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Cyclic Undrained Behavior of Sand-Silt Mixtures by Taking a Constant Sandy Matrix

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ABSTRACT

The liquefaction susceptibility of saturated sand-silt mixture samples is evaluated by cyclic undrained triaxial tests that were carried out on reconstituted specimens of three Algerian sands at a density index, I_D, of 0.5 and an initial confining pressure, σ'_c, of 100 kPa. The sand material matrix is kept as a constant parameter for the entire range of fines content due to the difficulty of determining experimentally the extreme void ratios of soil mixtures for fines content, FC, exceeding 15%. The test results were used to conclude on the effect of the fines content and other parameters on the liquefaction resistance of the sand-silt mixtures. Indeed, the fines content affects considerably the liquefaction resistance and the generated excess pore pressure. Moreover, the effect of fines is in good agreement with the published literature, where the cyclic resistance ratio decreases first to a threshold value of fines content and then increases. This study can be used in soil classification and liquefaction potential assessment of seismic zones with small fines content.

Introduction

Due to its location on the African plate which is in permanent collision with the Eurasian plate, northern Algeria is a constantly very instable zone subjected to intense seismic activity. Damages after each earthquake were important, making Algeria the country that has suffered significantly in the African continent. In addition, the earthquakes manifest its most terrible effects through the soil causing in some cases liquefaction phenomenon that occurred in Chlef and Algiers regions. Chlef, formerly known as El Asnam after 1962 and Orléansville before 1962, is located 210 km west of Algiers, the capital, and Boumerdes is situated 50 km east of Algiers. Spectacular failures of natural slopes and liquefaction of saturated sands followed by large-scale subsidence were recorded during the Chlef 1980 and Boumerdes 2003 earthquakes. Due to the generation of high excess pore pressure, liquefied sand appeared at the ground level creating craters (EERI 1983). The phenomenon of liquefaction was particularly observed on the banks of the Chlef River and the confluence of this river with its tributary the Fodda River. Moreover, several other types of damages caused by the earthquakes under consideration, especially that of Boumerdes 2003 were recorded (AFPS 2003).

Post-earthquake field investigations have indicated that grain size analyses of sand samples taken

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from sand boils at different sites showed an important percentage of fines. Furthermore, several soils encountered in geotechnical engineering applications are a mixture of sand-clay or sand-silt with plastic or non-plastic fines content. Their use inquires a reliable knowledge of their properties and their mechanical behavior.

For this purpose, the influence of low plastic fines on the liquefaction resistance of sand-fines mixtures has got considerable attention over the last two decades. Important data base is therefore available through the published geotechnical earthquake engineering literature; however, many of them are contradictory. Researchers have shown that increasing FC increases the liquefaction resistance of the sand-silt mixture (Amini and Qi 2000), whereas other published results indicate that the increase of fines decreases the liquefaction resistance (Lade and Yamamuro 1997). Other authors have found that the liquefaction resistance initially decreases with addition of fines to a threshold value and then increases again with the fines content (Xenaki and Athanasopoulos 2003; Yang et al. 2006).

Furthermore, sand-fines mixtures, tested by monotonic and cyclic drained and undrained triaxial tests, were prepared for fines content ranging from 0 to 100%. This method requires the determination of the extreme void ratios e_{min} and e_{max} for each mixture. However, the laboratory test standards (AFNOR-NF P 94-059 2000; ASTM D4253 2002; ASTM D4254 2002) recommended to soils containing percentage of fines not exceeding 12% for the French standards and 15% for American standards. Despite this limitation, other researchers use these standards for mixtures exceeding 15% (Yang et al. 2006; Papadopoulou and Tika 2008). Hence, our work takes place in this context; the samples were reconstituted by taking the same amount of clean sand while studying its behavior for fines content ranging from 0 to 15% depending on the type of the selected sand. The laboratory investigation was conducted by undrained cyclic triaxial tests at σ'_c=100 kPa and I_D=0.5. These data reflected the stress state of soil liquefaction that has been observed during the 1980 Chlef and 2003 Boumerdes earthquakes. Cyclic tests were carried out to assess the influence of the low plasticity fines content on the mechanical behavior of the sand-fines mixtures with stress-controlled using frequency sinusoidal signal, f, of 0.05 Hz and symmetric alternating loading conditions. The sample shearing was running in closed drainage to simulate the undrained field behavior during earthquakes.

Laboratory testing program

Materials properties

Three silty sand samples were collected from the liquefied layer of the soil deposit during the 1980 Chlef and 2003 Boumerdes earthquakes. They belong to two different areas, namely Chlef and Rass sands for the Chlef region, and Zemmouri sand for the Boumerdes region.

Chlef sand is originated from the Chlef River banks, which is considered as the longest river in Algeria crossing the Chlef city. This sand is light gray with some beige-dew elements containing an average percentage of silica (55.38% of SiO_2). However, Rass sand with beige color is originated from the edge of the Rass River banks lying to the west of the Chlef city. It has a special composition because it contains high level of silica (81.37%) and a minimum lime percentage (6.40% of CaO) compared to the other two sands (14.32% for Chlef sand and 10.38%

for Zemmouri sand). The third sand was extracted from the Zemmouri beach not far from buildings that have suffered significant disorders during the 2003 earthquake. This sand with gray color has a mostly similar chemical composition as Chlef sand (66.92% of SiO_2) and a lower percentage of fines (0.30%). Chlef and Rass sands contain naturally an average fines rate of 9.30 and 5.83%, respectively. Note that the fines are considered as elements less than 80µm. In this study, Rass and Chlef sands were considered naturally by mixing the clean sand with fines content of 5 and 10%, respectively; however, Zemmouri sand was used in its natural state. The grain size distribution curves and the index properties of the materials under study are given in Figure1 and Table 1. The plasticity index, Ip, of the fines used in this study is 13, 20 and 12, respectively for Chlef, Rass and Zemmouri proving that the used fines are classified as low plastic materials.

Table 1. Index properties of the tested materials

Sand	**G_s**	**D_{50} (mm)**	**C_u**	**C_c**	**ρ_{dmin} (g/cm^3)**	**ρ_{dmax} (g/cm^3)**	**e_{min}**	**e_{max}**	**Grain shape**
Chlef	2.65	0.39	2.72	1.18	1.459	1.773	0.495	0.817	Sub-angular to sub-rounded
Rass	2.67	0.35	1.90	1.01	1.484	1.778	0.501	0.799	
Zemmouri	2.69	0.33	1.66	0.97	1.411	1.702	0.580	0.906	

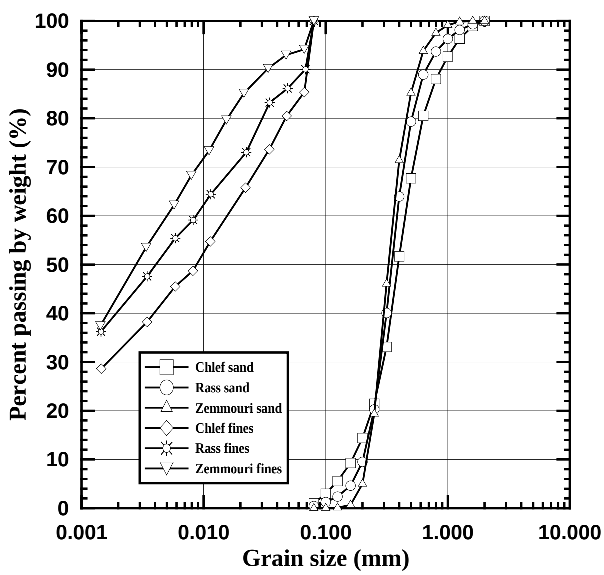


Figure 1. Grain size distribution curves of the tested materials

Test procedure

The apparatus used to perform cyclic tests is Buehl and Faubel triaxial device of Navier laboratory, located at Ecole des Ponts ParisTech, France, which is a pneumatic cyclic controlled triaxial cell with a cell designed for cylindrical samples of 70 mm diameter and 140 mm height (H/D=2). The method of dry funnel deposition has been used in which the sample is poured into the mold gently in seven layers, each one is 2 cm thick, using a funnel with a drop height of zero and slightly compacted with a tamper. The mixtures were prepared by keeping the same amount of clean sand to which a percentage of fines is added function of the content limit in the natural sand. This choice was made because it is difficult to determine in the laboratory the minimum and maximum voids ratios of mixtures for a fines content exceeding 15%. Saturation by carbon dioxide and deaerated water and the application of a back pressure of 200 kPa gives the coefficient of Skempton, B, greater or equal to 0.98 in most of the considered tests.

The laboratory study was carried out on three series of stress-controlled cyclic triaxial tests with different fines content function of the content limit in the three natural sands. Chlef sand samples was used in the first series with fines content ranging from 0 to 15% and cyclic stress ratio, $CSR=q_m/2\sigma'_c$, varying from 0.10 to 0.30 or 0.15 to 0.30 according to the accommodation state. In this case, the loading amplitudes, q_m, of the deviator stress is varying from 20 to 60 kPa or 30 to 60 kPa. For each value of the loading amplitude, the number of cycles, N_{Liq}, required to reach the liquefaction of sample was determined to draw the liquefaction potential curves. It was found that the liquefaction is obtained quickly for large amplitudes, i.e. the liquefaction resistance increases with decreasing the loading amplitude. The failure criterion used is that the excess pore pressure is equal to the initial confining pressure which corresponds, in most the tests under consideration, to a deformation of 5% double amplitude axial strain (Ishihara 1993). Similarly, the tests of the second series was performed on Rass sand samples with a percentage of fines varying from 0 to 10%; however, the third series of tests concerning Zemmouri clean and natural sands.

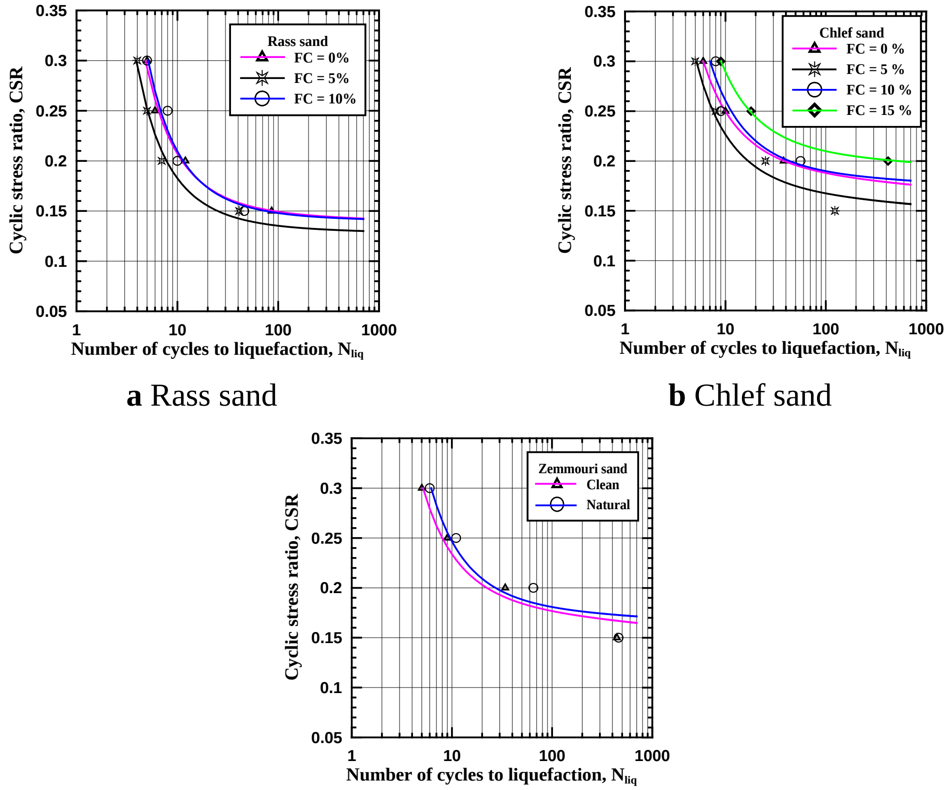
Test results and discussions

Analysis of cyclic Tests

The number of cycles of liquefaction potential curves increases exponentially with the decrement of the cyclic stress ratio (Figure 2). This implies that a threshold would exist below of which the instability would not be reached. Hence, the fitting curves of the materials were chosen in order to get a horizontal asymptote representing the accommodation state.

Zemmouri and Rass sands are vulnerable to liquefaction for CSR ranging from 0.3 to 0.15. Below a value of 0.15, these soils exhibit a state of accommodation. Excepted is the case of Chlef sand with fines content of 5%, which has a susceptibility to liquefaction limited by a CSR ranging from 0.3 to 0.2. The cyclic shear strength of Chlef sand is more or less close to the Zemmouri sand but larger than that of the Rass sand having the lowest cyclic liquefaction resistance.

By comparing the clean and natural sands, the soil samples under consideration exhibit different mechanical behaviors although their index properties are closer to each other. However, the effect of fines can lead to an increase, decrease or stabilization of the liquefaction resistance of the soil over the entire range of the tested cyclic stress ratios. Figure 2 indicates that the Rass clean sand presents higher cyclic shear strength than its natural sand. This observation is reversed for the Zemmouri sand that has only 0.3% of fines in its natural state while the Rass sand has 5.83% of fines. Chlef sand has a very special case although the level of fines is approaching 10%. Liquefaction resistance of clean or natural sand remains the same for all the cyclic stress ratio values. Moreover, the liquefaction resistance of Chlef and Rass sands initially decreases to a threshold value of fines, FC_{th}=5%, and then rises again with the increase in fines content. The present results are in good agreement with published literature (Xenaki and Athanasopoulos 2003; Yang et al. 2006). This can have effect on the volumetric response when the fines content increases, inducing a reduction in the liquefaction potential.



a Rass sand

b Chlef sand

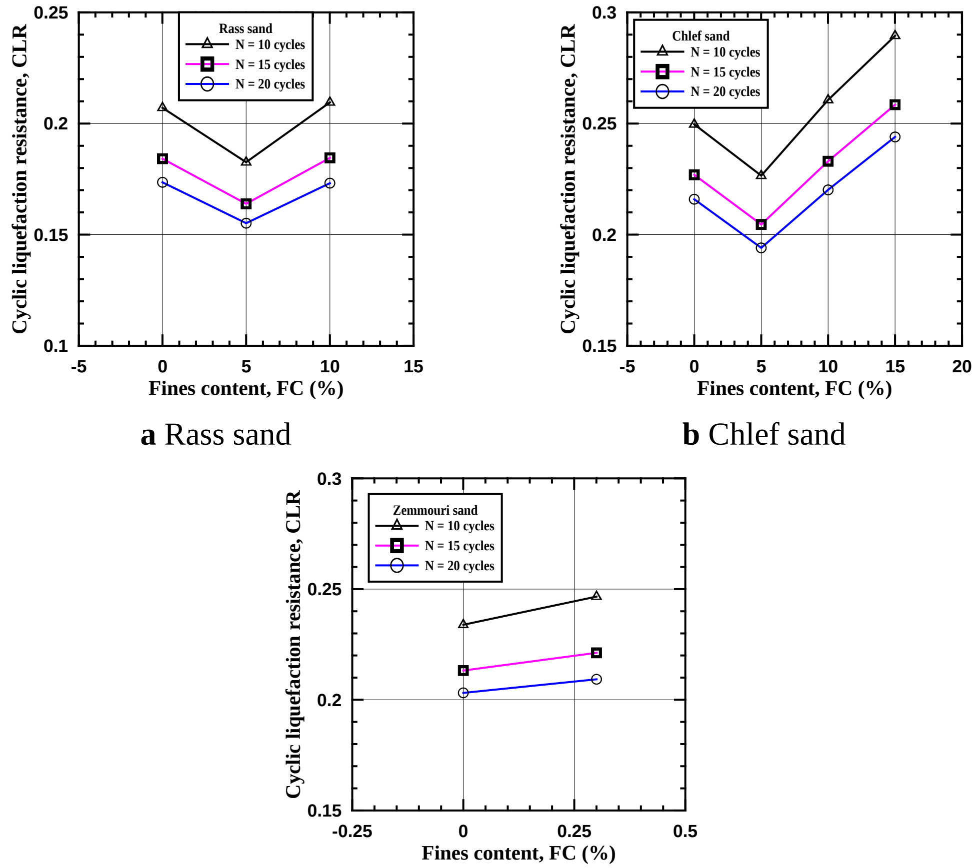
c Zemmouri sand

Figure 2. Liquefaction potential curves of the three sands

Influence of the cycles number

In order to emphasize previous observations, the cyclic shear strength curves describing the behavior of the three sands were representing taking into account the influence of fines corresponding to a number of cycles N=10, 15 and 20 cycles. Figure 3 shows that for the Chlef and Rass sands, the presence of fines reduces the liquefaction resistance of the soil up to 5% fines content, beyond which it sharply increases. On the other hand, the cyclic liquefaction resistance decreases with the increase of the cycle number.

Many researchers concluded that the effects of the fines on the liquefaction resistance were due to the use of the soil global void ratio parameter, *e*, to characterize the sand-silt mixture response. Indeed, the global void ratio is not a relevant parameter to describe the mechanical behavior of a soil containing fines because the fines occupy solely the available spaces between the particles up to a certain fine level, and therefore do not affect the behavior of the sand-silt mixture. Thevayanagam et al. 2002 studied the effect of fines content on the liquefaction resistance of sand-fines mixtures and recommended the use of the intergranular void ratio, e_s, for the interpretation of the observed behavior in the laboratory. More specifically, they proposed a conceptual framework in which the soil was assumed to be composed of two sub-matrices of spheres with two different sizes, one for coarse grained soil representing the sand and the other for fine grained soil. Taking into account possible interactions between these solid elements, the intergranular void ratio and interfine void ratio, e_f, were introduced as the main indices of the soil mixture density. They also introduced the concept of equivalent granular void ratio for higher fines content and this approach requires an additional parameter, b, which presents the fraction of fines participating in the force structure of the solid skeleton (Rahman et al. 2008).



a Rass sand

b Chlef sand

c Zemmouri sand

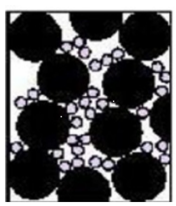
Figure 3. Effect of the number of cycles on the liquefaction resistance

Since the index density was 0.5 and the samples were reconstituted by taking the same amount of clean sand for the entire range of fines, the behavior of the sand-silt is analyzed on the effect of fines and coarse grains. For a low content $FC<FC_{th}$, fines are completely contained within the voids between the coarse grains, which are in contact each other (Thevayanagam et al. 2002). The fines only occupy the void spaces, and do not significantly affect the mechanical behavior of the sand-silt mixture. During shearing, the silt particles create great instability and

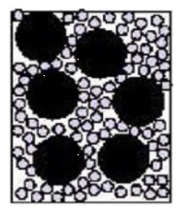
compressibility of the structure causing its collapse, resulting in the decrease of the resistance (Figure 4-a). For $FC>FC_{th}$, the mechanical behavior is dominated by fines contacts. The fines become activated and contribute to increase the soil resistance to liquefaction (Figure 4-b). However, for the Zemmouri sand, it was not possible to get enough data to draw clear conclusions as to say that the natural sand is stronger than the clean sand.

Excess pore pressure generation

Figure 5 shows the influence of the fines content on the generation of the excess pore pressure for CSR=0.20 corresponding to N=15. For Chlef sand, the excess pore pressure increases with the addition of fines until 5% to approach the initial confining pressure. This can be explained by the decrease of the cyclic shear strength which amplifies the contractancy phase. This is due to the effect of the fines on the liquefaction resistance leading to an increase in the pore pressure. Beyond that, the pore pressure decreases up to fines content of 10% and then rises again moderately. This effect is reversed for Zemmouri sand where the pore pressure decreases from the clean sand to the natural sand. After reaching the value of σ'_c=100 kPa, the pore pressure of the Rass sand remains constant regardless the fines content indicating that the liquefaction occurred to a cycle number less than 15 cycles.



a FC $<FC_{th}$



b FC $>FC_{th}$

Figure 4. Schematic diagrams representing sand-silt mixtures: (a) Coarse grains are in contact with each other, (b) coarse grains are swimming in the fines matrix

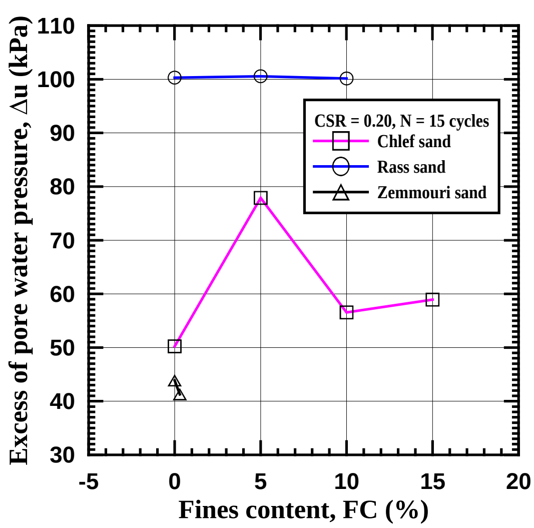


Figure 5. Effect of the fines content on the excess of pore water pressure

In the other hand, for the Chlef sand, the excess pore pressure increases with the increase of the cycle number. Beyond FC=5%, the pore pressure falls to half of the value achieved and increases again moderately in the range of 10-15%. The Zemmouri clean sand generated higher pore pressure reaching half of the initial confining pressure comparing to that of the Zemmouri natural sand. This is due to the mineralogical nature of the low plastic fines leading to the decrement of the soil mixture contractancy. For the Rass sand, the pore pressure is equal to the confining pressure making it more vulnerable to liquefaction comparing to the other sands.

Conclusions

A series of undrained cyclic triaxial tests were carried out on sand-silt mixture samples by taking the same amount of clean sand while studying its behavior for fines content ranging from 0 to 15% depending on the type of the selected sand. The following remarks can be drawn:
The influence of low plastic fines affects considerably the liquefaction resistance of sandy soil deposits due to their role to amplify the contractive response of the sand-silt mixtures. Comparing the clean and natural sands, the effect of fines can lead to an increase of the liquefaction resistance for Zemmouri sand, decrease or stabilization it for the Rass sand and Chlef sand, respectively. Moreover, the effect of fines on the Chlef and Rass sands is in good agreement with the published literature, where the liquefaction resistance decreases to FC_{th}=5% and then increases with the fines content. These conclusions can be attributed to the variation of the excess of the pore water pressure generation. Indeed, it increases with the increase of fines until 5% for Chlef sand. Beyond that, the pore pressure decreases up to fines content of 10% and then rises again moderately. Due to the mineralogical nature of the low plastic fines leading to the decrement of the soil mixture contractancy, it is found that the effect is reversed for Zemmouri sand where the pore pressure decreases from the clean sand to the natural sand. The pore pressure approaches sharply to the confining pressure for the Rass sand, inducing that the sand is more vulnerable to liquefaction comparing to the other sands.

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