Investigation of the influence of saturation degree on the cyclic behaviour of fine clear sand

Khai Hoan Tran[1,2], Saber Imanzadeh[1,3], Said Taibi[1], Hanène Souli[4], Jean Marie Fleureau[5], Mahdia Hattab[6]

[1] *Normandie Université, UNIHAVRE, Laboratoire Ondes et Milieux Complexes, CNRS UMR 6294, Le Havre, France*

[2] *Thai Nguyen University of Technology, Thai Nguyen, Vietnam*

[3] *Normandie Univ., INSA Rouen Normandie, Laboratoire de Mécanique de Normandie, 76801 Saint-Etienne du Rouvray, France*

[4] *Ecole Nationale Supérieure de Saint Etienne, Laboratoire de Tribologie et and Dynamique des Systèmes, CNRS UMR 5513, 42023 Saint Etienne, France*

[5] *Université Paris-Saclay, CentraleSupélec, CNRS UMR 8579, Laboratoire de Mécanique des Sols, Structures et Matériaux, 91190, Gif-sur-Yvette, France*

[6] *Université de Lorraine, Laboratoire d'Etude des Microstructures et de Mécanique des Matériaux, CNRS UMR 7239, Arts et Métiers ParisTech, F-57000 Metz, France.*

ABSTRACT: In literature, there have been many studies on the liquefaction of soil; however, most of them are to study the liquefaction of saturated soil and it is necessary to have more results on the liquefaction of unsaturated soil. In this study, a series of triaxial test on both saturated and unsaturated samples was carried out to have better understand of the liquefaction of unsaturated sand in very dense state. All the samples were reconstituted using wet tamping method at a relative density of 83%. After wetting and consolidating, the samples were subjected to cyclic loading with stepping Cyclic Stress Ratio (CSR). The results show that the saturation degree affects significantly liquefaction potential of soil. The decrease of saturation degree results on the decrease of liquefaction potential of soil. Besides, the effects saturation degree on the friction angle and the slope of failures lines at the liquefaction state were also considered.

Key words: Liquefaction, quasi-saturated, Skempton's coefficient B, fine clear sand.

I. INTRODUCTION

In geotechnical engineering and soil mechanics domain, it has been well known that the saturation degree affects significantly the characteristics of soil. The liquefaction in the 1964 Niigata earthquake has attracted many studies on this phenomenon; however, most of studies has focused on the liquefaction of saturated soil. The initial researches on the liquefaction of unsaturated soils were carried out with the aim to evaluate the errors of saturated tests due to the appearance of air bubbles and to study the behaviour of some soils not saturated in natural condition. Recently, due to some reasons, there have been more and more studies on the liquefaction of soil with saturation degree lower than 100% (Arab et al. 2016). The first reason is that there is more solid proof for the appearance of air bubble below water table and some investigations have pointed out that the soil in liquefied area is not fully saturated. Mase et al. (2019) took the undisturbed samples from area which had been liquefied during the earthquake in Kobe in 1985. The result shows that the sample is not saturated. Another reason is that the Induced Partial Saturation (IPS) technique is now feasible as a very effective technique to mitigate the liquefaction potential of soil (He et al. 2013). This method is implemented by generating air bubbles in the soil to reduce its saturation. Although having achieved many results in studying the liquefaction of unsaturated soils, there are some points not clearly mentioned in literature and needed to be clarified such as: (i) the cyclic liquefaction behaviour of unsaturated soil in very dense state; (ii) the effect of the saturation degree on the cyclic behaviour of different soil types (Tran et al. 2021). This study is to answer a part of these issues.

II. MATERIAL AND APPARATUS

In this study, the fine clear RF Hostun sand was used to reconstitute the samples, this material is also widely used in literature to investigate the liquefaction phenomenon. This material has the specific gravity of 2.65g/cm^3, the maximum grain size of 0.6mm and the minimum grain size of 0.12mm. Other parameters are shown in table 1 and the picture of the sand in figure 1.

TABLE 1. Material parameters.

D_{50} (μm)	D_{10} (μm)	D_{60} (μm)	e_{max}	e_{min}
300	200	400	1.041	0.648

- *D_{10}, D_{50}, D_{60} are the particle size distributions of RF Hostun sand*

- *e_{max} and e_{min} are the maximum and minimum value of void ratio*

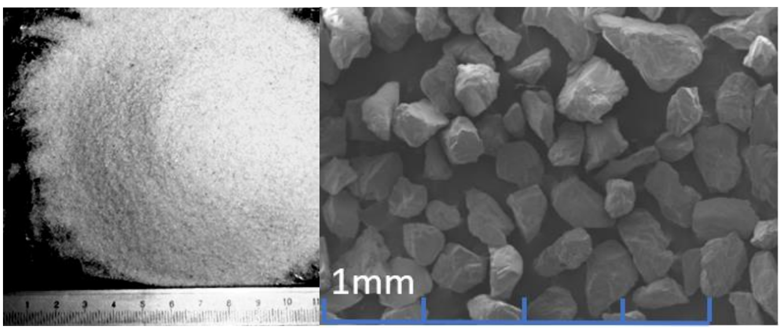


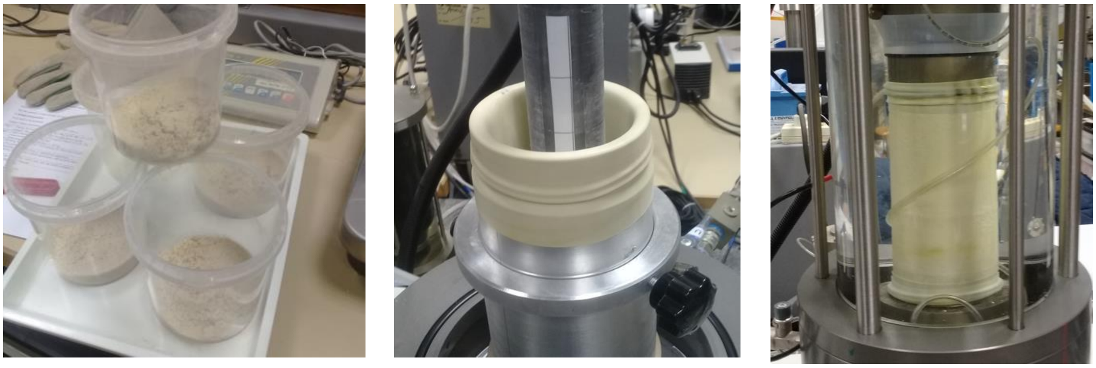
FIGURE 1. RF Hostun sand in different scales

The Cyclic Triaxial Testing System used in this study is also the apparatus presented in Tran et al. 2021. This apparatus can perform cyclic loading at a given value of deviator stress. The axial strain is measured by a transducer fixed on the piston. The load is measured by a load transducer put between the piston and the sample top cap. Maximum value of cell pressure is 900 kPa.

IV. TESTING STEPS

A. Reconstituting the samples

There are some methods usually used to prepare the sample in liquefaction test and the effect of sample preparation on the results of tests is sometimes controversial (Tran et al. 2021). In this paper, the wet tamping method is chosen to reconstitute the samples. This method is done by compacting layer by layer of the samples. For each layer, the compaction finish when reaching the desired void ratio. In this study, all the sample is prepared at the relative density of 83% or void ratio of 0.73. The sample dimensions are 140 mm in heigh and 70 mm in diameter.



(a) Five parts of samples (b) Sample compaction (c) Sample in triaxial cell

FIGURE 2. **Sample reconstituting by the wet tamping method**

B. Sample wetting and saturation degree estimation

There are three techniques usually used to saturate partly or completely the samples reconstituted by the wet tamping method as mentioned in Tran et al. (2021). In this study, the samples were initially wetted using de-aired water for circulation. After that is the increase of back pressure and cell pressure to dissolve the remaining air bubbles inside the samples.

One method which is usually used to evaluate the sample saturation degree in triaxial test is using Skempton coefficient parameter B. In isotropic pressure condition, this parameter is calculated as equation (1) (Skempton 1954). In fully saturated sample, because the water is considered as uncompressible material the B value is theoretically equal to 1. However, in practice, with sand, the samples can be considered fully saturated if B is higher than 0.96. In this study, the sample is fully saturated if B ≥ 0.97. This value is also presented and well explanted in Tran et al (2021). After B measurement, the samples were consolidated by an effective stress of 100 kPa.

$$B = \frac{\Delta u_w}{\Delta \sigma_3} \quad \text{(Eq. 1)}$$

$\Delta\sigma_3$ is the increase of cell pressure in B measurement; Δu_w is the increment of pore water pressure caused by the $\Delta\sigma_3$.

B. Loading condition

In liquefaction test, one important parameter is Cyclic Stress Ratio (CSR). This parameter is calculated following equation (2). In this study, in one test, the value of CSR was chosen initially of 0.15, after 100 cycles of loading, the CSR was increased to higher level (0.2, 0.25, 0.3, and so on). This loading protocol is better to liquefy the unsaturated samples in very dense state (Tran et al. 2021).

$$CSR = \frac{q}{2.\sigma_3'} \quad \text{(Eq. 2)}$$

q is the maximum deviator stress. σ_3' is the initial effective stress (effective stress before cyclic loading or isotropic consolidation effective stress).

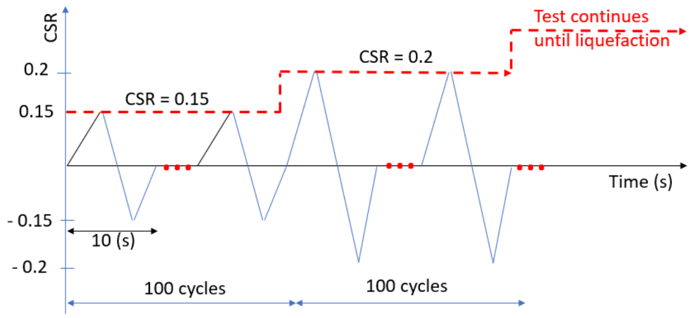


FIGURE 3. Cyclic loading with stepping CSR

V. RESULTS AND CONCLUSION

The results of tests are summarized in table 2, the saturated test with B of 0.97 was liquefied after 222 cycles at the CSR of 0.25 while the unsaturated test with B value of 0.6 liquefy after 432 cycles at the CSR of 0.35. Figure 4 shows the behaviour of saturated sample for the last 10 cycles (cycles from 212th to 222th). In figure 4a, the axial strain develops rapidly each time the deviator stress passes zero and in figure 4b, it can be seen that the stress path is butterfly form, a characteristic of cyclic mobility phenomenon. Figure 5 shows the behaviour of unsaturated samples for the last ten cycles (cycles from 422th to 432th). It can be seen that the failure line in both cases have the same slope of 1.5 for the upper lines and -1 for the low lines. It means that the slope of the failure lines does not depend on the saturation degree. These slopes of the failure lines correspond to the friction angle $\emptyset_{crit} = 37°$ following the equations 3 and 4.

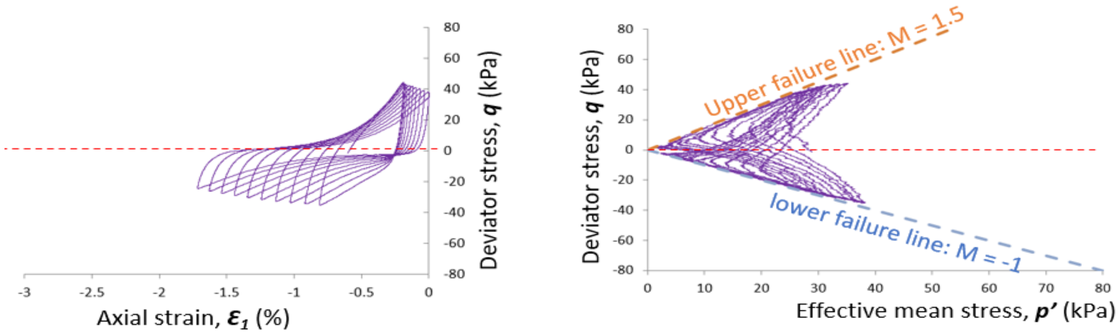
$$M = \frac{6.sin\emptyset_{crit}}{3-sin\emptyset_{crit}} \quad \text{(Compression)} \quad \text{(Eq. 3)}$$

$$M = \frac{6.sin\emptyset_{crit}}{3+sin\emptyset_{crit}} \quad \text{(Extension)} \quad \text{(Eq. 4)}$$

TABLE 2. Test results

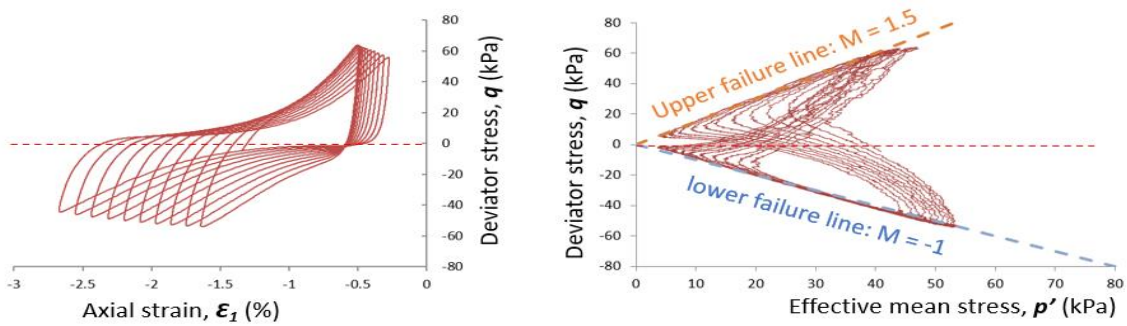
Test	B	Numbers of cycles					Total number of cycles
		CSR=0.15	CSR=0.2	CSR=0.25	CSR=0.3	CSR=0.35	
Test 1	0.97	100 (NL)	100 (NL)	22 (L)	-	-	222
Test 2	0.6	100 (NL)	100 (NL)	100 (NL)	100 (NL)	32(L)	432

NL: No Liquefaction observed at the end of loading; L: Liquefaction at the end of loading



(a) Axial strain versus deviator stress **(b) Deviator stress versus effective mean stress**

FIGURE 4. Last ten cycles of saturated test (B = 0.97) with CSR of 0.25



(a) Axial strain versus deviator stress **(b) Deviator stress versus effective mean stress**

FIGURE 5. Last ten cycles of unsaturated test (B = 0.6) with CSR of 0.35

REFERENCES

Arab, A., Belkhatir, M., & Sadek, M., 2016, Saturation effect on behaviour of sandy soil under monotonic and cyclic loading: A laboratory investigation. Geotechnical and Geological Engineering, 34(1), 347–358. https://doi.org/10.1007/s10706-015-9949-6

Mase, L.Z., Likitlersuang, S., Tobita, T., 2019, Cyclic behaviour and liquefaction resistance of Izumio sands in Osaka, Japan, Journal Marine Georesources & Geotechnology, Volume 37, 2019 - Issue 7, https://doi.org/10.1080/1064119X.2018.1485793

Skempton, A.W., 1954, The pore-pressure coefficients A and B. Géotechnique 4 (4):143-47.

Tran, K. H., Imanzadeh, S., Taibi, S., Souli, H., Fleureau, J.M., Hattab, M., 2021, Effect of saturation on liquefaction potential and residual strength: laboratory investigation. European Journal of Environmental and Civil Engineering https://www.tandfonline.com/doi/full/10.1080/19648189.2021.1999333

He, J., 2013, Mitigation of liquefaction of sand using microbial methods. Doctoral thesis, Nanyang Technological University – Singapore.