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Effect of confining pressure and depositional method on the undrained shearing response of medium dense sand

Efecto de la presión de confinamiento y el método de deposición sobre la respuesta de corte no drenada de arena de densidad media

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Abstract

This study examines the effects of the confining pressure and sample preparation method on the shearing behavior shown by sand from the Chlef River (Algeria). Undrained monotonic triaxial compression tests were performed on samples with an initial relative density of 50% at initial confining pressures of 50 to 200 kPa. Samples were prepared using two depositional methods: dry funnel pluviation and wet deposition. Our results reveal marked differences in the undrained shearing responses produced under identical conditions of density and stress and therefore determined by the soil fabric. Thus, at low confining pressures, samples prepared by the wet deposition method showed complete static liquefaction (zero effective confining pressure and zero stress difference). For both sample types, as confining pressures increased, effective stress paths exhibited increasing resistance to liquefaction indicated by increasing dilatant tendencies.

Keywords: liquefaction, sand, dry funnel oluviation, wet deposition, triaxial, confining pressure

Resumen

En este trabajo se han estudiado los efectos de la presión de confinamiento y los métodos de preparación de muestras sobre el comportamiento de rotura de arena Chlef. Los resultados de las pruebas sin escurrir monótona de compresión triaxial realizadas en muestras con una densidad relativa inicial del 50% y presiones de confinamiento inicial variaron desde 50 hasta 200 kPa. Las muestras fueron preparadas por dos métodos de deposición seca con embudo de pluviacion y deposición húmeda. Se encontró que existía una marcada diferencia en el comportamiento sin escurrir a pesar de que las condiciones de la densidad y el estrés eran idénticas. La conclusión fue que la estructura del suelo fue la responsable de este resultado. Los resultados también indicaron que a baja presión de confinamiento, las muestras preparadas mediante un método de deposición húmedo, completan la licuefacción estática (ninguna presión de confinamiento efectiva y ninguna diferencia de estress). Los resultados indicaron también que a bajas presiones de confinamiento, los especímenes reconstituida por el método de deposición húmeda expuesto licuefacción estática completa (cero de la presión efectiva de confinamiento y cero diferencia de estrés). Como las presiones de confinamiento se incrementaron, las trayectorias de tensiones efectivas aumentaron la resistencia a la licuefacción, mostrando aumento de la tendencia dilatante.

Palabras clave: licuefacción, arena, *dry funnel pluviation*, deposición húmeda, triaxial, presión de confinamiento

1. Introduction

During static or cyclic loading, ground shaking may cause saturated cohesionless soils to lose their strength and behave like a liquid. This phenomenon is called soil liquefaction and will cause buildings to settle or tip, along with the failure of earth dams, earth structures and slopes. Interest in soil liquefaction has been mounting since numerous liquefaction-induced failures occurred during the 1964 earthquake in Niigata, Japan. A proper understanding is therefore needed of the effects of factors such as soil properties and the nature of loading on the severity of soil liquefaction.

Numerous studies have shown that the behavior of sands can be greatly influenced by the initial state of the soil. Polito and Martin (2003) reported that the factors relative density and skeleton void ratio were able to explain variations in experimental results. Yamamuro and Lade (1997), Yamamuro and Lade (1998) and Yamamuro and 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 and Seed (1988) also observed that liquefaction resistance increased with increasing confining pressure.

While several specimen reconstitution techniques are currently used, tamping and pluviation are the methods most commonly employed. The objective of such methods is always to replicate a uniform sand specimen at the desired void ratio and effective stresses to simulate the sand mass in-situ. However, the effect of the sample preparation method has been a subject of dispute. Many authors have reported a greater resistance to liquefaction for samples prepared by sedimentation than by the dry funnel pluviation or wet deposition methods (Zlatovic and Ishihara, 1997). Other studies have shown that specimens prepared by dry funnel pluviation tend to be less resistant than those reconstituted by wet deposition (Mulilis *et al.*, 1977; Yamamuro and Wood, 2004). Other researchers have indicated that tests on samples prepared by dry funnel pluviation are more stable and dilatant than those prepared by wet deposition (Benahmed *et al.*, 2004; Canou, 1989). Vaid *et al.* (1999) confirmed this finding and also showed that wet deposition promotes the quicker onset of liquefaction compared to pluviation under water. In their laboratory investigation, Yamamuro *et al.* (2008) concluded that dry pluviation causes the instability of samples as opposed to the method of sedimentation. Wood *et al.* (2008) noted a reduced effect of the deposition method on undrained behavior with increased density. These authors also found that this influence diminished as the fines content increased, particularly for the lower densities. In undrained monotonic tests on loose and dense samples of Chlef sand, Della *et al.* (2009) reported that the dry pluviation method induces a higher liquefaction resistance than the wet deposition method. The objective of this latter study was to identify differences in undrained triaxial compression behavior that could arise from the use of different reconstitution techniques to create silty sand specimens.

Since different possible modes of formation of natural sandy solid masses exist, we simulated two deposition modes for the Chlef River sand to best characterize the behavior of this sand to liquefaction. According to Durville and Méneroud (1982), the phenomenon of liquefaction arose during the last earthquake (October 10th, 1980) in a vast alluvial valley crossed by the Chlef River and in the zone of confluence of this river with the Fodda River, as shown in figures 1 and 2.

2. Experimental research

2.1. Tested material and procedures.

This laboratory investigation sought to determine the effects of initial state on the undrained behavior of silty sand. A series of undrained triaxial compression tests were performed under monotonic loading conditions on reconstituted samples of natural sand from the Chlef River containing 0.5% non plastic (PI= 5.81%) silt. Individual sand particles are subrounded and predominant minerals are feldspar and quartz. The samples were prepared at the same relative density as undisturbed samples to represent the medium dense state (RD= 50%) using two different techniques: the dry funnel pluviation and wet deposition methods (described in the following section) and consolidated isotropically at initial confining pressures of 50 kPa, 100 kPa and 200 kPa. Sand samples

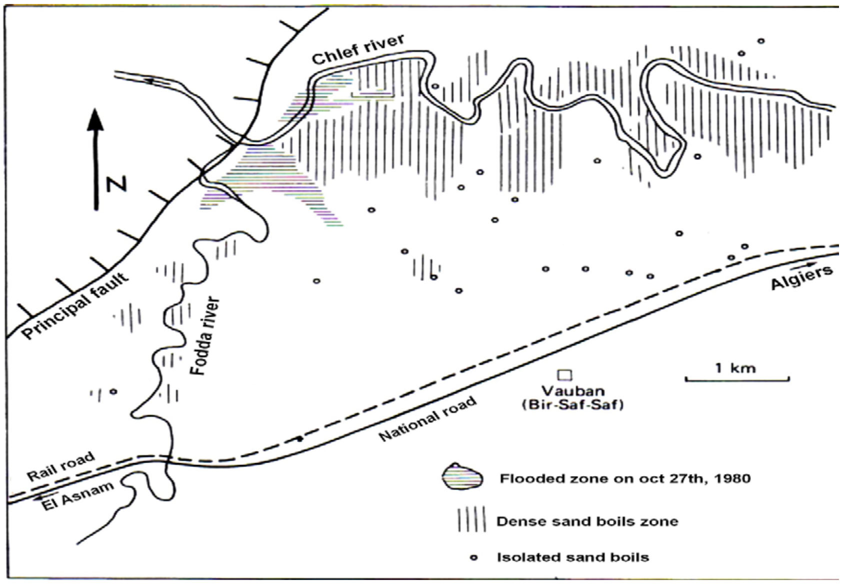

Fig. 1.- Chlef river valley showing the areas of sand boils arising from liquefaction.
Fig. 1 .- Valle del río Chlef y localización de la arena que aparece debido al fenómeno de la licuefacción.

were collected from a liquefied layer of the deposit area close to the epicentre of the Chlef earthquake (October 10th, 1980). The index properties of the soil used in the study are provided in Table 1. Figure 3 shows the grain size distribution curve for the material tested.

The cylindrical samples were 70 mm in diameter and 70 mm in height (Yamamuro and Wood, 2004; Lanier, 1987; Hettler and Vardoulakis, 1983; Bouvard and Stutz, 1984) with smooth lubricated end-plates. The mass of sand was tested according to the desired density (the initial volume of the sample is known).

Material	e_{min}	e_{max}	γ_{dmin} g/cm^3	γ_{dmax} g/cm^3	γ_s g/cm^3	Cu D_{60}/D_{10}	D_{50} mm	D_{10} mm	Grain shape
O/Chlef	0.54	0.99	1.34	1.73	2.67	3.2	0.45	0.15	Rounded

Table 1.- Properties of the tested soil.
Tabla 1.- Propiedades del suelo.

After the specimen had been formed, the specimen cap was sealed with O-rings, and a partial vacuum of 20 kPa applied to the specimen to reduce disturbances. In the saturation phase, the technique of Lade and Duncan (1973) was used, purging the specimen with carbon dioxide for approximately 30 min. De-aired water was then introduced into the specimen via the bottom drain line. The quality of saturation was assessed by measuring the coefficient of Skempton (B) according to a classic procedure. A B-value of at least 0.99 was used to indicate full saturation.

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 at a constant strain rate of 0.167% per minute.

All triaxial tests were carried out at the same strain rate, which was slow enough to allow the pore pressure change to equalize throughout the sample with pore pressure measured at the base of sample. All tests were continued up to a 20% axial strain.

2.2. Depositional techniques.

Two methods were used to reconstitute the specimens of sand: the wet deposition and dry funnel pluviation. The first method consists of mixing the previously dried sand as homogeneously as possible with a small quantity of water fixed at 3% and depositing the moist soil in the mould. The soil is deposited layer by layer. To obtain a homogeneous isotropic structure, a constant number of strokes is needed. In the dry funnel pluviation method, the dry soil is deposited in the mould with the help of a funnel whose height can be regulated. This method consists of filling the mould by raining the dry sand through the funnel.

2.3. Experimental device used.

Figure 4 shows the automated triaxial testing apparatus used for the monotonic compression tests.

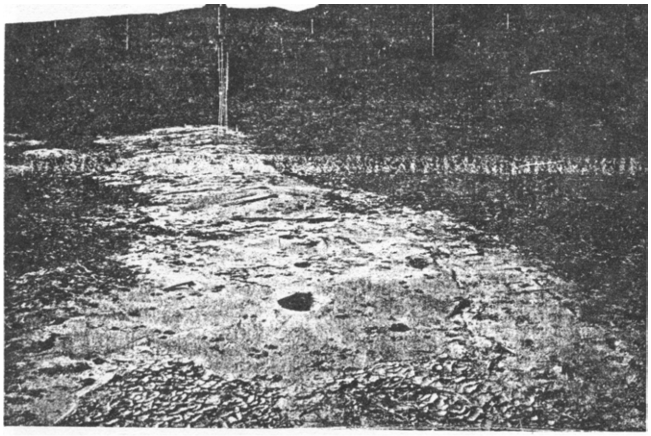

Fig. 2.- Sand boils produced by liquefaction.
Fig. 2 .- Arena rebosando debido al fenómeno de la licuefacción.

3. Experimental results

3.1. *Effect of confining pressure.*

Soil specimens were isotropically consolidated under confining pressures of 50 to 200 kPa. The effect of varying effective confining pressure on the sand's liquefaction resistance is shown in figures 5 and 6. As the confining pressure increased, the liquefaction resistance of the sands increased for both the dry funnel pluviation and wet deposition methods. Figure 5 shows effective stress paths for the undrained triaxial compression tests plotted on Cambridge p'-q diagrams. As may be observed in Figures 5a and 5b, complete static liquefaction occurred in the test conducted at the lowest confining pressure (50 kPa) for the wet deposition method. Static liquefaction coincided with the formation of large wrinkles in the membranes surrounding the specimens.

Figures 5a and 5b also reveal that when the initial confining pressure is increased beyond 50 kPa, effective stress paths respond by increasing stability or increasing resistance against liquefaction. This may be seen in the stress-strain curves in figures 6a and 6b. Initial confining pressures are shown for each test. The curves for initial confining pressures of 100 and 200 kPa show that the stress difference does not reach zero, as in the test indicating complete liquefaction, rather they drop to a minimum before increasing to levels well above the initial peak (dry funnel pluviation method) or stabilize around an ultimate stationary very weak value (wet deposition method). This is the condition of temporary liquefaction. Increasing confining pressure has the effect of increasing the dilatant tendencies of the soil.

Temporary liquefaction is described as the condition whereby the undrained stress difference first achieves an initial peak, and thereafter declines to a minimum value. This is caused by rapidly rising pore pressure, which reduces the effective stresses.

Increasing dilatancy or resistance 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 figure 7 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 behavior. The inset to figure 7 shows

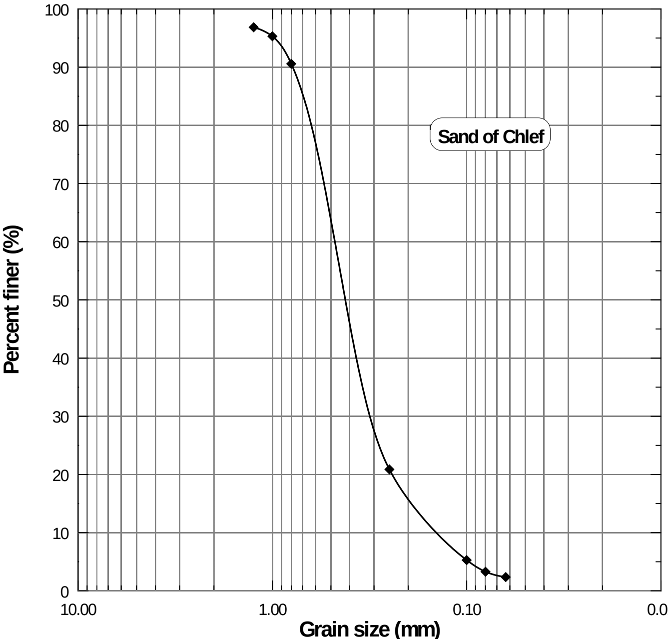

Fig. 3.- Grain size of the sand used.
Fig. 3 .- Tamaño de grano de la arena utilizada.

Fig. 4.- Photograph of the automated triaxial test setup.
Fig. 4 .- Fotografía de la prueba triaxial automatizada.

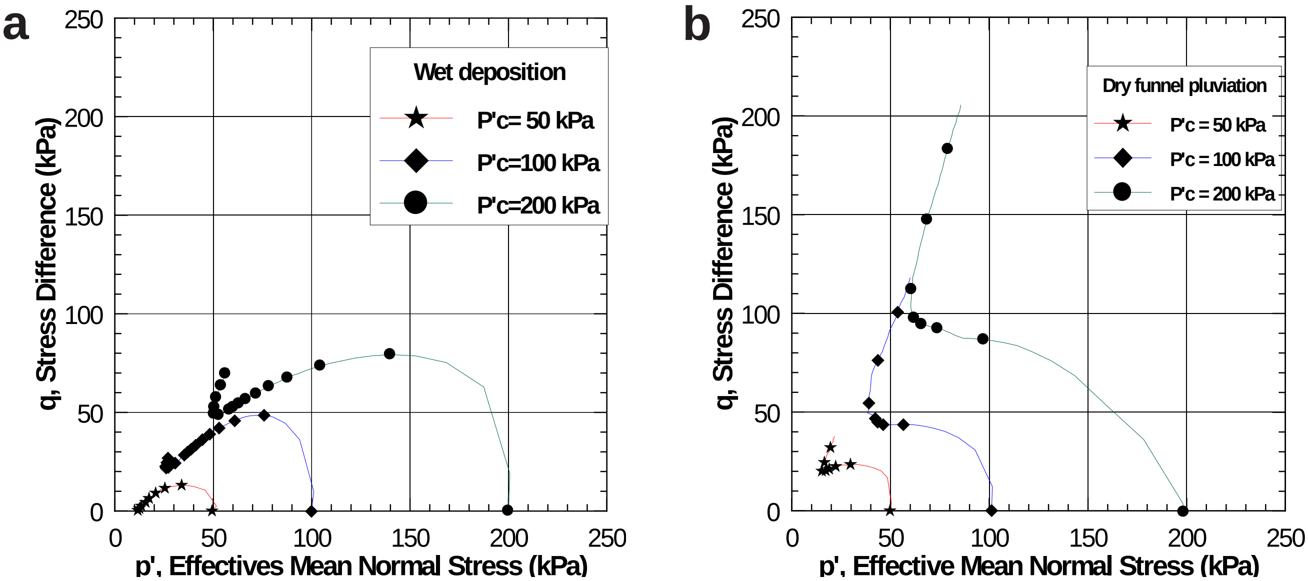

Fig. 5.- Undrained effective stress paths shown in a p’-q diagram on samples prepared by: (a) the wet deposition method, or (b) dry funnel pluviation method.

Fig. 5.- Pruebas de stress efectivo no drenado en el diagrama p’-q en muestras preparadas por: (a) deposición húmeda, (b) en seco, con método de embudo de pluviación.

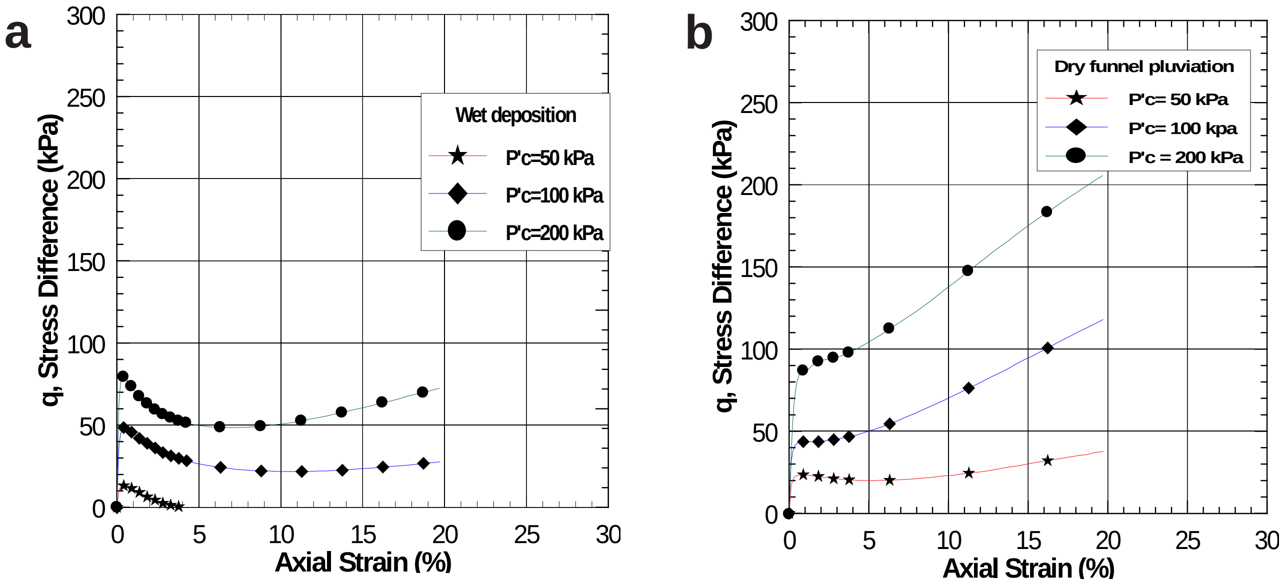

Fig. 6.- Undrained stress-strain curves on samples prepared by: (a) the wet deposition method, or (b) dry funnel pluviation method.

Fig. 6.- Curvas de tensión-deformación no drenadas de las muestras preparadas por:(a) deposición húmeda, (b) método en seco de embudo de pluviation.

that this ratio is zero at an 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, therefore, more resistance to liquefaction.

3.2. Influence of sample reconstitution method.

The effect of the specimen reconstitution method on maximal deviatoric stress is shown in Figure 8a. The figure illustrates that the dry funnel pluviation method gives rise to more significant values of the maximal deviator and consequently much higher resistance to liquefaction, while the wet deposition method yields weaker values of the maximal deviator, with progressive stabilization around a very weak or ultimate stationary value of zero indicating liquefaction of the sample.

The same tendencies were noted for variations in peak deviatoric stress shown in Figure 8b. Thus, the samples prepared by the dry funnel pluviation method exhibit

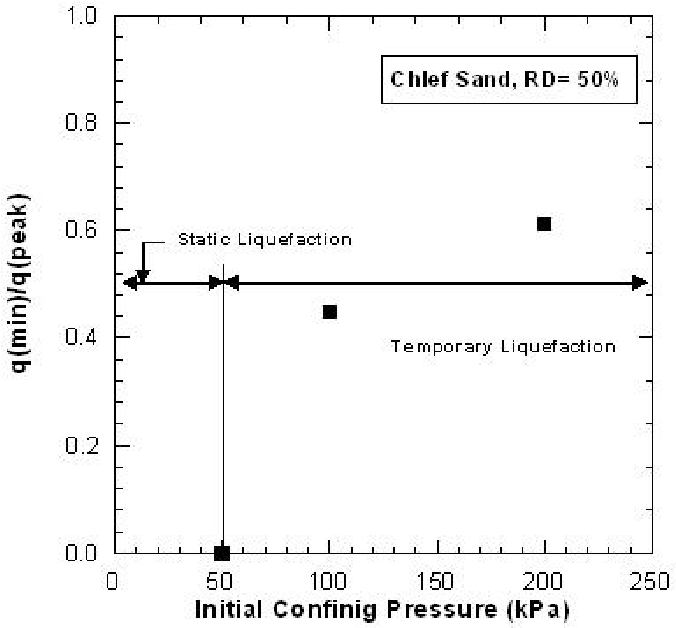

Fig. 7.- Resistance to liquefaction for the wet deposition method.
Fig. 7.- Resistencia a la licuefacción por el método de deposición húmeda.

slightly higher resistance to monotonic shearing than the samples prepared by wet deposition.

The influence of the sample preparation methods on excess pore pressure is illustrated in the plots in Figure 9. The pore pressure curves in Figure 9a for the dry funnel pluviation method show two stages: an initial high rate of generation reflecting the intense contracting nature of the Chlef sand followed by a steadily declining rate with increasing axial strain, indicating the dilating character of the material. The excess pore pressure developed in the samples prepared by the wet deposition method is represented in Figure 9b. These samples show a very highly contracting character with an elevated expansion rate shown from the start of shearing followed by a slow stabilization stage related to the stabilization of deviatoric stress.

The results illustrated in figures 8 and 9 are in perfect agreement with those displayed in figures 5 and 6. Thus, dry funnel pluviation leads to increased resistance to monotonic shearing of the samples while wet deposition accelerates the instability of the samples, which show weak resistance, and may even cause liquefaction of the sand for the weak confinements leading to their collapse. These differences in behavior may be explained by the fact that the molecules of water contained in the structures prepared by the wet deposition method are macropores that are easily compressible at the time of the shearing and at the same time prevent grain-grain adhesion. These results confirm the tendency observed by Della *et al.* (2009) for loose and dense sands.

4. Conclusion

In this series of tests, we examined the behavior of a sandy soil and the effects on this behavior of confining pressure and sample preparation. Undrained triaxial compression tests were performed on Chlef silty sand at an initial relative density of 50%, representing a medium dense state, at confining pressures of 50 to 200 kPa. The methods of sample preparation compared were dry funnel pluviation and wet deposition. Our findings indicate that:

1- Within the range of conditions used, the sample preparation method had an appreciable effect on undrained behavior. The dry funnel pluviation method gave rise to a more volumetrically dilatant or stable response, while samples prepared using the wet deposition method exhibited more contractive or unstable behavior.

2- As the confining pressure increased, the liquefaction resistance of the sand increased for both the dry funnel pluviation and wet deposition methods. Maximal deviatoric stress and peak strength increased with increasing initial confining pressures. Complete static liquefaction occurred at a low confining pressure for the samples prepared by the wet deposition method, and as the confining pressures increased, the soil became more dilatant and more resistant to liquefaction.

3- Excess pore water pressure increased for both preparation methods with a decreasing tendency shown for the dry funnel method and a stabilization tendency for the wet deposition method with increasing axial strain.

One of the practical implications of these results relates to the characterization of wet sandy materials used as hydraulic fill for embankment construction. Thus, the lack of effective in situ compaction could lead to massive structural instability under liquefaction. If to this we add the effects of the high seismicity of the region, the behavior of these wet sandy soils under static loading is far from ideal.

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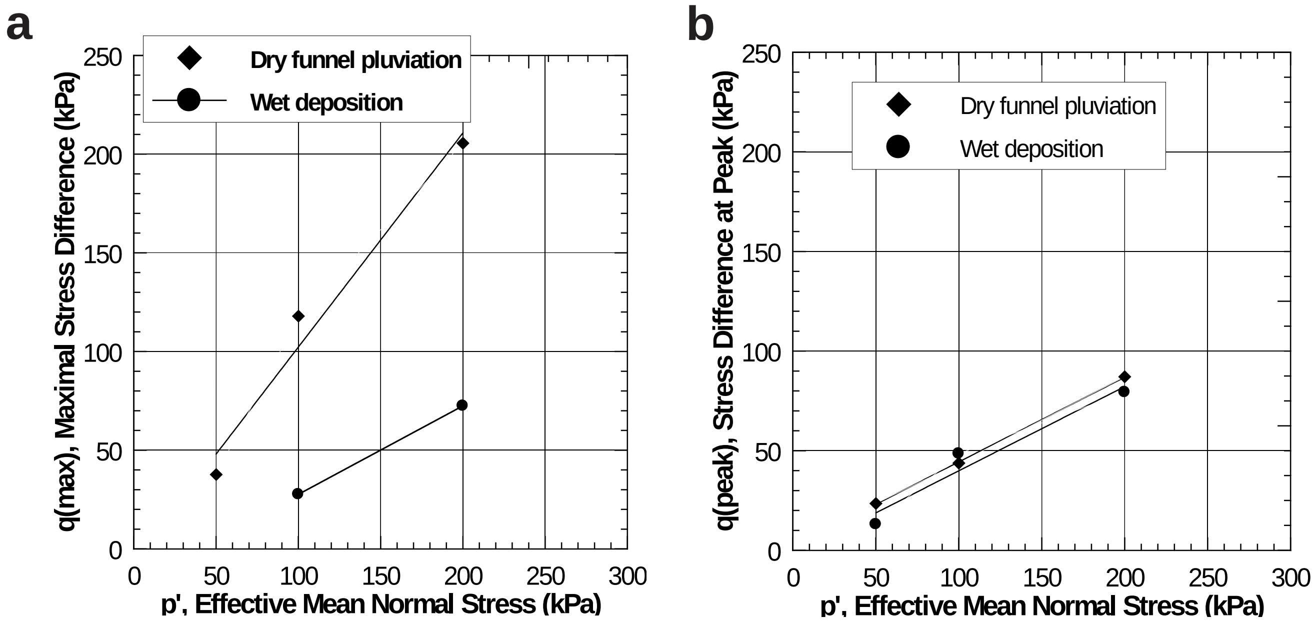

Fig. 8.- Effect of the depositional method on maximal deviatoric stress (a) and peak deviatoric stress (b).

Fig. 8.- Efecto del método de deposición en la tensión desviadora máxima (a) y el pico de tensión desviadora (b).

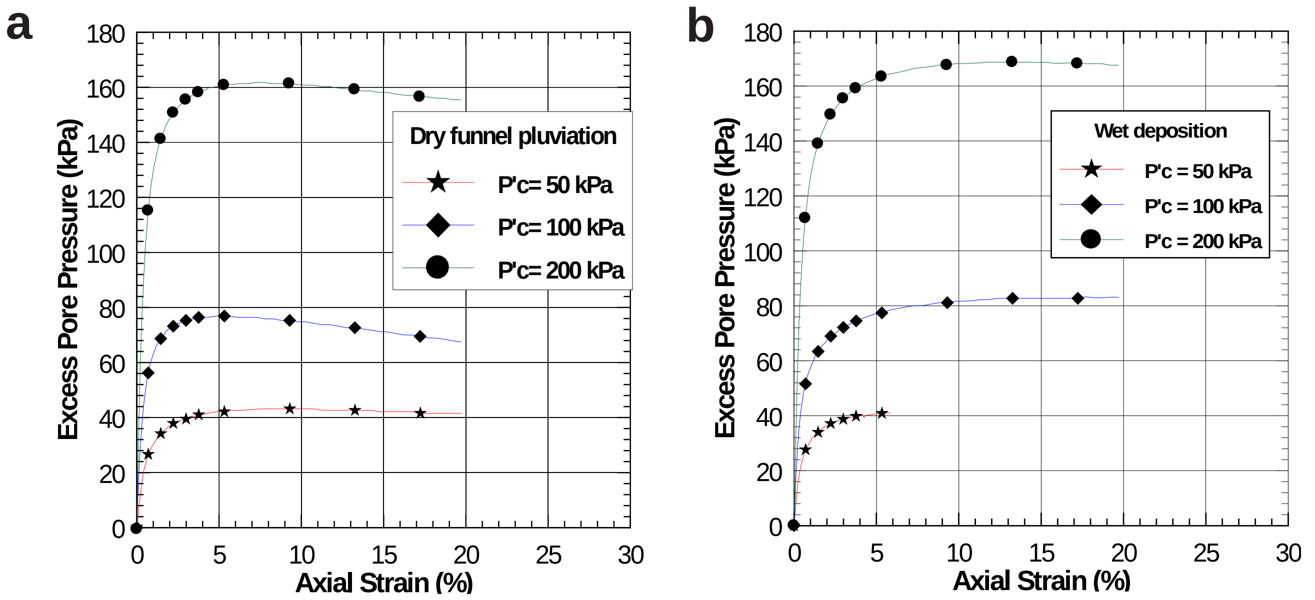

Fig. 9.- Effect of the sample reconstitution method on excess pore pressure: (a) dry funnel pluviation method, (b) wet deposition method.

Fig. 9.- Efecto del método de reconstitución de la muestra en exceso de presión de poro: (a) en seco mediante método de embudo de pluviation, (b) mediante método de deposición húmeda.

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