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Influence of saturation degree and role of suction in unsaturated soils behaviour: application to liquefaction

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Abstract. The effect of the pore fluid compressibility on liquefaction has been studied by various authors. But few papers have been published about the role of suction in cyclic behavior of unsaturated soils. Most of these works use Skempton coefficient B as a reference in terms of saturation degree to analyze their results. The use of B in experimental conditions is convenient, but is not accurate when studying liquefaction behavior, since effects of suction are neglected. In this paper, the influence of saturation degree on mechanical behavior of a soil under dynamic loads is studied. Cyclic undrained triaxial tests were performed on sand samples, under various levels of saturation. Soil-water characteristic curve was used, in order to study influence of suction. The first results confirm that when the degree of saturation decreases, the resistance increases. Initial positive suction tends to stiffen the soil. It also appears that the presence of air delays the occurrence of liquefaction, but doesn't prevent it. Indeed, liquefaction is observed, whether the soil is saturated or not.

1 Introduction

Since the 1950', unsaturated soils' behavior study has witnessed a growing interest within scientific community. Volumetric behavior and shear strength have been studied and gave birth to adapted models for unsaturated soils behavior, but we observed a lack of data on liquefaction.

Liquefaction has already caused tremendous damages, particularly in seismic areas: Niigata, Japan [1] (1964), Anchorage, Alaska [2] (1964), or more recently in the Tokyo Bay area, Japan [3] (2011). During earthquake, or any vibratory disturbance, local collapses of the soil structure occur, meanwhile pore water pressure within the soil increases, and equals in some cases the total pressure. It leads to a zero effective stress state, and loss of the shear strength. It is commonly admitted that unsaturated soils are riskless towards liquefaction, and the study of unsaturated soils behavior under cyclic loading suffers from a lack of data.

Meanwhile, climate changes affects soils' hydric conditions; they undergo more pronounced wetting-drying cycles. As a result, we are likely to be more and more confronted to unsaturated soils, but their hydro-mechanical behavior under cyclic loading is not entirely understood. This lack of knowledge leads to an unappropriated risks management policy, and eventually to an understatement of liquefaction risks.

Various studies have already shown interesting results regarding the liquefaction instability of unsaturated soils ([4], [5] and [6]). It is now admitted that the saturation degree influences liquefaction resistance: the lower the saturation degree, the higher the resistance to liquefaction. But the majority of these works use the Skempton coefficient B to quantify the level of saturation of the sample. The use of B in experimental work is convenient, but is not satisfactory when studying influence of saturation on cyclic behaviour. It does not provide a simple relation between physical and mechanical parameter of the soil.

B depends on the pore air compressibility, while we know that the presence of air within the soil creates suction, which tends to stiffen the material. Pore compressibility and suction have opposite effects; it is then not accurate to analyse potential of liquefaction of unsaturated soil considering only volume compressibility of the soil skeleton. The use of B as saturation level reference would be relevant if air compressibility was the only difference between saturated and unsaturated soil. But many authors ([7], [8], [9]) have used the fact that another state variable is needed to differentiate unsaturated soils behavior from saturated one: suction. The use of B only as an indicator of saturation in results' analysis is not enough considering suction, whose effects on hydro-mechanical behaviour are proved.

Some authors, like Yoshimi et al. [10], or Arab et al. [11] used a theoretical relation between B and Sr, introduced by Lade et al. in 1977 [12]. But it appeared that this theoretical relation was not entirely accurate. Moreover, if these studies were innovative because they provided a

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relation between a value of B and resistance to liquefaction, the only parameter considered is pore fluid compressibility.

Another approach was developed by Okamura et al. [6]: they quantified a saturation degree measuring the volume of air within the specimen, estimated from Boyle's law with the measured volume of the water introduced in the sample. They establish a unique relationship between liquefaction resistance and the potential volumetric strain, but again neglecting other effects of partial saturation.

As far as we know, only few experimental campaigns aiming to study cyclic behaviour of unsaturated soils have already been performed with suction-controled conditions. Unno et al. [13, 14] conducted triaxial cyclic tests, under various suction conditions, using axis translation technique. They observed that the air entry value of the soil characteristic curve was a major factor of influence towards liquefaction instability of the material. The air entry value appears to be a critical value. Such studies, exploring the effects of suction on cyclic behaviour of unsaturated soils, are few and further investigations need to be carried out.

In this context, and through this paper, we want to:

- confirm that initial saturation degree does have an influence to liquefaction resistance,
- show that unsaturated soils can liquefy.

Contrary to most of the studies, we will quantify saturation degree in terms of Sr, and not only in terms of B. This will provide us to relate observed effects, and values of initial suction, which is rarely done. This study is a preliminary work, first part of an overall project. The final goal will be to give a framework regarding liquefaction risks evaluation: link physical and mechanical parameter, set critical limits in terms of Sr, in order to improve liquefaction risks management.

2 Influence of initial saturation degree

It is noteworthy to specify that this work is preliminary; indeed, it aims to highlight the influence of initial saturation degree and initial suction on the cyclic behaviour of sands, using predictive model of the B-Sr relation, and the soil-water characteristic curve. Further tests are about to begin in our laboratory, realized under controlled initial suction, and suction monitoring conditions. We will be able to:

- confirm the accuracy of our numerical predictions;
- realize triaxial cycling tests on unsaturated specimens quantifying saturation degree in terms of Sr.

2.1 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 ([15], [16]).

Cyclic triaxial tests are performed, using a Bishop and Wesley triaxial cell (Bishop et al., [17]). The samples are reconstituted in laboratory, by the wet tamping technique (initial moisture of 3%). This process was chosen in order 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 amplitude of 50 kPa.

2.2 Initial experimental conditions

Thanks to a numerical model developed in our laboratory, we are able to accurately relate values of B, measured before triaxial testing, and saturation degree.

Three triaxial cyclic tests have been realized, and the initial parameters of the sample are presented in Table 1:

Table 1. Initial experimental parameters.

Test	B	Sr
triaxcyc100CUfontainSr1	0.98	1
triaxcyc100CUfontainSr98	0.53	0.98
triaxcyc100CUfontainSr95	0.22	0.95

2.3 Results of undrained cyclic shear test

2.3.1 Pore water pressure ratio

Pore-water pressure ratios stands for the pore water pressure, normalized by the total stress σ_c. When pore-water pressure ratio equals 1, liquefaction occurs. Figure 1 shows the pore-water pressure ratio evolution versus number of cycles. It shows that independently from the saturation degree, the pore-water pressure ratio increases under undrained cyclic loading. Nevertheless, differences are remarkable between each sample tested: initial increasing rate of pore-water pressure ratio depends on the initial saturation degree. The higher the saturation degree, the higher the increase of pore-water pressure within the soil sample. Indeed, for 20 loading cycles, the sample initially totally saturated has reached a 0.91 pore-water pressure ratio value; the sample initially 98%-saturated has reached a 0.74 pore-water pressure ratio value, while the sample initially 95%-saturated has only reached a 0,65 pore-water pressure ratio value.

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Figure 1 also shows that initial saturation degree affects the number of cycles needed to trigger liquefaction: for Sr = 1, liquefaction occurs after 40 cycles. For Sr = 0,98, liquefaction occurs after 51 cycles and for Sr = 0,95, liquefaction occurs after 54 cycles. It depicts the fact that lower initial saturation degree delays the occurrence of liquefaction. Moreover, the most significant difference in terms of applied cycles before liquefaction is between saturated sample and unsaturated samples. It seems that only small quantity of air is needed to observe significant differences. But pore-water pressure ratio eventually equals 1 for the three tested samples, meaning that unsaturated soils can liquefy.

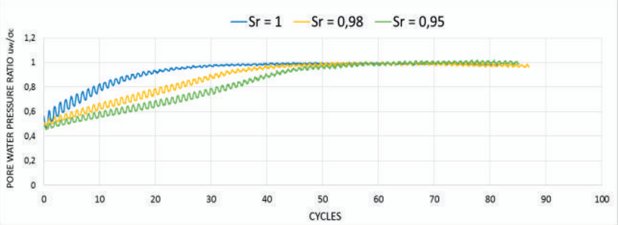


Figure 1. Pore-water pressure ratio evolution with number of loading cycles applied, for three different initial saturation degree

2.3.2 Axial strain

Figure 2 depicts axial strain evolution with number of loading cycles applied, for each tested sample.

It shows that presence of air within the soil affects strain development: if we consider a fixed strain level of 5%, totally saturated sample reaches this rate after 36 cycles. For Sr = 0,98, this 5%-rate is reached after 47 cycles, and for Sr = 0,95 after 53 cycles. That is, the smaller the saturation degree, the faster the development of significant strain rates. But, eventually, for the same number of applied cycles (80 cycles), the three samples have reached the same final level of strain (19%).

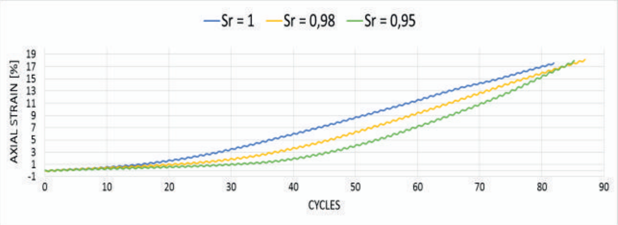


Figure 2. Axial strain evolution with number of loading cycles applied, for three different initial saturation degree

Table 2 summarize the previous graphic results:

Table 2. Summary table for the results obtained on three samples with different initial saturation degree.

Sr	Nb of cycles before liquefaction	Nb of cycles before reaching 5% axial strain
1	40	36
0,98	51	47
0,95	54	53

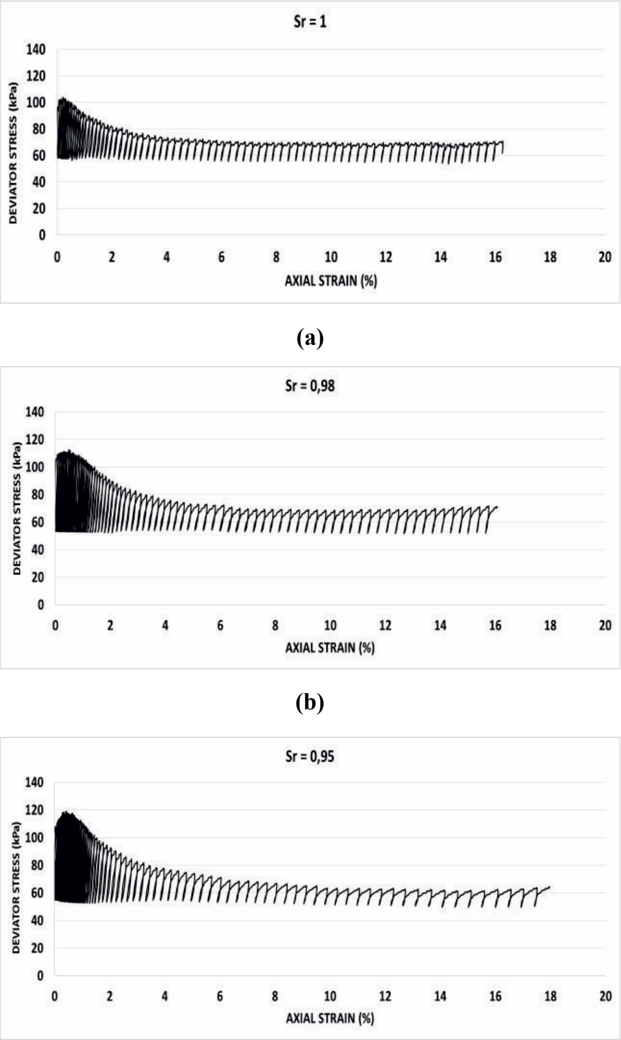
2.3.3 Stress-strain relationship and effective stress paths

Figure 3 (a), (b) and (c) and Figure 4 (a), (b) and (c) depicts the stress-strain relationship for the three tested samples, corresponding to three different initial saturation degree. Figure 5 (a), (b) and (c) depicts the effective stress paths for the three tested samples.

Firstly, Figure 3 (a), (b) and (c) show that deviator peak decreases with increasing axial strain during the cyclic loading, regardless the initial saturation degree. We can also highlight the fact that stiffness decreases with the application of the undrained cyclic loading.

Despite the stress-feedback control, deviator stress is not maintain at a constant value during the cyclic loading. This is due to the fact that under cyclic loading, sand loses its resistance, and deforms plastically. The loading device, controlled under pressure-volume conditions, is no longer able to achieve stress and velocity feedback control. But this material limitation underlines the fact that for lower saturation degree, the initial deviator stress reaches the 50kPa-setpoint value, while saturated one only reaches 40 kPa. It shows that the lower saturation degree, the higher cyclic shear resistance.

Comparing Figure 4 (a), (b) and (c) shows that initial stiffness is higher for lower initial saturation degree. Indeed, stress-strain curve's initial slope for unsaturated samples is greater than totally saturated one. Moreover, the lower the saturation degree, the tighter the stress-strain cycles, which shows that decreasing saturation degree decreases residual (plastic) strain between each cycle. But if stiffness decreases in each loading cycle for every sample, it appears that for important strain rates (from about 10%), unsaturated samples are more affected; indeed, the strain increment between each cycles becomes more important for unsaturated samples than for saturated one, for significant axial strain rates (Figure 3 (a), (b) and (c)). These results show that the presence of air, implicitly meaning positive suction, increases initial soil stiffness. But they also underlined that major plastic strain appeared for unsaturated samples, meaning that suction state is being modified during the loading.

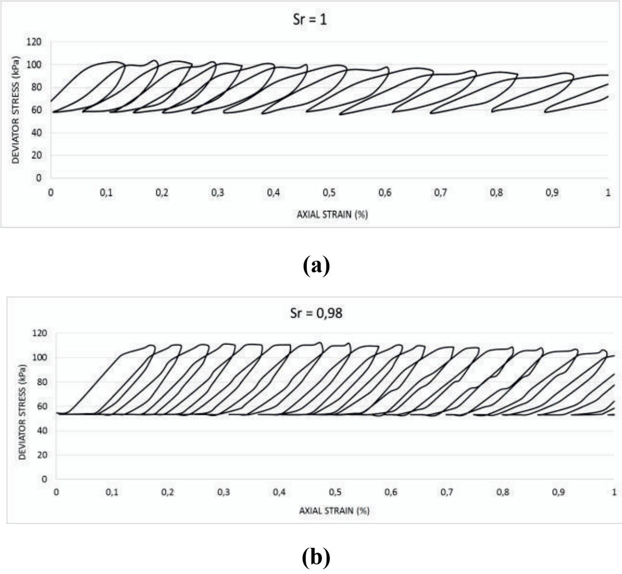


(a)

(b)

(c)

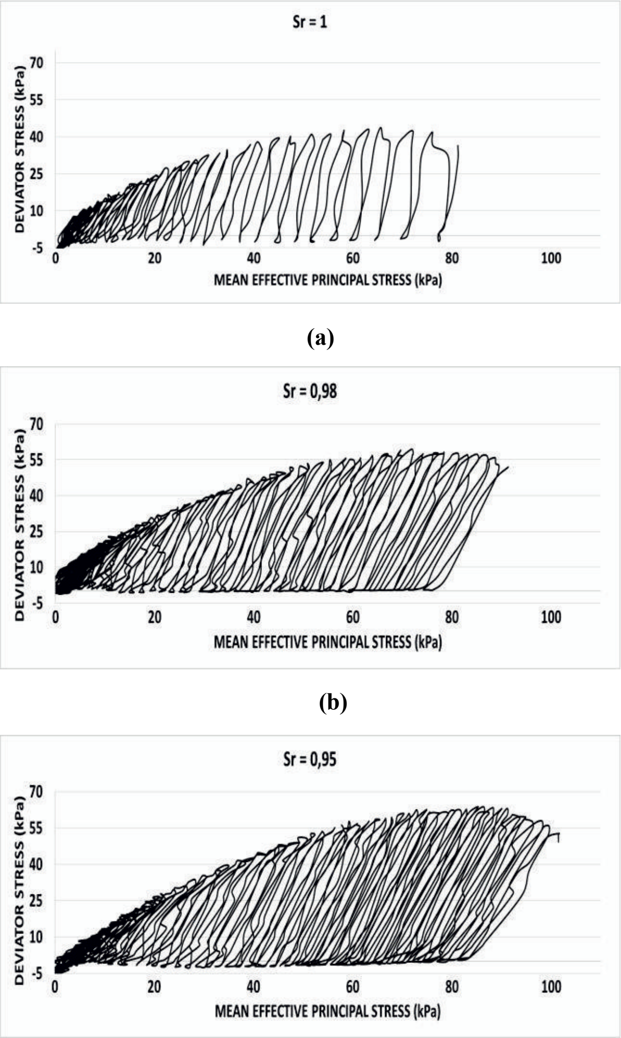
Figure 3. Stress-strain relationship for undrained cyclic triaxial tests



(a)

(b)

Figure 4. Focus on small strain behaviour

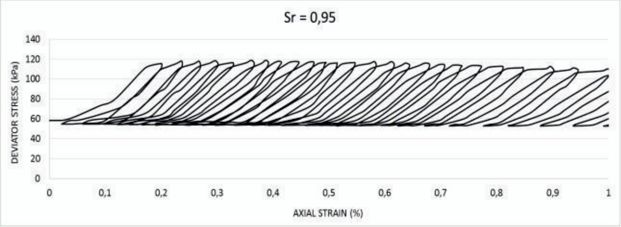


(a)

(b)

(c)

Figure 5. Effective stress paths for undrained cyclic triaxial tests



(c)

Comparing Figure 5 (a), (b) and (c) shows that unsaturated samples maintain a higher initial shear resistance level: totally saturated sample undergoes quick decreasing of main effective stress, with vertical effective stress path. The loss of mean effective stress between two cycles is less important for unsaturated samples.

However, for the three tested samples, the effective stress path reaches zero, which means that liquefaction occurred, disregarding initial saturation degree.

This paragraph showed influence of initial saturation degree on cyclic shear behaviour of triaxial sand samples. The lower initial saturation degree, the later the occurring of liquefaction, and development of important strain within the soil sample. It appeared that initial saturation degree equally has an impact on initial soil stiffness: unsaturated samples showed higher initial stiffness. But it was degraded under cyclic loading, and residual strain between each cycle becomes more important for unsaturated samples. Finally, it was pointed out that if the loss of effective stress between each cycles was less important for unsaturated sample than for saturated one, the effective stress path reached zero for all the tested samples. This may be caused by volumetric strain under cyclic loading, inducing increasing saturation degree, and leading to a state close to total saturation of the sample. This may be studied by measuring local volumetric strain during the loading.

It confirms that complex mechanisms are engaged in cyclic behaviour of unsaturated soils, and particularly suction. The influence of this state variable will be discussed in the next paragraph.

3 Influence of initial suction

Through previous results, it appeared that initial saturation degree affects the cyclic soils' behaviour. Various authors studied the effect of decreasing saturation degree on liquefaction behaviour, but level of saturation was quantified by the Skempton coefficient B. In this study, we suggest that using Sr would be more appropriate, in order to include suction values to our analysis.

3.1 Soil-water characteristic curve

The relation between Sr and suction is obtained by the soil-water characteristic curve (Figure 6). The experimental curve is obtained by the filter paper method (ASTM Standards [18]; Bicalho et al., [19]). The model curve arises from a numerical model developed by Aubertin et al. [20].

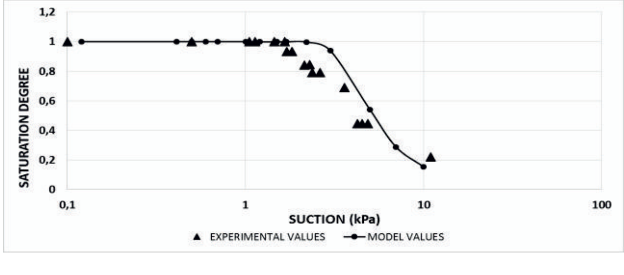


Figure 6. Soil-water characteristic curve – Experimental and model

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) [21]:

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

The simulation gave the following parameters: s_e = 2kPa, and α = 0.35.

Table 3 summarizes saturation degrees and corresponding suctions.

Table 3. Corresponding saturation degrees and suction obtained through soil-water characteristic curve (filtrer paper method)

Sr	Suction (kPa)
1	0 - 2
0.98	2
0.95	2,2

3.2 Discussion

The suction increases with decreasing saturation degree. Meanwhile, we know that suction increases soil stiffness. Relating those values with experimental results presented in previous paragraph, we confirm that initial soil stiffness increases with positive suction value. Moreover, initial suctions of each samples are extremely close from each other. It leads us to the conclusions that even small changes in suction state can induce significant modification in soil's behaviour.

The suction air entry value (SAEV) of the soil, obtained from the model is approximately 2 kPa, meaning that the tested samples have initial suction that bracket the air entry value of the soil. It is pertinent, since Unno et al. [14] have showed that SAEV stands for a critical value regarding liquefaction instability.

In his paper, Unno [13] showed that samples with initial suction lower than SAEV of the soil liquefied; while samples with initial suction greater than SAEV did not. Our results do not allow conclusions to be drawn regarding Unno's results. Further tests need to be done, under higher initial suction.

4 Conclusions and perspectives

Influence of saturation degree has been studied. Thanks to a model developed in our laboratory, we were able to quantify level of saturation in terms of Sr, and not only in terms of B like it is commonly done. We showed that:

- The higher the saturation degree, the faster liquefaction instability appear;
- The presence of air within the soil increases initial stiffness;
- Increasing of soil stiffness is due to suction, but the mechanism, especially evolution of this parameter under cyclic loading needs to be investigated;
- But liquefaction was observed for all tested samples, regardless the initial saturation degree.
- Regarding suction values of the tested samples, it was highlighted that very small changes in initial suction state lead to significant change in behaviour toward cyclic loading.

Through this work, we aimed to highlight the fact that liquefaction of unsaturated soil exist, contrary to what is commonly admitted. Lack of knowledge about the subject has leaded to a misunderstanding of mechanisms, and an unappropriated risks management in practice. This work stands for a solid basement in the overall project of liquefaction risks management, aiming to give a practical and convenient framework, and pertinent criteria to anticipate better liquefaction risks of all type of soils. Further tests will be realized, under lower saturation degree.

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