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A laboratory study of liquefaction of partially saturated sand

Estudio en laboratorio sobre licuefacción de arena parcialmente saturada

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Abstract

This experimental study was designed to assess the effects of soil water saturation on the liquefaction of Hostun RF sand. Cyclic undrained triaxial tests were conducted at different soil saturation levels, as given by Skempton's coefficient, and liquefaction potential curves constructed for each value of this coefficient. Our findings indicate that a lower soil saturation level results in the increased resistance of the sand to liquefaction, in agreement with the tendency observed in other sands. In addition, the variation in sand resistance to liquefaction produced with Skempton's coefficient was found to be consistent with the semi-empirical relation proposed by Yang *et al.* (2004).

Keywords: sand, partial saturation, liquefaction, Skempton's Coefficient, triaxial

Resumen

Este estudio experimental fue diseñado para comprobar los efectos de la saturación de agua en suelos bajo la licuefacción de arena RF Hostun. Tests cíclicos de tipo triaxial no drenado fueron elaborados a diferentes niveles de saturación del suelo, como se obtiene por el coeficiente de Skempton, y se obtuvieron curvas de potencial de licuefacción para cada uno de los valores de este coeficiente. Nuestros resultados indican que un nivel de saturación bajo de suelo durante el incremento de la resistencia de la arena a la licuefacción, estando de acuerdo con la tendencia observada en otras arenas. Por otro lado, se observó que la variación de la resistencia de las arenas a la licuefacción producida mediante el coeficiente de Skempton es consistente con la relación semiempírica propuesta por Yang *et al*. (2004).

Palabras clave: arena, saturación parcial, licuefacción, Coeficiente de Skempton, triaxial

1. Introduction

The phenomenon of soil liquefaction has been observed in response to moderate and large earthquakes, for example those of Loma (1989), Luzon (1990), Manjil (1990), Kobe (1995), Manzanillo (1995), Chi-Chi (1999), Kocaeli (1999), and Bhuj (2001) (Bird *et al*., 2004). Understanding the mechanism of liquefaction in water-saturated soils and developing methods to evaluate their liquefaction potential have been the subjects of intense research (Seed and Idriss, 1971; Seed, 1979). However, in geotechnical engineering partially saturated soils are frequently encountered, especially above the water table. Further, due to the presence of small air bubbles, soils below the water table could also be partially saturated and this issue has been explored in both experimental and analytical analyses. Thus, Mulilis *et al.* (1978) reported that a change in Skempton's coefficient (B) from 0.91 to 0.97 moderately affected the liquefaction of Monterey sand. Chaney (1978) specified that coefficient B has to be higher than 0.96 so that the soil is well saturated and Sherif *et al.* (1977) showed that a fine or clayey sand could be considered saturated if the value of B exceeded 0.8. More recently, laboratory test results have indicated that the liquefaction resistance of sands increases with a decreasing degree of saturation (Ishihara *et al*., 2001; 2004; Yang, 2002; Yang *et al.*, 2004; Atigh and Byrne, 2004; Bouferra *et al*., 2007). As an in situ measure of the level of water saturation of a soil, Berryman *et al*. (1988) and Santos *et al.* (1990) reported the use of compression wave speed. Recently, a constitutive relation based on the multiphase approach was used to address the liquefaction of partially saturated sand (Bian and Shahrour, 2009).

In triaxial tests, the extent of saturation (S_r) is generally controlled by means of Skempton's coefficient (B) according to the following equation:

$$B = \frac{1}{1 + n\frac{K_s}{K_w} + nK_s\frac{(1-S_r)}{u_a}} \quad (1)$$

where, K_s and K_w are the bulk modulus of the solid skeleton and water, respectively; n is the porosity of the soil and u_a is the water pore pressure.

The aim of the present laboratory study was to determine the influence of soil saturation level on the liquefaction of Hostun RF sand across a wide range of Skempton coefficient B values (between 0.25 and 0.90). After describing the experimental procedure, we analyse the experimental results obtained by constructing liquefaction potential curves for several values of the Skempton coefficient B. These results are then compared to those reported in the literature for other sands and fitted to the equation proposed by Yang *et al*. (2004) to describe how sand resistance to liquefaction varies according to Skempton's coefficient.

2. Experimental procedure

Laboratory tests were conducted on samples of medium grained Hostun RF sand. This sand is composed of angular particles of mean grain size D_{50}=0.47 mm (Fig. 1); its properties are summarized in Table 1. This sand is widely used in France to investigate sand behaviour under complex loading paths and conditions. It arose from a thick series of Eocene sand layers that fill karst pockets on the western side of Vercors at Hostun (Drôme, France). Experimental results for this sand obtained at low confining pressures may be found in Lancelot *et al*. (2004, 2006).

Alternating undrained cyclic triaxial tests were performed on soil samples at an initial relative density $I_D=0.65$ across a wide range (0.25 to 0.9) of the Skempton coefficient (B). Table 2 shows the values of B used in this study with their corresponding saturation values calculated using Equation 1.

For each value of B, tests were conducted at several loading levels (CSR) to construct liquefaction potential curves (Table 3). The loading level (CSR) was defined as:

$$CSR = \frac{q_m}{2\sigma'_c} \quad (2)$$

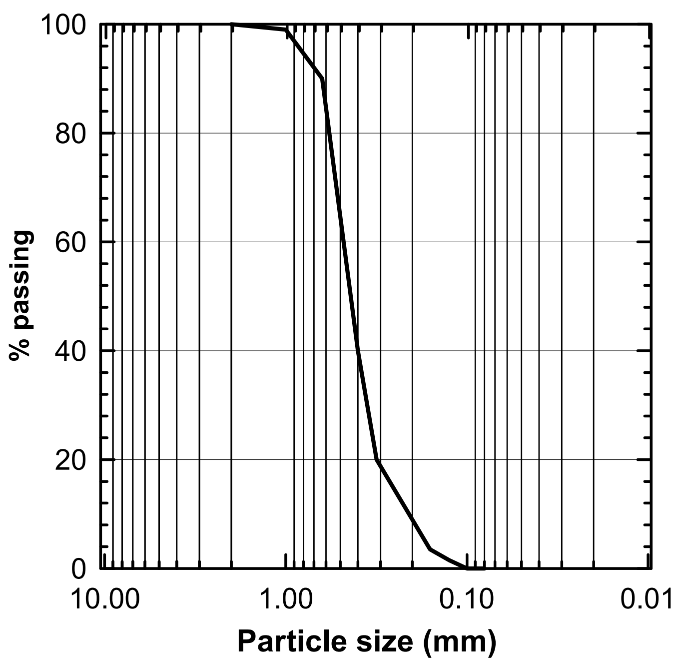


Fig. 1. - Grain size distribution of Hostun RF sand.
Fig. 1.- Distribución del tamaño de grano de la arena RF Hostun.

e_{max}	e_{min}	D_{10}	D_{50}	$Cu\ (D_{60}/D_{10})$
0.983	0.622	0.19	0.47	2.27

Table 1. Properties of Hostun RF sand.
Tabla 1. Propiedades de la arena RF Hostun.

Skempton's coefficient (B)	Saturation (%)
0.90	100
0.85	99.8
0.73	99.7
0.67	99.7
0.53	99.4
0.36	98.9
0.25	98.2

Table 2.- Values of Skempton's coefficient used in the laboratory study and corresponding saturation levels (Equation 1)
Tabla 2.- Valores del coeficiente de Skempton utilizados en el estudio de laboratorio correspondiendo a los niveles de saturación (Ecuación 1).

Skempton's coefficient (B)	Cyclic loading level (CSR)	Number of cycles until liquefaction
0.9	0.35	7
	0.25	16
	0.20	63
	0.15	NL
0.85	0.35	11
	0.30	17
	0.25	32
0.73	0.35	22
	0.25	200
0.67	0.50	9
	0.40	12
	0.35	21
0.53	0.30	51
	0.35	27
	0.30	43
0.36	0.50	10
	0.35	46
	0.25	NL
0.25	0.50	12
	0.40	52
	0.35	NL

Table 3.- Tests conducted on the Hostun RF sand.
Tabla 3.- Test de comportamiento de arenas RF Hostun.

where q_m and σ'_c are the cyclic loading amplitude and initial mean effective stress, respectively.

Experiments were conducted in two stages. In the first stage, we prepared the partially saturated sand samples, and in the second stage, conventional undrained cyclic triaxial tests were performed using a Bishop cell. To ensure good control of the degree of saturation, the carbon dioxide procedure was used (Skempton, 1954). In the first stage, the soil sample is purged with carbon dioxide for 20 minutes and then percolated with deaired water until a volume of water greater than one and a half times the sample volume has been collected. Samples of different saturation level were obtained by varying the time of carbon dioxide passage and percolation with deaired water.

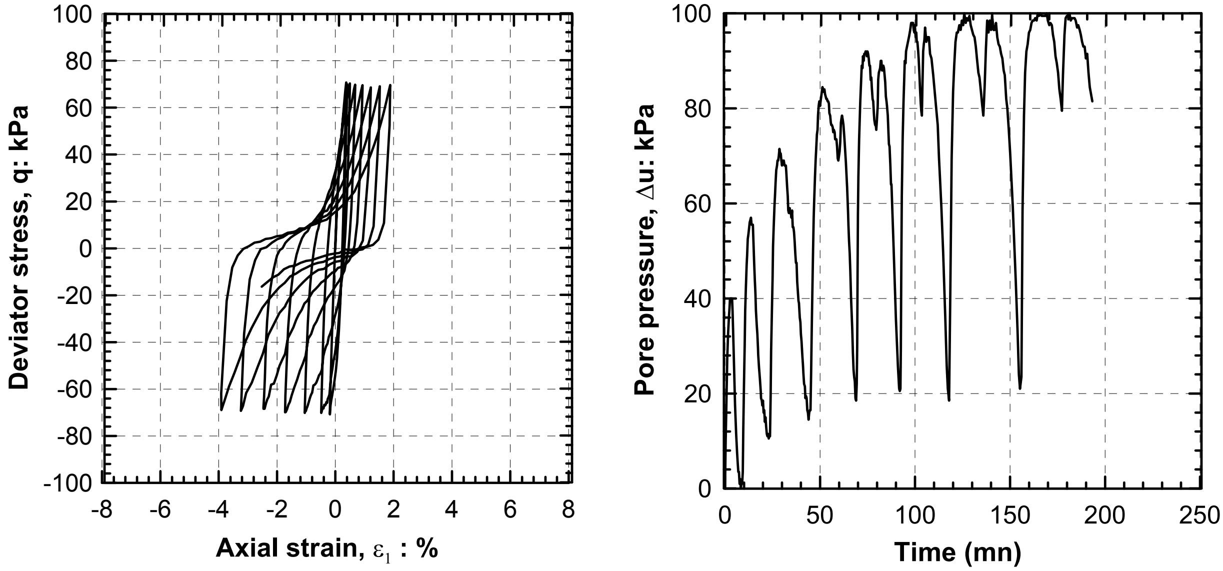
3. Results and discussion

Figures 2 to 5 provide the results obtained in tests performed for 4 values of the Skempton coefficient (B = 0.90, 0.67, 0.53, and 0.25) at the cyclic loading level CSR = 0.35. The figures illustrate that for the quasi-saturated sample (B = 0.9), water pore-pressure increased regularly and reached the value of the initial effective confining pressure (100 kPa) after 7 cycles at an axial deformation of 2%. This state corresponds to liquefaction of the sand through cancellation of the effective confining pressure. For the soil sample whose B = 0.67, we observed a similar trend in water pore-pressure but the rate of increase was lower than that observed for B = 0.9. Liquefaction occurred after 21 cycles.

For B = 0.53, a regular increase in water pore-pressure was also detected but at a rate lower than that observed for B = 0.67. Liquefaction took place after 27 cycles; initial effective pressure was cancelled at an axial strain of 4%.

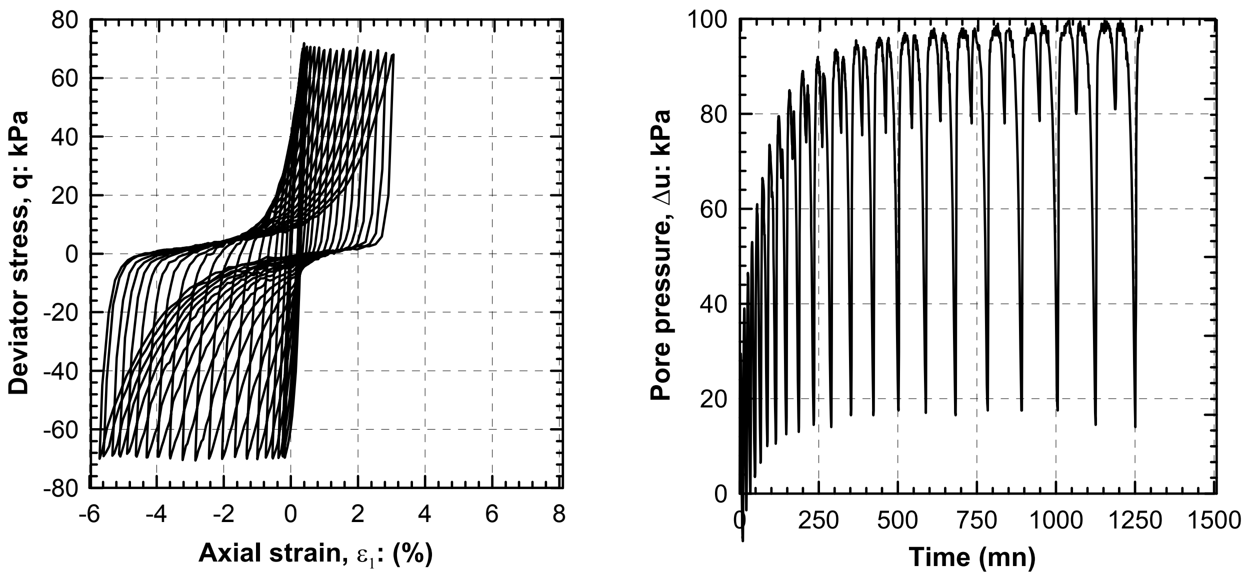
For B = 0.25, we noted a slight increase in water pore-pressure and stabilization of the amplitude of axial strain at 0.4%. Liquefaction was only observed for higher loading levels. Thus, an increase in the cyclic loading level to CSR = 0.4 led to liquefaction after 52 cycles (Fig. 6). When the loading level was substantially increased (CSR = 0.5), liquefaction was observed after 12 cycles (Fig. 7).

Further tests were conducted for each value of B to obtain data for the liquefaction potential curves (Table 2). Figure 8 shows the results obtained for the different values of B. For each level of loading (CSR), the curves give the number of cycles needed for liquefaction. Analysis of these results revealed a general tendency for an increase in the number of loading cycles necessary for liquefaction (N_{liq}) as Skempton coefficient B decreased. To better illustrate this tendency, Figure 9 shows how N_{liq} varies with coefficient B for each value of the loading level.



Deviator stress versus axial strain *Changes in pore pressure over time*

Fig. 2. - Undrained cyclic tests conducted on quasi saturated sand (B = 0.90) CSR= 0.35.
Fig. 2. - Test de comportamiento cíclico en arenas casi saturadas (B = 0.90) CSR= 0.35.

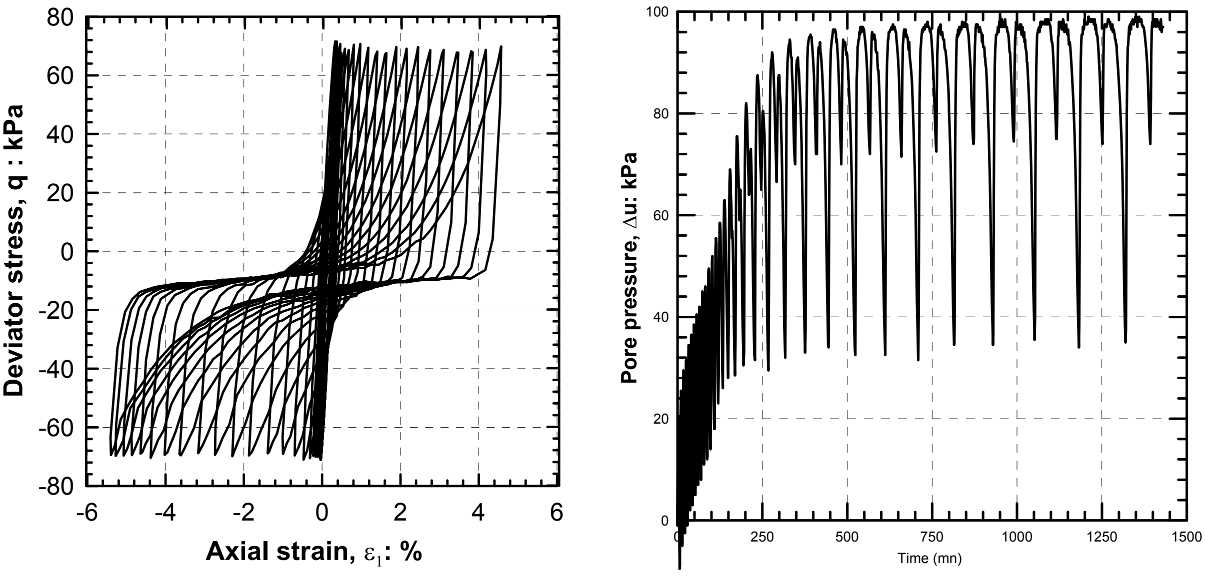


Deviator stress versus axial strain *Changes in pore pressure over time*

Fig. 3. - Undrained cyclic tests conducted on partially saturated sand (B = 0.67) CSR= 0.35.
Fig. 3. - Test de comportamiento cíclico no drenado en arenas parcialmente saturadas (B = 0.67) CSR= 0.35.

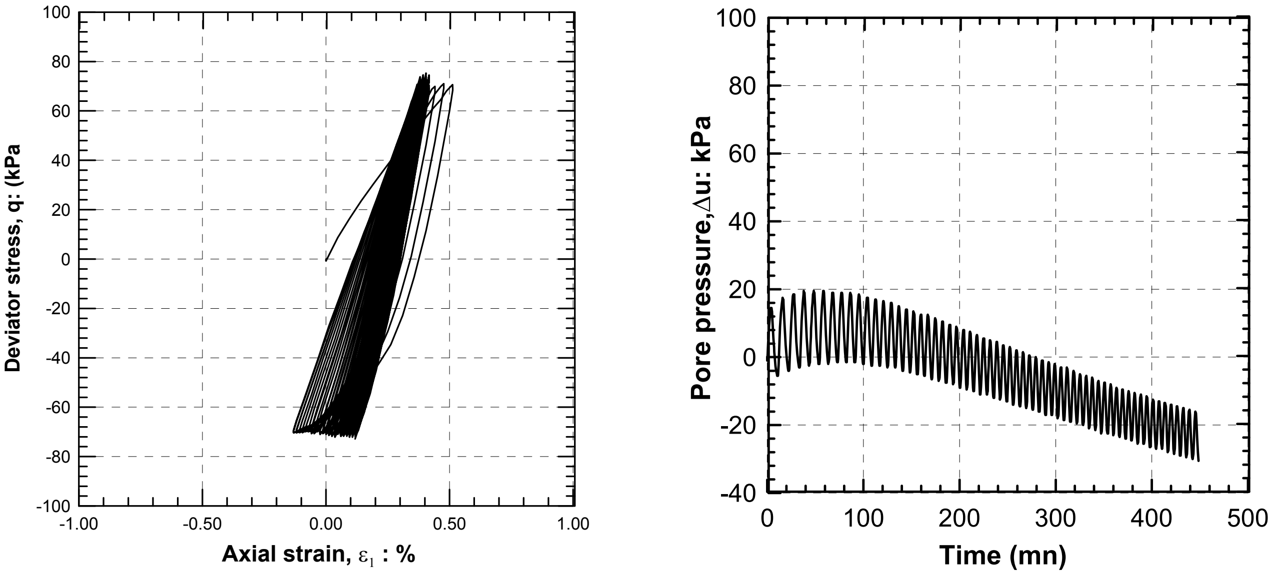
Hence, for the low cyclic loading levels (CSR = 0.25 and 0.3), significant variation in N_{liq} with coefficient B was observed. Specifically for CSR = 0.25, N_{liq} increased from 12 to 200 cycles as B diminished from 0.9 to 0.73. Conversely, for the higher of loading levels (CSR= 0.4 and 0.5), scarce variation in N_{liq} was produced according to coefficient B such that for CSR = 0.50, N_{liq} increased from 9 to 12 cycles as B fell from 0.73 to 0.25.

Figure 10 shows the influence of Skempton's coefficient (B) on the sand resistance to liquefaction (CR), which is defined as the cyclic loading level required to cause initial liquefaction within 15 cycles. Thus, the Skempton's coefficient has an important impact on this resistance (CR), which increases from 0.25 to 0.40 when



Deviator stress versus axial strain *Changes in pore pressure over time*

Fig. 4. - Undrained cyclic tests conducted on partially saturated sand (B = 0.53) CSR= 0.35.
Fig. 4. - Test de comportamiento cíclico no drenado en arenas parcialmente saturadas (B = 0.53) CSR= 0.35.



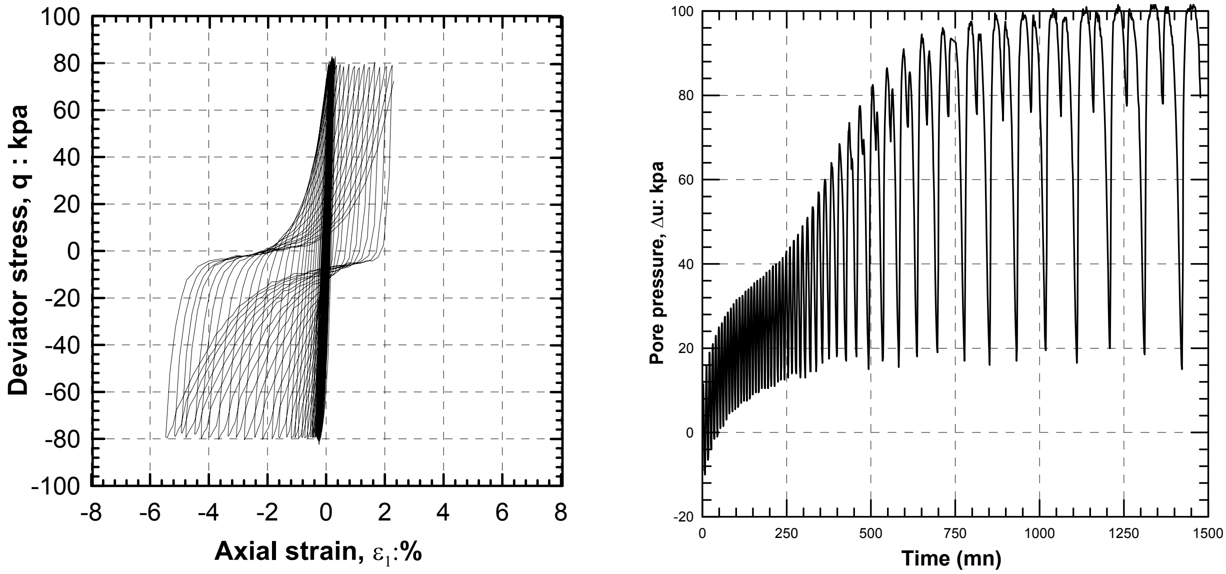
Deviator stress versus axial strain *Changes in pore pressure over time*

Fig. 5. - Undrained cyclic tests conducted on partially saturated sand (B = 0.25) CSR= 0.35.
Fig. 5. - Test de comportamiento cíclico no drenado en arenas parcialmente saturadas (B = 0.25) CSR= 0.35.

B decreases from 0.85 to 0.67, and from 0.40 to 0.48 when B decreases from 0.67 to 0.25.

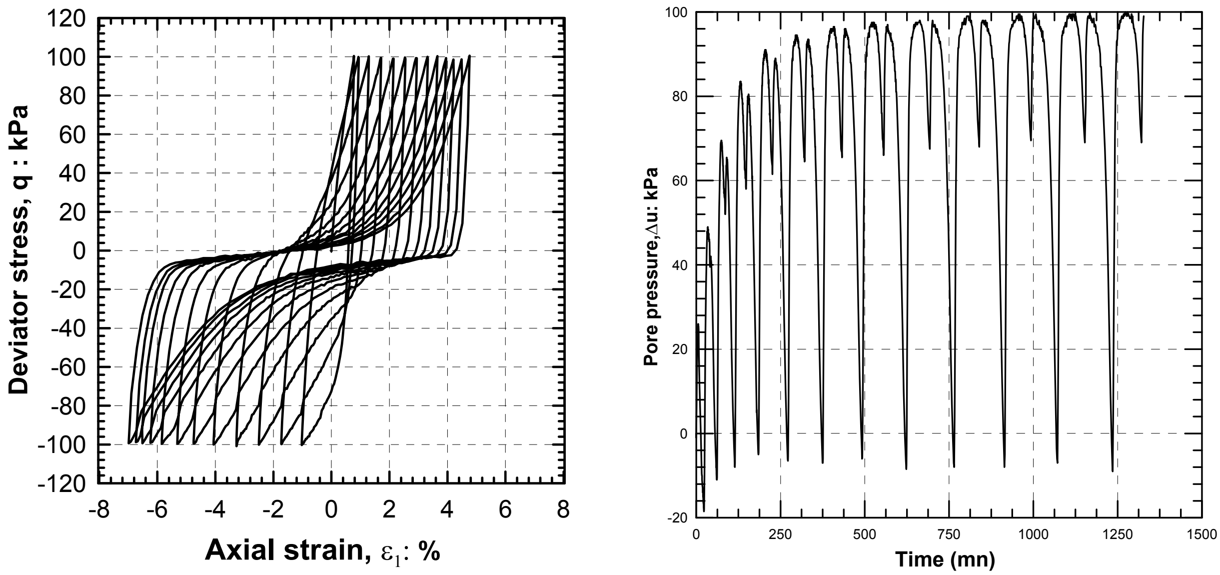
To quantify the saturation effect on sand resistance to liquefaction, Yang (2002) used normalized cyclic resistance (RLn), which is the ratio between resistance to liquefaction of a partially saturated sand (CR) to that of a saturated sand. In Figure 11 we compare the results obtained here with those reported for other soils. These data indicate good agreement between our experimental results for Hostun sand and results for the other sands, especially Ottawa sand (Sherif *et al*., 1997) and Tongjiazhi sand (Xia and Hu, 1991).

Yang *et al*. (2004) proposed the following equation to describe the variation in normalized cyclic resistance to



Deviator stress versus axial strain *Changes in pore pressure over time*

Fig. 6. - Undrained cyclic tests conducted on partially saturated sand (B = 0.25) CSR= 0.40.
Fig. 6. - Test de comportamiento cíclico no drenado en arenas parcialmente (B = 0.25) CSR= 0.40.



Deviator stress versus axial strain *Changes in pore pressure over time*

Fig. 7. - Undrained cyclic tests conducted on partially saturated sand (B = 0.25) CSR= 0.50.
Fig. 7. - Test de comportamiento cíclico no drenado en arenas parcialmente (B = 0.25) CSR= 0.50.

liquefaction with Skempton's coefficient (B):

$$RLn = e^{\alpha(1-B)} \qquad (3)$$

Parameter α indicates the slope of the linear regression in the (($Log(RLn)$, B) plane. Figure 12 shows how this equation can be applied to the data obtained in the tests conducted on the Hostun RF sand. The linear approximation in the ($Log(RLn)$, B) plane gives α= 1.03 with a correlation coefficient Cc = 0.99.

4. Conclusions

This paper describes a laboratory study designed to assess the liquefaction of partially saturated sand using Skempton's coefficient (B) as a measure of soil saturation. Tests were conducted at several levels of cyclic loading (CSR) to construct liquefaction potential curves for 7 values of coefficient B ranging between 0.25 and 0.90.

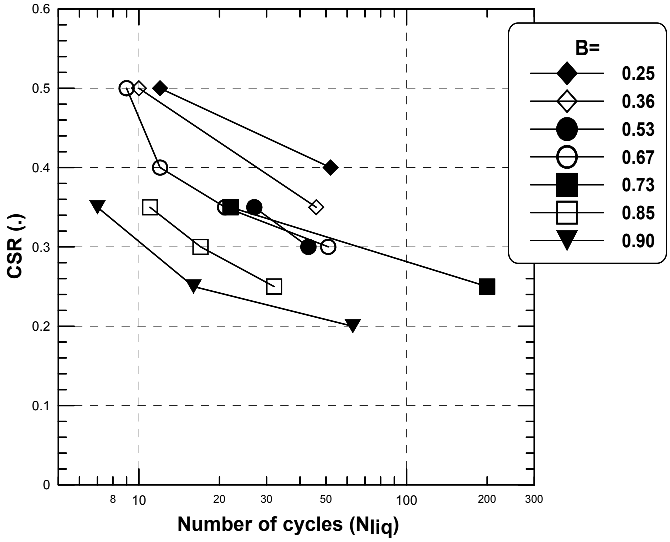


Fig. 8. - Effect of Skempton's coefficient B on the liquefaction potential of Hostun RF sand.

Fig. 8.- Efecto del coeficiente B de Skempton en el potencial de licuefacción de arena de tipo RF Hostun.

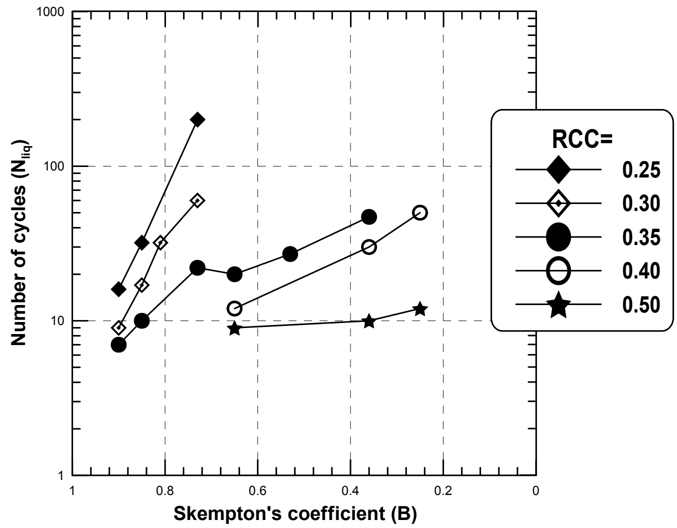


Fig. 9. - Effect of Skempton's coefficient on the liquefaction potential of Hostun RF sand

Fig. 9.- Efecto del coeficiente Skempton en el potencial de licuefacción de arena RF Hostun.

Our experimental results clearly show that a decrease in the Skempton coefficient leads to a large increase in the number of cycles necessary for sand liquefaction, in particular, for low cyclic loading levels (CSR < 0.3). Thus, liquefaction resistance, defined here as the level of cyclic loading (CSR) that leads to liquefaction in 15 cycles, appreciably decreases with coefficient B. In addition, our data showed good fit to the equation proposed by Yang *et al*. for the variation in normalized resistance to liquefaction *RLn* (ratio of the liquefaction resistance of a partially saturated to a saturated soil) produced with coefficient B: ($RLn = e^{\alpha(1-B)}$) where $\alpha = 1.03$.

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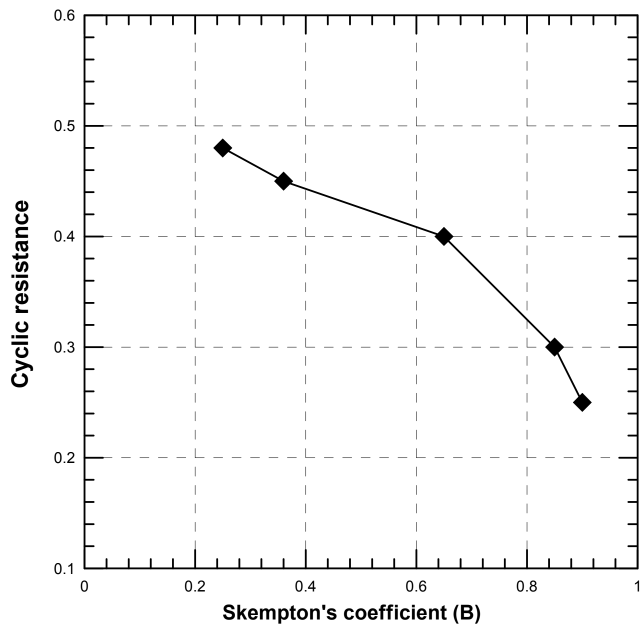

Fig. 10. - Influence of Skempton's coefficient on the resistance to liquefaction of Hostun RF sand (cyclic loading level that leads to liquefaction in 15 cycles).

Fig. 10.- Influencia del coeficiente de Skempton en la resistencia a la licuefacción de arena RF Hostun (nivel de carga cíclica que rebaja la licuefacción en 15 ciclos).

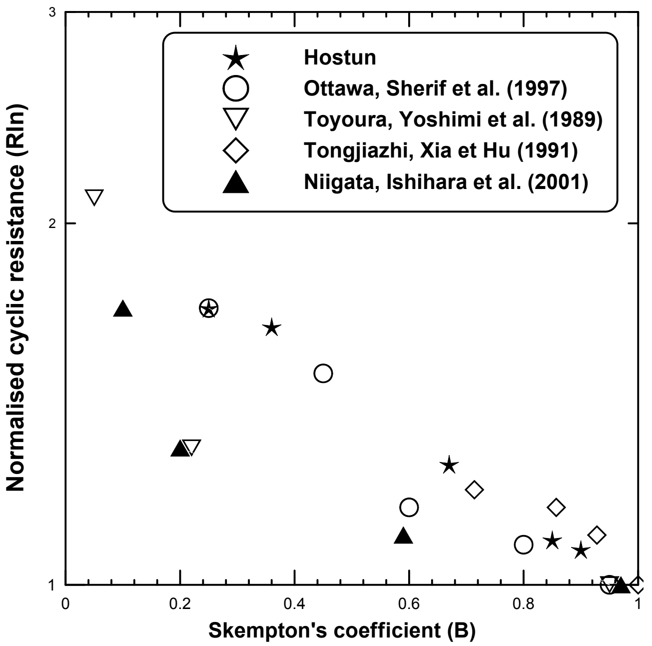

Fig. 11. - Comparing the experimental results of this study to those conducted on a further four sands.

Fig. 11.- Comparación de los resultados experimentales de este estudio con otros cuatro de otros estudios.

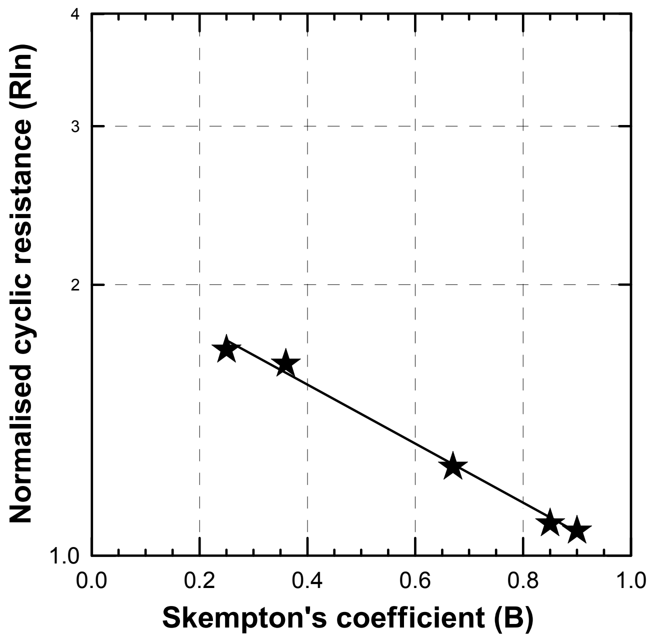

Fig. 12. - Fitting the test results for Hostun RF sand to the equation described by Yang et al. (2004).

Fig. 12.- Ajuste del test de resultados de la arena RF de Hoston a la ecuación descrita por Yang et al. (2004).

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