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EXPERIMENTAL EVIDENCE INTO THE IMPACT OF SAMPLE RE-CONSTITUTION ON THE PORE WATER PRESSURE GENERATION OF OVERCONSOLIDATED SILTY SAND SOILS

Youcef Mahmoudi [1*], Abdellah Cherif Taiba [1], Leila Hazout [2], and Mostefa Belkhatir [1,3]

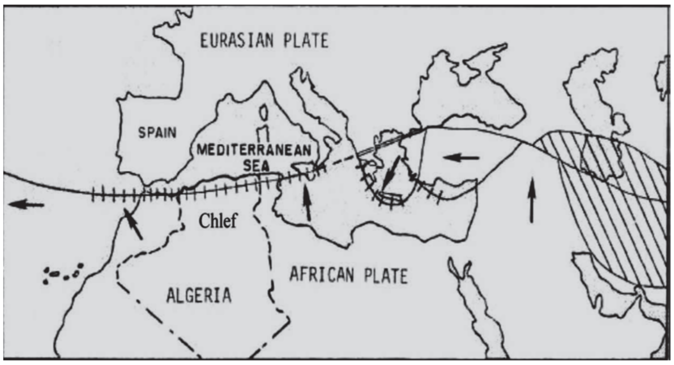
ABSTRACT

The objective of this laboratory investigation is to study the effect of the sample reconstitution on the excess pore water pressure (Δu) of medium dense (D_r = 52%) normally consolidated and overconsolidated sand-silt mixtures under monotonic loading conditions. For this purpose, a series of undrained monotonic triaxial tests were carried out on reconstituted saturated silty sand samples with fines content ranging from 0% to 40%. The confining pressure was kept constant to 100 kPa. The samples were prepared using two depositional methods named: dry pluviation and wet deposition for different overconsolidation ratios (OCR = 1, 2, 4, and 8). The test results show that normally consolidated and overconsolidated wet deposition samples exhibit higher excess pore water pressure in comparison to normally consolidated and overconsolidated dry funnel pluviation samples. The obtained soil trend can be attributed to the effect of water during the preparation of the wet deposited samples cane which is at the origin of initiating higher void ratios and consequently, making the structure of the soil more compressible during the shear process. In the other hand, the normally consolidated and overconsolidated dry pluviation samples showed an excess pore water pressure increase with the increase of fines content and the inverse trend was observed in the case of normally consolidated and overconsolidated wet deposited samples. This is due to the nature of the low plastic fines in making the soil structure more or less compressible and consequently increase or decrease the excess pore water pressure of dry funnel pluviated and wet deposited samples respectively. The obtained data confirm the existence of a reliable relationship between the excess pore water pressure of overconsolidated and normally consolidated sand-silt mixtures for both sample preparation techniques under consideration (dry funnel pluviation "DFP" and wet deposition "WD").

Key words: Excess pore water pressure, silty sand, fines content, dry pluviation, wet deposition, overconsolidation ratio.

1. INTRODUCTION

Northern Algeria is well characterized by high seismic activities due to its location on the African plate which is in permanent collision with the Eurasian plate. The northwest movement of the African plate to the Eurasian plate makes permanently this region in instability. The velocity of shortening between the considered plates is evaluated at 4 to 6 mm/year in the northern Algeria (Fig. 1). The dynamic tectonic of the two plates (African and Eurasian) induces stress accumulation that is at the origin of the occurrence of fractures or reactivate old faults generating earthquakes. Recorded seismic activities over the last century in Chlef region (Algeria) include the Orleansville earthquake in 1954 (M_L = 6.5) and El-Asnam earthquake in 1980 (M_L = 7.3). The 1980 El Asnam earthquake occurred in the Algerian town of Chlef (formerly known as El Asnam) within the central part of the Chelif valley. Measuring 7.3 on the Richter scale, it was the largest earthquake in Algeria, and was followed 3 hours later by a magnitude 6.3 aftershock. Both quakes caused considerable damage and a high death toll. The initial earthquake occurred at 12.24 GMT. Reports initially put the death at around 20,000. The final death toll, however, ended up being around 3,500. The town's main hospital, a big department store, the central mosque, a girls' school and two housing complexes were destroyed. Around 300,000 people were left homeless. The earthquake was the largest in the Atlas range



The movement direction of the African plate. (The stress accumulation that is at the origin of the occurrence of fractures or reactivate old faults generating earthquakes)

Fig. 1 Movement of the African and Eurasian plates (From the CTC institution – Controle Technique de Construction – Algeria)

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[1*] Ph.D. (corresponding author), Laboratory of Materials Sciences and Environment, University of Chlef, Algeria (e-mail: mahmoudiyoucef16@yahoo.fr).

[2] Ph.D., Saâd Dahlab University of Blida, Algeria.

[3] Professor, Laboratory of Soil Mechanics, Foundation Engineering & Environmental Geotechnics, Bochum Ruhr University, Germany.

since 1790 Ambraseys (1981). The most important effects of the earthquake on the buildings were observed at a radius of more than 60 km around the area of Chlef town. Studies that were conducted after the earthquake have shown the existence of a reverse fault near Beni-Rached which is located at 27 km to the north-east of Chlef town, characterized by a length of 40 km and a vertical displacement of 2m that appeared on the surface and considered as the origin of several other earthquakes. Aeolian and alluvial overconsolidated geological soil deposits as well as compacted fill within different earth structures exist extensively in the Chlef region, where seismic disasters such as landslides and soil subsidence occurred during the last two earthquakes. Numerous slope failures were observed in the city of Chlef and in the surrounding mountains, some involving the whole side of hills in the region attributable to fault movements. Soil liquefaction occurred over widespread areas in the flood plain of the Chlef River, particularly in the region of Chlef and neighborhood areas. This earthquake has been extensively described by Belkhatir *et al.* (2010, 2012) considering the influencing parameters on the generated excess pore water pressure and consequently on the undrained shear strength (known as the liquefaction resistance).

2. LITERATURE REVIEW

Liquefaction of saturated granular soils during earthquakes is one of the most important problems in the field of geotechnical earthquake engineering. It is well established that the mechanism for the occurrence of liquefaction under monotonic or cyclic loading conditions is the generation of excess pore water pressure. Generation of excess pore water pressure and subsequent liquefaction of saturated sandy soils with or without fines has been a topic of extensive laboratory research since last 50 years. Liquefaction (or initial liquefaction) usually occurs if the excess pore water pressure becomes equal to the initial effective stress. Numerous researches have been reported on different factors influencing the soil liquefaction phenomenon such as the confining pressure, initial relative density, overconsolidation ratio, sample preparation, sample size, fines content, size and shape of the grains and appear to have an effect on the excess pore water pressure and consequently impact the undrained shear strength response (Gratchev *et al.* 2007; Belkhatir *et al.* 2012, 2014a, 2014b). The effects of inherent fabric caused by the method used to prepare samples have been subjected to extensive research, and several studies have reported that the samples prepared with the method of sedimentation exhibit higher liquefaction resistance than that for samples prepared with other methods, such as the dry funnel pluviation or the wet deposition (Zlatovic and Ishihara 1997); others find that the samples prepared with wet deposition present higher liquefaction resistance than those prepared with dry funnel pluviation (Yamamuro and Wood 2004). Benahmed *et al.* (2004) as well as Canou (1989) and Ishihara (1993) presented results showing that the samples prepared with dry funnel pluviation are more resistant than those prepared with wet deposition. Vaid *et al.* (1999) confirmed this outcome, while showing that wet deposition encourages the initiation of the liquefaction in relation to a setting up by pluviation under water. Della *et al.* (2011) reported that the dry pluviation method induces a higher liquefaction resistance than the wet deposition method. Yamamuro and Wood (2008) showed that the method of dry pluviation supports the instability of the samples contrary to the method of sedimentation. Wood *et al.* (2008) found on their side that the effect of the deposition method on the undrained behavior decreases, when the density increases. They also found that this influence decreases with the increase of the fines content, particularly for lower initial relative densities. Among these different sample preparation techniques related to sample reconstitution, wet compaction method has the advantage that it is relatively easy to control the global specimen density achieved, even for loose samples (Frost *et al.* 2003). Laboratory observations have consistently found that two samples of sand prepared with different reconstitution methods to the same density may display quite different responses to applied monotonic loading under similar conditions (Vaid *et al.* 1999; Yang *et al.* 2008). The differences are thought to be linked to the different fabrics of the samples reconstituted by the different techniques, which can be defined as the spatial arrangement of sand particles and associated voids (Oda *et al.* 1999). Wichtmann *et al.* (2005) reported that varying sample reconstitution techniques lead to different initial soil fabrics (inherent anisotropy). Slightly elongated grains tend to lie with their longer axes in the horizontal plane if they are dry pluviated, whereas a random distribution of the orientations is achieved by layering and tamping of moist sand samples. Ladd *et al.* (1974) observed that sand samples which were prepared by moist tamping could sustain around four times more cycles to liquefaction than samples that were dry pluviated and compacted by vibration. How to take fabric effects into account in geotechnical analysis remains a difficult problem that attracts efforts on both theoretical and practical levels. A recent attempt was made by Yang *et al.* (2008), who measured soil fabrics introduced by moist tamping and dry deposition, two commonly used methods for laboratory preparation of sand samples (Ishihara 1993), and then introduced the measurements into a constitutive framework to model the monotonic behavior of sand. Several other researchers studied the influence of the overconsolidation ratio on the undrained shear behavior of soils and showed that the overconsolidation ratio has a significant effect on the liquefaction resistance of the soils (Seed *et al.* 1975; Ishihara *et al.* 1979; Della *et al.* 2011). The results obtained by Ishihara *et al.* (1978) showed on soils having various contents of fines elements that the liquefaction resistance increases with the overconsolidation ratio. This effect is accentuated with the increase in the percentage of fines elements. Khin *et al.* (2007), conducting triaxial drained and undrained sand on the Nakdong River, found that the liquefaction resistance decreased with increase of overconsolidation ratio. By carrying out cyclic tests on the Hostun sand, Bouferra (2000) found that with an overconsolidation ratio of 7, liquefaction is obtained at the end of 17 cycles; whereas with a normally consolidated sample, 6 cycles are needed to obtain liquefaction.

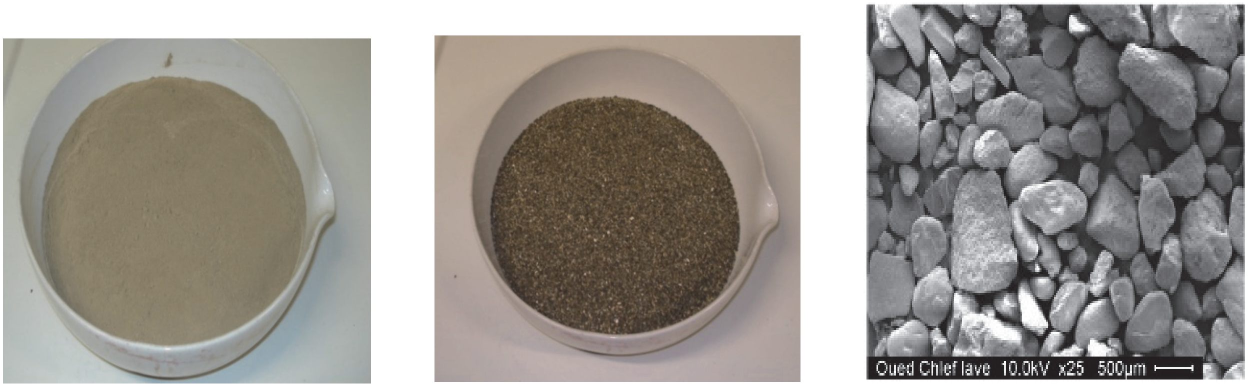
This laboratory investigation aims to study the effects of low plastic fines fraction (F_c = 0%, 20%, and 40%), sample reconstitution technique (dry funnel pluviation and wet deposition) and overconsolidation ratio (OCR = 1, 2, 4, and 8) on the generated excess pore water pressure response of silty sand samples reconstituted in the laboratory with the same silty fines fraction. The obtained sand-silt mixture packing configurations produce different initial fabrics, thereby changes of excess pore water pressure characteristics behavior of soil. Factors such as confining pressure, degree of saturation, sample size, and relative density have been kept constant. A detailed laboratory investigation has been presented in the subsequent sections.

3. EXPERIMENTAL PROGRAM

3.1 Index Properties of Tested Materials

Natural Chlef sandy soil material (Algeria) was collected at shallow depth along the banks of Chlef River where liquefaction phenomenon occurred during the 1980 El Asnam earthquake (October 10th, 1980). Figure 2 shows some observed craters of liquefied silty sand soil on the banks of Chlef River. The liquefaction phenomenon was also observed through a vast alluvial valley crossed by the Chlef River and in the confluence zone of the Fodda River with Chlef River (Della *et al.* 2011). Figure 3 presents the materials under consideration and the scanning electronic microscope image of Chlef sand. The preliminary tests were carried out on Chlef sand mixed with low plastic fines ($I_p = 5.0\%$) according to a fines content ranging between 0% and 40%. Tables 1 and 2 present the index properties of the materials under study. The grain size distribution curves of the tested silty sands are shown in Fig. 4. As it can be seen, the granulometric curves lie in between those proposed by Tsuchida (1970) classified as liquefiable soils. Vibratory table (ASTM D 4253-00 2002) and standard and modified Proctor tests were used to determine the minimum void ratio ($e_{\min}$) for all the sand–silt mixtures under study. The vibratory table tests yielded minimum void ratios similar to those produced by the modified Proctor test. The vibratory table test minimum void ratios were used in this laboratory investigation because they were found to produce more repeatable results. Our results are parallel to the findings of Polito *et al.* (2001). The maximum void ratios ($e_{\max}$) for the different sand–silt mixtures were determined in general accordance with the specification ASTM D 4254-00 (2002). The results reproduced by method B were found more repeatable than those of method C, and they were found in good agreement with Polito *et al.* (2001). The variation of $e_{\max}$ (maximum void ratio corresponding to the loosest state of the soil sample) and $e_{\min}$ (minimum void ratio corresponding to the densest state of the soil sample) determined for 0 ~ 100% range of fines content F_c (the ratio of the weight of silt to the total weight of the sand-silt mixture) is given in Fig. 5. According to this figure, the different void ratio indices decrease with the increase of the fines content until $F_c = 30\%$. They increase with further fines content increase. Figure 6 illustrates the variation of $e_{\max}$ with $e_{\min}$ through a linear relationship.

Fig. 2 Recorded liquefaction case (sand boils) during the El Asnam earthquake (1980)



(a) Chlef silt (b) Chlef sand (c) SEM of Chlef Sand

Fig. 3 View of tested materials

Table 1 Index properties of sand and silt under study

Properties	Materials	
	Chlef sand	Silt
G_s	2.652	2.667
$D_{\max}$ (mm)	2.0	0.08
D_{10} (mm)	0.266	–
D_{50} (mm)	0.596	0.023
C_u	2.634	–
C_c	0.999	–
$e_{\max}$	0.795	1.563
$e_{\min}$	0.632	0.991
I_p (%)	–	5.0
USCS	SP	ML
Grain Shape	Sub-rounded	Sub-rounded

Table 2 Index properties of sand-silt mixtures

Properties	Silty sand	
F_c (%)	20	40
G_s	2.655	2.658
D_{10} (mm)	0.023	0.003
D_{50} (mm)	0.488	0.236
C_u	27.24	120.51
C_c	3.997	3.300
$e_{\max}$	0.697	0.759
$e_{\min}$	0.458	0.505

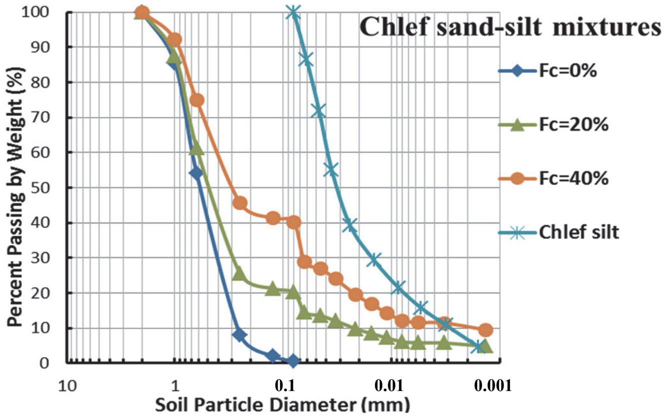


Fig. 4 Grain size distribution curves of Chlef sand-silt mixtures

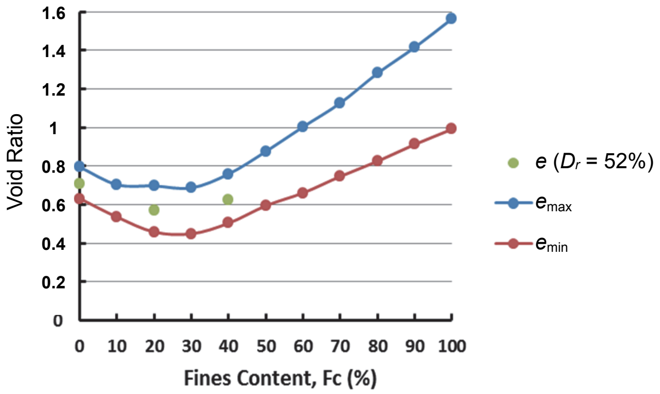


Fig. 5 Void ratios of sand-silt mixtures versus fines content

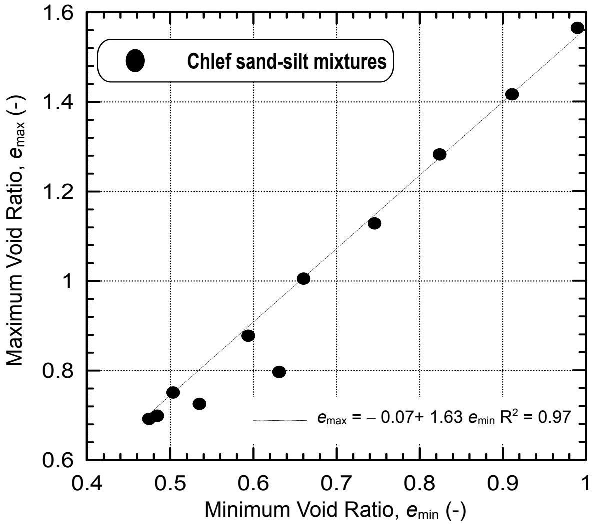


Fig. 6 Maximum void ratio versus minimum void ratio of sand-silt mixtures

3.2 Sample Reconstitution

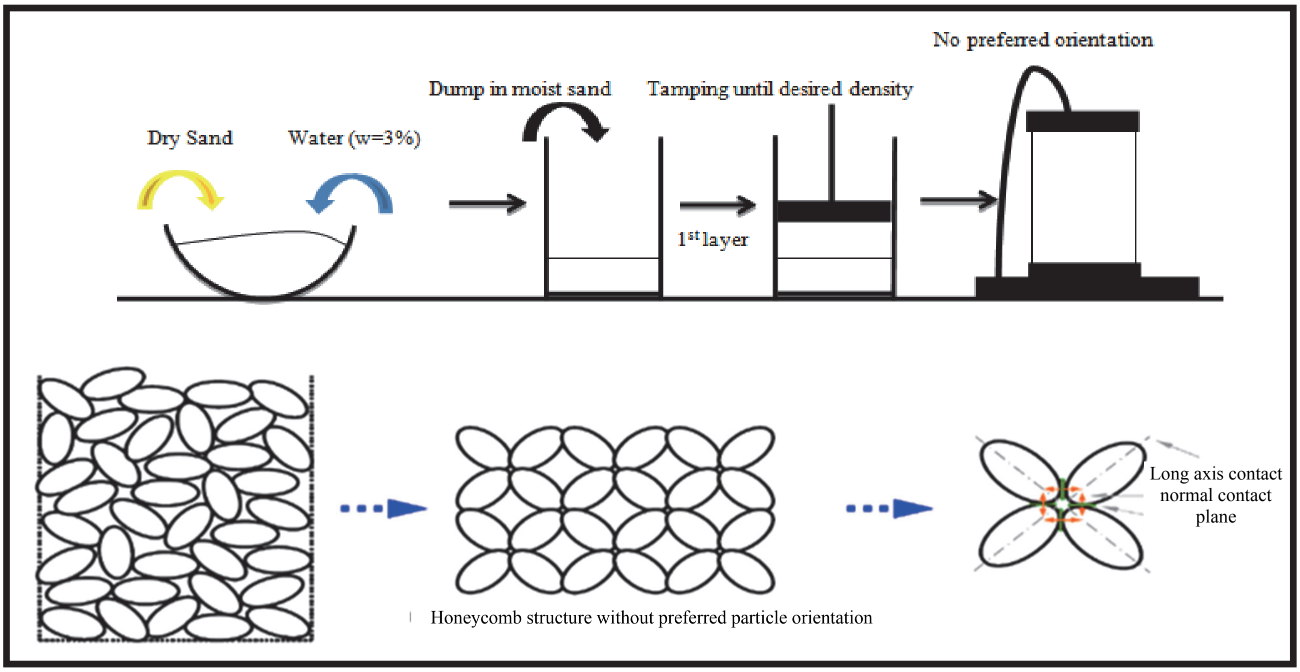
The most important feature of laboratory work is to test samples that are really representing their in-situ conditions. Since undisturbed samples of cohesionless soils are typically too difficult or costly to obtain, reconstituted samples need to be prepared using a depositional technique that most closely replicates the in-situ stress, density, and fabric. Published literature has clearly shown the impact of sample preparation methods on the sand-silt mixtures shear strength, and it is believed that wet deposition method most closely approximate the in-situ fabric of fluvial soils (Ishihara 1993; Vaid *et al.* 1999; Yamamuro and Wood 2004; Mahmoudi *et al.* 2016a, 2016b; Sadrekarimi and Olson 2012; Cherif Taiba *et al.* 2016, 2017, and 2018). Shear strength behavior of sand-silt mixture soils depends primarily on the sample preparation techniques and consequently the arrangement of the particles and the overall fabric represented by grains and pores. In general, the term "fabric" refers to the microstructure of the soil itself but it is basically composed of geometric and kinetic arrangement of the particles. The contact forces between particles and the distribution of these inter-particle forces come together to form the "microstructure" with "bonding". Two laboratory sample preparation methods: dry funnel pluviation (DFP) and wet deposition (WD) are used in this study. The two methods are subsequently described. In the first one, the dry soil is deposited into the mould using a funnel by controlling the height. This method consists of filling the mould by raining the dry sand through the funnel. However, the second one consists of mixing the previously dried sand-silt mixtures with a small quantity of water ($w = 3\%$) and then placing the wet soil in the mould in successive layers. A constant number of strokes is applied to get a homogeneous and isotropic structure. The fabric study showed that granular materials composed of fines and sand grains acquire different fabrics when different methods of sample preparation are used. Deposition of materials into the mold resulted in a microstructure characterized by an orientation of grains acquiring different arrangements: no preferred orientation of soil particles in the case of wet deposition (Fig. 7(a)) and preferred particles orientation in the case of dry funnel pluviation (Fig. 7(b)) confirmed by Sze *et al.* (2014). Triaxial tests are performed on cylindrical samples with 100 mm in diameter and 200 mm in height ($H/D = 2.0$). The amount of sand deposited in the mould is determined according to the relative density that is defined by:

$$D_r = \frac{e_{\max} - e}{e_{\max} - e_{\min}} \tag{1}$$

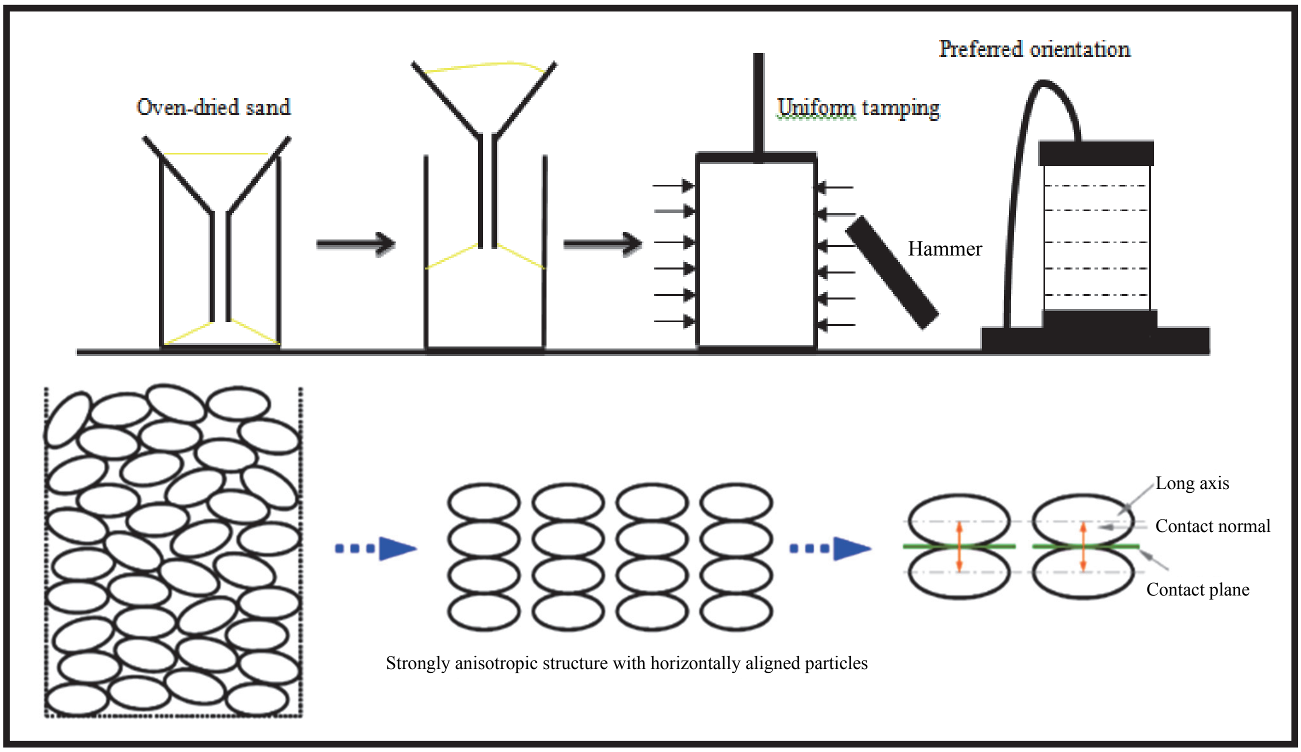
where e is the target void ratio, $e_{\max}$ is the maximum global void ratio, and $e_{\min}$ is the minimum global void ratio

3.3 Saturation and Consolidation

The saturation of the sample represents an important stage in the experimental procedure because the sample response under undrained loading conditions depends on its quality. To achieve a higher saturation degree, the technique of carbon dioxide elaborated by Lade *et al.* (1973) was used. After doing necessary measurements, the samples have been first subjected to CO_2 for at least to 30 min and then saturated by de-aired water. The evaluation of the degree of saturation is done by means of Skempton's pore pressure parameter B as the ratio of measured pore water pressure increase induced by an increase in cell pressure in undrained conditions and the corresponding increase in cell pressure. The B value was measured to test samples saturation and a minimum value greater than 0.97 is obtained for all tests. In this study, backpressure of 200 kPa has been applied during the tests to further improve the saturation state. The samples were consolidated under isotropic effective confining pressure of 100, 200, 400, and 800 kPa; and then unloaded to final current effective pressure of 100 kPa corresponding to OCR = 1, 2, 4, and 8, respectively.



(a) Wet deposition



(b) Dry funnel pluviation

Fig. 7 Schematic illustration of sample reconstitution (Sze *et al.* 2014)

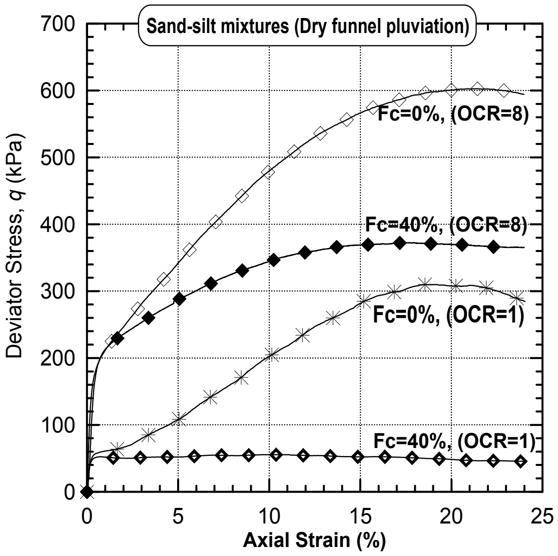
3.4 Shear Loading

All undrained monotonic triaxial tests for this study were carried out at a constant strain rate of 0.2 mm per minute, which was slow enough to allow pore pressure change to equalize throughout the sample with the pore pressure measured at the base of sample. All the tests were continued up to 24% axial strain.

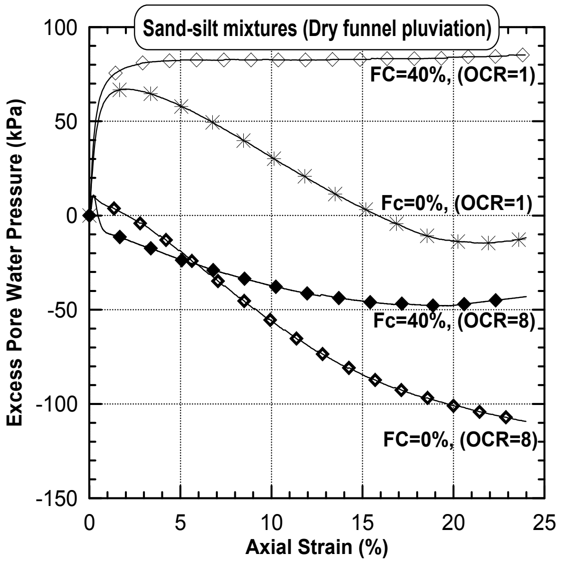
4. MONOTONIC TRIAXIAL COMPRESSION TEST RESULTS

4.1 Effect of Overconsolidation Ratio and Fines Content

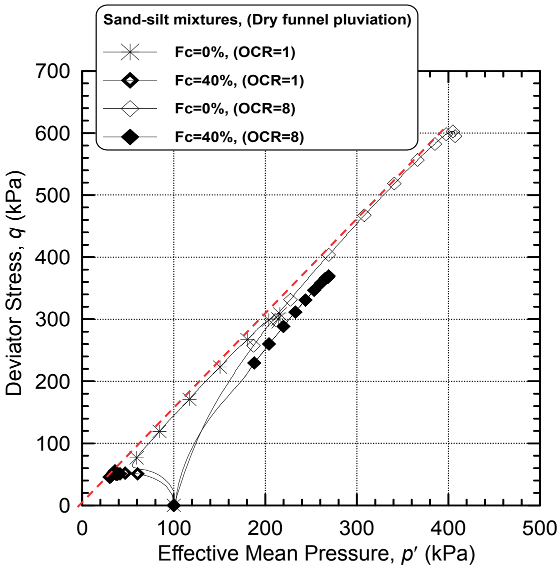
Figure 8(b) shows the excess pore water pressure of sand–silt mixture samples reconstituted with low plastic fines content of 0%



(a) Deviator stress versus axial strain



(b) Pore water pressure versus axial strain

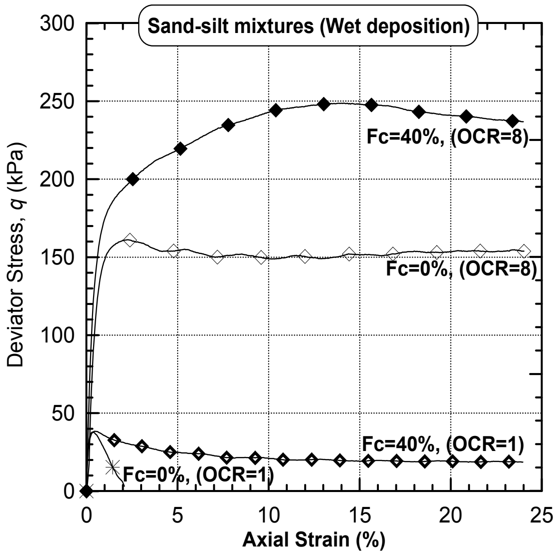


(c) Stress path diagram

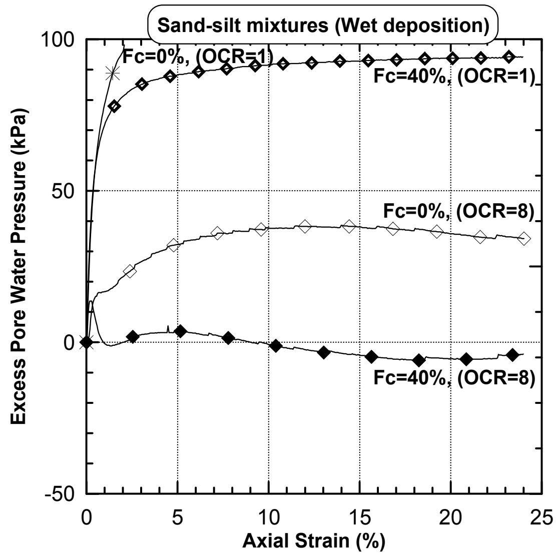
Fig. 8 Undrained monotonic response of dry funnel pluviated Chlef sand-silt mixtures ($\sigma'_3 = 100$ kPa, $D_r = 52\%$)

and 40% and subjected to a constant confining pressure of $\sigma'_3 = 100$ kPa. The samples with OCR = 1 and 8 were reconstituted with dry funnel pluviation method at an initial relative density ($D_r = 52\%$). In general, the overconsolidation ratio parameter (OCR = 1 and 8) has significant influence on the excess pore water pressure (Δu). The test results indicate that the excess pore water pressure decreases with the increase of overconsolidation ratio for (OCR = 1 and 8) for both fines fraction ($F_c = 0\%$ and 40%) at an initial relative density under consideration ($D_r = 52\%$). This decrease can be attributed to the role of the overconsolidation in increasing the particle interlocking due to the existence of smaller silt particles between larger sand particles and the dilation phase of the sand–silt mixtures leading to a more stable structure of the samples. Thus, the excess pore water pressure of the mixtures decreases as illustrated in (Fig. 8(a)). The influence of the overconsolidation ratio (OCR = 1 and 8) on the excess pore water pressure is clearly observed for OCR = 1 ($\Delta u = 67.1$ kPa and $\Delta u = 85.4$ kPa) and becomes significantly smaller for OCR = 8 ($\Delta u = 10$ kPa and 10.8 kPa) for the considered initial relative density ($D_r = 52\%$) and fines content range (0% ~ 40%). The outcome of the present study is in good agreement with the experimental work reported by Ishihara *et al.* (1978) and Della *et al.* (2011). The stress-strain and stress path in the p′, q plane show clearly the significant role of the overconsolidation ratio parameter to increase the deviator stress and the average effective mean pressure and consequently decrease the produced excess pore water pressure during the shear process (Fig. 8(c)).

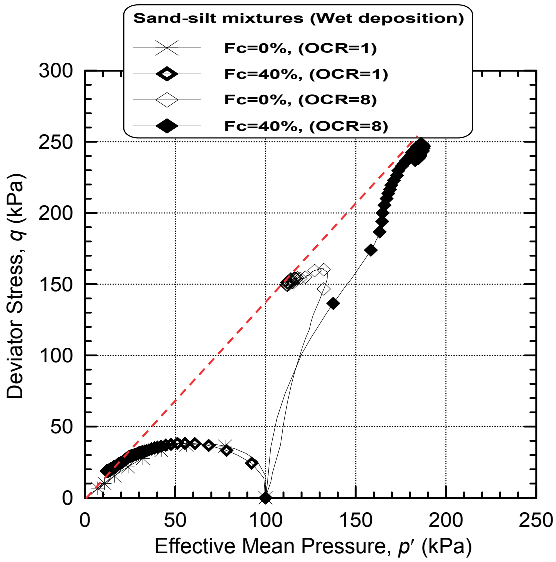
Figure 9(b) shows the excess pore water pressure of sand–silt mixture samples reconstituted with low plastic fines content of 0% and 40% and subjected to a constant confining pressure of $\sigma'_3 = 100$ kPa. The normally consolidated (OCR = 1) and overconsolidated (OCR = 8) samples were reconstituted with wet deposition method at an initial relative density ($D_r = 52\%$). It is observed that the excess pore water pressure (Δu) tends to decrease with increasing overconsolidation ratio, which becomes more obvious at larger overconsolidation levels. The overall trend of decreasing excess pore water pressure with increasing overconsolidation ratio can be attributed to the role of the overconsolidation in increasing the particle interlocking due to the existence of smaller silt particles between larger sand particles and the dilation phase of the sand–silt mixtures leading to a more resistant structure of the samples. Thus, the pore water pressure of the mixtures decreases as illustrated in (Fig. 9(b)). However, liquefaction (the excess pore water pressure becomes equal to the initial effective stress) cases of sand-silt mixture samples were recorded, particularly, for the lower overconsolidation ratio (OCR = 1) for both fines contents ($F_c = 0\%$ and 40%). The observed pore water pressure trend is a result of the fact that wet deposition method induces contractive behavior to the sand–silt mixture soil leading to unstable structure of the samples. This behaviour can be explained by the fact that the initial moisture content considered in the samples reconstituted by wet deposition method (WD) initiates to the formation of samples with higher void ratios that are easily compressible. The obtained results are in good agreement with those of Canou (1989), Ishihara (1993), Vaid *et al.* (1999), Benahmed *et al.* (2004), and Della *et al.* (2011). The stress-strain (Figure 9(a)) and stress path in the (p', q) plane (Figure 9(c)) show clearly the role of low plastic fines and overconsolidation ratio to increase the effective mean pressure and the maximum deviator stress. Complete static liquefaction cases were observed for normally consolidated (OCR = 1) sand-silt mixture samples for both fines contents ($F_c = 0\%$ and 40%).



(a) Deviator stress versus axial strain



(b) Pore water pressure versus axial strain



(c) Stress path diagram

Fig. 9 Undrained monotonic response of wet deposited Chlef sand-silt mixtures ($\sigma'_3 = 100$ kPa, $D_r = 52\%$)

Table 3 presents the summary of the pore water pressure response of the different sand-silt mixture samples under study.

Table 3 Summary of monotonic triaxial tests of silty sand

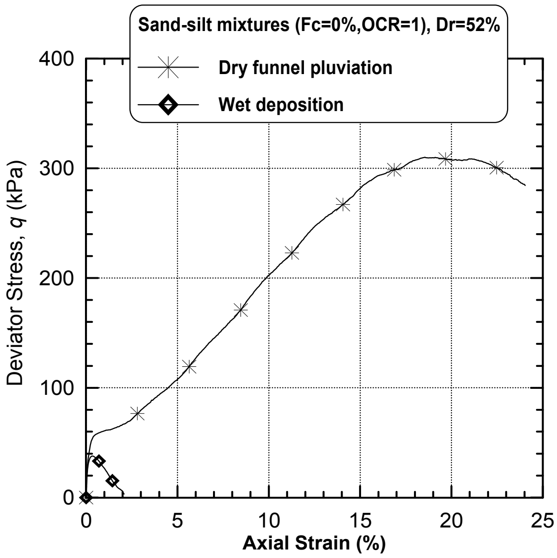
F_c (%)	0				20				40			
OCR	1	2	4	8	1	2	4	8	1	2	4	8
Δu_{DFP} (kPa)	67.1	50.1	24.1	10	77.6	60.6	25.8	10.2	85.4	70.2	42.5	10.8
Δu_{WD} (kPa)	98.1	97.3	96.8	38.6	97	82.1	65.6	11.9	94.2	81.4	58	13.6

4.2 Effect of Sample Preparation

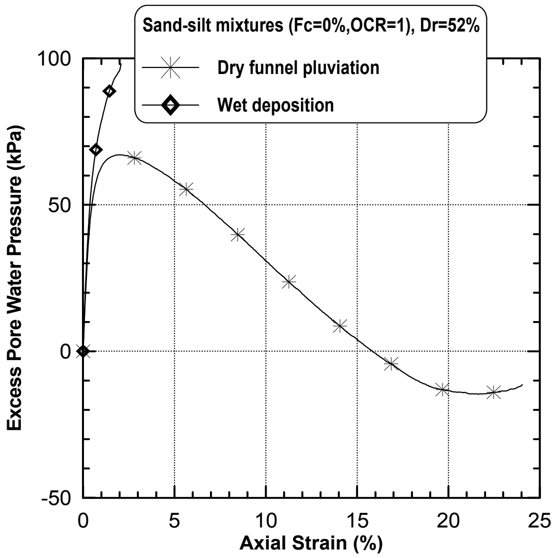
Figures 10 and 11 show the effect of sample reconstitution on the excess pore water pressure response of normally consolidated (OCR = 1) and overconsolidated (OCR = 8) Chlef sand-silt mixtures. The different samples were reconstituted with dry funnel pluviation (DFP) and wet deposition (WD) methods at an initial relative density ($D_r = 52\%$) and subjected to an initial confining pressure ($\sigma'_3 = 100$ kPa). As can be seen from these Figures, the samples reconstituted with wet deposition exhibits higher excess pore water pressure (Δu = 98.1 kPa and 39.6 kPa) than samples reconstituted with dry funnel pluviation (Δu = 67.1 kPa and 10 kPa) and normally consolidated (OCR = 1) samples show higher excess water pressure (Δu = 98.1 kPa and 67.1 kPa) than overconsolidated samples (OCR = 8) (Δu = 38.6 kPa and 10 kPa). The dry funnel pluviation reconstitution of samples gives rise to a more dilative or stable soil character, while the wet deposition method exhibits more contractive or unstable behavior.

These observations of the contractive and dilative responses are due to the pace of excess pore water pressure generation which was faster in the case of wet deposited samples exhibiting a decrease of the contacts and creating new orientations of soil particles comparing to the dry funnel pluviated samples characterized by lower pace of excess pore water pressure where its effects on particle contacts and orientations were insignificant, thus leading to higher liquefaction potential of the WD sand-silt mixtures compared to liquefaction potential of DFP sand-silt mixtures. The outcome of this research is in good agreement with the observations of Canou (1989), Ishihara (1993), Vaid *et al.* (1999), Benahmed *et al.* (2004), and Della *et al.* (2011).

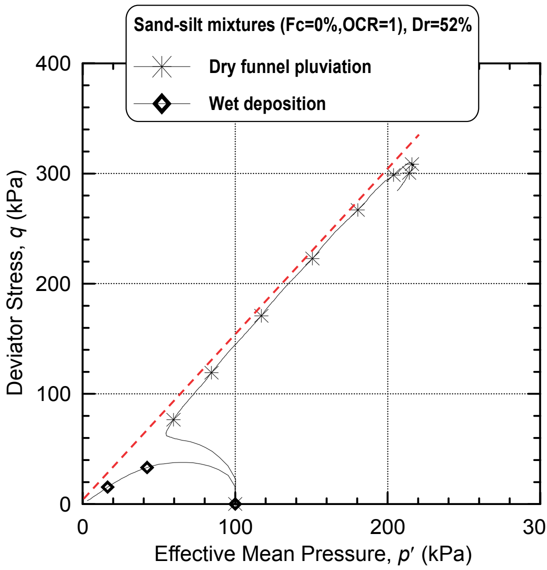
For the purpose of analyzing the effects of the depositional methods (DFP and WD) and overconsolidation ratios (OCR = 1 and 8) on the Chlef sand-silt mixture excess pore water pressure response, Figures 12 and 13 reproduce the test results obtained from the current study. It is clear from the plots that the normally consolidated dry funnel pluviation and wet deposition silty sand samples exhibit strength softening indicating static liquefaction occurrence. However, overconsolidated dry funnel pluviation and wet deposition silty sand samples show dilative character indicating strength hardening of the material under consideration. The obtained results indicate also that the normally consolidated samples reconstituted with wet deposition and dry funnel pluviation exhibit an average excess pore water pressure decrease of 86.5% in comparison to the overconsolidated samples reconstituted with the same depositional methods. The normally consolidated silty sand material under undrained conditions shows an excess water pressure decrease of 9% from normally consolidated wet deposition silty sand samples to normally consolidated dry funnel silty sand samples and 21% excess water pressure decrease from overconsolidated wet deposition to overconsolidated dry funnel deposition silty sand samples.



(a) Deviator stress versus axial strain

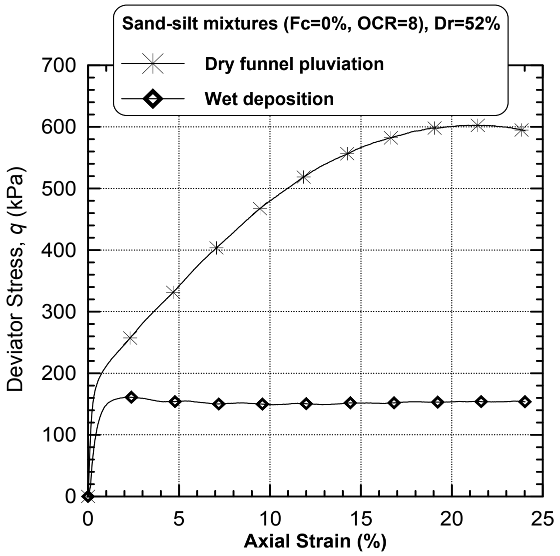


(b) Excess pore water pressure versus axial strain

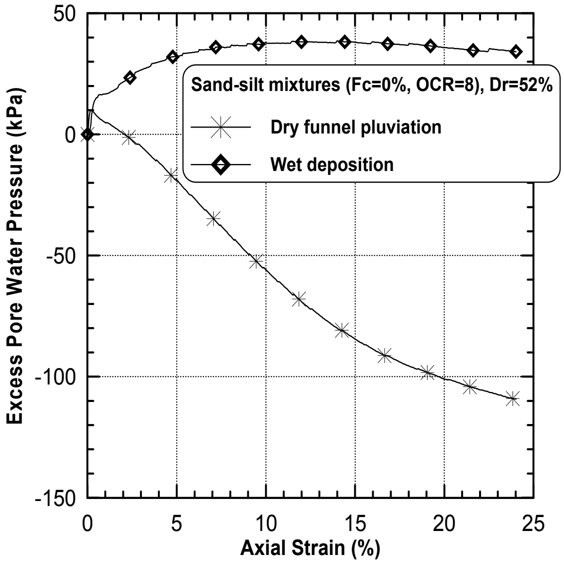


(c) Stress path diagram

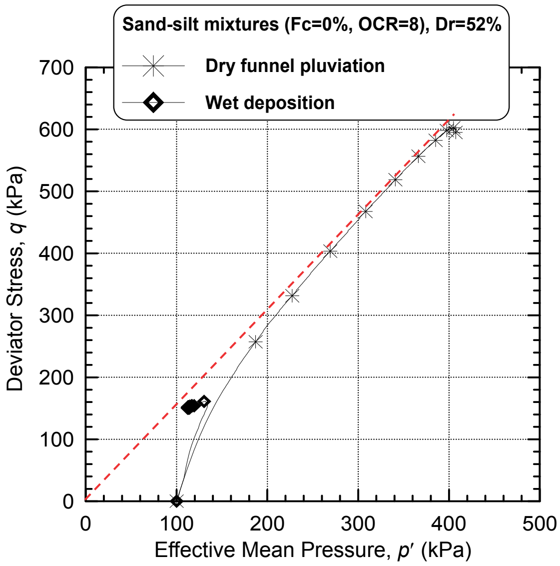
Fig. 10 **Undrained monotonic response of Chlef sand-silt mixtures ($F_c = 0\%$, OCR = 1, $\sigma'_3 = 100$ kPa, $D_r = 52\%$)**



(a) Deviator stress versus axial strain

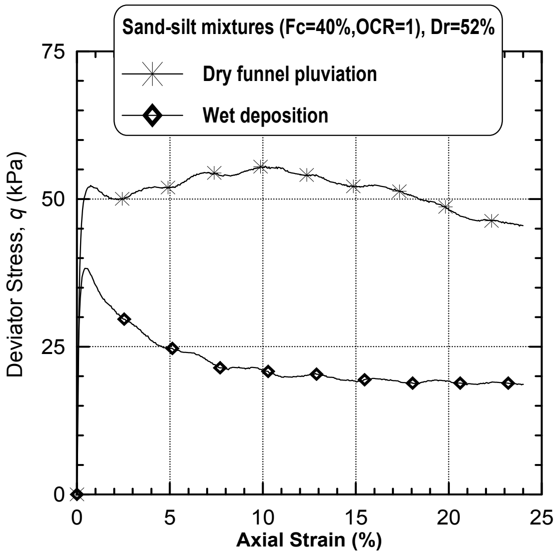


(b) Excess pore water pressure versus axial strain

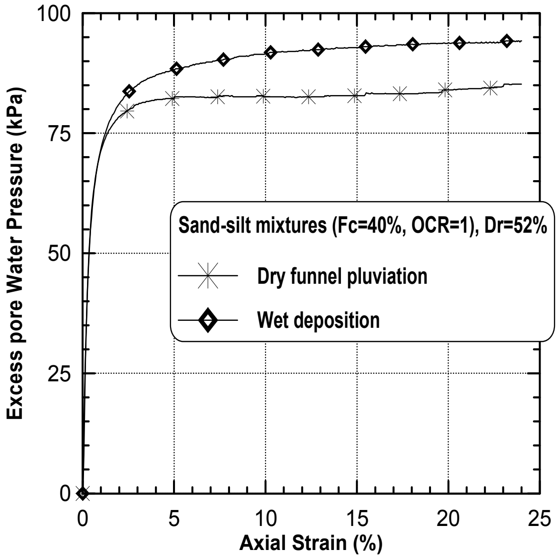


(c) Stress path diagram

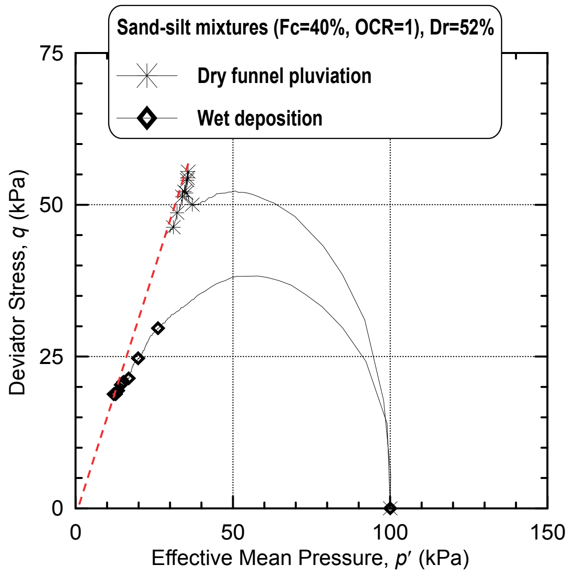
Fig. 11 **Undrained monotonic response of Chlef sand-silt mixtures ($F_c = 0\%$, OCR = 8, $\sigma'_3 = 100$ kPa, $D_r = 52\%$)**



(a) Deviator stress versus axial strain

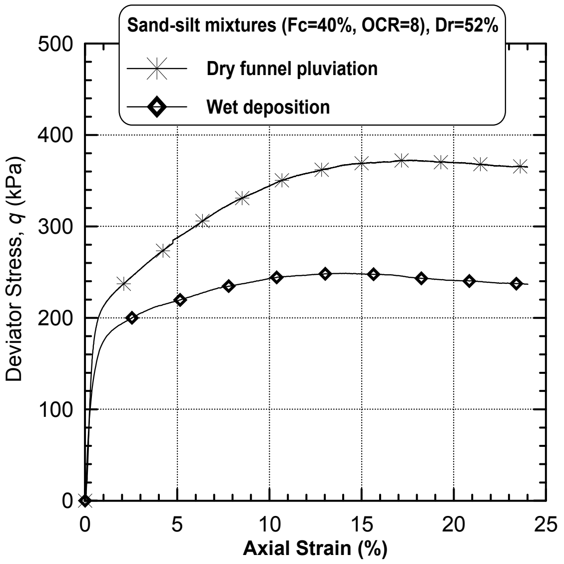


(b) Excess pore water pressure versus axial strain

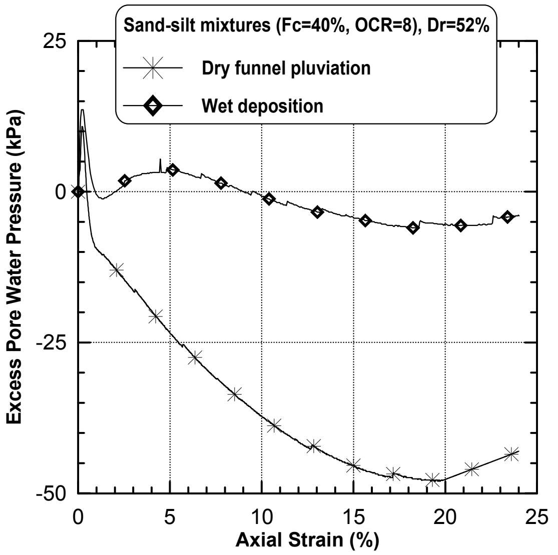


(c) Stress path diagram

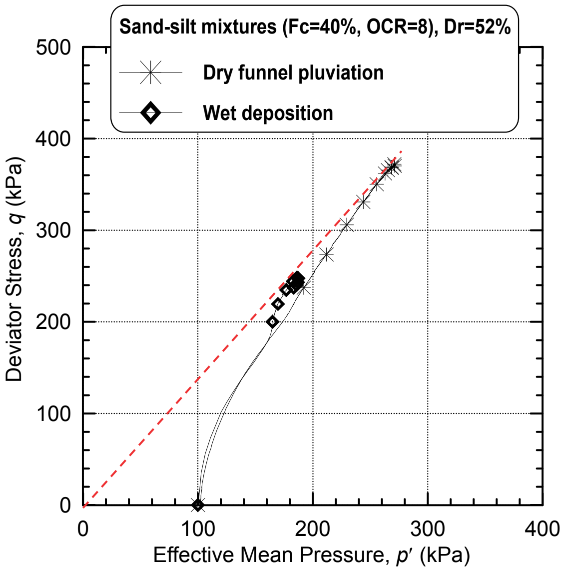
Fig. 12 Undrained monotonic response of Chlef sand-silt mixtures ($F_c = 40\%$, OCR=1, $\sigma'_3 = 100$ kPa, $D_r = 52\%$)



(a) Deviator stress versus axial strain



(b) Excess pore water pressure versus axial strain



(c) Stress path diagram

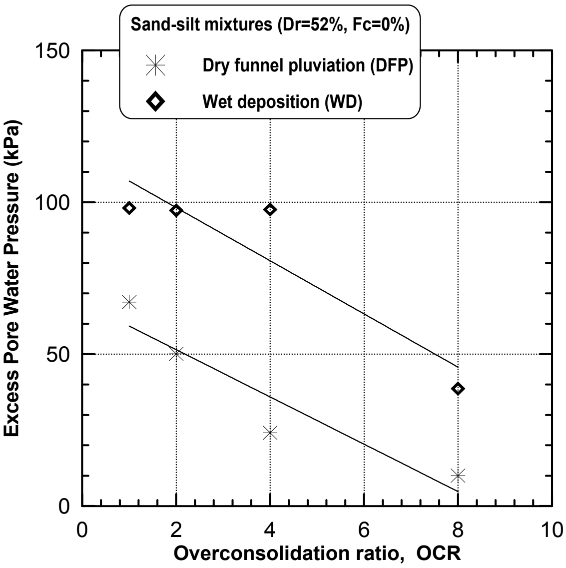
Fig. 13 Undrained monotonic response of Chlef sand-silt mixtures ($F_c = 40\%$, OCR = 8, $\sigma'_3 = 100$ kPa, $D_r = 52\%$)

4.3 Effect of the Overconsolidation on the Maximum Positive Excess Pore Water Pressure

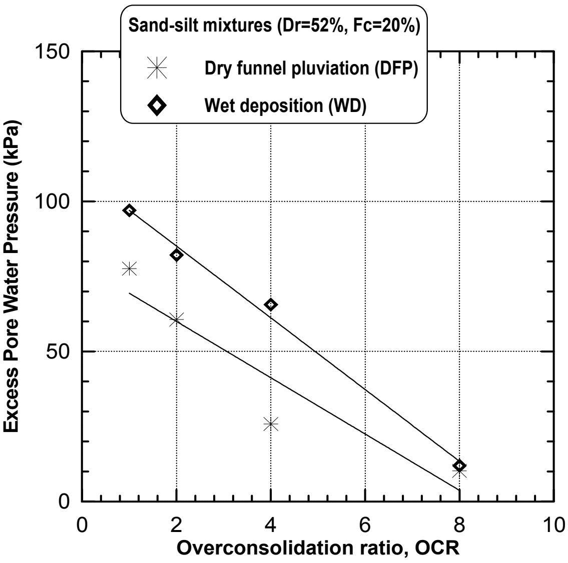
Data from the present study (Figs. 8 and 9) are reproduced in Fig. 14 for the purpose of analyzing the effects of the overconsolidation ratio (OCR = 1, 2, 4, and 8) and sample preparation (dry funnel pluviation and wet deposition) considering the range of fines content ($F_c = 0\% \sim 40\%$). It is observed from the plot that the maximum excess pore water pressure (Δu) decreases with the increase of the overconsolidation ratio from 1 to 8 and a linear relationship may express the correlation between the excess pore water pressure and the overconsolidation ratio for the range of fines content and initial relative density under study ($D_r = 52$ %). Moreover, the samples reconstituted by dry funnel pluviation are more stable and dilatant than those prepared by wet deposition. Thus, dry funnel pluviation appears to promote lower excess pore water pressure of the samples while wet deposition accelerates the instability of the samples showing higher excess pore water pressure, and may even cause liquefaction susceptibility of the sand-silt mixture samples for the lower overconsolidation ratios ($1 \leq$ OCR ≤ 4) leading to their collapse. These differences in behavior may be explained by the fact that the moisture contained in the samples prepared by the wet deposition method initiates to the formation of soil particles arrangements with higher void ratios characterized by high compressibility at the time of the shearing. The results of this research work are in good agreement with the findings of Della *et al.* (2011), where they reported that dry funnel pluviation method appeared to reconstitute a more dilative character or stable samples, while wet deposition method appeared to exhibit a more contractive character of the material and consequently reconstitution of unstable structure of the samples.

4.4 Effect of the Fines Content on the Maximum Positive Excess Pore Water Pressure

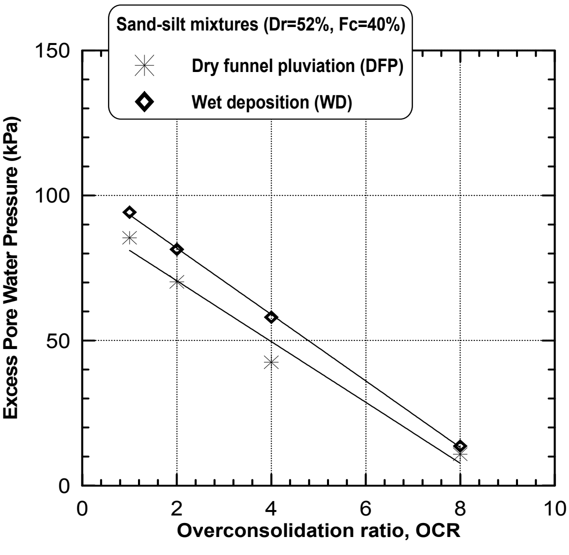
For the purpose to analyze the effects of the presence of the low plastic fines fraction on the excess pore water pressure of overconsolidated sand-silt mixtures (OCR = 1, 2, 4, and 8) considering two different soil fabrics (dry funnel pluviation and wet deposition). Figure 15 reproduces the test results obtained from the current study. It is clear from the plots that the excess pore water pressure increases linearly with the increase of the fines content ($0\% \leq F_c \leq 40\%$) and overconsolidation ratio ($1 \leq$ OCR ≤ 8) in the case of the dry funnel deposition. However, the reverse trend was observed in the case of wet deposition. The observed excess pore water pressure tendency is a result of the fact that the low plastic fines in combination with dry funnel pluviation and wet deposition induce contractive and dilative character to the sand–silt mixture soil respectively. Moreover, the increase of the low plastic fines content induced an increase in the excess pore water pressure of dry pluviated silty sand samples and consequently leads to contractive behavior of the tested materials. This behavior can be attributed to the contribution of the low plastic silty fines in making the soil structure more compressible and more unstable (Shen *et al.* 1977; Troncoso *et al.* 1985; Singh *et al.* 1994; Lade and Yamamuro 1997; Belkhatir *et al.* 2010, 2012; Cherif Taiba *et al.* 2017, 2019a, 2019b). In contrast, for the wet deposited silty sand samples, the increment of low plastic fines leads to a decrease in the excess pore water pressure of silty sand and consequently to a contractive behavior of the wet deposited silty sand samples under consideration. This soil trend can be explained by the fact that water ($w = 3\%$) remains intact occupying the particle pores in the



(a) $F_c = 0\%$

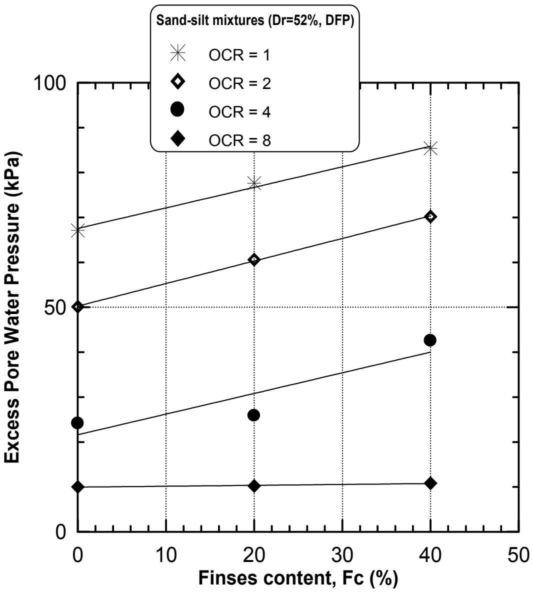


(b) $F_c = 20\%$

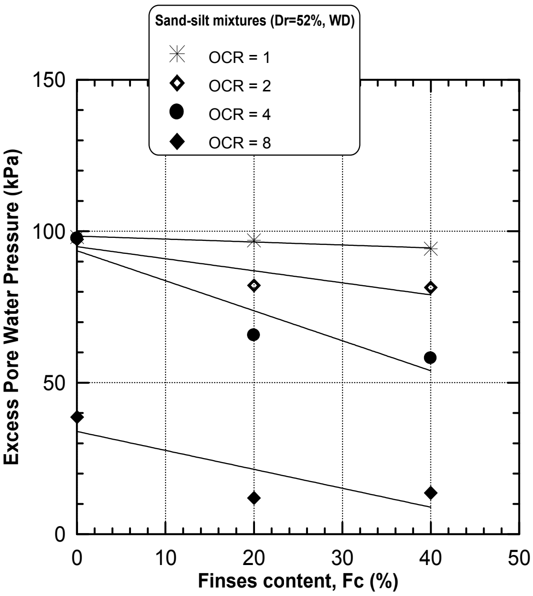


(c) $F_c = 40\%$

Fig. 14 Excess pore water pressure versus overconsolidation ratio of Chlef sand-silt mixtures ($\sigma'_3 = 100$ kPa, $D_r = 52\%$)



(a) Dry funnel pluviation



(b) Wet deposition

Fig. 15 Peak excess pore water pressure versus fines content of Chlef sand-silt mixtures ($\sigma'_3 = 100$ kPa, $D_r = 52\%$)

case of clean sand ($F_c = 0\%$), but absorbed by silty fines in the case of sand-silt mixtures ($F_c = 20\%$ and $F_c = 40\%$) and consequently decrease the excess pore water pressure for wet deposited silty sand compared to clean sand ($F_c = 0$ %). The influence of the overconsolidation ratio on the generated excess pore water pressure is clearly observed for the wet deposition soil reconstitution, and becomes very pronounced for dry pluviation method. Moreover, it is clearly observed that the excess pore water pressure decreases with the increase of the overconsolidation ratio for a given fines content for both fabric methods (DFP and WD). This is parallel to the findings of Ishihara *et al.* (1978) and Della *et al.* (2011). The following expressions are suggested to express the excess pore water pressure (Δu) in terms of fines content (F_c) for the range of the overconsolidation ratio under study (OCR = 1, 2, 4, and 8) considering the two depositional methods (DFP and WD):

$$\Delta u = C \times (F_c) + A \tag{2}$$

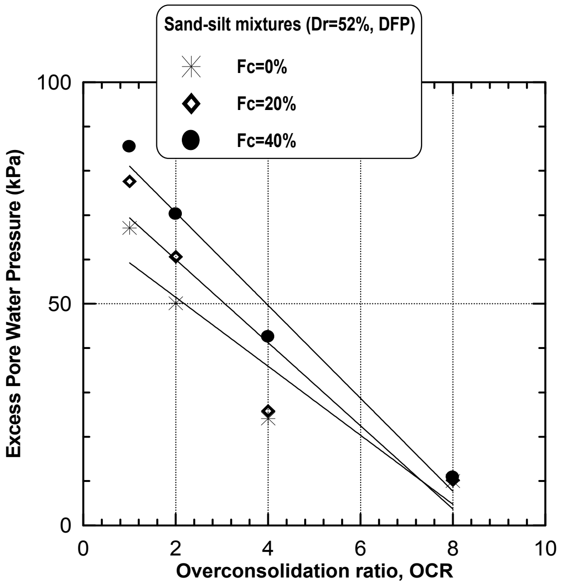
Table 4 illustrates the coefficients A, C, and the corresponding coefficient of determination (R^2) for the selected material under consideration.

4.5 Effect of the Overconsolidation and Fines Content on the Maximum Excess Pore Water Pressure

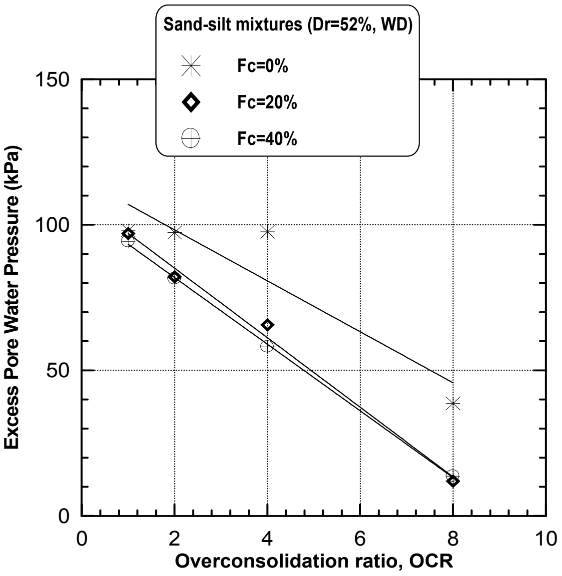
Data from the present study (Figs. 8 and 9) are reproduced in Fig. 16 for the purpose of analyzing the effects of the overconsolidation ratio (OCR = 1, 2, 4, and 8), low plastic silty fines content

Table 4 Coefficients A, C, and R^2 for Eq. (2)

Depositional method	DFP				WD			
OCR	1	2	4	8	1	2	4	8
A	67.55	50.25	21.6	9.93	98.38	94.88	93.53	33.87
C	0.46	0.50	0.46	0.02	– 0.097	– 0.39	– 0.99	– 0.62
R^2	0.99	0.99	0.82	0.92	0.94	0.78	0.89	0.70



(a) Dry funnel pluviation



(b) Wet deposition

Fig. 16 Excess pore water pressure versus overconsolidation ratio of Chlef sand-silt mixtures ($\sigma'_3 = 100$ kPa, $D_r = 52\%$)

(F_c = 0%, 20%, and 40%) and sample depositional fabric (DFP and WD). It is observed from the plots that the excess pore water pressure (Δu) generally decreases linearly with the increase of the overconsolidation ratio for the range of fines contents and sample fabric methods under consideration. The observed trend results from the role of the overconsolidation ratio in increasing the particle interlocking due to the existence of finer silty particles between coarser sandy particles and the dilative character of the sand-silt mixtures leading to a more stable structure of the samples. The influence of the overconsolidation ratio is clearly observed for the overconsolidated samples reconstituted by wet deposition, and becomes very pronounced for overconsolidated samples reconstituted by dry funnel pluviation. The following equation is proposed to express the excess pore water pressure (Δu) as a function of the overconsolidation ratio (OCR):

$$\Delta u = C \times (\mathrm{OCR}) + A \tag{3}$$

Table 5 illustrates the coefficients A, C, and the corresponding coefficient of determination (R^2) for the selected material under consideration

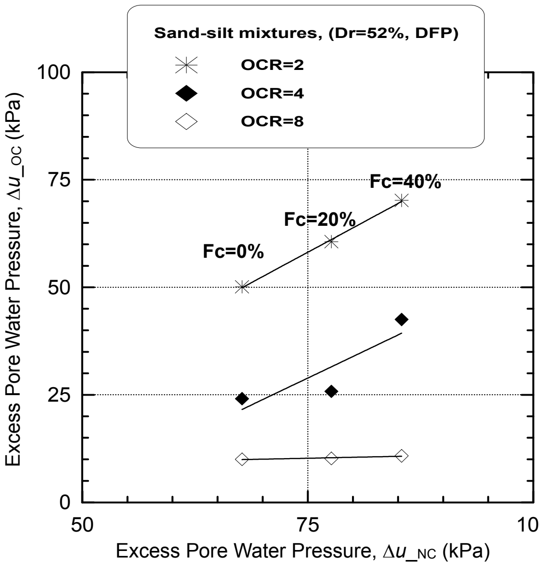
4.6 Relationship between Overconsolidated and Normally Consolidated Excess Pore Water Pressure

Figure 17 shows the plot of the excess pore water pressure of overconsolidated sand-silt mixtures ($\Delta u\__{\mathrm{OC}}$) versus excess pore water pressure of normally consolidated sand-silt mixtures ($\Delta u\__{\mathrm{NC}}$) for both sample reconstitution techniques under consideration (DFP and WD). The samples were reconstituted with an initial relative density of D_r = 52% and subjected to 100 kPa as initial confining pressure. It can be noted from Fig. 17 that the excess pore water pressure of overconsolidated dry funnel pluviated samples increases linearly with the increase of the excess pore water pressure of normally consolidated dry funnel pluviated samples for the range of fines content tested and lower overconsolidation ratio (OCR = 2 and 4) (Fig. 17(a)). However, the variation of the excess pore water pressure of overconsolidated sand-silt mixtures with the excess pore water pressure of normally consolidated sand-silt mixtures remains insignificant in the case of higher overconsolidation ratio (OCR = 8). The reverse trend was observed in the case of wet deposited sand-silt mixture samples. The wet deposition sample reconstitution technique appears to produce important variation in the excess pore water pressure for the different tested overconsolidation ratios (OCR = 2, 4, and 8) and range of fines content (F_c = 0%, 20%, and 40%) in comparison to the dry pluviation sample reconstitution technique. The following equation is suggested to express the excess pore water pressure of overconsolidated sand-silt mixtures ($\Delta u\__{\mathrm{OC}}$) as function of the excess pore water pressure of normally consolidated sand-silt mixtures ($\Delta u\__{\mathrm{NC}}$) for both sample preparation techniques (DFP and WD):

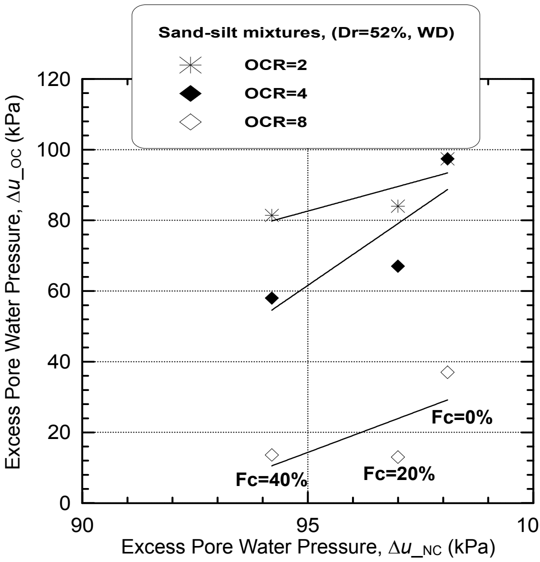
$$\Delta u\__{\mathrm{OC}} = C \times (\Delta u\__{\mathrm{NC}}) + A \tag{4}$$

Table 5 Coefficients A, C, and R^2 for equation (3)

F_c (%)	0		20		40	
Depositional Method	DFP	WD	DFP	WD	DFP	WD
A	67	115.72	78.72	108.95	91.51	104.74
C	− 7.78	− 8.75	− 9.38	− 11.94	− 10.47	− 11.45
R^2	0.88	0.84	0.88	0.99	0.98	0.99



(a) Dry funnel pluviation



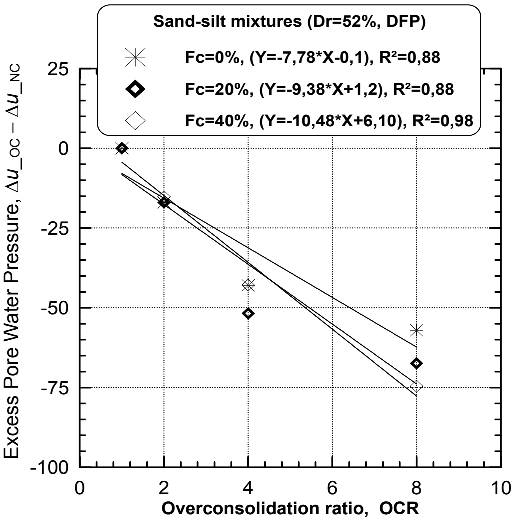
(b) Wet deposition

Fig. 17 **Excess pore water pressure of overconsolidated sand-silt mixtures versus excess pore water pressure of normally consolidated sand-silt mixtures (σ'_3 = 100 kPa, D_r = 52%)**

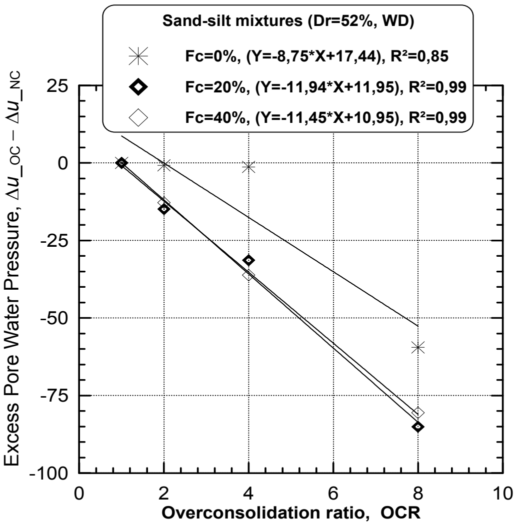
Table 5 illustrates the coefficients A, C, and the corresponding coefficient of determination (R^2) for the selected material under consideration.

4.7 Effect of the Overconsolidation and Fines Content on the Maximum Excess Pore Water Pressure Difference

The effects of overconsolidation ratio, fines content, and sample preparation on the excess pore water pressure difference of the sand–silt mixtures are discussed in this section. Data from the present study (Figs. 8 and 9) are reproduced in Fig. 19 for the purpose of analyzing the effects of the overconsolidation for different sand-silt mixture samples reconstituted with dry funnel pluviation and wet deposition. It is observed from the plot that the maximum excess pore water pressure difference ($\Delta_{u}\_{\mathrm{OC}} - \Delta_{u}\_{\mathrm{NC}}$) generally decreases with the increase of overconsolidation ratio from 1 to 8 and a linear relationship may express the correlation between the



(a) Dry funnel pluviation



(b) Wet deposition

Fig. 18 Excess pore water pressure difference versus overconsolidation ratios of Chlef sand-silt mixtures ($\sigma'_3 = 100$ kPa, $D_r = 52\%$)

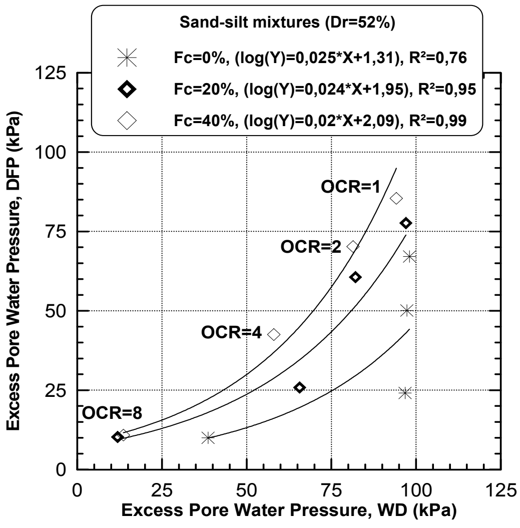


Fig. 19 Excess pore water pressure of dry funnel pluviated samples versus excess pore water pressure of wet deposited samples ($\sigma'_3 = 100$ kPa, $D_r = 52\%$)

maximum excess pore water pressure difference and the overconsolidation ratio for the range of fines content ($0\% \le F_c \le 40\%$) considering the two sample depositional techniques under study (dry funnel pluviation and wet deposition). This decrease results from the role of the overconsolidation (OCR = 1, 2, 4, and 8) in increasing the dilation phase of the sand–silt mixtures. Moreover, it can be seen from this Figure that the overconsolidation ratio has a significant influence on the excess pore water pressure difference for higher fines contents ($F_c = 20\%$ and $F_c = 40\%$) in comparison to lower fines content ($F_c = 0\%$). The following expression is suggested to correlate the excess pore water pressure difference of sand-silt mixture samples with overconsolidation ratio for the range of the fines content under study (F_c = 0%, 20%, and 40%) considering the two fabric methods (DFP and WD):

$$(\Delta u\_{\mathrm{OC}} - \Delta u\_{\mathrm{NC}}) = C \times (\mathrm{OCR}) + A \tag{5}$$

4.8 Relationship between Dry Funnel Pluviation and Wet Deposition Excess Pore Water Pressure

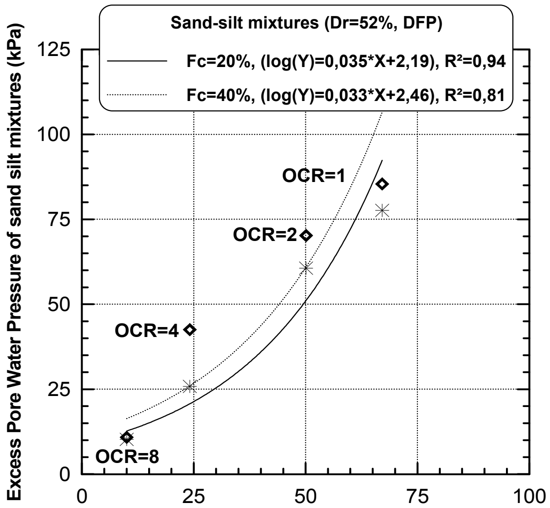
Figure 19 shows the variation of the excess pore water pressure of dry funnel pluviated samples versus excess pore water pressure of wet deposited sand-silt mixture samples. It can be seen that the excess pore water pressure of dry funnel pluviated samples increases in an exponential manner with the excess pore water pressure of wet deposited samples. For selected fines content, the excess pore water pressure of dry funnel pluviated samples correlates very well ($R^2 = 0.76$ for $F_c = 0\%$, $R^2 = 0.95$ for $F_c = 20\%$, and $R^2 = 0.99$ for $F_c = 40\%$) with the excess pore water pressure of wet deposited sand-silt mixture samples for the range of overconsolidation ratio (OCR = 1, 2, 4, and 8) under consideration. The variation of the excess pore water pressure of dry funnel pluviated samples with the excess pore water pressure of wet deposited sand-silt mixture samples is very pronounced for lower overconsolidation ratios (OCR = 1 and 2) in comparison to higher overconsolidation ratios (OCR = 4 and 8). Moreover, it is clearly observed that for the different graded sand–silt mixtures, the one with the higher fines content (F_c) and lower overconsolidation ratio (OCR) is more susceptible to liquefaction.

4.9 Relationship between Clean Sand and Sand-Silt Mixtures Excess Pore Water Pressure

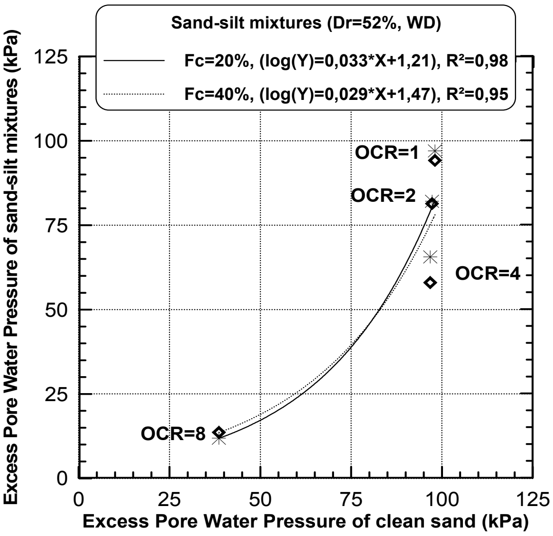
Figure 20 illustrates the evolution of the excess pore water pressure of the sand-silt mixtures with the excess pore water pressure of the clean sand for the two samples preparation techniques (DFP and WD) used. It is observed from the plot that the sand-silt mixture excess pore water pressure increases with the increase of clean sand excess pore water pressure according an exponential relationship for the two fines contens (F_c = 0% and 40%) and the range of overconsolidation ratio ($1 \le \mathrm{OCR} \le 8$) considering the two sample depositional techniques under study (dry funnel pluviation and wet deposition). The dry pluviation samples are clearly

Table 6 Coefficients A, C, and R^2 for Eq. (4)

Methods	DFP			WD		
OCR	2	4	8	2	4	8
A	– 26.77	– 46.20	6.94	– 247.27	– 769.76	– 439.82
C	1.13	1.00	0.04	3.48	8.75	4.78
R^2	0.99	0.76	0.88	0.67	0.73	0.50



(a) Dry funnel pluviation



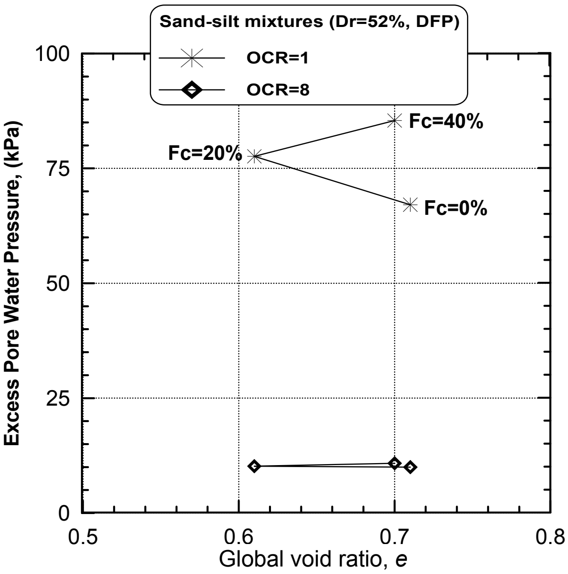
(b) Wet deposition

Fig. 20 Excess pore water pressure of sand-silt mixtures versus excess pore water pressure of clean sand (σ'_3 = 100 kPa, D_r = 52%)

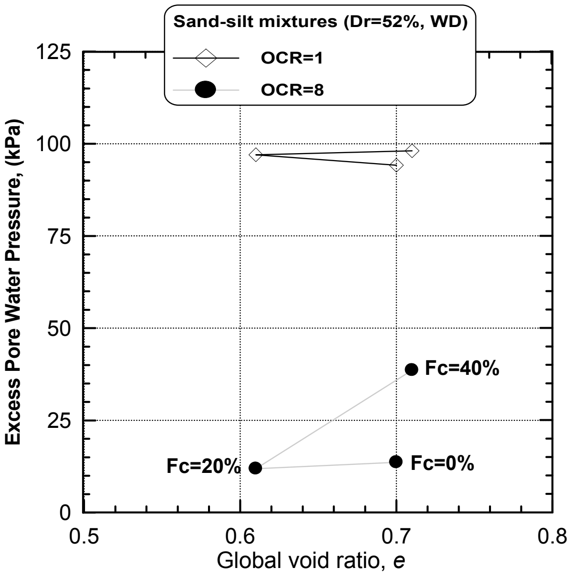
affected by the presence of low plastic fines. However, the 20% and 40% fines content exhibit similar trend regarding the variation of the sand-silt mixture versus the clean sand excess pore water pressure for the wet deposition samples.

4.10 Effect of the Global Void Ratio on the Maximum Excess Pore Water Pressure

Figure 21 shows the excess pore water pressure versus the initial global void ratio at different fines content of overconsolidated sand-silt mixtures reconstituted with dry funnel pluviation and wet deposition. It is clear from Fig. 21(a) that the dry pluviated excess pore pressure increases as the initial global void ratio decreases, and fines' content increases up to 20% fines content. Beyond 20% of fines content, the dry pluviation excess pore pressure continues to increase with increasing global void ratio and fines content for the lower overconsolidation ratio (OCR = 1). However, the dry pluviation excess pore pressure variation with the fines content remains insignificant for the higher overconsolidation ratio (OCR = 8). The tendency inverse was generally observed for wet deposition excess pore pressure variation. The global void ratio appears to be a parameter not as pertinent in sand fines mixtures as in clean sands for characterizing the mechanical response due to the fact that the global void ratio decrease and the fines content increase induced a decrement of the undrained shear strength. The obtained results are in good agreement with the results of Belkhatir *et al.* (2012).



(a) Dry funnel pluviation

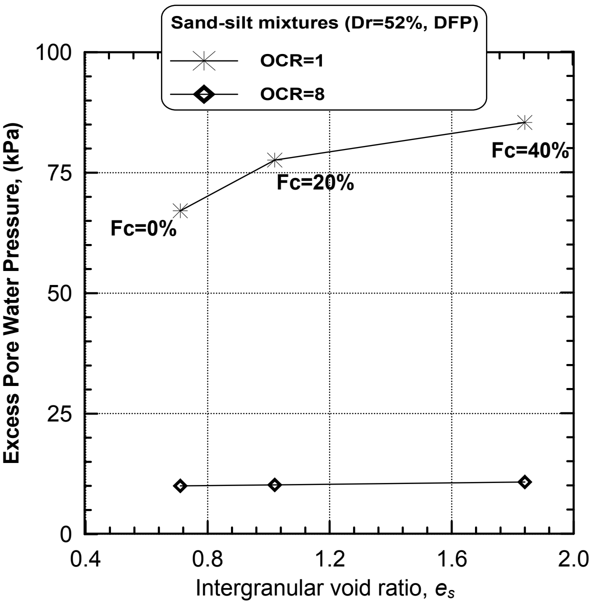


(b) Wet deposition

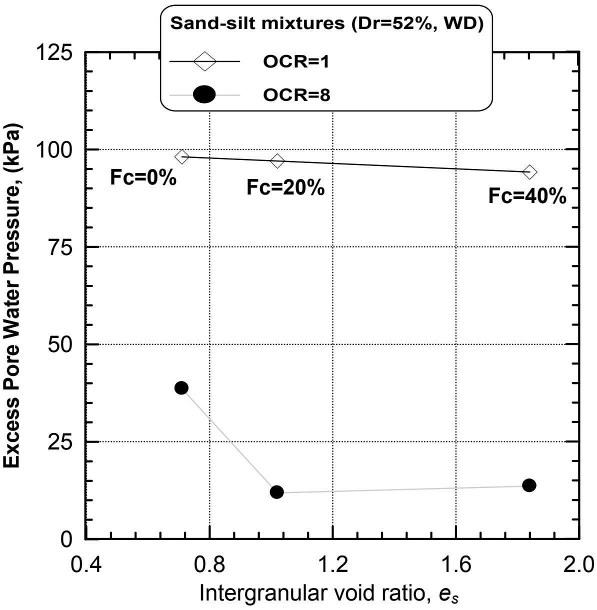
Fig. 21 Excess pore water pressure versus global void ratio of Chlef silty sand

4.11 Effect of Intergranular Void Ratio on the Maximum Excess Pore Water Pressure

The effects of the intergranular void ratio and silty fines content on the maximum excess pore water pressure of the dry funnel pluviated and wet deposited sand–silt mixture samples are discussed in this section. Data from the present study (Figs. 8 and 9) are reproduced in Fig. 22 for the purpose of analyzing the effects of the intergranular void ratio and silty fines content on the excess pore water pressure of the dry funnel pluviated and wet deposited sand–silt mixture samples considering the overconsolidation parameter. It is observed from Fig. 22(a) that excess pore water pressure generally increases with the increase of the intergranular void ratio and fines content from 0 % to 40 % for the lower overconsolidation ratio (OCR = 1). However, the excess pore water pressure versus the intergranular void ratio variation remains almost constant in the case of the higher overconsolidation ratio (OCR = 8) for the dry pluviated samples (Fig. 22(a)). The tendency inverse was observed in the case of the wet deposited samples, where the excess pore water pressure decreases with the increase of intergranular void ratio of silty sand (Fig. 22(b)).



(a) Dry funnel pluviation



(b) Wet deposition

Fig. 22 Excess pore water pressure versus intergranular void ratio of Chlef silty sand

5. CONCLUSIONS

A comprehensive laboratory work was undertaken to study the effects of low plastic fines, sample reconstitution and overconsolidation ratio on the maximum positive excess pore water pressure response of Chlef sand-silt mixture samples reconstituted at an initial relative density of 52% and subjected to a confining pressure of 100 kPa through a series of undrained monotonic triaxial tests that were carried out on disturbed samples. The important findings of this study are summarized below:

1. Undrained monotonic triaxial compression tests performed on laboratory reconstituted sand–silt mixture samples by dry funnel deposition and wet deposition showed that the low plastic fines and overconsolidation ratio control in a significant manner the excess pore water pressure of sand-silt mixture samples.
2. The excess pore water pressure of samples reconstituted by the wet deposition are higher than those reconstituted with dry pluviation (the samples reconstituted by the dry funnel pluviation are more resistant than those prepared by wet deposition). The dry funnel pluviation method produces more dilative or stable soil character, while the wet deposition method exhibits more contractive or unstable behavior. This is supported by Canou (1989), Ishihara (1993), Vaid *et al.* (1999), Benahmed *et al.* (2004), and Della *et al.* (2011).
3. The excess pore water pressure of the sand-silt mixture samples decreases with the increase of the overconsolidation ratio for both the dry funnel pluviation and wet deposition methods. The effect of the overconsolidation ratio on the excess pore water pressure is more significant for the dry funnel pluviation method in comparison to the wet deposition. The obtained results are in good agreement with the findings of Ishihara *et al.* (1978) and Della *et al.* (2011).
4. Complete static liquefaction occurs at a lower overconsolidation ratios (OCR = 1, 2, and 4) for the samples prepared by the wet deposition method, and as the overconsolidation ratio increases, the soil became more dilatant and more resistant to liquefaction.
5. The excess pore water pressure increases with increase of fines content for dry funnel pluviation for all the range of the overconsolidation ratio range under study. However, the normally consolidated and overconsolidated wet deposition samples show excess water pressure increase with the increase of fines content for the same overconsolidation ratio range. This results from the role of low plastic fines to increase the contractive and dilative character of sand-silt mixture samples reconstituted by dry funnel pluviation and wet deposition respectively. The present material response was explained by Shen *et al.* (1977), Troncoso *et al.* (1985), Singh *et al.* (1994), Lade and Yamamuro (1997), Belkhatir *et al.* (2010, 2012), Mahmoudi *et al.* (2018), and Cherif Taiba *et al.* (2017, 2019a, b) in a way that the low plastic silty fines make the soil structure more or less compressible and consequently increase or decrease the excess pore water pressure of normally consolidated and overconsolidated samples respectively.
6. The global void ratio appears to be a parameter not as pertinent in sand fines mixtures as in clean sands for characterizing the mechanical response due to the fact that the global void ratio decrease and the fines content increase induced a decrement of the undrained shear strength. The obtained results are in good agreement with the results of Belkhatir *et al.*

(2012).

7. The dry pluviated sand-silt mixture samples exhibit insignificant excess pore water pressure versus intergranular void ratio variation in the case of the higher overconsolidation ratio (OCR = 8). The tendency inverse was observed in the case of the wet deposited sand-silt mixture samples.

NOTATIONS

F_c	Fines content (%)
G_s	Specific gravity of solids (-)
D_{10}	Effective grain size (mm)
D_{50}	Mean grain size (mm)
D_r	Initial relative density (%)
C_u	Coefficient of uniformity (-)
C_c	Coefficient of curvature (-)
$e_{\max}$	Maximum global void ratio (-)
$e_{\min}$	Minimum global void ratio (-)
I_p	Plasticity index (%)
Δu	Maximum positive excess pore water pressure (kPa)
Δu_OC	Maximum positive excess pore water pressure of overconsolidated samples (kPa)
Δu_NC	Maximum positive excess pore water pressure of normally consolidated samples (kPa)
Δu_DFP	Maximum positive excess pore water pressure of DFP samples (kPa)
Δu_WD	Maximum positive excess pore water pressure of WD samples (kPa)
e	Global void ratio (-)
e_s	Intergranular void ratio (-)
ML	Inorganic silt
SP	Poorly graded sand
OCR	Overconsolidation ratio (-)
B	Skempton's pore pressure parameter (%)
σ'_3	Initial confining pressure (kPa)
A, C	Constants of Equation (-)
R^2	Coefficient of determination (-)
USCS	Unified Soil Classification System
DFP	Dry funnel pluviation
WD	Wet deposition
D	Diameter of the sample (mm)
H	Height of the sample (mm)
H/D	Height to diameter ratio of the sample (-)

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