

Laboratory testing of the Monotonic behavior of partially saturated sandy soil

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ABSTRACT

This paper presents a laboratory study on the influence of the saturation evaluated in term of Skempton's pore pressure coefficient B on the behavior of Chlef sand. The study is based on drained and undrained compression tests which were carried out for Skempton's pore pressure coefficient varying between 13 and 90%. The tests were conducted on medium dense sand samples having an initial relative density $I_d = 0.50$ at an effective stress of 100 kPa. The paper is composed of two parts. The first one presents the characteristics of the sand used in this study. The second provides an analysis of the experimental results and discusses the influence of Skempton's pore pressure coefficient (B) on the mechanical characteristics of the sand. The tests show that the increase in the Skempton's pore pressure coefficient (B) reduces the soil dilatancy and amplifies the phase of contractancy and reduces the frictional and characteristic angle of the sand. The residual strength decreases with the increase in the Skempton's pore pressure coefficient B.

Keywords: sand, compression, drained, undrained, saturation, frictional angle.

RESUMEN

Este artículo presenta un estudio de laboratorio sobre la influencia de la saturación evaluada en términos de coeficiente de presión de poro de Skempton B en el comportamiento de la arena Chlef. El estudio se basa en pruebas de compresión drenadas y no drenadas, llevadas a cabo con coeficiente Skempton variando entre 13 y 90%. Las pruebas se llevaron a cabo en muestras de arena con una densidad inicial relativa = 0.50 UNIDADES y un esfuerzo efectivo de 100 kPa. Este trabajo se compone de dos partes. El primero presenta las características de la arena utilizada en este estudio. El segundo ofrece un análisis de los resultados experimentales y se evalúa la influencia del coeficiente de presión de poro de Skempton B en las características mecánicas de la arena. Las pruebas muestran que el aumento del coeficiente de presión de poro de Skempton B reduce la dilatancia del suelo, amplifica la fase de la contractancia y reduce el ángulo de fricción y característico de la arena. La resistencia residual disminuye con el aumento de la presión del poro del coeficiente B de Skempton

Palabras clave: arena, compresión, drenaje, sin drenaje, saturación, ángulo de fricción.

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Introduction

In the neighbourhoods of the town of Chlef (Algeria), unsaturated zones exist on the top of the phreatic ground which underwent a significant folding back following the dryness which touches the area since the Eighties. During the past decades, advanced researches helped us better understand the liquefaction of the grounds based on experiments carried out in laboratory, the physical modeling and the numerical analysis. The majority of the investigations on the liquefaction of the granular soils were based on completely saturated material. The study of the influence of the saturation degree on the liquefaction of the soils is of practical interest, because we often find structures built on the top of the phreatic ground; what implies the presence of partially saturated grounds. The incidence of a partial saturation on cyclic resistance was approached in a theoretical way by Martin et al. (1978). Mulilis et al. (1978) examined the effect of the saturation degree on the liquefaction of Monterrey sand. They noted that the variation of the 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, the recent results of the 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 (Ishihara et al., 2001 and Nakazawa et al., 2004) or the presence of gas bubbles in the marine sediments and sands containing oils as noted by Mathioban and Grozic (2004). The effects of a condition of partial saturation on liquefaction were approached by some researchers (as by Atigh and Byrne, 2004; Mathioban and Grozic, 2004; Pietruszczak et al., 2003; Yang and Sato, 2001). The condition of saturation of soil samples in laboratory can be evaluated by measuring the value of the coefficient of Skempton B or the speed of compression waves V_p as suggested by Ishihara et al. (2001). In situ, the saturation can be evaluated by the

measurement of the velocity of the of compression wave (V_p).The results of the laboratory tests showed that the resistance to the liquefaction of sands increases when the saturation degree decreases (Martin et al., 1978; Yoshimi et al., 1989; Bouferra, 2000; Ishihara et al., 2001 and 2004; Yang, 2002; Yang et al., 2004; Bouferra et al., 2007).

Mullilis et al., (1978) and Tatsuoka et al..(1986) 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. (1977) show that a fine or clayey sand can be considered saturated if the value of B exceeds 0.8, Chaney (1978) stressed that the coefficient B must exceed 0.96 so that the soil is well saturated. On the other hand, Giroud and Cordary (1976) noted that for values of B superiors to 0.85, the degree of saturation is very close to 1. Tests of liquefaction were carried out by Yoshimi et al. (1989) on the sand of Toyoura of medium density ($I_d = 0.60$) with samples having 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 have a liquefaction of the sample; whereas we need eight cycles to obtain liquefaction of the specimens having a coefficient B close to 0.5.

In this article, we present the results of a laboratory investigation on the influence of the saturation degree evaluated in term of coefficient of Skempton (B) varying between 13 and 90% on the behavior of granular sand. These tests allow us to better understand the influence of saturation on the mechanical behavior of granular sand. The article is composed of two parts. In the first part, we present the material used, the second part gives an analysis of the experimental results of the tests carried out and discusses the influence of the degree of saturation evaluated in term of coefficient of Skempton (B) on the resistance to liquefaction.

Material used

The tests were carried out on the sand of Chlef (Algeria) containing 0.5% of silt of the Chlef river which crosses the town of Chlef (formerly El-Asnam). The tests have been carried out on specimen collected from the region where the phenomenon of liquefaction was observed during the last earthquake (October 10th, 1980) (see Fig. 1) with an index of density $I_d = 0.50$ and at initial confining pressure of $\sigma'_c = 100$ kPa.

The granular grading curve of sand used is given in Fig. 2. The sand of Chlef is a medium sand, rounded with an average diameter $D_{50} = 0.45$ mm. The silt contained is not very plastic with an index of plasticity of 6%. Table 1 gives the physical characteristics of the sand used.

Experimental procedures

The used experimental device is presented in Fig. 3. It contains:

- An autonomous triaxial cell type Bishop and Wesley (Bishop and Wesley, 1975),
- Two controllers of pressure / volume type GDS (200cc),
- A void pump joined to a reservoir in order to deaire the demineralized water,
- A microcomputer equipped with software permitting the piloting of the test and the data acquisition.

Sample preparation

The sample preparation method used is dry pluviation where the dry soil is deposited in the mould using a funnel with a rigorous control of the drop height



Figure 1. Sand boils due to the liquefaction phenomenon at Chlef region

Table 1: Properties of soil testd

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)	Particle Shape
O/Chlef	0.54	0.99	1.34	1.73	2.67	3.2	0.45	0.15	Rounded

Where e_{min} and e_{max} indicate the minimum and the maximum void ratio, respectively, γ_{dmin} =minimum dry unit weight; γ_{dmax} =maximum dry unit weight; γ_s =solid grain unit weight; Cu=uniformity coefficient; D₅₀=average diameter; D₁₀= effective diameter.

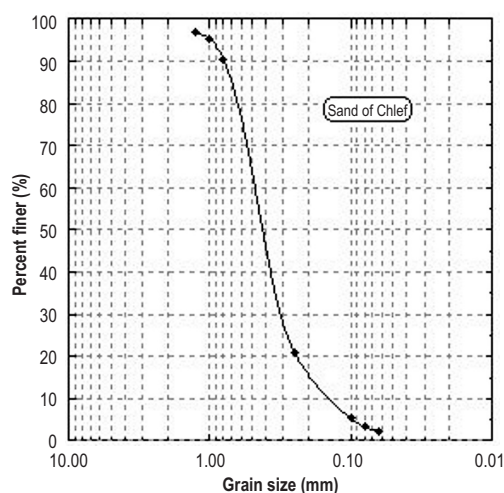


Figure 2. Grain size distribution of tested material.

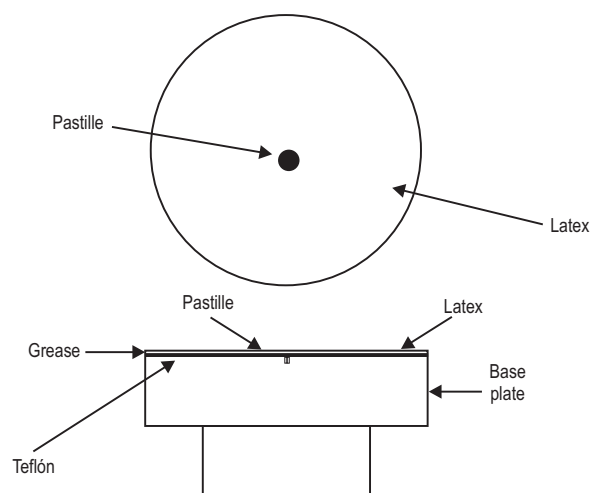


Figure 4. antifretage System used

of the sand which must be quasi-null for the loose samples. With the aim of having medium dense homogeneous samples, we have used the method recommended by Ladd (1978); this method consists in dividing the sample in several layers. The relative density of each layer varies to 1% from bottom upwards. The average layer has the same value of the relative density as the sample.

The used samples are cylindrical in shape of 70mm of diameter and 70mm height ($l/d=1$). To make sure of a good homogeneity of the stresses and deformations within the samples, several researchers (Lee, 1978; Robinet et al., 1983; Tatsuoka et al., 1984; Colliat 1986, and Al mahmoud 1997) insisted on the need for reducing frictions between the sample and the superior and inferior base plates; this can be obtained by base plates of smooth or lubricated surface (antifrettag system). The antifrettag system used is represented on Fig. 4 (Al Mahmoud (1997)). The sand mass to be set up is evaluated according to the desired density (the initial volume of the sample is known), the state of density of the sample being defined by the relative density:

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

Saturation of the sample

Saturation is a significant stage in the experimental procedure because of its quality depends the answer of the sample under drained and undrained

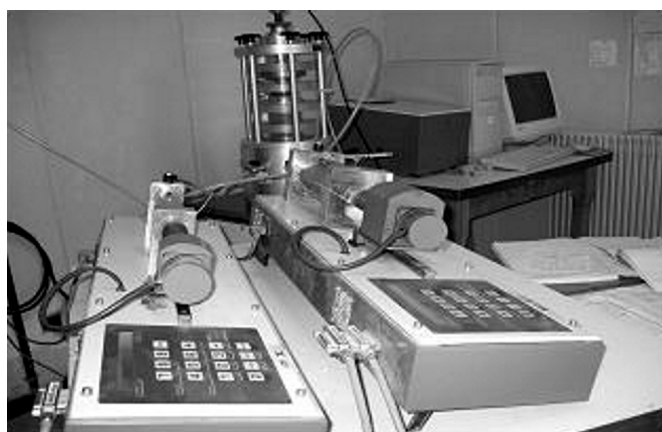


Figure 3. The experimental device used

loading. To obtain a good degree of saturation, the technique of carbon dioxide worked out by Lade and Duncan (1973) was used. The sample is firstly swept by carbon dioxide during twenty minutes, then we let circulate the deaerated and demineralized water until collecting a volume of water superior to one and a half the volume of the sample. To be able to obtain samples with various degrees of saturation, we have varied the time of passage of carbon dioxide and the duration of duct drainage deaerated water through the sample.

Consolidation of the sample

The phase of consolidation consists in applying simultaneously a rise of pressure in the cell by means of the volume/pressure controller (GDS1) and inside the sample (GDS2). The application of back pressure to the sample using the GDS2 improves the quality of the saturation by compressing the microbubbles of the interstitial gas which remains imprisoned between the grains of the soil. We maintain the pressures in the cell and the sample until stabilization of volumes (cell and sample). The quality of saturation is evaluated by measuring the coefficient of Skempton (B). This coefficient (B) is equal to $\Delta u / \Delta \sigma$. We give an increment $\Delta \sigma$ of 100 kPa to the GDS1 connected to the cell and we measure the variation of the pore water pressure Δu by the GDS2 connected to the sample. The back pressure used is of 400 kPa.

The degree of saturation is controlled during a triaxial compression test by the coefficient of Skempton which can be related to the degree of saturation by the following relation (Lade and Hernandez 1977):

$$B = \frac{1}{1 + nk_s \left(\frac{S_r}{K_w} + \frac{(1-S_r)}{W_a} \right)} \quad (2)$$

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.

Results of the tests

Drained compression Tests

Figure 5 shows the results of the drained compression tests carried out for coefficients of Skempton B ranging between 13 and 90%. It is clear from this

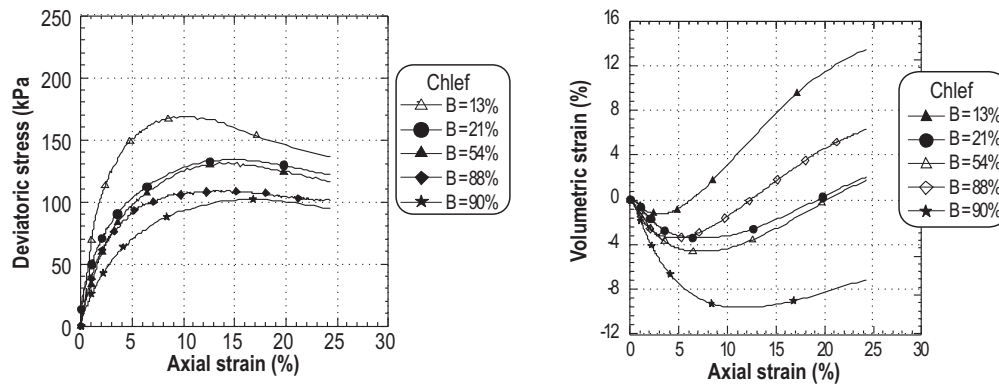


Figure 5. Influence of the coefficient of Skempton (B) on drained

figure that the coefficient of Skempton (B) significantly affects the variation of the deviatoric stress (Fig. 5a) and the volumetric deformation (Fig. 5b). The increase in the coefficient of Skempton (B) from 13 to 90% induces a reduction in the initial stiffness and resistance of the soil (maximal deviator). With regard to the volumetric deformation, we note that the increase in the coefficient of Skempton (B) delays the appearance of dilatancy; the sample with a degree of saturation B=13% dilatancy appears after 3% of axial deformation, while the sample with a degree of saturation B=90% we observe an amplification of the phase of contractance and dilatancy is delayed and appears after 12% of axial deformation. Also shown in Fig. 6 are the curves of variation of the volumetric deformations at the phase change (contractance-dilatancy) and at the steady state versus the coefficient of Skempton (B). We notice that the difference between these curves decreases with the increase in the coefficient of Skempton (B), showing the progressive disappearance of the phase of dilatancy and the appearance of only the phase of contractance for the sample with a coefficient of Skempton (B) equal to 90%.

Undrained compression tests

Figure 7 shows the results of the undrained triaxial compression tests performed in this study for various values of coefficient of Skempton (B)

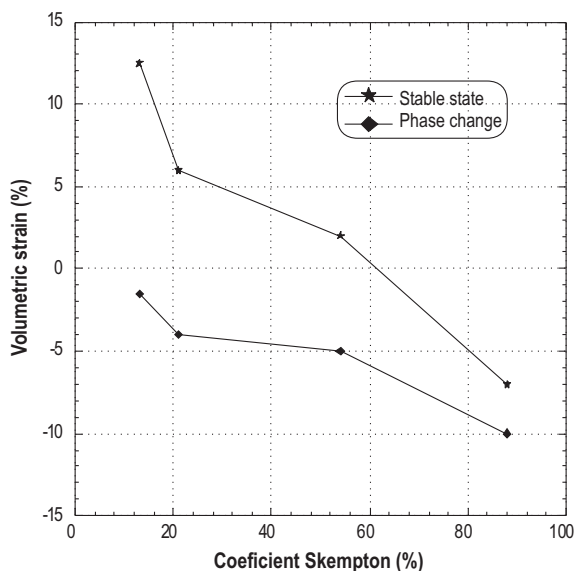


Figure 6. Influence of the coefficient of Skempton (B) on the volumetric deformations at the phase change and steady state

between 32 and 90% with an initial confining pressure of 100 kPa. As can be seen, increase in the degree of saturation characterized by the coefficient of Skempton (B) lead to a reduction in the resistance of the deviatoric stress (Fig. 7a) and an increase in the water pressure (Fig. 7b). This increase in the water pressure results from the role of the degree of saturation in the increase in the pore water pressure leads to a reduction of the effective confining pressure and consequently with a reduction of resistance as Fig. 7a illustrates. The stress path curve in the plan (p', q) shows well the role of the degree of saturation in the reduction of the effective mean stress and the maximal deviatoric stress (Fig. 7c).

Variation of the residual strength

When sands are subjected to an undrained shearing; after the peak of deviatoric stress, the resistance to the shearing falls with an almost constant value on a broad deformation. Conventionally, this resistance to the shearing is called residual strength or the shearing force at the quasi steady state (Q_{ss}). The residual strength is defined by Ishihara (1993) like:

$$S_{us} = (q_s/2) \cos\phi_s \tag{3}$$

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

Fig. 8 shows the evolution of the residual strength with the coefficient of Skempton (B). We note that the residual strength decreases in a significant and linear way with the increase in the coefficient of Skempton B resulting from the role of saturation as for the amplification of the contractance of the studied soil.

Conclusion

This experimental study investigated the effect of the saturation characterized by Skempton's pore pressure coefficient (B) on the behavior of a granular soil. Both drained and undrained triaxial compression tests were performed on specimens with an initial medium relative density I_d = 0.50, at an initial effective confining pressure of 100 kPa.

The study of the influence of saturation on the potential of liquefaction was carried out on the Chlef sand of varying the coefficient of Skempton (B). The results of the tests showed that the saturation has a detectable effect on the drained and undrained behavior. The tests show that the increase in the coefficient of Skempton induces a reduction of the initial stiffness and the resistance of the soil (maximal deviatoric stress); and increases the phase of

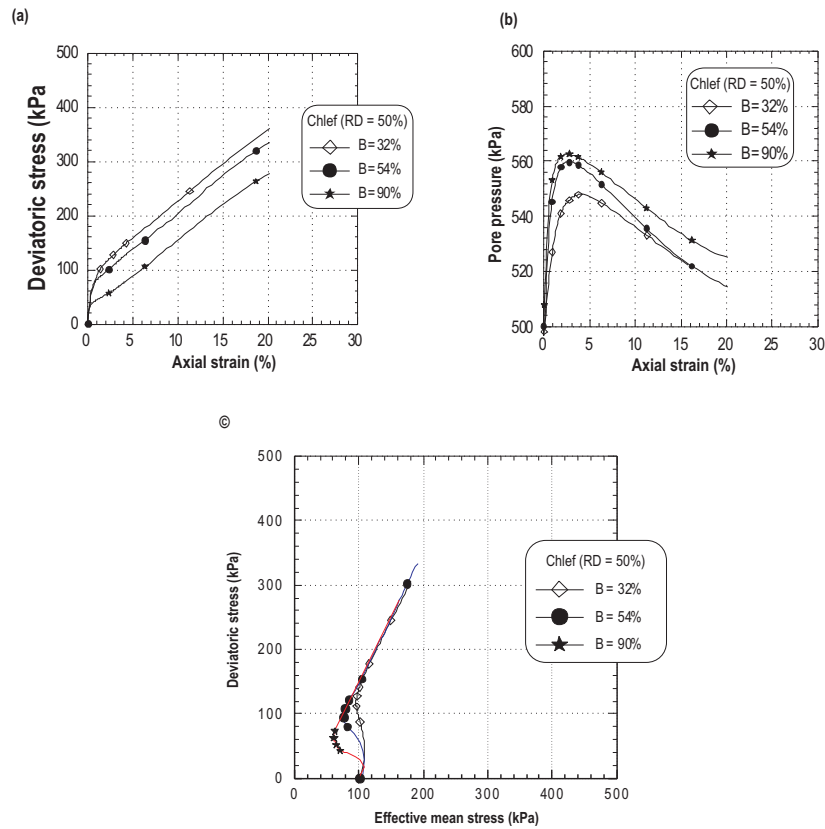


Figure 7. Influence of the coefficient of Skempton (B) on undrained behavior of Chlef sand

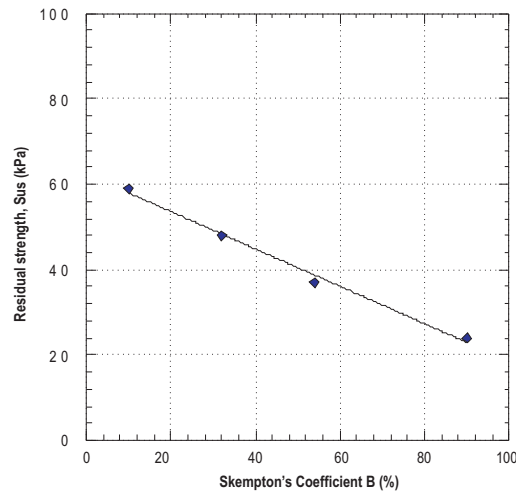


Figure 8. Influence of the coefficient of Skempton (B) on the Residual strength at the quasi steady state

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.

The residual effort (Sus) decreases in a significant and linear way with the increase in the coefficient of Skempton B resulting from the role of saturation as for the amplification of the contractance of the studied sand.

The reduction of the coefficient of Skempton, induces a reduction of the increasing rate in the pore water pressure, an improvement of the residual strength of the soil and consequently an increase in the resistance to the liquefaction. A partial saturation can eliminate any risk of liquefaction, this can have practical applications in the high-risk zones of liquefaction.

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