conditions, effects of suction are negligible. No initial suction was imposed to the sample. The initial saturation state was obtained by varying the time of circulation of de-aired water through the sample during the saturation phase. The Skempton coefficient B was measured, and linked to saturation degree thanks to a model developed in our laboratory (Morvan et al. 2016). Through these tests, we want to demonstrate the influence of pore fluid compressibility inherent to nearly saturated state of soils.

Figure 9 presents evolution of pore pressure during cyclic loading, for the two considered samples. It shows that the presence of air as a pore fluid delays increase of pore pressure within granular material. As a matter of fact, pore fluid compressibility inherent to nearly saturated conditions does improve soils properties toward liquefaction risks. However, after 80 cycles, for the two samples, pore pressure equals confining pressure.

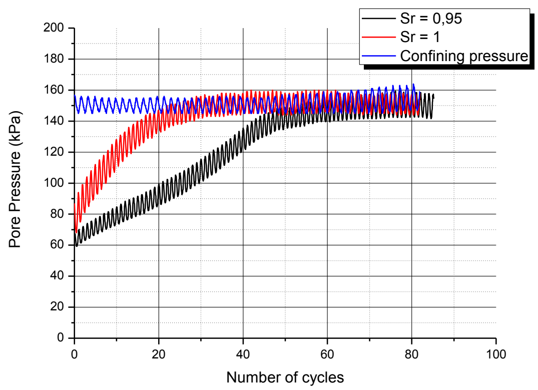

Figure 9 : Evolution of pore water pressures and confinig stress with number of cycles - Comparison between Sr = 1 (Test_Sat2) and Sr = 0.95 (Test_Unsat1)

Since it is difficult to qualify liquefaction state through effective stress concept for nearly saturated soil, and not relevant for unsaturated soils, we propose another definition of liquefaction instability, in terms of axial strain rate. It is, moreover, usually used in liquefaction studies (Vaid et al., 1983). A typical strain criteria for which we consider liquefaction instability triggered is 5%.

Figure 10 presents evolution of axial strain with number of cycles. We see that 35 cycles are needed to reach this strain for the totally saturated sample, while 53 cycles are required for the nearly saturated sample. It shows that air as a pore fluid has a positive effect on axial strain development for sand submitted to cyclic loading. Nevertheless, after 80 cycles, the two samples have reached the same strain rate (18%).

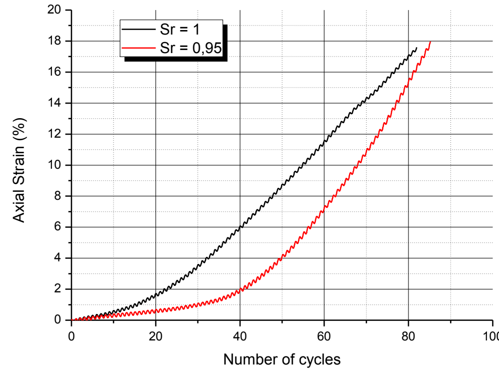

Figure 10 : Evolution of axial strain with number of cycles - Comparison between Sr = 1 (Test_Sat2) and Sr = 0.95 (Test_Unsat1)

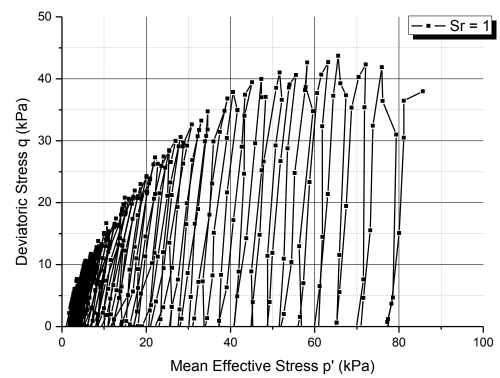

Figure 11 : Stress path - Sr = 1 (Test_Sat2)

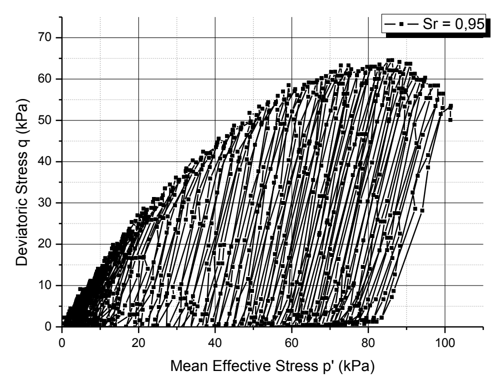

Figure 12 : Stress path - Sr = 0.95 (Test_Unsat1)

When looking at the stress paths (Figure 11 and Figure 12), two mains conclusions can be drawn. First, it clearly appears that decreasing saturation from 1 to 0.95 causes modification of mechanical behavior. While totally saturated sample quickly loses shear strength, nearly saturated sample maintains a higher resistance level (in terms of deviatoric stress and mean effective stress). It also appears that a greater number of cycles are counted when decreasing saturation degree before triggering of instability happens. However, the second main conclusion is that the two stress paths eventually migrate to the origin of the axis, regardless initial state of saturation.

Through this paragraph, we confirmed that decreasing saturation degree leads to better mechanical performance toward liquefaction behavior. Indeed, a higher number of cycles was needed to trigger instability for nearly saturated sample than for totally saturated sample. But, we also showed that liquefaction instability is observed for the two tested sample, wether the material was initially totally saturated or not. In this paragraph, only pore fluid compressibility was a variant parameter between the two tested samples. It seems that change in pore fluid compressibility, due to presence of dissolve air tends to delays consequences of liquefaction, but does not prevent from the risks. Next paragraph will investigate effect of suction on the mechanical behavior.

3.3 Influence of positive initial suction value

Third part of this experimental work deals with influence of initial suction state within granular material. Indeed, contrary to the previous paragraph, it is assumed in this part that air phase is continuous, since positive value of suction is applied to the sample. The distribution pattern of air and water phases is then different from the previous tests presented above. It is also noteworthy that the sample presented in this section (Test_Unsat2) has an initial suction value of 3kPa, that is higher than the air entry suction value of the Fontainebleau sand.

The loading conditions for this sample are the same than for previous samples, except that incremental steps of loading were performed on the sample, so as to investigate evolution of various parameters with increase of the applied shear stress.

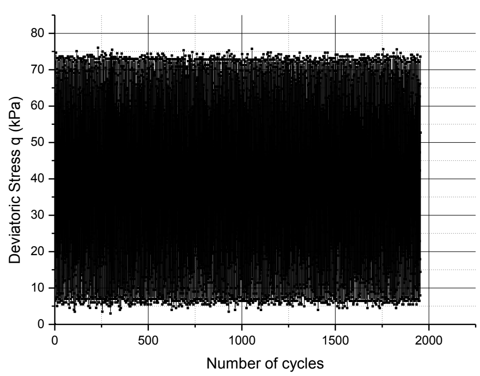

Figure 13: Evolution of deviatoric stress with number of cycles - First loading Step q = 70 kPa – Sr = 86%, s_i = 3 kPa (Test_Unsat2)

First step of cyclic loading is presented on Figure *13* and Figure *14*. It shows that contrary to previous samples (Test_Sat1, Test_Sat2 and Test_Unsat1) the deviatoric stress remains constant under the cyclic loading. No triggering of instabilities is observed, even after a large number of cycles. At the same time, axial strain remains very low, (1.3% after 1900 cycles). It highlights the fact that under the same level of stress applied, the initial suction of 3kPa magnitude within the granular material increases dramatically its shear strength and its stiffness. During this first step of loading (q = 70kPa) the suction remained constant, at its initial value of 3 kPa.

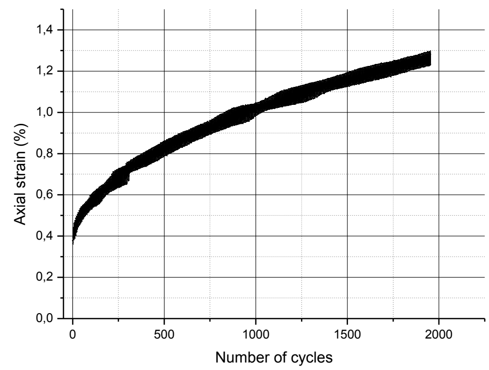

Figure 14: Evolution of axial strain with number of cycles - First loading Step q = 70 kPa – Sr = 86%, si = 3 kPa (Test_Unsat2)

In total, 7 loading steps were applied to the sample, from 70kPa to 310 kPa as described in Table *2*. Figure *15* shows evolution of deviatoric stress with number of cycles for the complete set of loading steps.

Table 2: Description of applied loading step - Test_Unsat2

Loading Step	Applied Deviatoric Stress (kPa)
1	70
2	100
3	130
4	200
5	240
6	270
7	310

It appears that until 200 kPa (Step 4), the sample's properties are not dramatically altered by the cyclic loading. But after reaching the 240 kPa step (Step 5), it seems that instability is triggered. As a matter of fact, deviatoric stress controlling condition cannot be reached, and stress starts to decrease, meaning that the sample loses its shear strength.

Axial strain evolution (Figure *16*) confirms what was previously observed; while Steps 1, 2 and 3 do not cause large strains to the sample (not greater than 4%), step 4 (q = 200 kPa) marks the beginning of the large deformation state. At the end of Step 4, axial strain has reached 8%. After 13000 cycles (Step 5), axial strain rate changes. Deformation develops strongly and quickly, which is a sign of high instability.

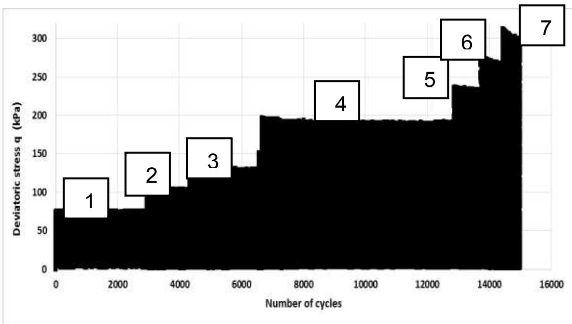

Figure 15: Evolution of deviatoric stress with number of cycle - Complete Step-Loading Test - Sr = 86%, s_i = 3 kPa (Test_Unsat2)

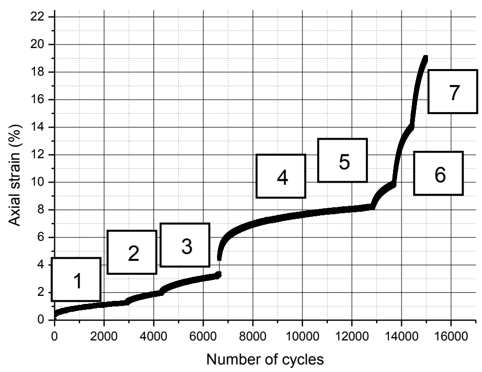

Figure 16: Evolution of axial strain with number of cycles - Complete Step-Loading Test - Sr = 86%, s_i = 3 kPa (Test_Unsat2)

In parallel, as can be seen on Figure *17*, volumetric strain progresses under the cyclic loading. Contrary to axial strain, volumetric strain develops continuously and regularly as the stress is increased. It confirms the effect of pore fluid compressibility on unsaturated soils samples, since volumetric strain reaches a high rate of 6%. Around 13000 cycles (Step 5), when the instability was previously noticed in terms of shear strength and axial strain, volumetric strain witnesses a bifurcation point, since the sign of the volumetric variation changes. We can imagine that after 13000 cycles, diffuse air within pore fluid has reached its maximum deformation under the cyclic loading. Pore fluid compressibility has no longer positive influence, and instability is triggered. As a result, volumetric strain decreases, the pore fluid becomes "less compressible" but the volumetric behavior remains contractive.

Concerning pore pressure evolution, Figure *18* shows evolution of pore water pressure, measured from the high air entry value porous stone. From -3kPa (initial suction of 3kPa, marked (1) on Figure *18*) it increased until reaching 0kPa, meaning that suction is canceled under the cyclic loading (marked 2 on Figure *18*). But pore water pressure never builds up higher than 0kPa, like was observed for the previous sample (Test_Sat1, Test_Sat2 and Test_Unsat1). Bishop and Blight (Bishop et al., 1961) proposed a enlarged effective stress :

$$\sigma'' = \sigma - u_a + s.Sr(u_a - u_w) \qquad [2]$$

With σ'' enlarged effective stress, σ total stress, u_a and u_w pore water and air pressure respectively, *s* suction and *Sr* saturation degree.

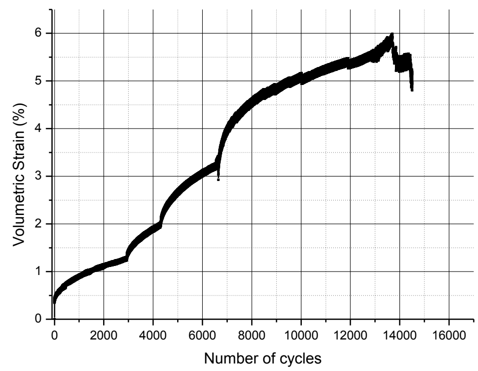

Figure 17: Evolution of volumetric strain with number of cycles - Complete Step-Loading Test - Sr = 86%, s_i = 3 kPa (Test_Unsat2)

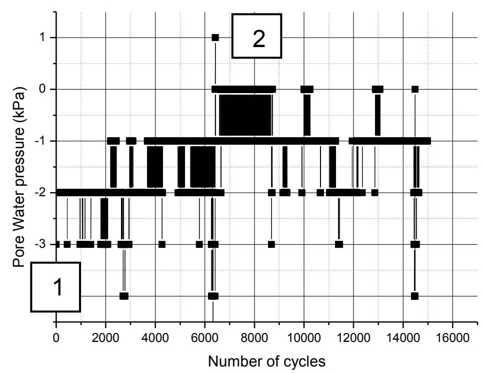

Figure 18: Evolution of pore-water pressure with number of cycles - Complete Step-Loading Test - Sr = 86%, s_i = 3 kPa (Test_Unsat2)

As a result, liquefaction as annulment of enlarged effective stress has not been observed for this sample, but instability (large strain and decreasing of shear strength) has been observed though.

As a conclusion, it was shown that a major difference in liquefaction behavior is observed between totally, or nearly saturated samples and unsaturated sample. It confirms that air entry suction value, and distribution pattern of the air phase may be a key parameter in cyclic behavior of sand.

4 CONCLUSIONS

Through this experimental work, influence of saturation degree on cyclic behavior of Fontainebleau sand was studied. Undrained triaxial tests were performed on four samples, with different initial saturation states. The aim of this study was to explore in particular three saturation zones, all close to the state of full saturation, but distinguished by the distribution pattern of air and water phases. In this study, the transition parameter between the nearly-saturated and unsaturated zone is assumed to be the air entry suction value of the material.

The results first highlighted the fact that presence of air within granular materials affects its mechanical behavior: the presence of air within the granular materials increases shear strength, and delays occurrence of liquefaction instabilities (especially strain development). This reinforces the conclusion that study of unsaturated soils mechanics is of major interest, since it strongly differs from saturated one.

Concerning liquefaction potential, this experimental work showed that if the presence of air does enhance mechanical properties towards liquefaction risks, it does not prevent the development of strain and under certain conditions the equalization of pore pressure to confining pressure.

We showed that when initial suction is higher than air entry suction value, triggering of instabilities are strongly delayed. Strain developed, but annulment of enlarged effective stress was never observed. High volumetric stain developed, until reaching a maximum and decreasing. Concerning totally saturated samples, and for samples initially submitted to suction value under than the air entry value, not only high strain rates were observed, but also severe damage of initial mechanical properties. For those samples, liquefaction state as annulment of effective stress as described by Terzaghi was observed.

According to these first results, it seems that distribution pattern of air and water phases within granular material is a key parameter regarding liquefaction potential. In this study, as a preliminary step, and according to previous results from the literature, we considered air entry suction value as the transition parameter between continuous and non-continuous air phase states. Further experiments need to be conducted, in order to confirm wether this parameter is relevant or not.

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