Influence of non-plastic fines on the cyclic resistance of sands to liquefaction

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Abstract. This paper presents an experimental study that investigates the influence of the non-plastic fines on the initiation of instability of sands under cyclic loading. The materials used for this study and the experimental device are first presented, then the results of typical liquefaction tests for both loose and medium dense specimens are presented with emphasis on the exhibited behaviour. The results of a series of cyclic undrained tests that were done with the aid of a triaxial apparatus for different percentages of fines are also presented and analysed. The results reveal that the increase in the non-plastic fines content lead to an increase in the liquefaction resistance of sands.

1 Introduction

The presence of fine particles (silt/clay) has been thought to affect the behaviour of sand under cyclic loading. Unfortunately, the literature presents contradictory results as to how altering the fine content affect the sands resistance to liquefaction phenomenon. The results of both field and laboratory tests have shown that increasing the non-plastic fines content will result in either an increase in the liquefaction resistance of sands [1, 2], decrease in the latter [3, 4] or decrease in the liquefaction resistance until a certain limiting value, that is the limiting fines content, followed by an increase in the latter [5, 6]. These contradictory results could be attributed to the fact that these authors have studied different types of sands as well as different types of fines. Moreover, they have evaluated the liquefaction susceptibility of these sands based on different criteria such as the evaluation of liquefaction in terms of specific relative density [7 - 9], others have used the intergranular void ratio [4, 10] for the evaluation of this phenomenon as well as the equivalent intergranular void ratio [11, 12].

This paper aims to present the results of an experimental study on the influence of the non-plastic fines content F_c on the liquefaction resistance of sand-fines mixtures. For this reason, a series of cyclic liquefaction tests have been realized on reconstituted specimens of sand and fines. The analysis of these results allows us to better understand and clarify the influence of non-plastic fines content on the resistance of sands to cyclic liquefaction.

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2 Materials and testing device

The experimental study was conducted on reconstituted mixtures of sand and non-plastic fines. The first component of the mixture was the Fontainebleau sand whereas the second component was the Silica C500. The physical properties of the Fontainebleau sand are given in table 1. Silica C500 is a fine silica flour ($\text{SiO}_2 > 99\%$) and it is characterized by a sub- angular grain shape, the gradation curve of Silica C500 is shown in figure 1. The reconstitution method chosen for the fabrication of the specimens is the well-known wet tamping method that consists of adding a small amount of water to the sand, 5% in our case, and then the addition of the appropriate quantity of fines depending on the values of fines content ($F_c = 1\%$, 3% and 5%). Then the mixture is divided into 10 layers and the specimen is prepared by compaction of each layer to a predetermined density.

The cyclic tests were performed with the aid of a triaxial apparatus, the dimensions of the specimens are 100 mm in diameter and 200 mm in height. A schematic view of the testing setup is shown in figure 2. All the tests were conducted at an initial consolidation stress equal to 400 kPa. Two density indices were chosen $I_{Dmat} = 0.10$ for loose state ($e_{mat} = 0.90$) and $I_{Dmat} = 0.50$ ($e_{mat} = 0.74$) for medium dense samples.

Table 1. Characteristics of Fontainebleau sand [13]

Sand	D50 (μm)	C _u	e _{min}	e _{max}	ρ _s (t/m3)	ρ _{dmin} (t/m3)	ρ _{dmax} (t/m3)
Fontainebleau	210	1.52	0.54	0.94	2.65	1.37	1.72

Fig 1. Gradation curve of Silica C500

Fig 2. Schematic view of the triaxial apparatus

3 Liquefaction tests

3.1 Phenomenon of total liquefaction (loose state)

Figure 3 presents a typical result corresponding to the phenomenon of total liquefaction obtained for a loose specimen of Fontainebleau sand and Silica C500 characterized by a density index of 0.10 and $F_c = 1\%$, an isotropic consolidation stress of 400 kPa and subjected to an alternating cyclic loading having an amplitude $\Delta q_{cyc} = 80$ kPa. The cyclic stress ratio defined by $T_{cc} = \tau_{cyc}/\sigma'_{c} = \Delta q_{cyc}/2\sigma'_{c}$ is equal to 0.1.

The evolution of the excess pore water pressure (EPWP) as a function of the number of cycles is presented in figure 4.a where it can be noted that the EPWP increases steadily and

continuously at the beginning of the test before it passes an accumulation phase at the middle of the test and finally it passes through the last phase which records a significant and sharp rise in the EPWP that reaches the value of the initial consolidation stress σ'_c . In fact, the mechanism of the generation of the EPWP corresponds to an increase in the pressure in the loading phase and decrease in the unloading phase with an accumulation for each cycle. According to Eurocode 8, the moment at which the sudden increase in the EPWP occurs and reaches the value of the consolidation stress ($\Delta u = \sigma'_c$) or when the axial deformation reaches 5% (crest to crest) corresponds to a particular cycle called “critical cycle”. For the present study, the chosen criterion for the definition of the critical cycle corresponds to the moment where the axial deformation reaches 5% from crest to crest, although for the loose specimens where total liquefaction occurs these two criteria occur at the same time for the same cycle, that is in this case the twenty third cycle ($N_{crit} = 23$). The axial deformations that remained limited and very small throughout the test (of the order 0.3%) rapidly pass into large deformations ($\epsilon_a = 5\%$) during and beyond this critical cycle (Figure 4.b).

The effective stress paths in the (q, p') plane shows a progressive migration of the cycles to the left until reaching the critical cycle at which the phenomenon of liquefaction is initiated in the extension phase (figure 4.c). The migration of the stress paths towards the origin of the axes accounts for the contracting character of the sample that is in agreement with its density state (loose sample).

3.2 Phenomenon of cyclic mobility (medium dense state)

The results of a cyclic test realized on a mixture of Fontainebleau sand and C500 are presented in figure 4. The test was conducted at an isotropic consolidation stress equal to 400 kPa, with a fines content $F_c = 1\%$ and subjected to an alternating loading of amplitude $\Delta q_{cyc} = 144$ kPa. The obtained results reveal the appearance of the phenomenon of cyclic mobility.

For this case of the matrix density, the notion of the initial liquefaction introduced is characterized by the double peak per cycle in terms of the pore water pressure curve where the latter approaches the initial value of the consolidation stress twice accompanied with large deformations at this stage.

The effective stress paths are represented in the (q, p') plane where it is noted that the stress paths first migrate gradually towards the origin. During the period of cycling loading the material becomes strongly contracting during the unloading phases in both compression and extension with generation of high EPWP and a rapid migration of the effective stress paths towards the origin. During the reloading phases, however, the material becomes dilatant and regains strength, which allows this mechanism to be maintained for a number of cycles in which this leads to the development of hysteresis loops (figure 4.c).

Fig 3. Phenomenon of cyclic liquefaction of sand-fine mixture (loose specimen) curves (a) Δu -N; (b) ϵ_a -N; (c) p' - q

Fig 4. Phenomenon of cyclic mobility (medium dense specimen) curves (a) Δu -N; (b) ϵ_a -N; (c) p' - q

4 Influence of fines content

In order to study the influence of the non-plastic fines on the liquefaction resistance of sands, a series of cyclic triaxial tests has been realized for different values of fines content ($F_c = 0\%$, 1% , 3% and 5%). All the specimens were prepared at the same initial conditions $I_{Dmat} = 0.10$, and subjected to the same initial consolidation stress $\sigma'_c = 400$ kPa. The specimens were subjected to a cyclic stress ratio equal to 0.1 that is equivalent to an alternating loading of amplitude $\Delta q_{cyc} = 80$ kPa. The results of these tests are presented in figure 5. It is noted that the four specimens exhibit the same behavior. Concerning the pore

water pressure, it can be noted that the latter increases steadily and continuously at the beginning of the test before it passes an accumulation phase that can be considered relatively linear at the middle of the test and finally it passes through the last phase which records a significant and sharp rise in the pressure that reaches the value of the initial consolidation stress. However, it can be noted that this generation rate decreases with the increase in fines content. In fact, it is interesting to note that the moment at which the sudden increase in the pore water pressure occurs which corresponds to the critical cycle increases with the increase in fines content from 0% to 5%. For example, the required number of cycles to liquefaction for cleans sand at the level of loading is equal to 6 cycles, this N_{crit} increases to 13 cycles as we increase the fines content to 1% and keeps increasing to 26 cycles and 43 cycles for the cases where $F_c = 3\%$ and 5% respectively.

Concerning the axial deformations, it is remarked that they all exhibit the same trend, that they remain practically insignificant until they reach a critical cycle where they develop suddenly and quickly a large and very important deformation. However, this occurs at different critical cycle each time depending on the value of the corresponding fines content. This increase in the resistance of sands with the increase in the non-plastic fines could be explained by the fact that these particles tend to densify the material and therefore they favour the dilatancy which lead to an increase in the latter.

Fig 5. Influence of fines content on the cyclic shear resistance of loose sand-fines mixtures curves (a) Δu -N; (b) ϵ_a -N; (c) p' - q

5 Conclusion

This paper has presented an investigation that aims to clarify the effect of the non-plastic fines content on the initiation of liquefaction instability under undrained cyclic loading for low fines content ($\leq 5\%$). The analysis of the obtained results have revealed that the increase in fines content up to 5% has increased the cyclic resistance of sands to liquefaction. Besides, this study has presented the behaviour of both loose and medium dense specimens of sand and fines mixtures under cyclic loading. The loose specimens have been characterized by the exhibition of total liquefaction phenomenon whereas the medium dense specimens have developed the cyclic mobility phenomenon.

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