Influence of saturation degree on soils behavior towards liquefaction.

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ABSTRACT: For a long time, it was systematically admitted that unsaturated conditions was a sufficient condition not to consider any risk of liquefaction. Various authors have shown that when saturation degree decreases, resistance to liquefaction increases. But recently, some authors have highlighted that even under unsaturated conditions, a soil sample could liquefy under cyclic loadings. However, few studies have been published, and more data are needed. Influence of pore fluid compressibility of unsaturated soils when submitted to cyclic loading has been studied by various authors. Indeed, air as a pore fluid modifies the volumetric behaviour, and has a positive impact on the liquefaction resistance; it delays the occurrence of liquefaction within the material. On the other hand, suction is a state variable necessary to fully described unsaturated soils behaviour but is rarely considered in liquefaction studies. In this paper, influence of saturation degree on liquefaction behaviour is studied. Both pore fluid compressibility and suction are under interest. A special experimental device has been developed, that permits to consider both aspects. A water column equipment was designed to impose initial suction to the sample, while local sensors are set up to observe volumetric behaviour during cyclic loading.

1 INTRODUCTION

Liquefaction risk is rarely evaluated considering degree of saturation. As a matter of fact, according to normative acts, risk of liquefaction should not be considered if the soil is not fully saturated. However, every year, liquefaction still causes damages all over the world, showing that some features are not fully understood yet.

Various studies have already shown interesting results regarding the liquefaction instability of unsaturated soils (Sherif et al. 1977, Chaney 1978, Okamura and Soga 2006). It is now admitted that the saturation degree influences liquefaction resistance: the lower the saturation degree, the higher the resistance to liquefaction.

However, some authors (Yoshimi et al. 1989, Unno et al. 2006, 2008, Okamura and Soga 2006, Arab et al. 2011) have highlighted the fact that risk of liquefaction still exists, even if the soil is not fully saturated. But those studies remain descriptive, and there is no precise description nor specific parameter that would be used to properly evaluate risk of liquefaction regarding degree of saturation. Meanwhile, climate changes affect soils' hydric conditions; they undergo more pronounced wetting-drying cycles. As a result, we are likely to be more and more confronted to un-saturated soils, but their hydro-mechanical behaviour under cyclic loading is not entirely understood. This lack of knowledge leads to an unappropriated risks management policy, and eventually to an under-statement of liquefaction risks.

In this context, this paper aims at:

- confirming that initial saturation degree does have an influence on liquefaction resistance,
- showing that unsaturated soils can liquefy.
- providing a simple parameter that could be used in the evaluation of potential of liquefaction of a soil, considering degree of saturation. materials and testing parameters.

1.1 *Material and testing system*

In this study, a fine clean sand was used as the testing material to study the influence of saturation degree on cyclic behaviour of unsaturated soil. The material is known as Fontainebleau sand, and is commonly used in experimental works, especially when liquefaction instability is studied (Dupla 1995, Benahmed 2001)

Cyclic triaxial tests are performed, using a Bishop and Wesley triaxial cell (Bishop and Wesley, 1975). Samples are reconstituted in laboratory, by the wet tamping technique (initial moisture of 3%). This process was chosen to satisfy low density criteria (e > 0.85). The saturation process consists in 30 minutes of CO_2 circulation through the sample, followed by deaired water circulation. The sample is consolidated under a pressure $\sigma_c' = 100$ kPa.

The level of saturation is experimentally quantified by the Skempton coefficient B. It is then associated to a value of Sr, like it will be introduced in the next paragraph.

The cyclic loading is then applied, with a 0.017Hz frequency, and an amplitude of 70 kPa. The frequency was determined based on unsaturated pore pressure equilibrium and the amplitude thanks to classical saturated undrained triaxial tests.

1.2 *Water retention curve*

The relation between saturation degree and suction is obtained by the soil-water characteristic curve (Figure 1). The experimental curve is obtained by the filter paper method (ASTM 1992, Bicalho et al. 2007). Continuous line stands for Brooks and Corey equation.

Filter paper method is a simple and convenient method to determine the soil-water characteristic curve. But it is limited in terms of accuracy, arising from the filter paper boundaries. In this regard, it is noteworthy that experimental values are consistent with predictive model values. In parallel, simulation was realized using a Brooks and Corey law (Equation 1) (Brooks and Corey 1954):

$$S_r = \left(\frac{s_e}{s}\right)^{\alpha} \tag{1}$$

The simulation gave the following parameters: s_e = 2kPa, and $\alpha = 0.35$.

1.3 *Initial experimental condition*

Potential of liquefaction must be evaluated regarding saturation degree. Based on the different studies and results from the literature (Fredlund and Rahardjo 1993; Salager 2007), this article proposes to investigate influence of saturation degree on liquefaction behaviour for three possible states of saturation for a soil, as presented in Figure 2.

The transition between totally saturated state and nearly saturated state is given by the air entry suction in the soil when saturation degree become less than 1.

The transition between nearly saturated state and unsaturated state is more difficult to apprehend. The difference between these states is the continuity of air phase. The assumption is made that if air phase is continuous (unsaturated state) the permeability of the soil to air will not be negligible. So, air permeability tests were performed on Fontainebleau sand. Results are presented in Figure 3. For the chosen void ratio (0.85), air permeability becomes very low for Sr=0.95. So, in our case of study, the transition between these two states lies at Sr=0.95.

Five tests were performed, one in unsaturated zone, two in nearly saturated zone and two in fully saturated zone.

Unsaturated zone investigation:
- Unsat_1-Initial suction 2kPa-Initial saturation degree 0.90

Nearly-saturated zone investigation:
- Nearly_Sat_1-Initial saturation degree 0.95
- Nearly_Sat_2-Initial saturation degree 0.98

Fully saturated zone investigation:
- Fully_Sat_1-Initial saturation degree 1
- Fully_Sat_2-Initial saturation degree 1

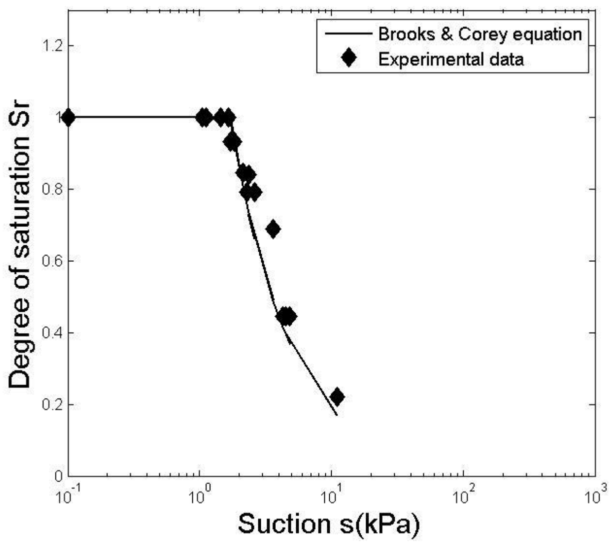

Figure 1. Soil-water characteristic curve – Experimental and model.

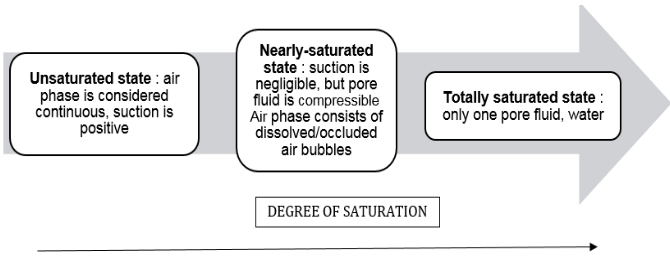

Figure 2. Three states of saturation studied.

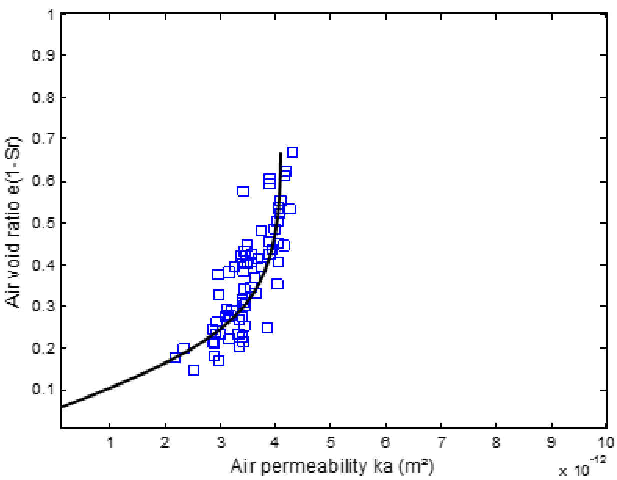

Figure 3. Air permeability tests results for Fontainebleau sand.

For Nearly and Fully saturated zone, the level of saturation is experimentally quantified by the Skemton coefficient B (Skempton, 1954). Skempton coefficient is a very common parameter used when dealing with triaxial tests. It is a parameter used to evaluate saturation of the triaxial sample, and specially employed to check the full saturation of the sample. It was introduced by Skempton in 1954 and is defined as (Skempton, 1954):

$$B = \frac{\Delta u}{\Delta \sigma_3} \qquad (2)$$

where $\Delta\sigma_3$ is increment of radial pressure applied to the triaxial sample, and Δu is increment of pore pressure measured. In 1978, Chaney stated that a sample can be considered fully saturated if Skemton coefficient B is greater than 0.96 (Chaney 1978). It is then associated to a value of Sr. This coefficient B is linked to saturation degree (Lade and Hernandez 1977, Morvan et al. 2016).

For unsaturated zone, the initial state of saturation was imposed to the tested samples through the control of initial suction. A high air entry (HEA) porous stone was installed to the pedestal of the triaxial. This special porous stone has very small pores, which permit to keep it fully saturated, even when the sample above is unsaturated. The initial suction was imposed to the samples using a Negative Water Column equipment, developed in the laboratory.

2 EXPERIMENTAL RESULT

In this part, results obtained for the three saturation states studied are presented.

2.1 *Fully saturated zone*

For fully saturated zone, two tests were performed. Results are presented in Figure 4 that show the evolution of water pressure compared to confining pressure for these two tests. After eleven cycles, pore water pressure reaches confining pressure and we observe liquefaction. Figure 5 shows the results in term of deviatoric stress versus mean effective stress. Stress amplitude cannot be reached after five cycles due to the loss of resistance of the sample. The effective stress path reaches zero, which means that liquefaction occurred. Figure 6 presents deviatoric stress versus axial strain. After 5 cycles, axial strains developed for each cycle increase. Plastic strains developed quickly. The results of the two tests are very close so we considered that our testing method is validated, and our samples are replicable.

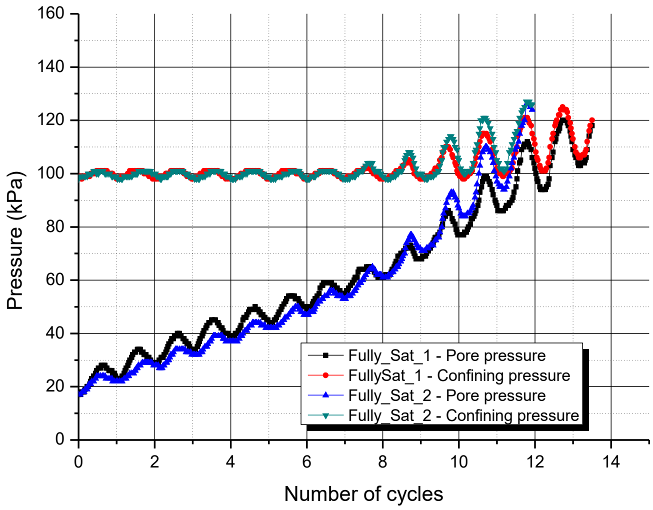

Figure 4. Liquefaction of saturated samples water pressure versus number of cycle.

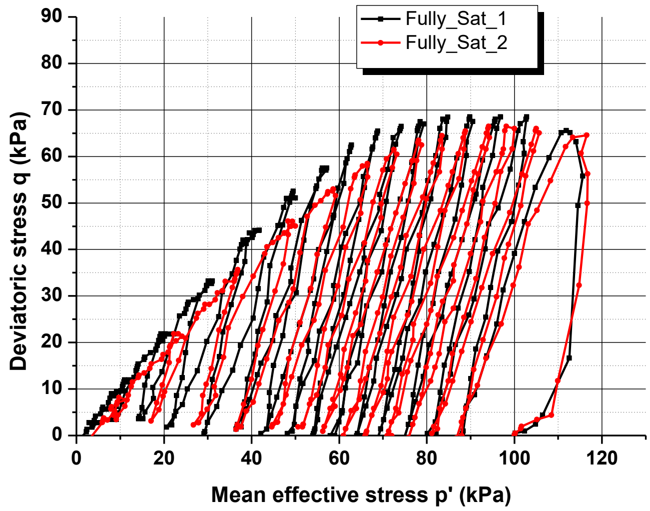

Figure 5. Liquefaction of saturated samples deviatoric stress versus mean effective stress.

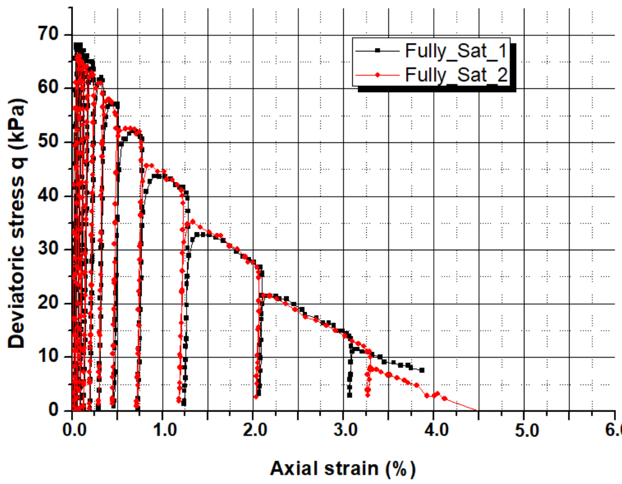

Figure 6. Liquefaction of saturated samples deviatoric stress versus axial strain.

2.2 *Nearly saturated zone*

For nearly saturated stage, two tests were performed. Figure 7 presents the evolution of pore pressure compared to confining pressure for these two samples. Although the saturation degrees, Sr=0.98 and Sr=0.95, are very close, results show differences for these two samples. Indeed, if the two samples liquefied, the number of cycles necessary for water pore pressure reaching confining pressure differs. Sample at Sr=0.98 liquefies after 30 cycles whereas sample at Sr=0.95 liquefies after 45 cycles.

Figure 8 shows evolution of axial strains with number of cycles. It takes 45 cycles for the sample at Sr=0.98 to reach 5% of axial strain and 55 for the sample at 0.95. After 85 cycles, both samples have reached a high axial strain rate (20%).

These two figures show that both sample liquefied. However, it is noteworthy that a small decrease of saturation degree delays the occurrence of liquefaction and appearance of axial strain.

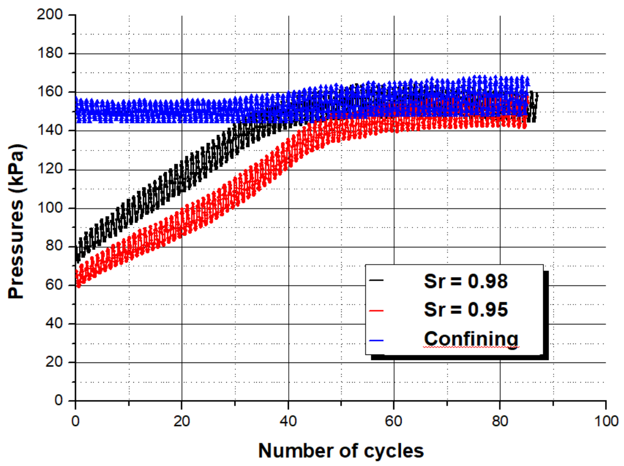

Figure 7. Liquefaction of nearly saturated samples water pressure versus number of cycle.

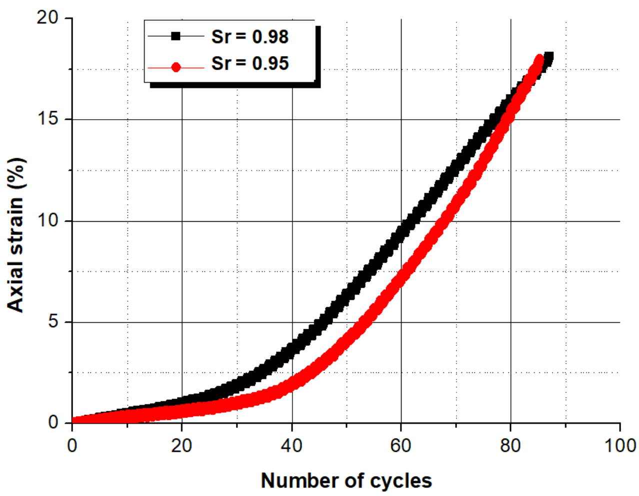

Figure 8. Liquefaction of nearly saturated samples axial strain versus number of cycle.

2.3 *Unsaturated zone*

One test was performed within unsaturated domain. Suction of 2kPa was initially imposed using water column technique. For this suction, saturation degree equals 0.90. Figure 9 presents the results in term of deviatoric stress versus axial and Figure 10 presents axial strain versus number of cycles. For this test, no liquefaction was observed. After 2000 cycles with a deviatoric stress of 70kPa, no sign of instability was observed (small strains and constant deviatoric stress reached). The amplitude of the cycles was increased progressively. Up to 250kPa, no sign of instability was observed either. But for 250kPa, instability is triggered. After 6000 cycles, axial strain development changes and a decrease in deviatoric stress can be observed.

So, for this sample liquefaction was not observed. However, liquefaction instabilities, described as development of axial strain and decrease of deviatoric stress were observed.

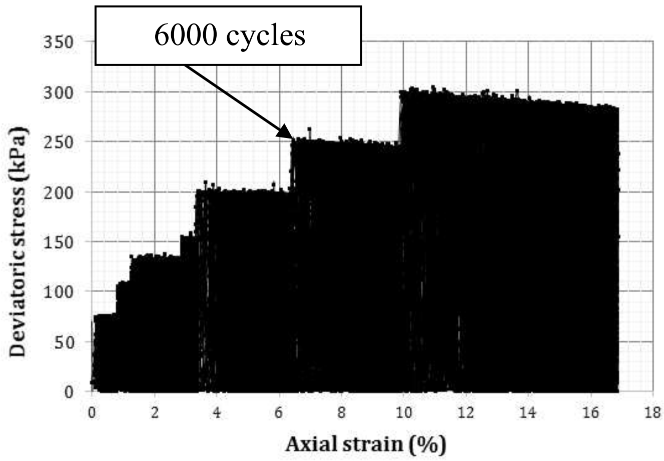

Figure 9. Liquefaction of unsaturated samples deviatoric stress versus axial strain.

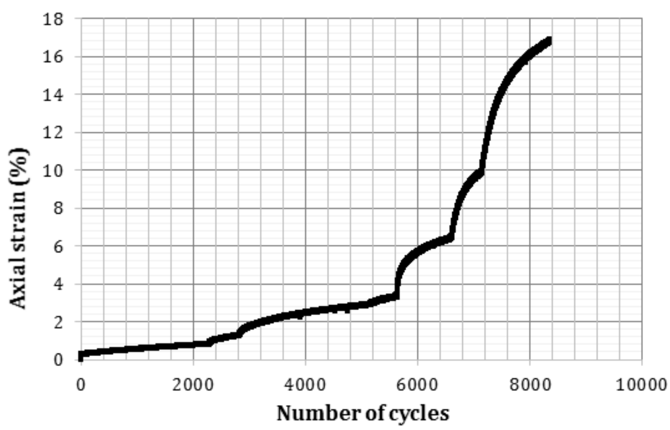

Figure 10. Liquefaction of unsaturated samples axial strain versus number of cycle.

3 CONCLUSIONS

To conclude, this article presents five undrained cyclic triaxial test results to study the influence of saturation degree on liquefaction. The two first samples were saturated and reached liquefaction after a very low number of cycles (11). The two nearly saturated samples had a very close saturation degree (0.98 and 0.95) and both reached liquefaction. However, we observed that liquefaction appearance is delayed by the decrease of saturation degree. For the sample at initial suction of 2kPa, liquefaction was not reached, and no instability was observed for the 2000 first cycles performed in the same condition as the four first ones.

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