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Drained and undrained shear strength of silty sand: effect of reconstitution methods and other parameters

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ABSTRACT

The effects of confining pressure, relative density and sample preparation methods on the shearing strength of Chlef sand were studied. Results are presented of drained and undrained monotonic triaxial compression tests, performed on samples with initial densities of 0.29 and 0.80, under initial confining pressures ranging from 50 to 200 kPa. Specimens were prepared by two depositional methods; dry funnel pluviation and wet deposition. There was a marked difference in the undrained behaviour, even though the density and stress conditions were identical. The soil fabric was responsible for this result. The results also indicated that at low confining pressures, the specimens reconstituted by the wet deposition method exhibited complete static liquefaction, (zero effective confining pressure and zero stress difference). As confining pressures and densities were increased, the effective stress paths indicated increasing resistance to liquefaction by showing increasing dilatant tendencies. The same trends were observed in drained tests results in the form of an increase in the volumetric strain and the rapid transition from the contractancy phase to the dilatancy phase.

Keywords: liquefaction, sand, drained, undrained, dry funnel pluviation, wet deposition, confinement, density, residual strength, volumetric strain.

1. INTRODUCTION

During static or cyclic loading, 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 settlement or tipping of buildings, failure of earth dams, earth structures and slopes. The modern study of soil liquefaction has been triggered by numerous liquefaction-induced failures during the 1964 Niigata, Japan earthquake. Therefore, it is necessary to obtain a proper understanding of the effect of parameters such as soil properties and the nature of the loading on the severity of soil liquefaction.

The region of Chlef situated near the Mediterranean Sea, to the North of Algeria, about 200 km to the west of the capital Algiers, by its proximity to the contact of the continental European and African plates as shown by Fig. 1, is constantly a very unstable zone subjected to intense seismic activity.

On October 10th, 1980 at 13h25 (local time), the region was hit by a disastrous earthquake of magnitude of 7.3 according to the calculations of PAPASTAMATIOU (1980), followed by strong aftershocks of magnitudes 6 and 6.1 some hours afterwards, and numerous more aftershocks during several subsequent months (OUYED, 1981). The main shock generated an important inverse fault, about 40 km long, appearing on the surface (AMBRASEYS, 1981). The epicenter of this earthquake was localized in the North East of El-Asnam.

The disaster of October 10, 1980 resulted in heavy loss of life (about 3000 deaths), the destruction of a large number of buildings, important damage to the linking infrastructures and to public equipment, and generated a certain number of

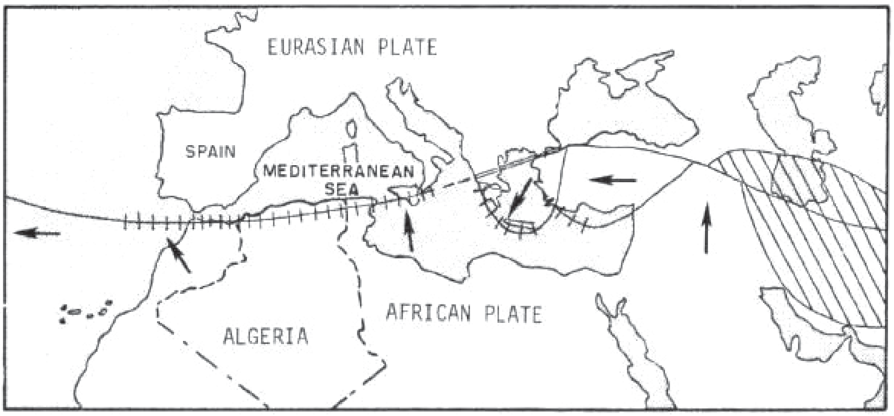

Figure 1: Movement of the Europe-African plate (from the CTC institution – Controle Technique de Construction).

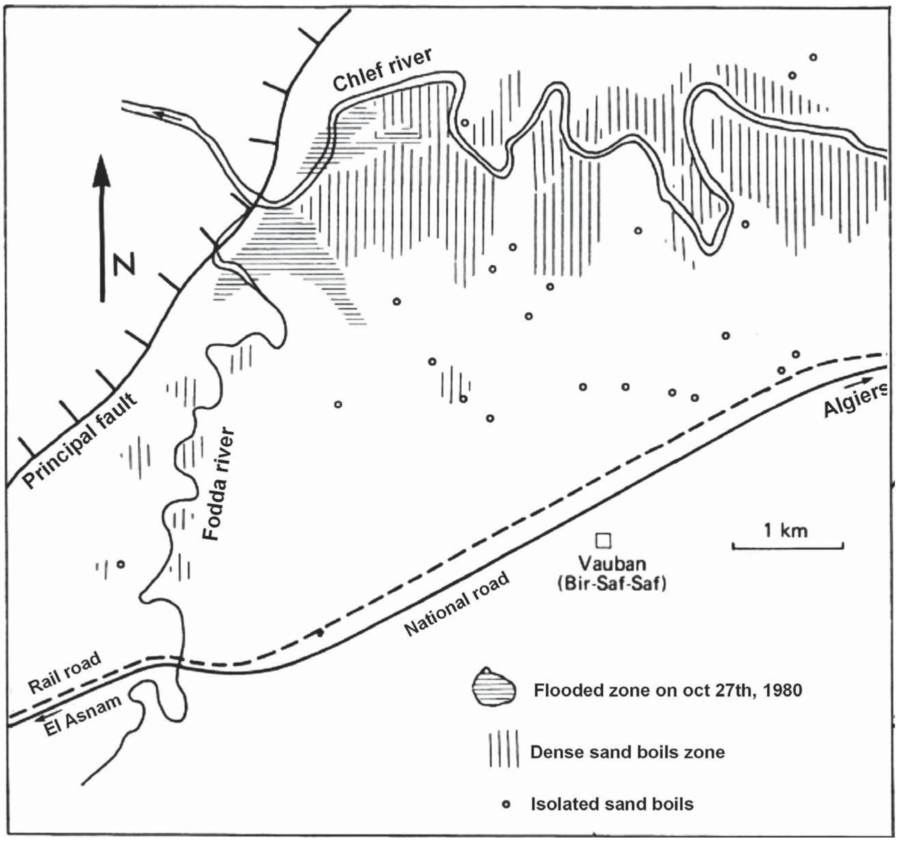

Figure 2: Valley of the Chlef River and localization of sand boils due to liquefaction (from the CTC institution – Controle Technique de Construction).

geodynamic phenomena at the surface of the ground: ground movements of variable nature and size, and especially the liquefaction of the sandy soils following a loss of shearing resistance. The phenomenon of liquefaction appeared on a vast alluvial valley crossed by the Chlef River and at the confluence of this river with the Fodda River as shown in Fig. 2 (DURVILLE & MENEROUD, 1982).

2. PRIOR STUDIES

Numerous studies have reported that the behaviour of sands can be greatly influenced by the initial state of the soil. POLITO & MARTIN (2003) asserted that the relative density and skeleton void ratio were factors that seemed to explain the variation in different experimental results. YAMAMURO & LADE (1997), YAMAMURO & LADE (1998) and YAMAMURO & COVERT (2001) 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 & SEED (1988) also observed that liquefaction resistance increased with increasing 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 is to replicate a uniform sand

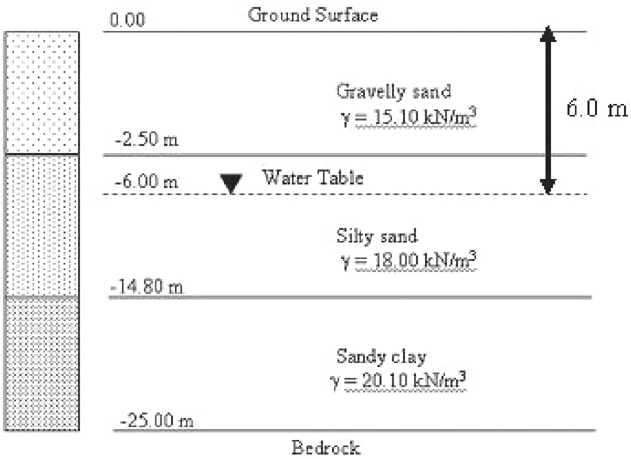

Figure 3: Geotechnical profile of the soil deposit at the site.

specimen at the desired void ratio and effective stresses to simulate the sand mass in-situ. However the effect of the preparation method of the samples has been subject to controversial research. Many studies have reported that the resistance to liquefaction is higher for samples prepared by the method of sedimentation than for samples prepared by dry funnel pluviation and wet deposition (ZLATOVIC & ISHIHARA, 1997); 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 (MULILIS et al., 1977; YAMAMURO & WOOD, 2004). Other researchers indicated that the tests prepared by dry funnel pluviation are more stable and dilatant than those prepared by wet deposition (BENAHMED et al., 2004; CANOU, 1989; ISHIHARA, 1993). VAID et al. (1999) confirm this result while showing that wet deposition encourages the initiation of liquefaction in relation to a setting up by pluviation under water. YAMAMURO et al. (2008) 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. (2008) found that the effect of the method of deposition on the undrained behaviour decreases, when the density increases. They also found that this influence decreases with the increase in fines content, particularly at lower densities. The focus of this study is to identify the differences in drained and undrained triaxial compression behaviour that can result from using different reconstitution techniques to create silty sand specimens.

3. EXPERIMENTAL METHODS

An experimental study of the behaviour of loose and dense sand under static loading conditions is presented below. Both drained and undrained tests were performed.

3.1. Sand tested

Silty sand samples were collected from the liquefied layer of the study areas at a depth of 6.0 m (Fig. 3) close to the Chlef earthquake epicentre (October 10th, 1980). Figs. 4A,B show craters of liquefied ground on the banks of the Chlef River. Fig. 5 illustrates a typical subsidence location of the liquefied soil and sample collection. All tests in the present study were performed on sand from Chlef (Algeria). The sand contains 0.5% silt of the River Chlef. The grain size distribution curve of this sand is given in Fig. 6. It is medium sand with rounded grains of medium diameter D_{50} = 0.45 mm and the predominant minerals are feldspar and quartz. The silt component is non plastic with a plasticity index of 5.81 %. The index properties of the sand used in this laboratory research work are presented in Table 1. The specimens were reconstituted at two densities (I_D = 0.29 and 0.80) representing the loose and dense states.

Figure 4: Craters of liquefied soil on banks of the River Chlef (a and b).

Figure 5: Subsidence of the Chlef River Banks due to liquefaction.

Table 1: Index properties of the used sand.

Material	e_{min}	e_{max}	γ_{dmin}	γ_{dmax}	γ_s	Cu	D_{50}	D_{10}	Grains shape
O/Chlef	0.54	0.99	13.4	17.3	26.7	3.2	0.45	0.15	Rounded

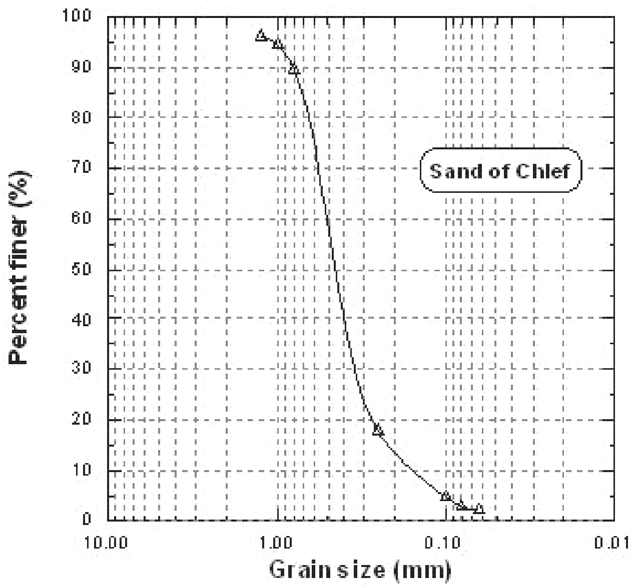

Figure 6: Grain-size distribution curve of tested material.

3.2. Testing equipment

An advanced automated triaxial testing apparatus, type Bishop and Wesley (BISHOP & WESLEY, 1975) was used to conduct the monotonic drained and undrained tests (Fig. 7).

3.3. Specimen preparation

In this study, two methods of sample preparation, which included dry funnel pluviation (DFP) and wet deposition (WD), were utilized, and as briefly described below.

In the first method, dry soil is deposited in the mould with the help of a funnel by controlling the height; this method consists of filling the mould by tipping in a rain of dry sand. To have loose samples, it is necessary that the fall height is almost nil.

Figure 7: The triaxial system set up.

The second method consists of mixing the previously dried sand with a small quantity of water (3 %) and then depositing the humid soil in the mould in a manner that is as homogenous as possible. The soil was placed in successive layers. A constant number of strokes were applied to get a homogeneous and isotropic structure.

Triaxial tests were performed on cylindrical specimens measuring 70 mm in diameter and 140 mm in height (H/D = 2.0). The mass of sand to put in place is determined according to the desired density (the initial volume of the sample is known). The density state of the sample was defined by the density index:

$$I_D = (e_{max} - e) / (e_{max} - e_{min}) \quad [1]$$

Where e_{min} and e_{max} indicate the minimum and maximum void ratios, respectively; e is the target void ratio and I_D the density index.

After the specimen has been formed, the specimen cap is placed and sealed with O-rings, and a partial vacuum of 15 to 25 kPa is applied to the specimen to reduce the disturbances.

3.4. Saturation and consolidation

Saturation of the specimens was accomplished by flushing the specimen with carbon dioxide for approximately 20 min (LADE & DUNCAN, 1973), after which de-aerated water was slowly added from the bottom of the specimen. Application of a back pressure improves the degree of saturation which was estimated by calculating Skempton's B-parameter 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 specimen saturation, and a minimum value greater than 0.96 was obtained for all tests. The triaxial test samples were isotropically consolidated under confining pressures ranging from 50 to 200 kPa prior to static loading.

3.5. Shear loading

All drained and undrained triaxial tests for this study were carried out at a constant strain of 0.167 % 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 20 % axial strain.

4. RESULTS OF UNDRAINED TRIAXIAL COMPRESSION TESTS

4.1. Effect of confining pressure and density

For the purpose of studying the effect of variation of effective confining pressure on liquefaction resistance, a series of tests were conducted. Figs. 8 and 9 show the results of the undrained triaxial compression tests performed. All tests were performed on specimens composed of Chlef sand, and each specimen was monotonically loaded in compression under undrained conditions. Figs. 8a and 9a present the undrained stress-strain curves, while Figs. 8b and 9b show the effective stress paths on the Cambridge p'-q diagram in which $p'=(\sigma'_1+2\sigma'_3)/3$ and $q=\sigma'_1-\sigma'_3$. It is noticed that as the confining pressures increased, the liquefaction resistance, (deviatoric stress), increased for both dry funnel pluviation and wet deposition methods. As can be seen for the samples reconstituted by the wet deposition method, complete static liquefaction occurred in two tests at the lowest confining pressure (50 kPa) irrespective of sand densities. Static liquefaction was coincidental with the formation of large wrinkles in the membranes surrounding the specimens. At a confining pressure of 100 kPa the specimens undergo temporary liquefaction characterized by the condition where the undrained stress difference first achieves an initial peak, after which it declines to a minimum value. Finally, at a confining pressure of 200 kPa the resistance to liquefaction increases for both loose and dense samples.

In Figures 8 and 9 for the dry funnel pluviation method, it is clear that when the initial confining pressure is increased from 50 kPa to 200 kPa, specimens with a density index of either 0.29 (loose) or 0.80 (dense) exhibit behaviour that is characterised by increasing stability or increasing resistance to liquefaction. The effect of increasing confining pressure is to increase the dilatant tendencies in the soil.

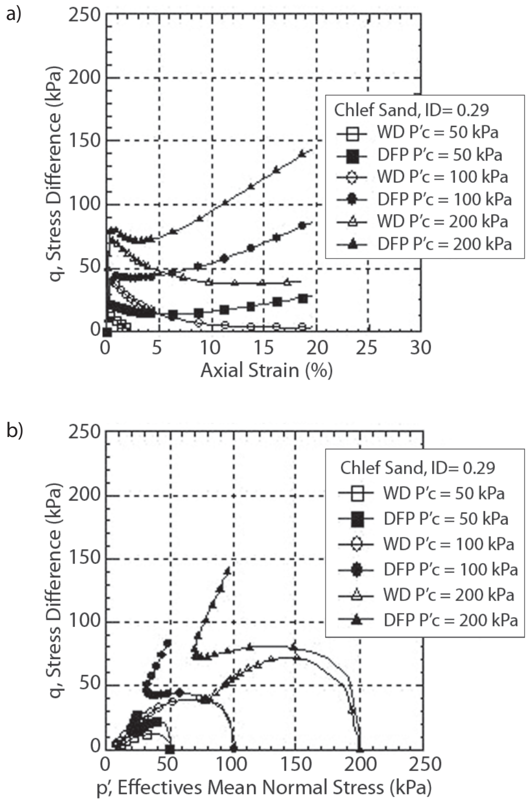

Figure 8: Undrained tests on loose sand: (a) deviator stress-strain curve, (b) stress path; DFP= Dry Funnel Pluviation, WD= Wet Deposition

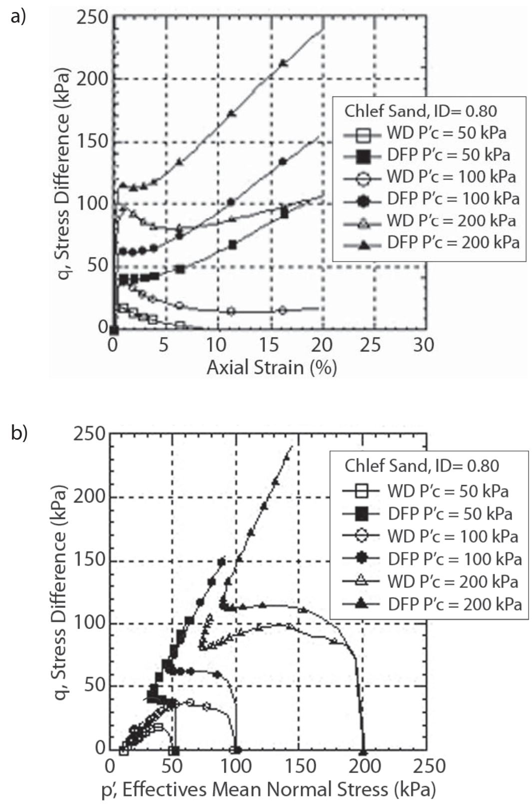

Figure 9: Undrained tests on dense sand: (a) deviator stress-strain curve, (b) stress path; DFP= Dry Funnel Pluviation, WD= Wet Deposition

Temporary liquefaction is described as the condition where the undrained stress difference first achieves an initial peak, after which it declines to a minimum value. This is caused by rapidly rising pore pressure which decreases the effective stress.

Increasing dilatancy or resistance to liquefaction can also be observed by examining the ratio of the minimum stress difference to the initial peak stress difference, (q(min)/q(peak)) shown in Fig. 10 for the wet deposition method. A q(min)/q(peak) ratio of zero indicates complete liquefaction, and a q(min)/q(peak) ratio of unity represents completely stable behaviour. The inset diagrams in Figs. 10a and 10b show that this ratio is zero at initial confining pressure of 50 kPa, indicating complete static liquefaction. The ratio then increases at initial confining pressures from 100 to 200 kPa, indicating that the specimen exhibits more dilatancy and, thereby, is more resistant to liquefaction.

Figure 11 illustrates the variation of the maximum undrained shear strength (qmax) with the initial density (I_D) at various confining pressures. It is clear from this figure that an increase in the relative density results in an increase in the maximum strength at a given confining pressure for both dry funnel pluviation and wet deposition, with a more pronounced increase for the method of dry funnel pluviation (Fig. 11a), contrary to the case of wet deposited samples where the evolution of the resistance is less pronounced (Fig. 11b). THEVANAYAGAM et al. (1997) and SITHARAM et al. (2004) report similar behaviour of increasing undrained shear strength with increasing relative density.

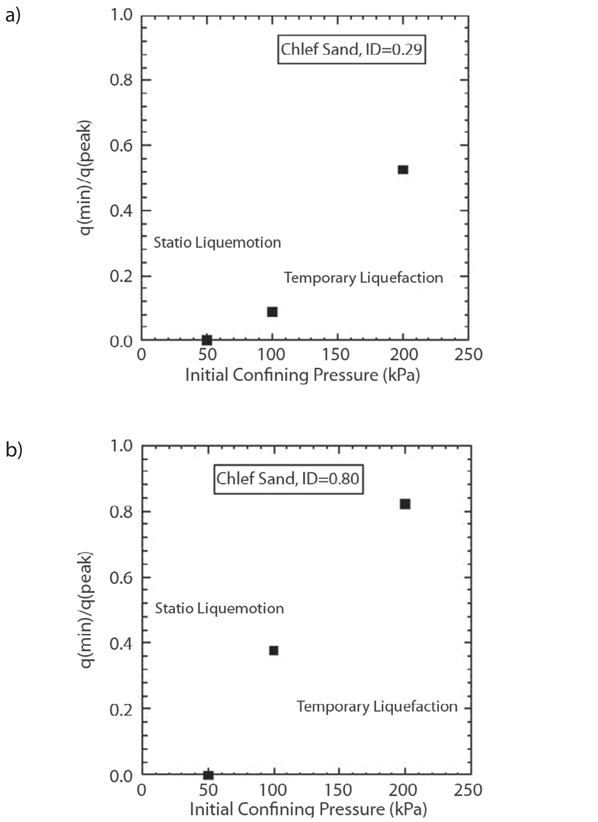

Figure 10: Resistance to liquefaction for the wet deposition method: (a) Loose state, (b) Dense state

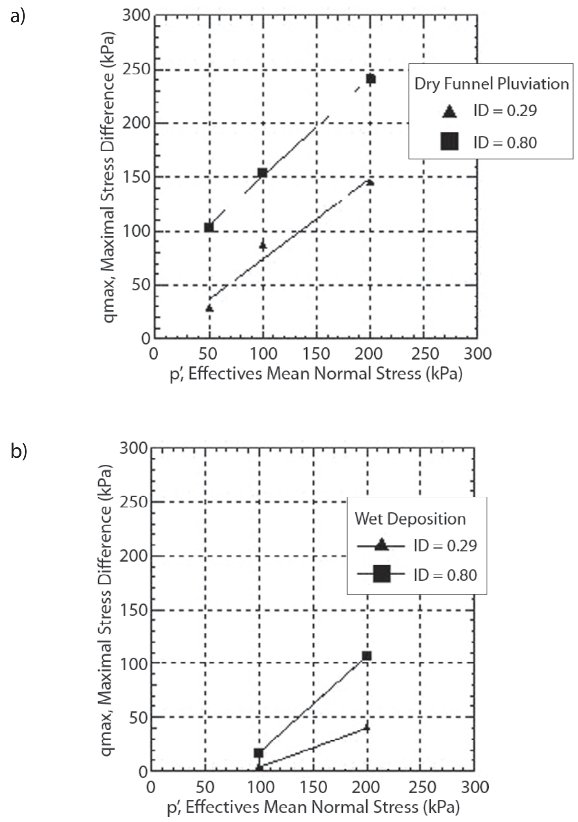

Figure 11: Effect of the relative density on the undrained response of sand.

4.2. Effect of the method of deposition

Figure 12 shows the variation of the undrained shear strength at the peak (qpeak) with the effective confining pressures using two methods of deposition. It can be seen from this figure that the dry funnel pluviation method shows higher values of the deviator at peak strain, therefore a much higher resistance to liquefaction, contrary to the wet deposition method where we note some lower values of the deviator at peak for low densities (loose state for $I_D = 0.29$), with progressive stabilization around a very small or nil ultimate stationary value representing liquefaction of the sample.

When loose and medium dense sandy soils are subjected to undrained loading beyond the point of peak strength, the undrained shear strength declines to a near constant value over large deformation. Conventionally, this shear strength is called the undrained steady-state shear strength or residual shear strength. However, if the shear strength increases after passing through a minimum value, the phenomenon is called limited or quasi-liquefaction. Even limited liquefaction may result in a significant strain and associated drop in resistance. ISHIHARA (1993) defined the residual shear strength S_{us} as:

$$S_{us} = (q_s/2)\cos\phi_s = (M/2)\cos\phi_s(p_s') \qquad [2]$$

$$M = (6 \sin\phi_s)/(3 - \sin\phi_s) \qquad [3]$$

Where q_s, p_s' and ϕ_s indicate the deviator stress (σ_1'- σ_3'), the effective mean principal stress (σ_1'+ 2σ_3')/3, and the mo-

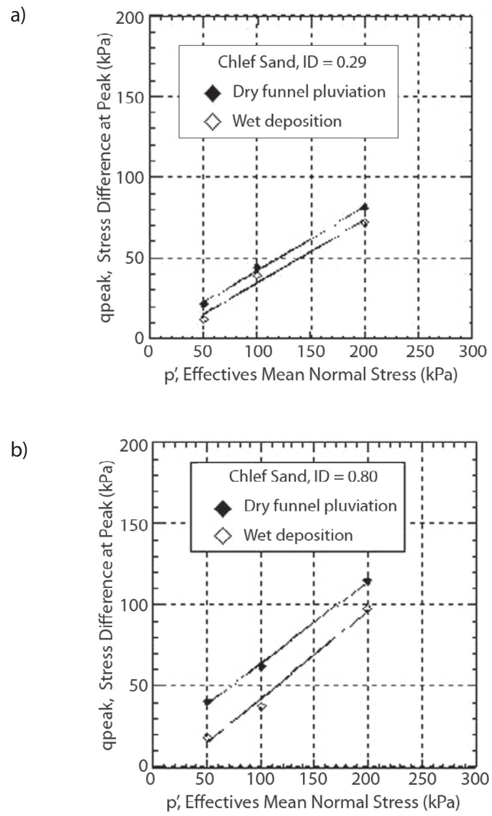

Figure 12: Effect of the deposition methods on the undrained shear strength at the peak.

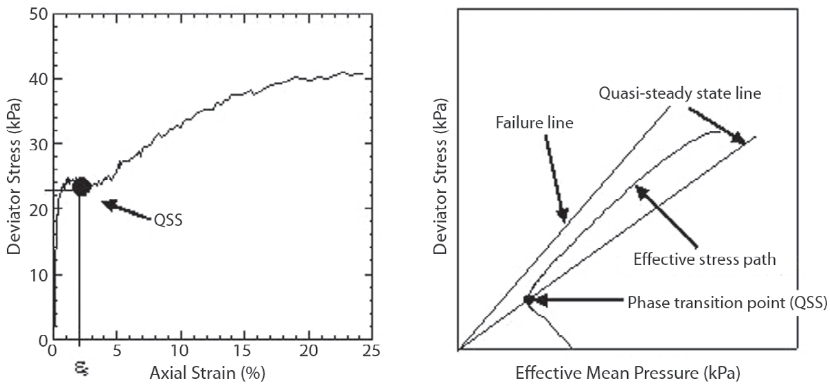

Figure 13: Determination of the phase transition point.

bilized angle of inter-particle friction at the quasi-steady state (QSS) respectively. For the undrained tests conducted at a constant confining pressure and various initial relative densities and fines content, the deviatoric stress (q_s) was estimated at a quasi-steady state point along with the mobilized internal friction angle (Fig. 13). Furthermore, the residual shear strength was calculated according to the relationship [2].

Figure 14 shows the evaluated undrained residual shear strength (Sus) and its variation with confining pressures and the reconstitution methods. It is clear from this figure that the sample preparation method considerably affects the evolution of the residual strength. Indeed this residual strength is nil for the samples prepared by wet deposition to a confinement of 50 kPa because of the collapse of samples, but for confinements of 100 and 200 kPa, the samples prepared by dry funnel pluviation mobilize a more significant residual strength than those prepared by wet deposition.

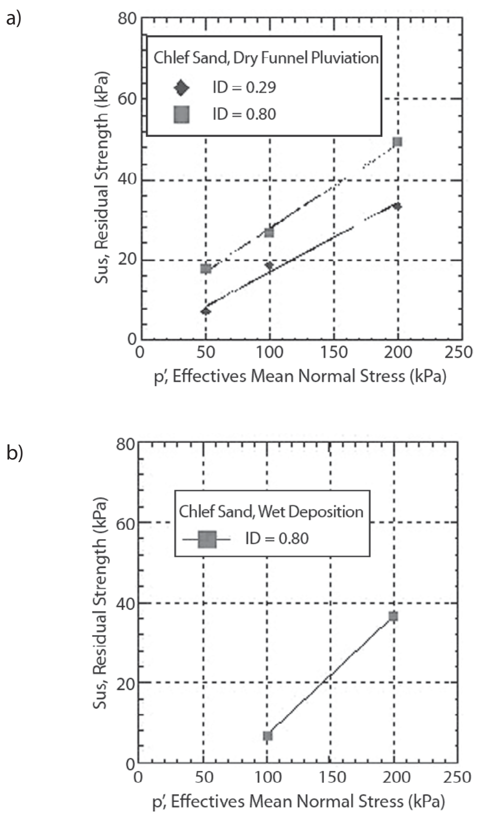

Figure 14: Effect of the deposition method on the undrained residual shear strength.

5. RESULTS OF DRAINED TRIAXIAL COMPRESSION TESTS

Figures 15 and 16 show the results of the drained tests on samples prepared by the method of dry funnel pluviation with two densities (I_D=0.29 and 0.80). Fig. 15 shows that the resistance to liquefaction represented by deviatoric stress increases with an increase in the confining pressure and density. Fig. 16 shows the evolution of the volumetric strain versus the axial strain. We note that the increase in the density accelerates the transition from the contractancy phase to the dilatancy phase.

The same tendencies can be observed in Figs. 17 and 18 which show the results of the drained tests on specimens reconstituted by the wet deposition method. As can be seen from Fig. 17 the resistance to liquefaction represented by the deviatoric stress, increases with an increase in the confining pressure and density. Fig. 18 shows the evolution of the volumetric strain versus axial strain. It can be noticed that the method of wet deposition increases the phase of contractancy. This increase in the phase of contractancy is highly marked for the loose specimens (Fig. 18a).

By comparing the results of Figs. 15−18, we concluded that the specimens reconstituted by the dry funnel pluviation method were more dilatant than those prepared by the wet deposition method.

The results of the drained and undrained tests are in perfect agreement with those given by BENAHMED et al. (2004) and ISHIHARA (1993) who discovered that samples prepared by dry funnel pluviation have a resistance to liquefaction higher than those prepared by wet deposition. ZLATOVIC & ISHIHARA (1997) discovered that the resistance of the samples prepared by the method of dry funnel pluviation decreases with the increase in the fraction of fines, while the samples prepared by sedimentation showed a reduction in resistance until a fines content of Fc=30%, then increase. MULILIS et al. (1977) concluded from their study, that the samples prepared by wet tamping present a resistance higher than those prepared by dry funnel pluviation.

These differences of behaviour noted between the two methods of deposition, can be explained by the fact that the

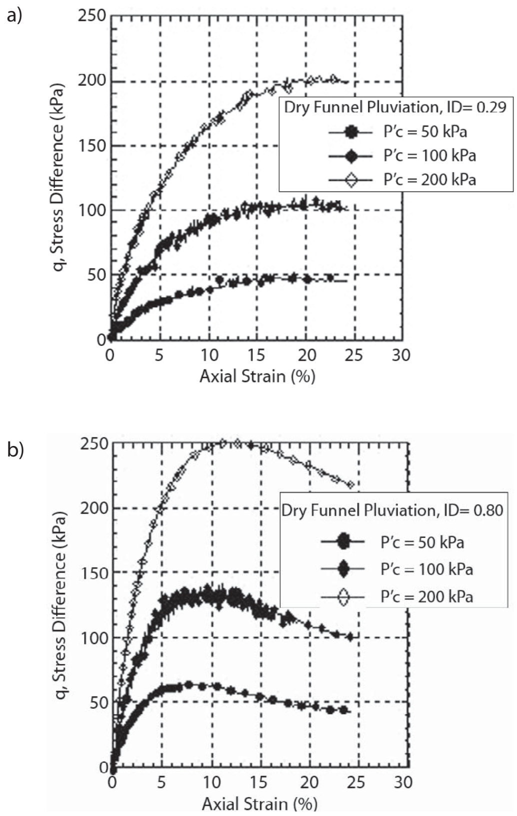

Figure 15: Dry funnel pluviation – evolution of the deviatoric stress versus axial strain: (a) Loose state (ID =0.29), (b) Dense state (ID =0.80).

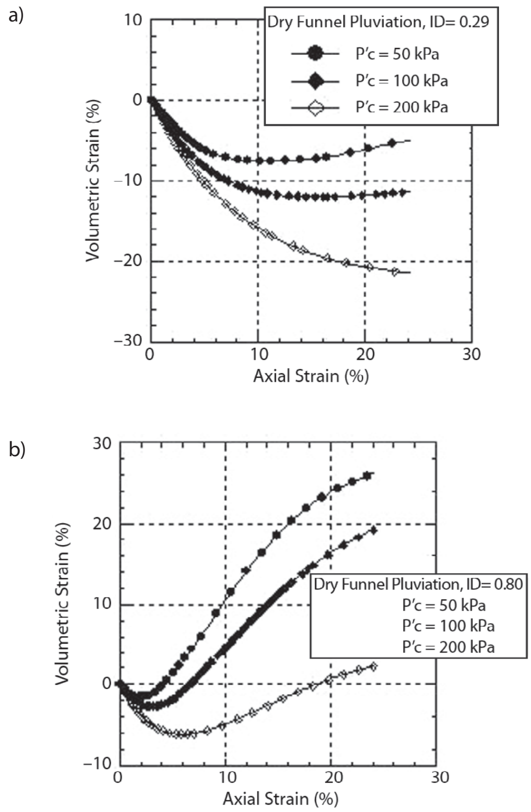

Figure 16: Dry funnel pluviation – evolution of the volumetric strain versus axial strain: (a) Loose state (ID =0.29), (b) Dense state (ID =0.80).

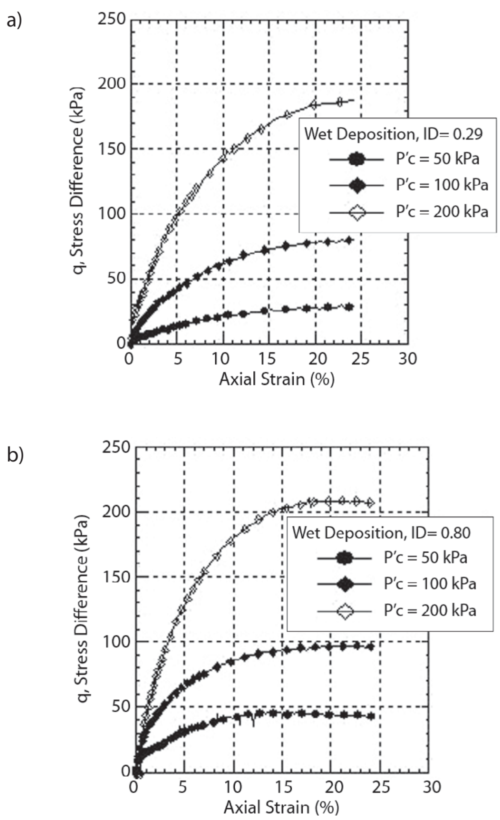

Figure 17: Wet deposition – evolution of the deviatoric stress versus axial strain: (a) Loose state (ID =0.29); (b) Dense state (ID =0.80).

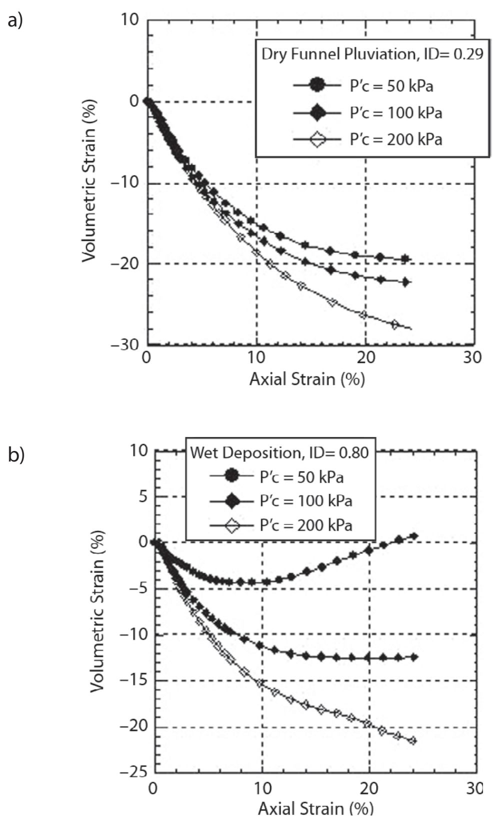

Figure 18: Wet deposition – evolution of the volumetric strain versus axial strain: (a) Loose state (Dr =0.29), (b) Dense state (Dr=0.80).

molecules of water contained in the structures prepared by wet deposition method prevent grain-grain adhesion. This trend accelerates the instability of the samples which show a very weak resistance and even provokes the phenomenon of liquefaction of the sand for low densities and low confinements leading to the collapse of the sample. This is contrary to the structures of samples prepared by the method of dry funnel pluviation that show a more dilatory behaviour.

6. CONCLUSION

A series of drained and undrained triaxial compression tests in monotonic loading conditions were performed on silty sand samples retrieved from liquefied sites on the Chlef River banks (Algeria). The effects of sample preparation methods and other parameters were studied. The study included drained and undrained triaxial tests that have been prepared at densities of 0.29 and 0.80 for confinements of 50,100 and 200 kPa. Based on the experimental results presented, the following conclusions can be drawn:

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 for both dry funnel pluviation and wet deposition. This observation correlates with most historic cases of apparent static and earthquake-induced liquefaction.

3. An increase in the density resulted in an increase in the maximum undrained shear strength of the sand in undrained tests, and accelerates the transition from the contractancy phase to the dilatancy phase in drained tests.

4. The peak and residual shear strengths of sand are sensitive to the sample preparation methods. The dry funnel pluviation method gives higher values of the peak and residual shear strengths than the wet deposition method.

5. The results also reveal that the method of reconstitution has a detectable effect on the drained behaviour of the sand in terms of volumetric strains. 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 behaviour.

REFERENCES

AMBRASEYS, N.N. (1981): The El-Asnam earthquake of 10 october 1980: conclusions drawn from a field study.− Q. J. Eng. Geol., London, 14, 143−148.

BENAHMED, N., CANOU, J. & DUPLA, J.C. (2004): Structure initiale et propriétés de liquéfaction statique d'un sable.− Comptes Rendus Mécanique, 332, 887−894. doi: 10.1016/j.crme.2004.07.009.

BISHOP, A.W. & WESLEY, L.D. (1975): A hydraulic triaxial apparatus for controlled stress path testing.− Géotechnique, 25, 657–670. doi: 10.1680/geot.1975.25.4.657.

CANOU, J. (1989): Contribution l'étude et à l'évaluation des propriétés de liquéfaction d'un sable, Thèse de Doctorat de l'Ecole Nationale Des Ponts et Chaussées, Paris.

DURVILLE, J.L. & MENEROUD, J.P. (1982): Phénomènes géomorphologiques induits par le séisme d'El-Asnam, Algérie.− Bull. Liaison Labo. P. et Ch., 120, juillet-août, 13−23.

ISHIHARA, K. (1993): Liquefaction and flow failure during earthquakes.− Géotechnique, 43/3, 351−415. doi: 10.1680/geot.1993.43.3.351.

KRAMER, S.L. & SEED, H.B. (1988): Initiation of soil liquefaction under static loading conditions.− J. Geotech. Engin., 114/4, 412−430. doi: 10.1061/(ASCE)0733-9410(1988)114:4(412).

LADE, P.V. & DUNCAN, J.M. (1973): Cubical triaxial tests on cohesionless soil.− Journal Soil Mechanics and Foundations Division ASCE, 99/SM10, 793−812.

MULILIS, J.P., SEED, H.B., CHAN, C.K., MITCHEL, J.K. & ARULANADAN, K. (1977): Effects of sample preparation on sand liquefaction.− J. Geotech. Engin. Div., ASCE, 103, 91−108.

OUYED, M. (1981): Le tremblement de terre d'El-Asnam du 10 octobre 1980: étude des répliques.− Unpubl. PhD Thesis, University of Grenoble, Grenoble, 200 p. (in French).

PAPASTAMATIOU, D. (1980): El-Asnam, Algeria earthquake of October 10, 1980: field evidence of ground motion in the epicentral region.− Geognosis Ltd., London.

POLITO, C.P. & MARTIN, II J.R. (2003): A reconciliation of the effects of non-plastic fines on the liquefaction resistance of sands reported in the literature.− Earthquake Spectra, 19/3, 635−651. doi:10.1193/1.1597878.

SITHARAM, T.G., GOVINDA, R.L. & SRINIVASA, M.B.R. (2004): Cyclic and monotonic undrained shear response of silty sand from Bhuj region in india.− ISET J. Earth. Tech. Pap., 450/41, 249−260.

THEVANAYAGAM, S., RAVISHANKAR, K. & MOHAN, S. (1997): Effects of fines on monotonic undrained shear strength of sandy soils.− ASTM Geotech. Test. J., 20/1, 394−406. doi: 10.1520/GTJ10406J.

VAID, Y.P., SIVATHAYALAN, S. & STEDMAN, D. (1999): Influence of specimen reconstituting method on the undrained response of sand.− Geotech. Test. J., 22/3, 187−195. doi: 10.1520/GTJ11110J.

WOOD, F.M., YAMAMURO, J.A. & LADE, P.V. (2008): Effect of depositional method on the undrained response of silty sand.− Can. Geotech. J., 45/11, 1525–1537. doi: 10.1139/T08-079.

YAMAMURO, J.A. & COVERT, K.M. (2001): Monotonic and cyclic liquefaction of very loose sands with high silt content.− J. Geotech. Geoenviron. Engin. ASCE, 127/4, 314− 324. doi: 10.1061/(ASCE)1090-0241(2001)127:4(314).

YAMAMURO, J.A. & LADE, P.V. (1997): Static liquefaction of very loose sands.− Can. Geotech. J., 34/6, 905−917. doi: 10.1139/cgj-34-6-905.

YAMAMURO, J.A. & LADE, P.V. (1998): Steady state concepts and static liquefaction of silty sands.– J. Geotech. Geoenvironmental Engineering ASCE, 124/9, 868–877. doi:10.1061/(ASCE) 1090-0241(1998)124:9(868).

YAMAMURO, J.A. & WOOD, F.M. (2004): Effect of depositional method on the undained behaviour and microstructure of sand with silt.– Soil Dyn. Earthq. Eng., 24, 751–760.

YAMAMURO, J.A., WOOD, F.M. & LADE, P.V. (2008): Effect of depositional method on the microstructure of silty sand.– Can. Geotech. J., 45/11, 1538–1555. doi: 10.1016/j.soildyn. 2004.06.004.

ZLATOVIC, S. & ISHIHARA, K. (1997): Normalized behaviour of very loose non-plastic soils: effects of fabric.– Soils Found., 37/4, 47–56.

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