

Fines Content and Cyclic Preloading Effect on Liquefaction Potential of Silty Sand: A Laboratory Study

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Abstract: This paper presents a laboratory study of the influence of low plastic fines and preloading on the cyclic behaviour of silty sand. The study is based on undrained triaxial cyclic tests which were carried out for fines content ranging from 0 to 40%. The paper is composed of three parts. The first one presents the characteristics of soils used in this study; the second provides an analysis of the effect of low plastic fines on the cyclic behaviour of the sand-silt mixtures. The third part presents the effect of the preloading on the soil liquefaction. The test results indicate that the liquefaction potential of the mixtures decreases with increasing the fines content until $F_c=20\%$, after which the potential of liquefaction increases moderately with the fines content $F_c=40\%$. The over-consolidation and the cyclic drained preloading of low stress amplitude improved the liquefaction resistance of the sand-silt mixtures.

Keywords: fines; sand; undrained; potential; liquefaction; over-consolidation; cyclic preloading

1 Introduction

The city of Chlef (Algeria) was touched by many earthquakes last century. One of the most violent earthquakes occurred on October 10, 1980 with a magnitude of 7.3 degrees on the Richter scale, causing several thousand casualties among the population (more than 2500 dead) and much damage to buildings. The phenomenon of liquefaction was observed in several places and especially on the banks of the Wadi Chellif (river), as shown in Figs. 1, 2 and 3. The soil deposits in the area of Chlef are composed of a mixture of sand and fine grained soils.

The former investigations and researches were initially carried out to study the liquefaction of clean sands. Since the nineties special interest has been given to the liquefaction of the sands mixed with fine grained soils in order to study the effect of plastic and non-plastic fines on the behaviour of those mixtures and their liquefaction. These studies did not lead to a consensus on the influence of fines on the behaviour of those soils. Indeed, certain studies reported that an increase in the amount of silt leads to an increase in the resistance to liquefaction [1, 5, 6]; others showed that this increase reduces the resistance to liquefaction [2, 8, 16, 22, 25, 26, 28, 29,]. Other studies showed that the increase in the fraction of fines initially leads to a decrease of the resistance to liquefaction until a certain limiting silt content, then the resistance increases [3, 13, 17, 19, 23]. Finally, some of the more recent studies [14, 22, 24, 26] showed that the resistance to liquefaction of silty sands is more closely related to the soil skeleton void ratio than to its silt content (fines).

The over-consolidated soils (preloaded) are often found in nature especially with the thawing of the glaciers, scouring of the grounds, phenomenon of erosion, fluctuation of ground water, etc.

Several researchers studied and showed that the over-consolidation ratio has a significant effect on the liquefaction resistance of soils [9, 20, 21]. They observed that liquefaction resistance increases with the over-consolidation ratio. This effect becomes very important with the increase in the percentage of fines. By carrying out cyclic tests on the sand of Hostun, [3] found that with an over-consolidation ratio of 7, the liquefaction is obtained at the end of 17 cycles, whereas with a normally consolidated sample, 6 cycles are needed to reach liquefaction phenomenon. [7] studied the influence of stress history on the liquefaction resistance of sands. They showed that this resistance increases when the sample is initially subjected to a small cycles of loading followed by a drainage; other authors showed that a pre-shearing with great amplitudes can lead to a reduction of the cyclic resistance. [10, 18] interpreted this behaviour using the concept of 'phase transformation line/characteristic state', while specifying that any cyclic loading followed by a drainage in the contracting zone leads to the densest state of the material without modifying its structure, resulting in an increase in the cyclic shear strength. In contrast, if the preloading comprises a way in the dilating field, there is an untangling of grains, leading to a new structure with a lower resistance.

Ishihara and Okada [11] studied the influence of preliminary strong distortions on the liquefaction resistance of sands. The tests were carried out with the traditional triaxial apparatus according to two procedures. In the first procedure, the initial cycle is stopped when the deviator stress is cancelled; in the second, the initial cycle is completed by a loading in extension or compression to cancel the residual strain. They showed that there is insignificant influence of the preliminary strain on the cyclic shear strength when the preloading ends with a compression phase. In contrast, when the initial loading ends with an extension phase, the behaviour of sand shows a contractance and the cyclic shear strength is greatly reduced. [4]

realized a series of tests on samples subjected initially to preloading for two levels of axial strain. They found that a large preloading in compression ($\varepsilon_1 = +5\%$) or in extension ($\varepsilon_1 = -5\%$) induces a significant reduction of the liquefaction resistance. [27] found that a sample without initial preshearing presented a low liquefaction potential whereas the samples subjected to preshearing of low amplitude had a very great potential of liquefaction.

In this paper, we present a laboratory study dealing with the behaviour of a sand-silt mixture to study the cyclic undrained shear response using different fines contents ranging from 0 to 40% for the purpose of reinforcing the soil that is prone to liquefaction. These tests were carried out to better understand the effect of low plastic fines on the cyclic behaviour of the mixtures (potential of liquefaction) as well as the influence of the preloading. The paper is composed of three parts. In the first part we present the materials. The second part provides an analysis of the test results and discusses the influence of fines on the behaviour of the sand-silt mixtures. The third part presents the effect of preloading on the liquefaction potential of the sand-silt mixtures.

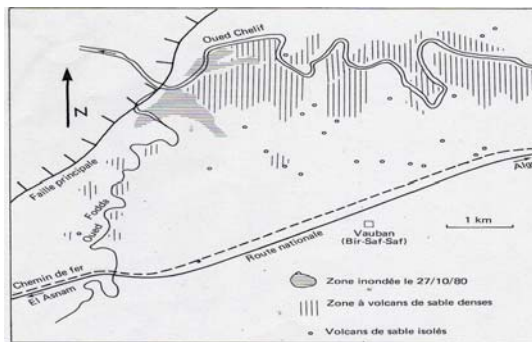


Figure 1

Location of liquefied soil (El Asnam, 1980)



Figure 2

Sand craters of liquefied zones (El Asnam, 1980)



Figure 3

Sliding of the Chlef River banks (El Asnam, 1980)

2 Materials Tested

The laboratory tests were carried out on reconstituted uniform sand samples of Rass (Algeria) mixed with the silt of Sidi-M'hamed having a plasticity index of 2.33 (classified as a low plastic silt).

The sand of Rass comes from the accesses of the bed of Oued/Rass River (confluence of Oued/Chlef and Oued/Rass). It is a medium sand with an average diameter of $D_{50} = 0.39$ mm. Fig. 4 shows the grain size distribution curve of Rass sand and the silt used (named with the symbol SM). Tables 1, 2 and 3 give the summary on index properties of the sand, silt and the chemical analysis.

The dimensions of the samples were 70 mm in diameter and 70 mm in height in order to avoid the appearance of the instability (sliding surfaces) and buckling. After the specimen was formed, the specimen cap was placed and sealed with O-rings, and a partial vacuum of 20 kPa is applied to the specimen to reduce disturbances. Saturation was performed by purging the dry specimen with carbon dioxide for approximately 30 min. De-aired water was introduced into the specimen from the bottom drain line. Water was allowed to flow through the specimen until an amount equal to the void volume of the specimen was collected in a beaker through the specimen's upper drain line. A minimum Skempton [25] test specimen were isotropically consolidated at a mean effective pressure of 100 kPa subjected to undrained monotonic and cyclic triaxial loading with a constant strain rate of 0.167% per minute.

The experimental program includes alternate cyclic undrained tests on the mixture sand-silt with a relative density of $Dr = 65\%$ and a silt content ranging from 0 to 40% (ratio of the mass of fines on the mass of the sample) under an initial effective confining pressure $\sigma'_c = 100$ kPa (Cell pressure = 500 kPa and Back pressure = 400 kPa). The amplitude levels of these cycles (q_m) are equal to 30, 50 and 70 kPa. The loading level (CSR) is defined by:-

Table 3
Chemical analysis

| Sand-Rass | |
|--|-----------|
| - Fire loss | 6.23 |
| - Total Silica..... | 78.20 |
| - Alumina (Al ₂ O ₃)..... | 2.03 |
| - Oxide of iron (Fe ₂ O ₃)..... | 5.58 |
| - lime (CaO)..... | 8.13 |
| - Magnésia (MgO)..... | Not dosed |
| - Potash (K ₂ O)..... | Traces |
| - Oxide of sodium (Na ₂ O)..... | Traces |
| - Sulphates SO ₄ | 0.24 |
| - Chlorides CL-Solubles in water..... | 0.14 |
| - Carbonates CaCO ₃ | 13.94 |
| - Insolubles..... | 0.93 |
| - Organic materials..... | Conform |

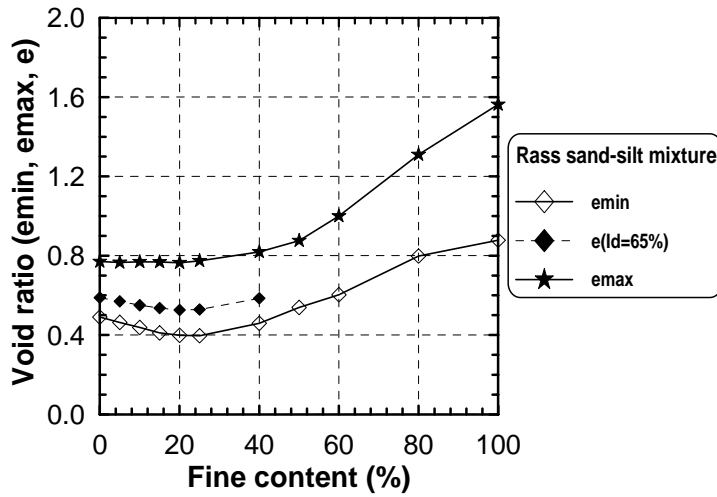


Figure 5
Minimal and maximal void ratios versus fines content

Table 4
Physical characteristics of the sand-silt mixture

| Silt Content (%) | 0 | 5 | 10 | 15 | 20 | 25 | 40 | 50 | 60 | 80 | 100 |
|------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| G _s | 2.664 | 2.668 | 2.673 | 2.768 | 2.682 | 2.687 | 2.701 | 2.711 | 2.720 | 2.739 | 2.758 |
| e _{max} | 0.770 | 0.766 | 0.769 | 0.767 | 0.764 | 0.773 | 0.710 | 0.742 | 0.786 | 0.947 | 1.317 |
| e _{min} | 0.490 | 0.463 | 0.437 | 0.410 | 0.398 | 0.396 | 0.386 | 0.393 | 0.455 | 0.594 | 0.776 |

Fig. 5 and Table 4 show the variation of maximal and minimal void ratios versus the fines content ($F_c=0\% \dots 100\%$). The maximal and minimal void ratios of the sand and mixture were determined according to ASTM standards (D 4253) and Modified Proctor Compaction (D 1557).

These tests were carried out by using a triaxial apparatus of mark GDS (Minidyn2Hz) with samples of diameter and a height of 70 mm; the confinement and the back pressure were applied through GDS devices. In order to obtain a uniform density throughout the specimen, the under-compaction method of specimen preparation was used, as suggested by Ladd [15]. The under-compaction method consists of placing each layer at a density slightly greater than the density of the layer below it in order to account for a decrease in volume and increase in density that occurs in the lower layers when the new layer is placed. Relative density was varied by 1% per layer in general. The experimental equipment included a vacuum pump, a demineralised water tank, a pressure gauge of depression, and a mould used for the preparation of the sample. The sample was saturated by flushing with CO_2 and de-aired water.

The samples were isotropically consolidated to reach the value of the effective confining pressure preceding the cyclic loading.

3 Presentation and Discussion of Results

3.1 Effect of Loading Level

Figs. 6 and 7 show the evolution of the pore water pressure and axial strain versus the time of a series of alternate cyclic tests realized on clean sand samples. The amplitudes of these cycles (q_m) are equal to 30, 50 and 70 kPa, respectively; this gives a cyclic stress ratio $\text{CSR} = 0,15, 0,25$ and $0,35$, ($\text{CSR} = q_m / 2\sigma'_c$). Fig. 6 illustrates clearly the increase in the rate of the water pore pressure with the increasing amplitude of cyclic loading. This increase is very important when q_m increases from 30 to 50 kPa.

For the test with $\text{CSR} = 0,35$, the sample develops shear stresses after 8 cycles, corresponding to 2% of double amplitude, and liquefaction was reached during the 9th cycle. For the samples with $\text{CSR} = 0,25$ and $0,15$, they develop shear stresses after 9 cycles corresponding to an axial strain of 2% of double amplitude; liquefaction was reached during the 12th cycle and 173 cycles for 2% of double amplitude, while liquefaction was observed after 176 cycles, respectively. It is clear that an increase in the amplitude of cyclic loading (q_m) accelerates the liquefaction process.

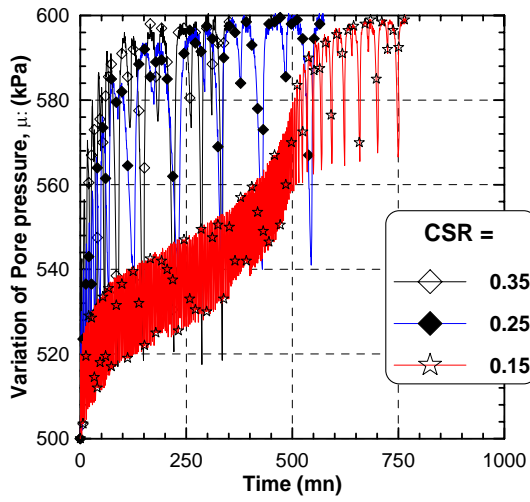


Figure 6
Evolution of the pore water pressure versus time

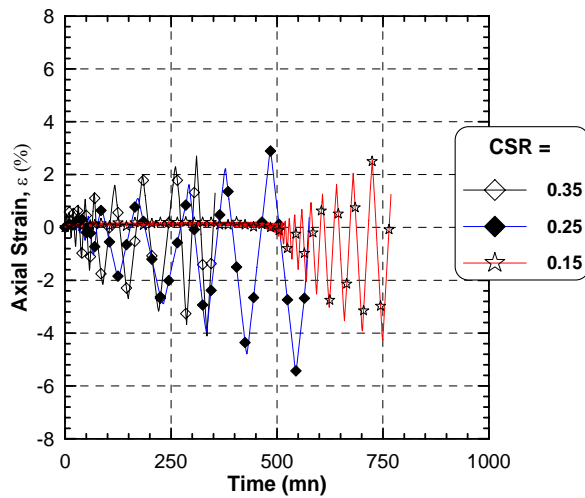


Figure 7
Evolution of the axial strain versus time

3.2 Effect of Fines on the Liquefaction Potential

Figs. 8a and 8b show the evolution of the axial strain and pore water pressure versus time for samples sheared with an amplitude $q_m = 30$ kPa (CSR = 0.15).

In Fig. 8a we notice that the sample with a silt content $F_c=10\%$ develops shear stresses after 15 cycles, increasing gradually to reach a double amplitude strain of 5% during the 22nd cycle; liquefaction was reached during the 23rd cycle. The sample with a silt content $F_c=20\%$ develops shear stresses after 7 cycles, reaching a double amplitude strain of 4% during the 12th cycle showing instantaneous liquefaction, whereas the sample with a silt content $F_c=40\%$ reached an axial strain of 4% during the 7th cycle, and 8% during the 13th cycle and the liquefaction of the sample was reached during the 14th cycle. To recall, the liquefaction of the clean sand ($F_c=0\%$) occurred at 176th cycle; however, with the sample with a silt content $F_c=10\%$ the liquefaction was reached after 23 cycles. With the sample with a silt content $F_c = 20\%$, the liquefaction was reached after 12 cycles; whereas with the sample with $F_c=40\%$, it was reached after 14 cycles (Figure 9). In Fig. 8b, we notice that the sample with $FC = 20\%$ generates the pore water pressure quickly, whereas the samples with $F_c=10\%$ and 40% required much more time to generate the pore water pressure. This is due to the effect of fines causing an increase in the sample contractancy until a certain limiting value beyond it, they cause an increase in the dilatancy of the mixture sand-silt.

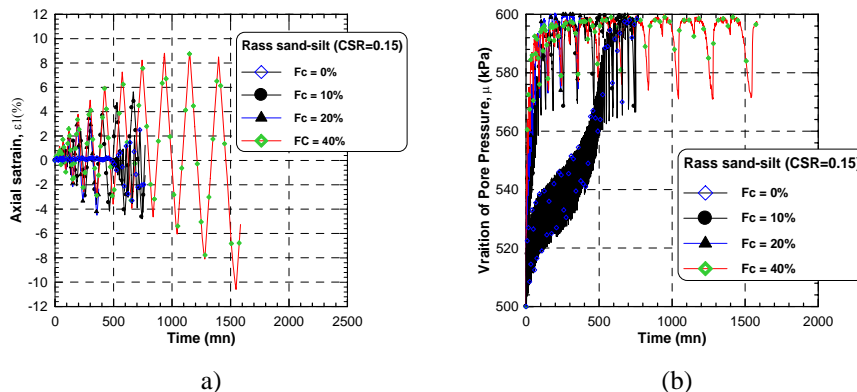


Figure 8

Influence of fines on the cyclic behaviour of the sand-silt mixtures

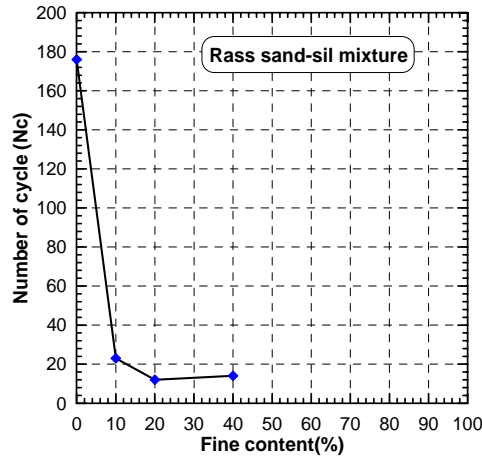


Figure 9

Evolution of the number of cycles versus fines content

Figs. 10a and 10b show the variation of the cyclic stress ratio ($CSR=q_m/2\sigma'_v$) and cyclic liquefaction resistance (CLR) versus the number of cycles (N_c). Resistance to liquefaction (RLC) is defined by the cyclic stress ratio giving liquefaction for 15 cycles (Ishihara 1993). We notice in Fig. 10a that the resistance of liquefaction of the mixture Rass sand-SM silt decreases with an increase in the amount of fines until the fines content $F_c = 20\%$; then we note a small increase in the liquefaction potential with the fines content $F_c = 40\%$. This increase is due to the active role of fines beyond 20% which take part in the resistance to liquefaction. Fig. 10b shows cyclic liquefaction resistance versus the fines content. We note that the cyclic liquefaction resistance decreases with an increase in the fines content up to 20% having $RLC = 0.14$, then it re-increases slightly to reach the value of $RLC = 0.15$ for the fines content $F_c = 40\%$.

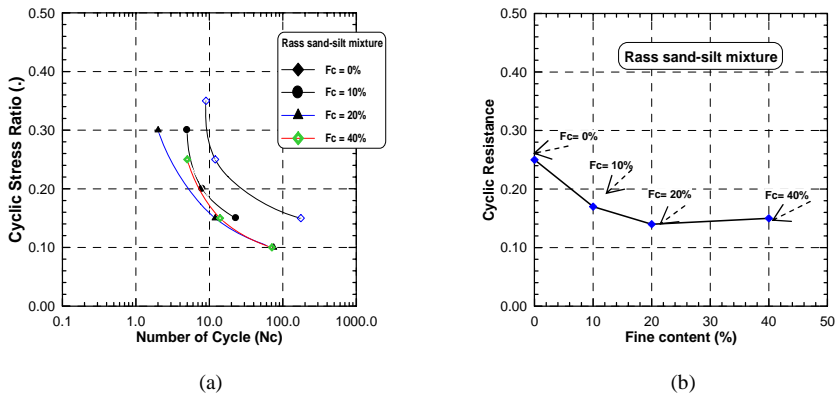


Figure 10

Effect of fines on the liquefaction potential of the Rass sand –SM silt mixtures

3.3 Effect of Preloading on the Resistance of Liquefaction

3.3.1 Effect of the Over-Consolidation

A series of undrained cyclic tests was carried out on Rass sand–SM silt mixture over-consolidated with an $OCR = 5$ (Figs. 11, 12 and 13). The tests were carried out with a initial relative density $I_d = 0.65$ for three loading amplitudes ($q_m = 30, 40$ and 60 kPa) in order to determine the influence of the over-consolidation on the liquefaction potential of the mixtures. As can be seen from Figs. 11, 12 and 13, the three loadings levels lead to the liquefaction of the soils. For the highest loading ($q_m = 60$ kPa), liquefaction was observed after 8 cycles, whereas for the same loading, the normally consolidated soil underwent a liquefaction after 5 cycles.

For the loading with an amplitude $q_m = 40$ kPa, the over-consolidated soil ($OCR=5$) was liquefied after 26 cycles whereas the normally consolidated soil ($OCR=1$) was liquefied after 8 cycles (Fig. 11).

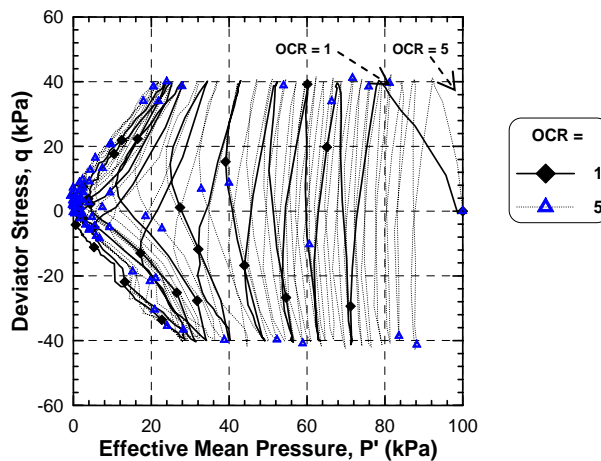


Figure 11

Undrained cyclic test on Rass sand-silt mixture ($F_c = 10\%$, $q_m = 40$ kPa, $Dr = 65\%$, $\sigma'_{c'} = 100$ kPa)

The influence of the lowest amplitude is even stronger. Indeed, for a loading $q_m = 30$ kPa, the normally consolidated soil was liquefied after 25 cycles compared to the 236 cycles necessary for the liquefaction of the over-consolidated soil. Figs. 12 and 13 show clearly that the over-consolidation of the soil attenuates the rate of increase in the axial strain and pore pressure, causing a delay in liquefaction. The normally consolidated sample develops double amplitude axial strain (2.5%) after 21 cycles, for which the full liquefaction was reached after 25 cycles; the over-consolidated sample develops double amplitude axial strain (2.5%) after 234 cycles and reached the full liquefaction after 236 cycles. It clearly shown in Fig. 13 that the over-consolidation delays the generation of pore pressure.

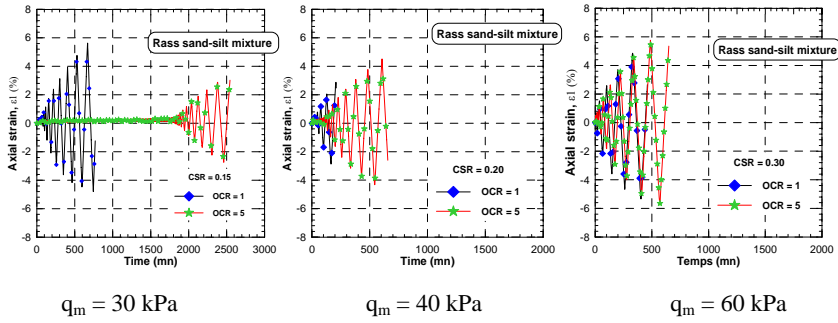


Figure 12

Influence of the over-consolidation on the liquefaction potential (axial strain versus time)

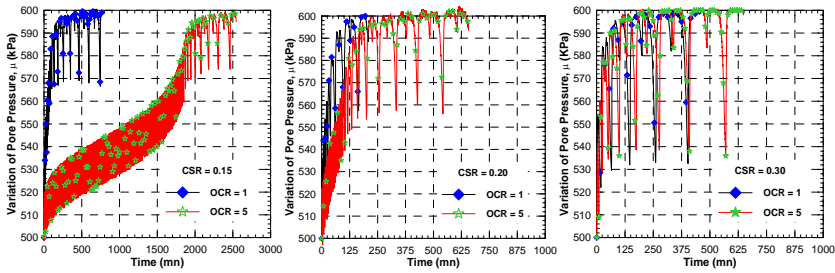


Figure 13

Influence of the over-consolidation on the liquefaction potential (pore pressure versus time)

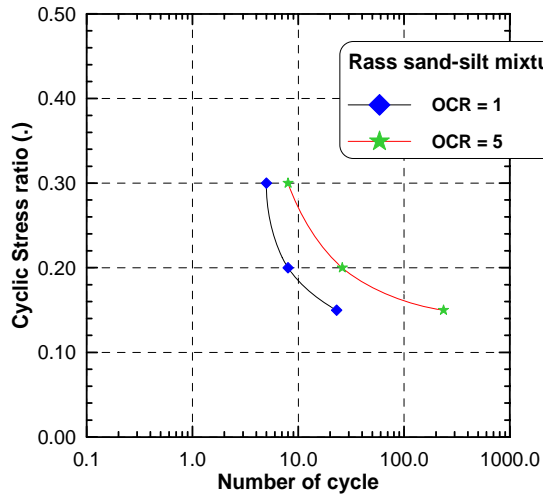


Figure 14

Influence of the over-consolidation on the liquefaction potential of Rass sand-sil mixture (FC = 10%)

Fig. 14 shows the influence of the over-consolidation on the resistance of liquefaction. It confirms clearly the results presented above, namely that the over-consolidation of soil increases its resistance to liquefaction. This is due to the fact that the over-consolidation amplifies the dilating character of the soils, inducing the attenuation in the rate of the water pressure under undrained loading condition.

3.3.2 Influence of Cyclic Preloading

A series of tests were carried out on the mixture Rass sand– RS silt (FC = 10%) on samples subjected to a cyclic drained loading in order to study the influence of a cyclic preloading on the potential of liquefaction.

Two test series were carried out. In the first, the samples were initially subjected to 5 cycles, while in the second they underwent 10 cycles of loading ($q_m = 30, 40$ and 60 kPa). Each series comprises several tests carried out for three amplitude levels ($q_m = 30, 40$ and 60 kPa).

We note that the whole number of the selected loadings leads to liquefaction. The effect of the preloading is to increase the liquefaction resistance. As an example:

- for the loading $q_m = 60$ kPa, liquefaction was observed after 11 cycles for the sample subjected to 5 cycles and after 16 cycles for the sample subjected to 10 cycles; it should be noted that the soil that did not undergo a cyclic loading was liquefied after 5 cycles.
- for the loading $q_m = 40$ kPa, liquefaction was observed after 31 cycles for the sample having undergone 5 cycles and after 37 cycles for the sample having undergone 10 cycles; it should be noted that the soil that did not undergo a cyclic loading was liquefied after 8 cycles.
- for the loading $q_m = 30$ kPa, liquefaction was observed after 80 cycles for the sample subjected to 5 cycles and after 95 cycles for the sample preloaded with 10 cycles; it should be noted that the soil that did not undergo cyclic loading was liquefied after 23 cycles.

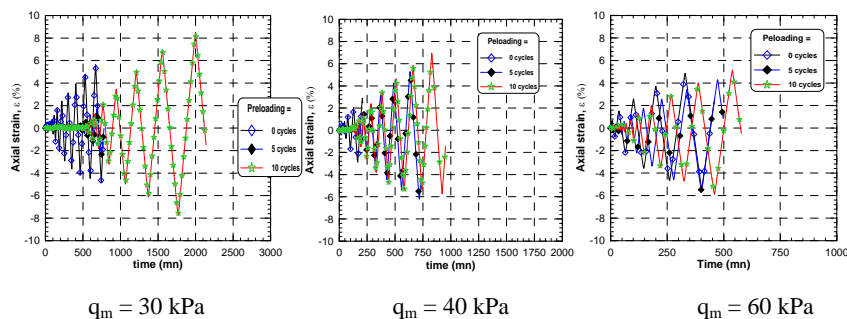


Figure 15

Influence of the cyclic preloading on the liquefaction potential (axial strain versus time)

Fig. 15 illustrates the influence of the preloading level on the evolution of the axial strain. It clearly shows that an increase in N_p (number of preloading) from 5 to 10 delays the development of the soil deformation. The sample preloaded with $N_p = 5$ and 10 reached an axial strain with double amplitude of 4% after 78 cycles, 92 respectively, with a loading $q_m = 30$ kPa. The same observation was then done for the samples with a loading of $q_m = 40$ kPa and 60 kPa. Fig. 16 shows the evolution of pore pressure versus cycle number. The three figures show clearly that the cyclic preloading delays in considerable manner the rate of pore pressure. The pore pressure values are determined on the top of deviator.

These results are summarized in Fig. 17, which confirms that the cyclic loading improves the resistance to liquefaction of the soils. We note that the effect of the first 5 cycles is more significant than that of the last 5 cycles. This result can be explained by the fact that the cyclic loading improves the soil density and consequently increases its dilatancy.

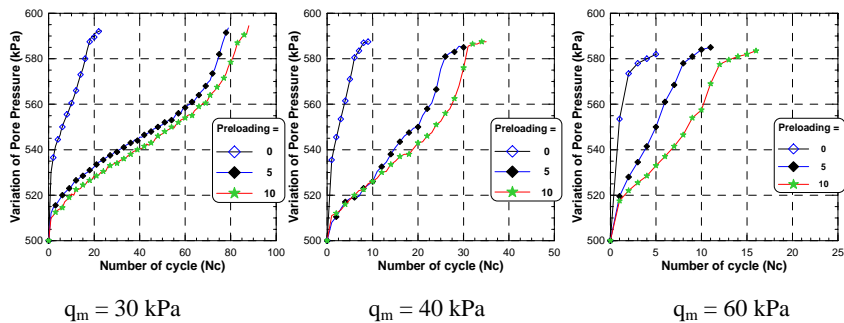


Figure 16

Influence of the cyclic preloading on the potential of liquefaction

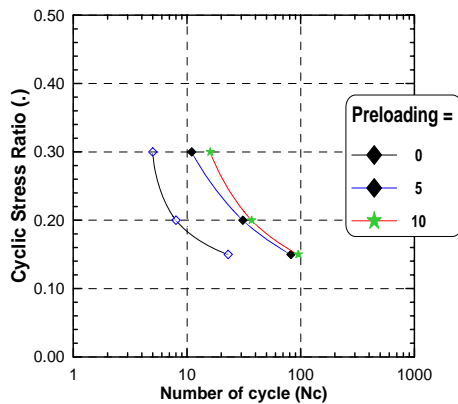


Figure 17

Cyclic preloading effect on the liquefaction potential of the mixture Rass sand - SM silt
(FC = 10%, $I_d = 0,65$)

Fig. 18 illustrates the evolution of the cyclic resistance to liquefaction versus the number of preloading. We observe a clear increase in the cyclic liquefaction resistance (previously defined) versus the level of preloading. The cyclic resistance increases in a linear manner with increasing the number on preloading. Drained cyclic preloading improves the resistance of the soil compared to the over-consolidation. The results give a CLR (cyclic liquefaction resistance) equal to 0.3 and 0.25 for the mixtures subjected to a preloading of $N_p=10$ and 5; for the mixture subjected to an over-consolidation ratio of $OCR=5$, the CRL is equal to 0.23. However, the mixture not that was subjected to any preloading the CLR is 0.15.

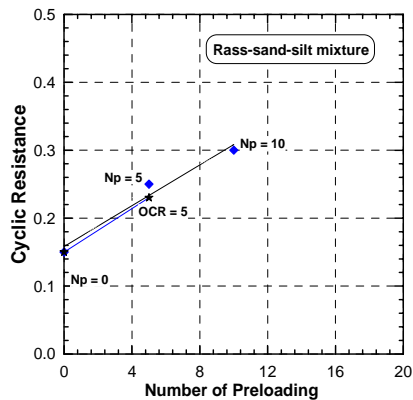


Figure18

Evolution of the liquefaction resistance (RLC) versus the preloading level

Conclusions

In this paper we have presented the results of a laboratory study of the influence of low plastic fines and preloading on the cyclic behaviour of silty sand. This study comprises cyclic undrained triaxial tests which were carried out with an index of density $I_D = 0.65$ for fines content varying between 0 and 40%.

The test results show that an increase rate in water pressure increases with the increase of the cyclic loading amplitude, and it becomes appreciable when the amplitude of loading varies from 30 to 50 kPa. The fines content (F_c) until a certain threshold ($F_c=20\%$ in our case) increases the sample contractancy; beyond this limit, it increases the dilatancy of the soil. The liquefaction potential of the mixture of Rass sand and SM silt decreases with an increase of the fines content until 20%, then we note a small increase in the liquefaction potential with the fines content of 40%. This increase is due to the active role of fines beyond 20% and which take part in the liquefaction resistance. The cyclic liquefaction resistance decreases from 0.26 to 0.14 with the increase of the fines content until the value of 20% having, then it re-increases slightly to reach the value of $CRL = 0.15$ for the fines content of 40%.

The over-consolidation of the soil increases its liquefaction resistance; due to the fact that it amplifies the dilating character of the soil, attenuating increase rate in the water pressure under undrained loading.

The drained cyclic loading improves the resistance to liquefaction of the soils; indeed, the effect of the first 5 cycles is more significant than that of the last 5 cycles. This result can be explained by the fact that the cyclic loading densifies the soil state and consequently increases its dilatancy. Drained cyclic preloading improves the resistance of the soil comparing to the over-consolidation.

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