

Laboratory Investigation on the Saturation and Initial Structure Effects on the Undrained Behavior of Granular Soil Under Static Loading

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Abstract: The effects of the initial state of the samples and the saturation evaluated in terms of Skempton's pore pressure B on the behavior of Chlef sand were studied in this article. For this purpose, the results of two series of undrained monotonic compression tests on medium dense sand ($RD= 50\%$) are presented. In the first test series, the influence of the specimens' fabric and confining pressure is studied. Triaxial specimens containing Chlef sand with 0.5% non plastic silt content were isotropically consolidated to 50 kPa, 100 kPa and 200 kPa. The specimens were formed using both dry funnel pluviation and wet deposition. The results indicate that the confining pressure and the method of sample preparation have a significant influence on the liquefaction resistance of the sand. In the second series of tests, the saturation influence on the resistance to the sand liquefaction is realized on samples at an effective stress of 100 kPa for Skempton's pore pressure coefficient varying between 32% and 90%. It was found that an increase in the Skempton's S pore pressure coefficient B reduces the soil dilatancy and amplifies the phase of contractancy.

Keywords: liquefaction; sand; dry funnel pluviation; wet deposition; confining pressure; pore pressure; compression; undrained; saturation

1 Introduction

The region of Chlef, situated in the North of Algeria about 200 km to the west of the capital Algiers, due to its proximity to the continental European and African plates, as is shown in Fig. 1, is constantly a very instable zone, subjected to intense seismic activity. Over the last centuries, it underwent destructive earthquakes (ex Orléansville, ex El-Asnam) in 1922, 1934, and 1954. This last earthquake, of magnitude 6.7, and which has been described well by Rothé [26], Thevenin [29] and Mckenzie [18], caused the deaths of 1340 people and significant damage to different civil engineering structures, as well as causing and the appearance of soils sliding and the liquefaction phenomenon.

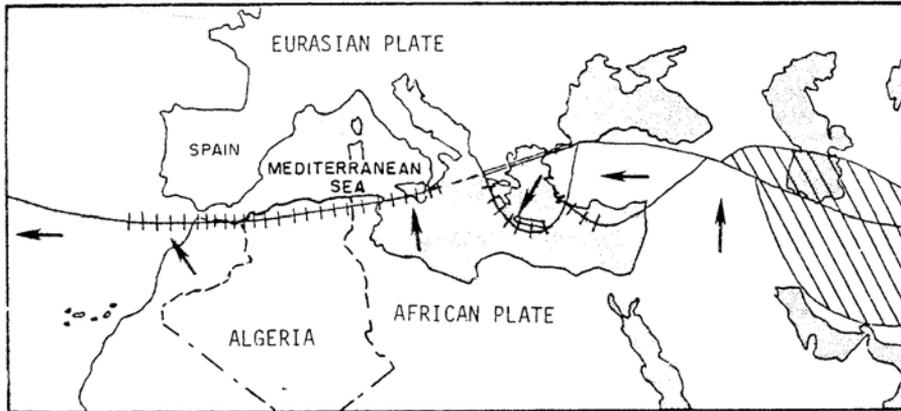


Figure 1
Movement of Europe-Afrique plate

On October 10, 1980 at 13h25 (local time), the region was the theater of a strong earthquake of a magnitude of 7.3 according to Papastamatiou's calculations [23], followed by two significant jolts of magnitudes 6 and 6.1 within an interval of several hours and by numerous shocks over the following months [22]. The main shock generated an significant inverse fault of about 40 km long in the surface [1]. The epicenter of this earthquake was located in the North East of El-Asnam around the village of Beni Rached.

The disaster of October 10, 1980 caused the loss of numerous lives (about 3000 deaths) and caused the destruction of a great number of buildings, and damage to the connecting infrastructures and to public equipment. If we put aside the merely tectonic demonstrations, as the spectacular fault appeared near El-Asnam. The seismic vibration also generated a number of geodynamic phenomena within the surface of the soil: movements of the ground of varied nature and size, and especially the liquefaction of the sandy soils following a loss of resistance to shearing.

According to Durville and Méneroud [8], the phenomenon of liquefaction appeared at a vast alluvial valley crossed by the Chlef river and at the zone of confluence of this river with the Fodda river, as is shown in Fig. 2.

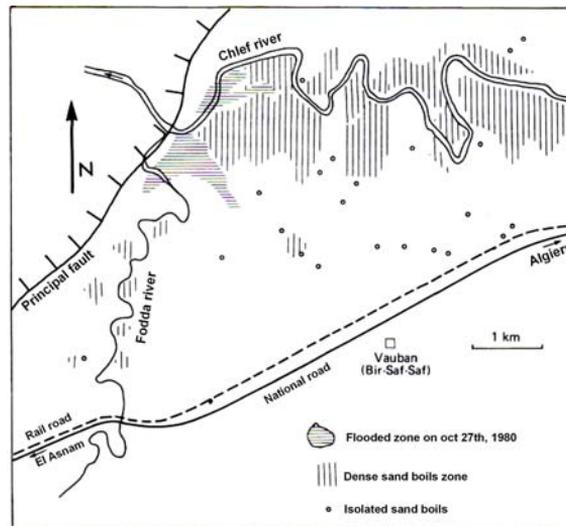


Figure 2

Valley of the Chlef river and location of the sand boils due to the liquefaction phenomenon

2 Literature Review

During earthquakes, the shaking of the ground may cause saturated cohesionless soils to lose their strength and behave like a liquid. This phenomenon is called soil liquefaction and will cause the settlement or tipping of buildings, as well as failures of earth dams, earth structures and slopes. The modern study of soil liquefaction was triggered by the numerous liquefaction-induced failures during the 1964 Niigata, Japan earthquake.

Numerous studies have reported that the behavior of sands can be greatly influenced by the initial state and the saturation of the soil. Polito and Martin [25] asserted that the relative density and the skeleton void ratio were factors that seemed to explain the variation in different experimental results. Yamamuro and Lade [33], [34] and Yamamuro and Covert [32] concluded that complete static liquefaction (zero effective confining pressure and zero effective stress difference) in laboratory testing is most easily achieved in silty sands at very low pressures. Kramer and Seed [13] also observed that liquefaction resistance increased with increased confining pressure.

Several specimen reconstitution techniques, tamping and pluviation being the most common, are in use in current practice. The objective in all of these cases is to replicate a uniform sand specimen at the desired void ratio and effective stresses in order to simulate the sand mass in-situ. However, the effect of the preparation method of the samples has been subject of conflicting research. Many studies have

reported that the resistance to the liquefaction is more elevated for samples prepared by the method of sedimentation than for samples prepared by dry funnel pluviation and wet deposition [41]; other studies have found that the specimens prepared by the dry funnel pluviation method tend to be less resistant than those reconstituted by the wet deposition method [19], [35]. Other researchers indicated that the tests prepared by dry funnel pluviation are more stable and dilatant than those prepared by wet deposition [3], [6]. Vaid *et al.* [30] confirm this result while showing that wet deposition encourages the initiation of liquefaction in relation to preparation by pluviation under water. Yamamuro *et al.* [36] concluded after their laboratory investigation that the method of dry pluviation supports the instability of the samples, contrary to the method of sedimentation. Wood *et al.* [31] found that the effect of the method of deposition on the undrained behavior decreases when the density increases. They also found that this influence decreases with an increase in the fines content, particularly with lower densities. The focus of this study is to identify the differences in undrained triaxial compression behavior that can result from using different reconstitution techniques to create silty sand specimens.

Additionally, in the neighborhoods of the town of Chlef (Algeria), unsaturated zones exist on top of phreatic ground, which underwent a significant folding back following the dry conditions which have affected the area since the 1980s. Over the past decades, advanced research has helped us better understand the liquefaction of the grounds based on experiments carried out in laboratory, on physical modeling and on numerical analysis. The majority of these investigations of the liquefaction of granular soils were based on completely saturated material. The study of the influence of the degree of saturation on the liquefaction of soils is of practical interest, because we often find structures built on top of phreatic ground; which implies the presence of partially saturated grounds. The incidence of partial saturation on cyclic resistance was approached theoretically by Martin *et al.* [16]. Mulilis *et al.* [20] examined the effect of the saturation degree on the liquefaction of Monterrey sand. They noted that a variation of Skempton's coefficient B between 0.91 and 0.97 does not significantly affect the liquefaction of this sand. This influence depends on the type of soil, the density and the initial confining pressure. However, recent results of in-situ tests include the measurements of the velocity of the compression waves (V_p) and indicate that the condition of partial saturation can exist above the level of the phreatic ground for a few meters due to the presence of bubbles of air [11], [21] or the presence of gas bubbles in the marine sediments and sands containing oils, as noted by Mathirobanand Grozic [17]. The effects of a condition of partial saturation on liquefaction were approached by several researchers [2], [17], [24],[38]. The condition of the saturation of soil samples in laboratory can be evaluated by measuring the value of Skempton's pore pressure (B) coefficient, as suggested by Ishihara *et al.* [11]. The results of laboratory tests showed that resistance to the liquefaction of sands increases when the saturation degree decreases [16], [40], [11], [12], [37],[39], [5].

Mullilis et al. [20] and Tatsuoka et al. [28] showed that in the case of loose sands, a good saturation requires high values of the coefficient B . On the other hand, for stiffer materials, the problem seems less critical. Sheriff et al. [27] showed that a fine or clayey sand can be considered saturated if the value of B exceeds 0.8. Chaney [7] more precisely noted that the coefficient B must exceed 0.96 so that the soil is well saturated. Giroud and Cordary [9] noted that for values of B superior to 0.85, the degree of saturation is very close to 1. Tests of liquefaction were carried out by Yoshimi et al. [40] on medium dense Toyoura sand with various degrees of saturation. The results show that the degree of saturation significantly affects the resistance to liquefaction: With a coefficient B higher than 0.8, it is enough to apply three cycles to achieve liquefaction of the sample; whereas we need eight cycles to obtain liquefaction of specimens having a coefficient B close to 0.5.

This literature survey reveals a real need for experimental data concerning the behavior of unsaturated soils under undrained monotonic loading. Such data improves our understanding of the influence of the saturation degree on the response of soils to undrained monotonic loading. This paper includes a contribution to existing experimental data. It presents results of undrained monotonic triaxial tests performed on Chlef sand for various values of Skempton's pore-pressure coefficient.

3 Laboratory Testing

3.1 Tested Material and Procedures

The current laboratory investigation was carried out in order to study the influence of initial state and saturation on the undrained behavior of silty sand. For this purpose, a series of tests of undrained triaxial compression under monotonic loading conditions were performed on reconstituted samples of natural Chlef sand containing 0.5% of non plastic ($PI= 5.81\%$) silt of the Chlef River. The samples were prepared at the same relative density of undisturbed ones to represent a medium dense state ($RD= 50\%$) using two different techniques: dry funnel pluviation and wet deposition (a detailed summary of the procedure for each method is provided in the following section) and consolidated isotropically at an initial confining pressure of 50 kPa, 100 kPa and 200 kPa. Sand samples were collected from a liquefied layer of the deposit area close to the epicentre of the Chlef earthquake (October 10, 1980). Fig. 3 shows the craters of liquefied ground on the banks of the Chlef River. Fig. 4 illustrates the typical subsidence locations of the liquefied soil. The index properties of the soil used in the study are summarized in Table 1. The grain size distribution curve for the tested material is shown in Fig. 5.



Figure 3

Sand boils due to the liquefaction phenomenon in the Chlef region



Figure 4

Subsidence of the Chlef River banks due to liquefaction

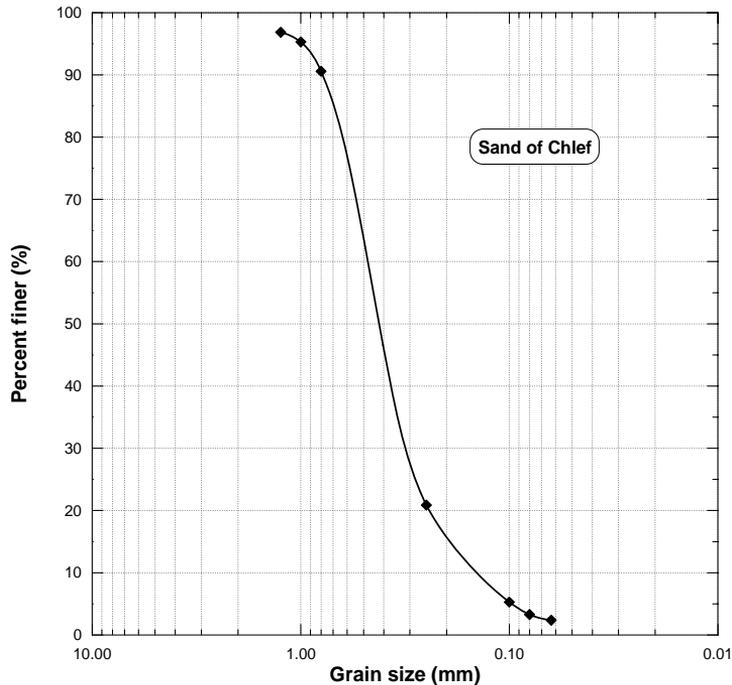


Figure 5
Grain size distribution of the tested soil

Table 1
Index properties of sand

Material	e_{\min}	e_{\max}	$\gamma_{d\min}$ g/cm^3	$\gamma_{d\max}$ g/cm^3	γ_s g/cm^3	Cu D_{60}/D_{10}	D_{50} mm	D_{10} mm	Grains shape
O/Chlef	0.54	0.99	1.34	1.73	2.67	3.2	0.45	0.15	Rounded

The samples were 70 mm in diameter and 140 mm in height with smooth lubricated end-plates. After the specimen was been formed, the specimen cap was placed and sealed with O-rings, and a partial vacuum of 20 kPa was applied to the specimen to reduce the disturbances. In the Saturation phase, the technique of Lade and Duncan [14] was used by purging the specimen with carbon dioxide for approximately 30 min. De-aired water was then introduced into the specimen from the bottom drain line. The degree of saturation was controlled during a triaxial compression test by Skempton's coefficient, which can be related to the degree of saturation by the following relation (Lade and Hernandez [15]):

$$B = \frac{1}{1 + nk_s \left(\frac{S_r}{k_w} + \frac{(1 - S_r)}{U_a} \right)} \quad (1)$$

where K_s and k_w indicate the bulk modulus of the soil skeleton and the water, respectively; n =the soil porosity, u_a = water pore pressure.

All test specimens were isotropically consolidated at a mean effective pressure of 50 kPa, 100 kPa and 200 kPa, and then subjected to undrained monotonic triaxial loading.

3.2 Depositional Techniques

Wet deposition and Dry funnel pluviation were used to reconstitute the specimens. The first method consists of mixing with the highest possible homogeneous manner, the sand previously having been dried, with a small quantity of water fixed at 3%, and the deposition of the humid soil in the mold with control of the content in water. The soil was placed finely by successive layers. A constant number of strokes was applied to get a homogeneous and isotropic structure. In the dry funnel pluviation method, the dry soil was deposited in the mold with the help of a funnel with the height controlled. This method consists of filling the mold by tipping in a rain of the dry sand.

3.3 Equipment

An advanced automated triaxial testing apparatus was used to conduct the monotonic tests (see Fig. 6).



Figure 6

The experimental device used

4 Experimental Results

4.1 Effect of Confining Pressure

The effect of varying the effective confining pressure on the liquefaction resistance of sand is shown in Figs. 7 and 8. As the confining pressures increased, the liquefaction resistance of the sands increased for both the dry funnel pluviation and the wet deposition methods. The results in Figs. 7a and 7b with an initial density of 50% (medium dense state) for specimens reconstituted by the first method at a confining pressure of 50 kPa show a weaker resistance than those shown at a confining pressure of 100 kPa and 200 kPa. Its resistance increases at the beginning of the loading up to a value of 25 kPa, corresponding to an axial strain of 0.5%, then it decreases up to an axial distortion strain of 5% to stabilize passing nearly a quasi steady state (QSS); then the sample mobilizes a residual strength increasing the resistance of the sample in the steady state. The stress path diagram (Fig. 7b) presents a reduction of the effective mean stress until a value of 10 kPa, then a migration towards higher values, characterizing a dilating state. The same trends are signaled for the samples at confining pressures of 100 and 200 kPa, with peak deviatoric stresses of 48 kPa and 90 kPa respectively.

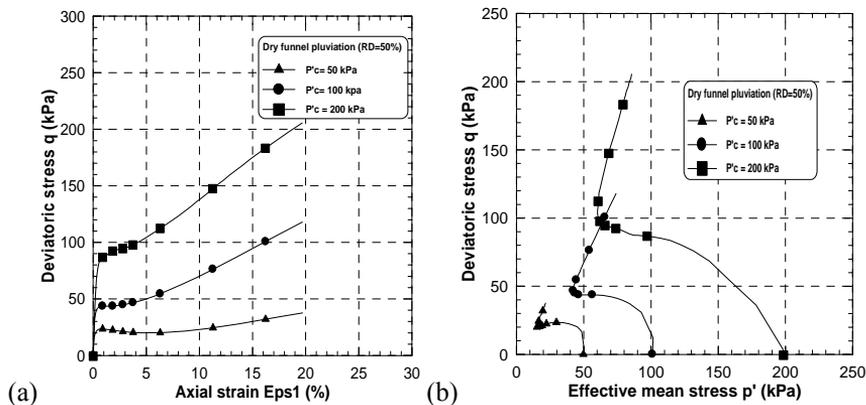


Figure 7

Undrained tests for samples prepared by the dry funnel pluviation method:

(a) deviatoric stress-strain curve, (b) stress path

Effective stress paths for undrained triaxial compression tests on Chlef sand for samples prepared by the wet deposition method with initial relative densities of 50% are plotted on the p' - q diagrams shown in Fig. 8b. As can be seen, complete static liquefaction occurred in the test with the lowest confining pressure (50 kPa). Static liquefaction was coincidental with the formation of large wrinkles in the membranes surrounding the specimens.

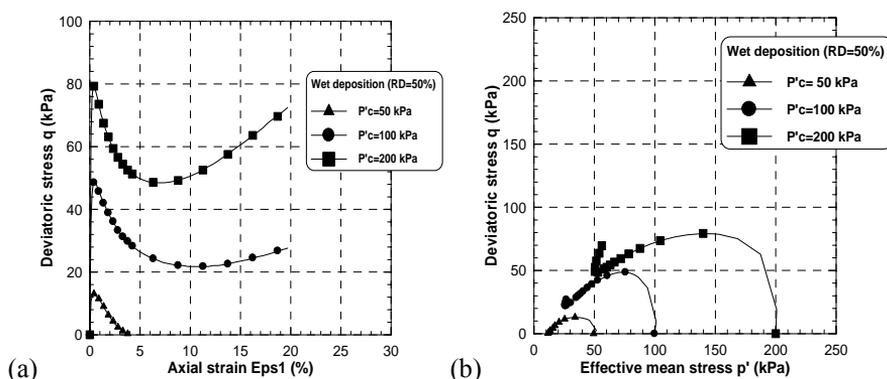


Figure 8

Undrained tests for samples prepared by the wet deposition method:

(a) deviatoric stress-strain curve, (b) stress path

Fig. 8b also shows that when the initial confining pressure is increased beyond 50 kPa, the effective stress paths exhibit behavior that is characterized by increasing stability or increasing resistance to liquefaction. This is demonstrated by examining the stress-strain curves in Fig. 8a. The initial confining pressures and densities are shown for each test. The stress-strain curves of the 100 and 200 kPa initial confining pressure tests show that the stress difference does not reach zero as in the test indicating complete liquefaction, but decreases to a minimum before increasing to levels well above the initial peak, or, with progressive stabilization, around an ultimate stationary value very weak. This is the condition of temporary liquefaction. The effect of increasing the confining pressure is to increase the dilatant tendencies in the soil.

4.2 Influence of Sample Reconstitution Method

The effect of the specimens' reconstitution method on maximal deviatoric stress is shown in Fig. 9a. It can be noticed from the results of these figures that the dry funnel pluviation method (DFP) gives more significant values of the maximal deviator, and therefore a much higher resistance to liquefaction, in contrast with the wet deposition method (WD), where some weaker values of the maximal deviator were noted, with progressive stabilization around a very weak or nil ultimate stationary value, meaning the liquefaction of the sample.

The same tendencies are noted for the variations of the values in the peak deviatoric stress given in Fig. 9b. As can be seen, the samples formed by the dry funnel pluviation method exhibit a resistance to monotonic shearing, superior to those made by the wet deposition method.

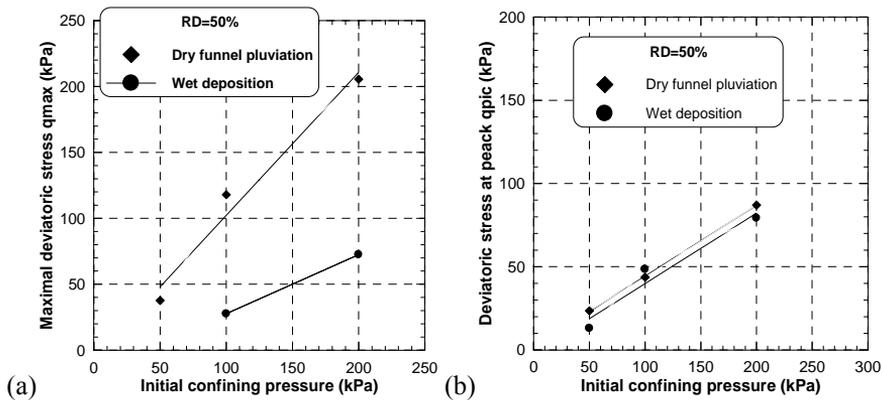


Figure 9

Effect of the depositional method on the maximal deviatoric stress (a) and the peak deviatoric stress (b)

The influence of the sample preparation methods on excess pore pressure is illustrated in Fig. 10. As shown in Fig. 10a, for the dry funnel pluviation method, the variation of the pore pressure curves presents two phases: the first shows a very high initial rate of generation, giving account of the strongly contracting character of the Chlef sand. In the second phase, this rate decreases progressively with the axial strain, reflecting the dilating character of the material. The developed excess pore pressure in the samples prepared by the wet deposition method is presented in Fig. 10b. It can be seen that the samples exhibit a very high contracting character, with an expansion rate highly elevated from the beginning of the shearing and progressive stabilization toward an ultimate value, associated to the stabilization of the deviatoric stress.

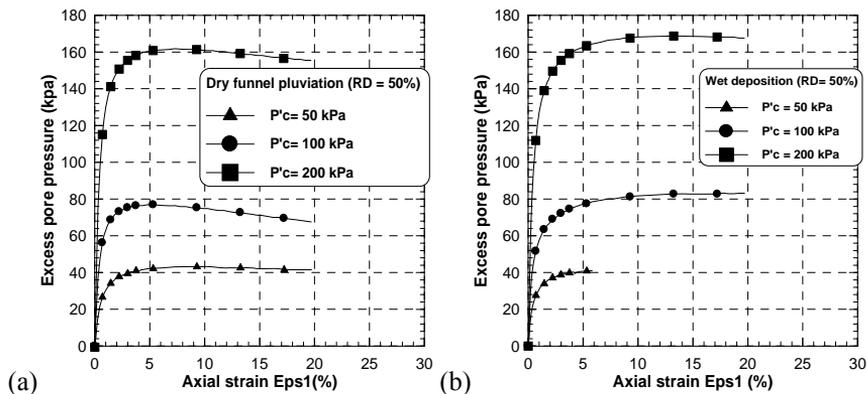


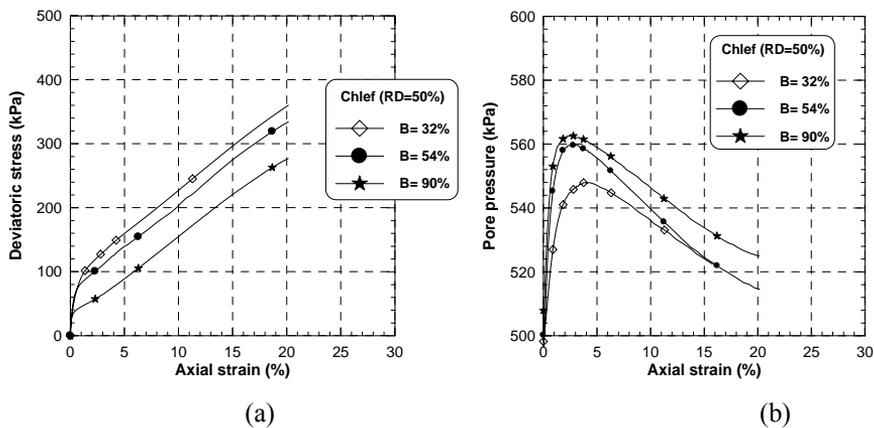
Figure 10

Effect of sample reconstitution methods on excess pore pressure: (a) Dry funnel pluviation method, (b) Wet deposition method

The results of Figs. 9 and 10 are in perfect agreement with those of the Figs. 7 and 8, showing that the method of dry funnel pluviation encourages the increase of resistance to the monotonic shearing of the samples, in contrast to the wet deposition method, which accelerates the instability of the samples, which show a very weak resistance, and even provokes the phenomenon of liquefaction of the sand for the weak confinements, leading to the collapse of the sample.

4.3 Effect of the Saturation Degree

Fig. 11 shows the results of the undrained triaxial compression tests performed in this study for various values of coefficient of Skempton (B) between 32% and 90% with an initial confining pressure of 100 kPa. As can be seen, increases in the degree of saturation characterized by the coefficient of Skempton (B) lead to a reduction in the resistance of deviatoric stress (Fig. 11a) and an increase in water pressure (Fig. 11b). The increase in the water pressure results from the role of the degree of saturation in the increase in the phase of contractance observed during the drained tests. The increase in the pore water pressure leads to a reduction in the effective confining pressure and consequently with a reduction of resistance as Fig. 10a illustrates. The stress path curve in the plan (p' , q) shows well the role the degree of saturation plays in the reduction of the effective mean stress and the maximal deviatoric stress (Fig. 11c).



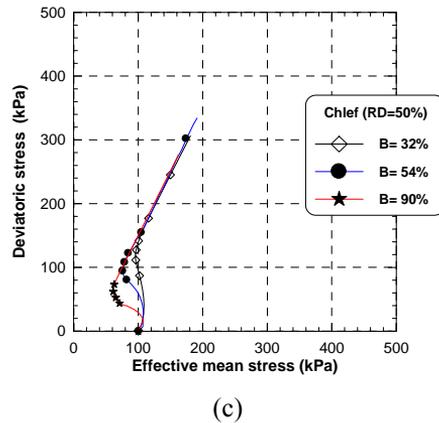


Figure 11

Influence of the coefficient of Skempton (B) on undrained behavior of Chlef sand

(a) Deviatoric stress, (b) excess pore pressure, (c) stress path

Fig. 12 shows the evolution of the maximal deviatoric stress versus the coefficient of Skempton (B). We note that the resistance to monotonous shear decreases in a linear manner with the increase of the coefficient of Skempton (B); the maximal deviator passes from a value of $q=360$ kPa for $B=32\%$ to a value $q=276.73$ kPa for $B=90\%$. Fig. 13 shows the evolution of the pore water pressure to the peak versus the the coefficient of Skempton (B). We note that the pore water pressure to the peak increases with the increase in the coefficient of Skempton (B); the pore water pressure to the peak passes from 547.90 kPa for $B=32\%$ to a value of 562.53 kPa for $B=90\%$.

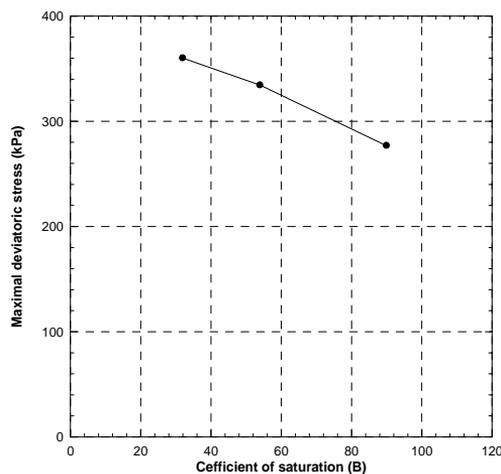


Figure 12

Evolution of maximal deviatoric stress versus Skempton's coefficient (B)

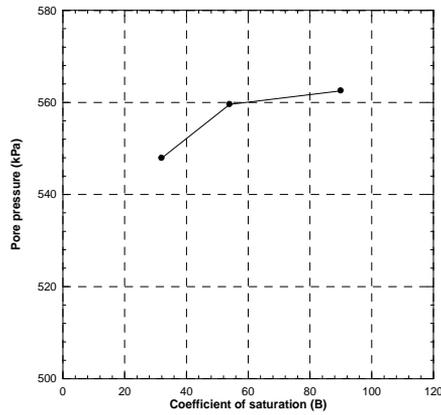


Figure 13

Evolution of peak pore pressure versus Skempton's coefficient (B)

4.4 Variation of the Residual Strength

When sands are subjected to an undrained shearing, following the peak of deviatoric stress, the resistance to the shearing falls with an almost constant value on a broad deformation. Conventionally, this resistance to shearing is called residual strength, or the shearing force at the quasi steady state (Qss). The residual strength is defined by Ishihara [10] as:

$$S_{us} = (q_s/2) \cos\phi_s \tag{2}$$

where q_s and ϕ_s indicate the deviatoric stress and the mobilized angle of interparticle friction at the quasi steady state.

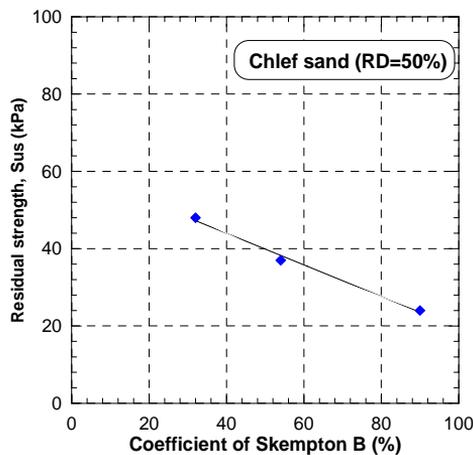


Figure 14

Influence of the coefficient of Skempton (B) on the Residual strength at the quasi steady state

Fig. 14 shows the evolution of the residual strength with Skempton's coefficient (B). We note that the residual strength decreases in a significant and linear way with the increase in Skempton's coefficient (B) resulting from the role of saturation as for the amplification of the contractance of the studied soil.

Conclusion

A comprehensive experimental program to study the effects of initial state and saturation on the undrained monotonic behavior of sandy soil was undertaken, in which two series of tests were performed. All the tests were carried out on medium dense specimens. Based on the results from this investigation, the major conclusions are as follows:

- 1 Complete static liquefaction occurred at low confining pressure (50 kPa) for the wet deposition method.
- 2 As the confining pressure increased, the liquefaction resistance of the sand increased. This observation correlates with most historic cases of apparent static and earthquake-induced liquefaction. The results reveal as well that the method of reconstitution has a detectable effect on the undrained behavior. The dry funnel pluviation method appeared to indicate a more volumetrically dilatant or stable response, while the wet deposition method appeared to exhibit a more contractive or unstable behavior.
- 3 The saturation has a detectable effect on the undrained behavior. The results showed that an increase in the Skempton's pore pressure coefficient (B) induces a reduction in the initial stiffness and the resistance of the soil (maximal deviatoric stress); and increases the phase of contractance. This, results in a significant effect on the volumetric response inducing an amplification of the phase of contractance when the coefficient of Skempton B increases.
- 4 The residual effort (Sus) decreases in a significant and linear way with the increase in the Skempton's pore pressure coefficient (B) resulting from the role of saturation as for the amplification of the contractance.

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