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Evaluation of Excess Pore Water Pressure Behaviour During Cyclic Triaxial Tests on a Non-plastic Silt

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ABSTRACT

Cyclic loading can be responsible for pore water pressure build-up in soils, which may subsequently cause liquefaction and surface settlements. Recent studies emphasize that as increasing pore water pressure reaches a value equal to the initial confining stress, cyclic stress ratio and relative density of soil play a great role in buildup of excess pore water pressure. Nonetheless, pore water pressure is also a function of axial strain. In this study, cyclic triaxial tests were carried out to evaluate the pore water pressure buildup behavior of a nonplastic silt. It was aimed to calculate the dependence of pore water pressure, double amplitude of axial strain and number of cycles on cyclic stress ratio. In this scope, stress-controlled cyclic triaxial tests at a loading frequency and confining pressure of 0.1 Hz and 100 kPa were carried out on saturated samples. It is evident that number of loading cycles leading to liquefaction were decreased by increases in cyclic stress ratio and relative density of soil. The data obtained in this study, bringing an insight into pore water pressure build-up behavior of nonplastic silts, can be used for practical purposes.

Keywords: *Cyclic triaxial tests, Nonplastic silt, Excess pore water pressure.*

Plastik Olmayan bir silt zemin üzerinde yapılan çevrimsel üç eksenli deneyler sırasında oluşan aşırı boşluk suyu basıncı davranışının değerlendirilmesi

ÖZET

Çevrimsel yükleme, zemin bünyesinde boşluk suyu basınçlarında artışlar meydana getirerek, sonrasında sıvılaşma ve oturmalara yol açabilmektedir. Yakın zamanda yapılan çalışmalarda, boşluk suyu basıncının ilksel çevre basıncına eşit olması durumunda, çevrimsel gerilme oranı ve zeminin izafi sıkılığının aşırı boşluk suyu basıncının gelişiminde büyük rolü olduğu vurgulanmaktadır. Bununla birlikte, boşluk suyu basıncı aynı zamanda eksenel deformasyonun bir fonksiyonudur. Bu bağlamda, plastik olmayan bir silt zeminin boşluk suyu basıncı gelişim davranışının değerlendirilebilmesi için bir dizi çevrimsel üç eksenli basınç deneyi yapılmıştır. Deneyler ile, boşluk suyu basıncı, çift genlikli eksenel deformasyon ve çevrim sayısının çevrimsel gerilme oranına bağımlılığı

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araştırılmıştır. Bu amaçla, suya doygun örnekler üzerinde gerilme kontrollü çevrimsel üç eksenli basınç deneyleri 0.1 Hz frekansta ve 100 kPa çevre basıncında tatbik edilmiştir. Sıvılaşmaya neden olan çevrim sayısının, artan çevrimsel gerilme oranı ve izafi sıkılık ile azaldığı elde olunmuştur. Çalışmada elde edilen veriler, plastik olmayan silt zeminin boşluk suyu basıncı gelişim davranışına ışık tutmaktadır ve pratik amaçlarla kullanılabilir.

Anahtar Kelimeler: *Dinamik üç eksenli deneyler, Plastik olmayan silt, Aşırı boşluk suyu basıncı.*

I. INTRODUCTION

Seismic activities, pile driving action or machine foundations are several examples of cyclic loading on foundation soils. Apart from hydrostatic pressure, additional or excess pore water pressure (PWP) is likely to develop during cyclic loading and the development pattern is affected from number of loading cycles and soil type, but mostly dependent on permeability of the soil and frequency of loading. As known from the effective stress concept, the increase in PWP can cause liquefaction. However, the behavior of PWP should be investigated in detail since during generation of excess pore water pressures, effective stress, rigidity and strength characteristics of different soils do not show a unique behavior [1-3]. In this scope, many studies are carried out to evaluate the PWP behavior of different types of soils [4-10]. However, these studies are mostly focused on cyclic behavior of sands and sandy soils. After 1999 Kocaeli-Düzce earthquake damages, several attempts were made to assess liquefaction and cyclic behavior of fine grained soils [11].

In order to evaluate the development of excess PWP, Lee and Albaisa [12] suggests stress-controlled testing, by plotting pore pressure response against cycle ratio. The variation of PWP ratio-cycle ratio is limited within narrow ranges of relative densities and consolidation pressures [12-13]. Strain-controlled testing is an alternative, Silver and Seed [4], later Dobry [14] revealed that, generation of excess pore water is a strain-dependent phenomenon. Subsequent studies suggest use of “threshold strain” concept for evaluation of excess pore water pressure build-up behavior [15-17]. The effects of silt content is also another research subject, Singh [18] reported a decrease in generation of excess PWP, on the contrary, Polito and Martin [7] observed an initial constant PWP behavior until a threshold silt content is reached, which is followed by a drastic decrease. Sadek and Saleh [19], by increasing silt content of a silty sand, pointed out formation of an initial peak followed by a severe fall in cyclic resistance.

In the short literature survey above, some of the conflicting results are presented. It is also understood that studies on pure silt is relatively rare. Although the information available in literature is still rather limited on the pore pressure build-up and the associated degradation of stiffness and strength of silts under cyclic loading, the response is reported to be dependent on several parameters including stress history, attributes of loading as well as the material characteristics such as plasticity index. Yet, the findings are often contradictory and influences of such factors are on soil response is not well understood. Accordingly, the need is clear for further controlled laboratory studies to improve the present level of knowledge and to clarify the seismic behavior of silts as emphasized by Sanin and Wijewickreme [20] and Boulanger and Idriss [21].

A detailed experimental program concerning application of stress controlled cyclic triaxial tests was established for investigation of cyclic strength and undrained pore water pressure response behavior of nonplastic a silt soil. In this study, a total of 20 cyclic triaxial compression tests were performed on specimens with 60% and 70% relative densities. The results are presented in detail.

II. MATERIAL AND METHODS

The silt soil used in this study is collected from Izmir city center. This soil is classified as nonplastic silt according to the USCS. The maximum and minimum void ratios in accordance with ASTM D4253 standard [22] are determined as 1.352 and 0.894, respectively. The specific gravity of silt is found as 2.67 in accordance with ASTM D854-14 [23]. Many tests were conducted to assess the PWP behavior of silt in terms of cyclic stress ratio (CSR), PWP and double amplitude of axial strain (DA). Accuracy and repeatability of test results were ensured by rerunning randomly selected test cases under similar cyclic stress ratio and loading conditions. Stress controlled dynamic triaxial tests were carried out using a DTC-S367 cyclic triaxial system manufactured by Seiken Inc. The main components of this system consist of vertical pressure loading unit with air and water panel, triaxial cell, pneumatic sine loader, an electric measurement unit including, pressure and displacement transducers and volume change transducer, strain amplifiers, and dynamic data acquisition system. Confining and back pressures are controlled by two pneumatic servo valves. Water flow is completely controlled by distribution panel controls. The volume change is measured automatically. The dynamic triaxial is supplied with a single column load frame. The machine has a servo-pneumatic actuator with external LVDT. The servo system supplies a sinusoidal vibration frequency ranging between 0.001 to 10 Hz. Axial deformations can be measured up to 50 mm distance. The load cell capacity of the dynamic triaxial test machine is 2kN. The load is measured inside the triaxial cell. A double burette type volume change apparatus containing a transducer with a stroke of 25 ml is used to measure the volume changes of saturated specimens (Fig. 1). The experiments were carried out on 50 mm x 100 mm samples. During specimen preparation, a porous stone and a filter paper were placed on the pedestal. A cylindrical rubber membrane was connected to the pedestal and secured with O-rings. Using a split mold on the lower plate of the triaxial cell, vacuum was supplied and upper part of the membrane was secured. Required amount of oven-dried silt was separated to ten equal parts by weight, and each part was carefully introduced into the mold from a constant height of 2 cm. Ten layers were compacted using a wooden rod until the desired height corresponding to a certain relative density was ended. Top of each densified layer was slightly cleared off before compacting next layer to ensure a more uniform structure. A porous paper and stone were placed above the soil. The rubber membrane was slipped to the specimen cap. The specimens were prepared and tested according to JGS 0520-2000 and JGS 0542-2000[24-25]. The specimens are flooded with CO_2 followed by de-aired water flush. Then back pressure is applied to saturate the soils. Before consolidation stage, great care was paid to obtain a Skempton’s pore water pressure coefficient (B) over 0.96. Soil samples were isotropically consolidated to 100 kPa effective stress. Then sinusoidal loading is applied. According to JGS 0542-2000 standard, liquefaction in saturated specimens occur when the pore water pressure ratio reaches to a value of 95% or double-amplitude axial strain (DA) reaches 5%. Therefore, the number of cycles were recorded if a DA level of 5% is reached, otherwise, a loading sequence of maximum 20 cycles is applied to reach a specified level of cyclic stress under a loading frequency of 0.1 Hz. During cyclic loading, continuous data is acquired including excess pore water pressure (u), cyclic axial strain (ε_c), and cyclic deviatoric stress ratio (CSR) measurements.

Figure 1. *Test set up*

III. RESULTS AND DISCUSSION

Typical dynamic triaxial test results are shown in Fig. 2 (Relative density=70%, effective stress=100 kPa). Fig 2a shows the stress path of the specimen. Two-way cyclic loading, namely, compression and extension was applied to simulate dynamic conditions, as can be understood from the regular change of q/σ_0` between +0.08 and -0.08. Variation of the stress path with cyclic axial strain and PWP with loading cycle numbers is given in Fig. 2b and 2c, respectively. It is clear that, relationship among pore water pressure ratio and number of cycles follows a steady trend. At the end of 20 cycles, the pore water pressure ratio exceeds 50%, showing that cyclic axial strains is changed within a small range. In Fig. 2d, when the PWP ratio reaches 50%, at the end of the 20 cycles, specimen reaches to +0.40 and −0.05% strain levels, a total strain of 0.45%. Fig. 2 also shows that liquefaction is still not visible.

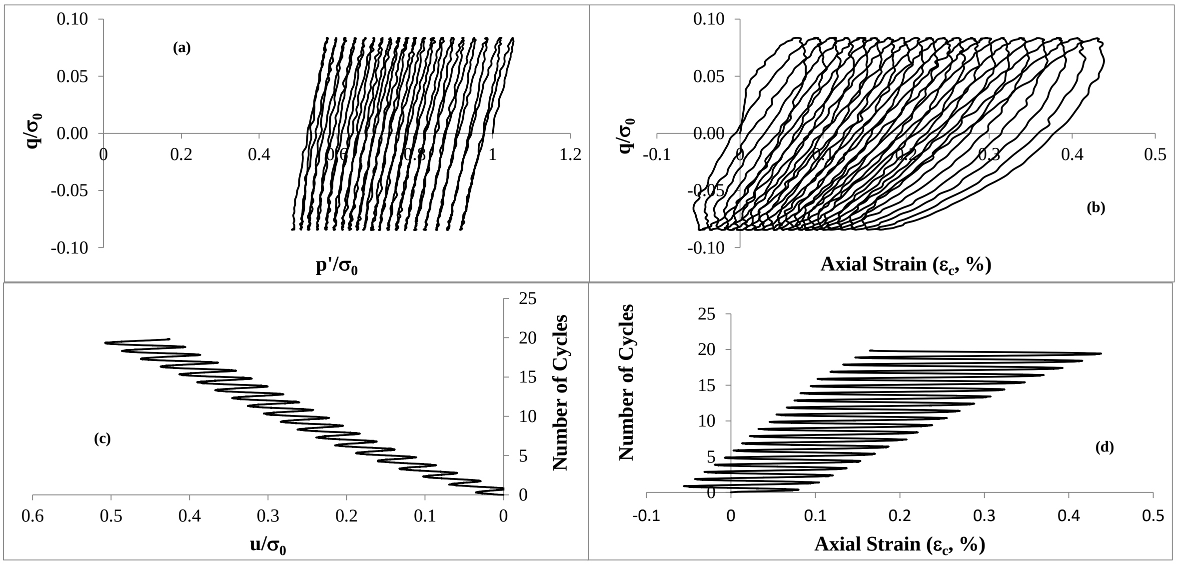

Figure 2*. Variation of* ***(a)*** *q/σ_0 against p'/σ_0* ***(b)*** *q/σ_0 with cyclic axial strain* ***(c)*** *PWP ratio against number of cycles,* ***(d)*** *number of cycles with cyclic axial strain (CSR= 0.168, D_r = 70%, σ_0' = 100 kPa.)*

Results of cyclic triaxial test performed on a specimen of 60% relative density subjected to a cyclic stress ratio of 0.111 is shown in Fig. 3. A fixed deviatoric stress was applied to samples until development of 100% excess pore water pressure (Fig. 3a). In Fig. 3b, induced axial strain is plotted against number of cycles. An excess pore water pressure of 100% was observed after application of 13 cycles of loading. Additionally, variation of pore water pressure ratio with number of cycles is presented in Fig. 3c. It is clear that deviatoric stress stayed unchanged until the end of the experiment. Initially, axial strain increases in soil remained at a lower level, however, to the end of test, it is increased by a high rate. This high rate of increase in axial strain seems to be leveraged beyond an excess pore water pressure in the vicinity of 70%, most probably based on a significant decrease in stiffness of the specimen due to build-up of excess pore water pressure. Furthermore, rate of pore water pressure increase is accelerated beyond aforementioned PWP level. The effective stress path of the silt is illustrated in Fig. 3d. It is shown that the silt loses all its strength and stiffness after build-up of 100% excess PWP. The behavior observed in all tests was similar.

An analysis of pore water pressure build-up behavior is shown in Fig. 4. Test results on samples prepared at a constant relative density (D_r=60%) in agreement with the procedure proposed by Lee and Albaisa is shown [12]. In figure 4, the peak PWP ratio with cycle ratio is obtained for different cyclic stress ratio values. Excess pore water ratio (R_u) is calculated by dividing the generated excess pore water pressure during a particular cycle of loading by initial effective confining pressure. Likewise, the peak pore pressure ratio is the greatest value of PWP ratio at a particular cycle of loading. The cycle ratio is computed by dividing number of loading cycles to total loading cycles until build-up of 100% excess pore water pressure. It is should be emphasized that, pore water pressure build-up behavior for silt is somewhat different from those of clean sands due to effect of particle size, as shown in Figure 4. Effect of number of loading cycles on magnitude of pore water pressure is essentially a function of shearing strain. However, when the same sample is subjected to higher cyclic axial stresses (CSR=0.111 to 0.216) the pore water pressure builds up faster causing a drastic decrease in the effective stress and thereby inducing liquefaction phenomenon under lower cycles of uniform loading.

Lee and Albaisa [12] performed stress controlled dynamic triaxial compression tests on Monterey and Sacramento River sands. They suggested an empirical relationship among excess pore-water pressure ratio (R_u) and cycle number ratio ($N=N_{liq}$). Seed et al. [26] suggested an empirical formula as given in Eq. (1)

$$r_u = \left\{\frac{1}{2} + \frac{1}{\pi} sin^{-1}\left[2 * \left(\frac{N}{N_{liq}}\right)^{\frac{1}{\alpha}} - 1\right]\right\} \tag{1}$$

where, α is related with the test and soil properties. Seed et al. [26] stressed that the average value of α is 0.7. N is the number of loading cycles to liquefaction. The recommended equation was afterwards simplified by Booker et al. [27], adopted in a probabilistic model by Chameau and Clough [28], and later used by Wang and Kavazanjian [29] for prediction of response of pore water pressure under transient loading. Later, this expression was included in a finite element model by Liyanapathirana and Poulos [30]. A statistical reevaluation to method of Seed et al. [26] was made by Polito et al. [7]. The authors emphasized that the equation coefficient α should be calculated as a function of cyclic stress ratio (*CSR*), fines content (*FC*), and D_r, by use of the following equation:

$$\alpha = 0.01166 * FC + 0.007397 * Dr + 0.01034 * CSR + 0.5058 \tag{2}$$

It is suggested that Eq. (2) should be used for soils with a fine content less than 35%. For clean sands of 0% fines content, D_r takes the role as the main controlling parameter. For the obtained coefficients, the α value is between 0.73 and 1.14. A comparison of updated models makes it possible to choose among better functional form and accuracy.

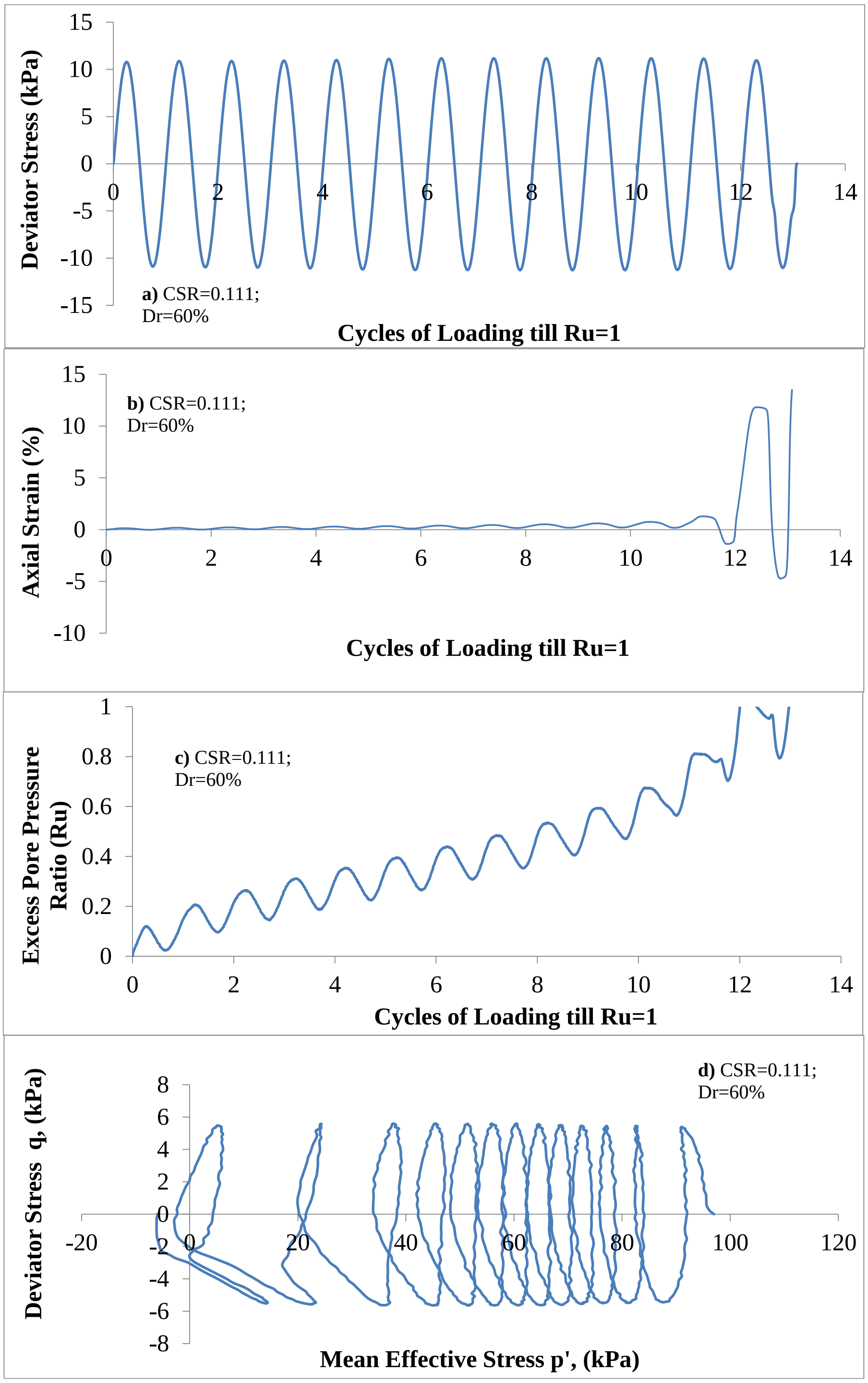

Figure 3. *Plots of **a)** Deviatoric stress against loading cycles till $R_u = 1$; **b)** axial strain against loading cycles till $R_u = 1$; **c)** pore water pressure response till $R_u = 1$; **d)** effective stress path*

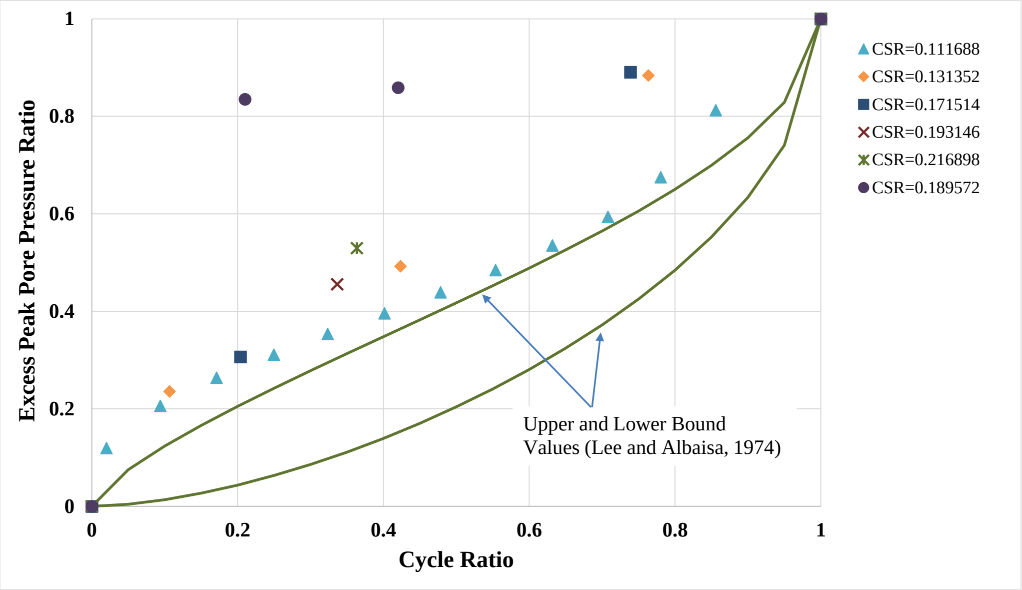

Figure 4. *Typical pore pressure response against cycle ratio as per the method suggested by Lee and Albaisa (1974).*

Table 1. *Summary of limit-state functions, coefficients, and model performances*

Model	Limit State Functions	Model Parameters					MSE
			α_1	α_2	α_3	α_4	
Seed et al. (1975)	$r_u = \frac{1}{2} + \frac{1}{\pi} sin^{-1} \left[2 \left(\frac{N}{N_{liq}} \right)^{1/\alpha_1} - 1 \right]$	O	0.7				0.0374
		U	1.357				
Polito et al. (2008)	$r_u = \frac{1}{2} + \frac{1}{\pi} sin^{-1} \left[2 \left(\frac{N}{N_{liq}} \right)^{1/(\alpha_1 FC+\alpha_2 Dr+\alpha_3 CSR+\alpha_4} - 1 \right]$	O	0.01166	0.007397	0.01034	0.5058	0.0375
		U	0.48007	0.498099	0.500669	0.49543	

O:Original; U:Updated.

Maximum likelihood approach is employed for estimation of model coefficients in updated models. The equations of model parameters and limit state functions are illustrated in Table 1. The performances of the equations are evaluated by simple statistical analysis, by use of mean square error.

In Fig. 5, variation of pore pressure response against cycle ratio is presented, as proposed by Seed et al. [24]. In Fig. 5a, PWP ratio and ratio of number of cycles were plotted for six values of CSR ranging among 0.111 and 0.2168. Afterwards, Eq. 1 was used to calculate corresponding α values for each test and updated data was shown in Fig. 5b.

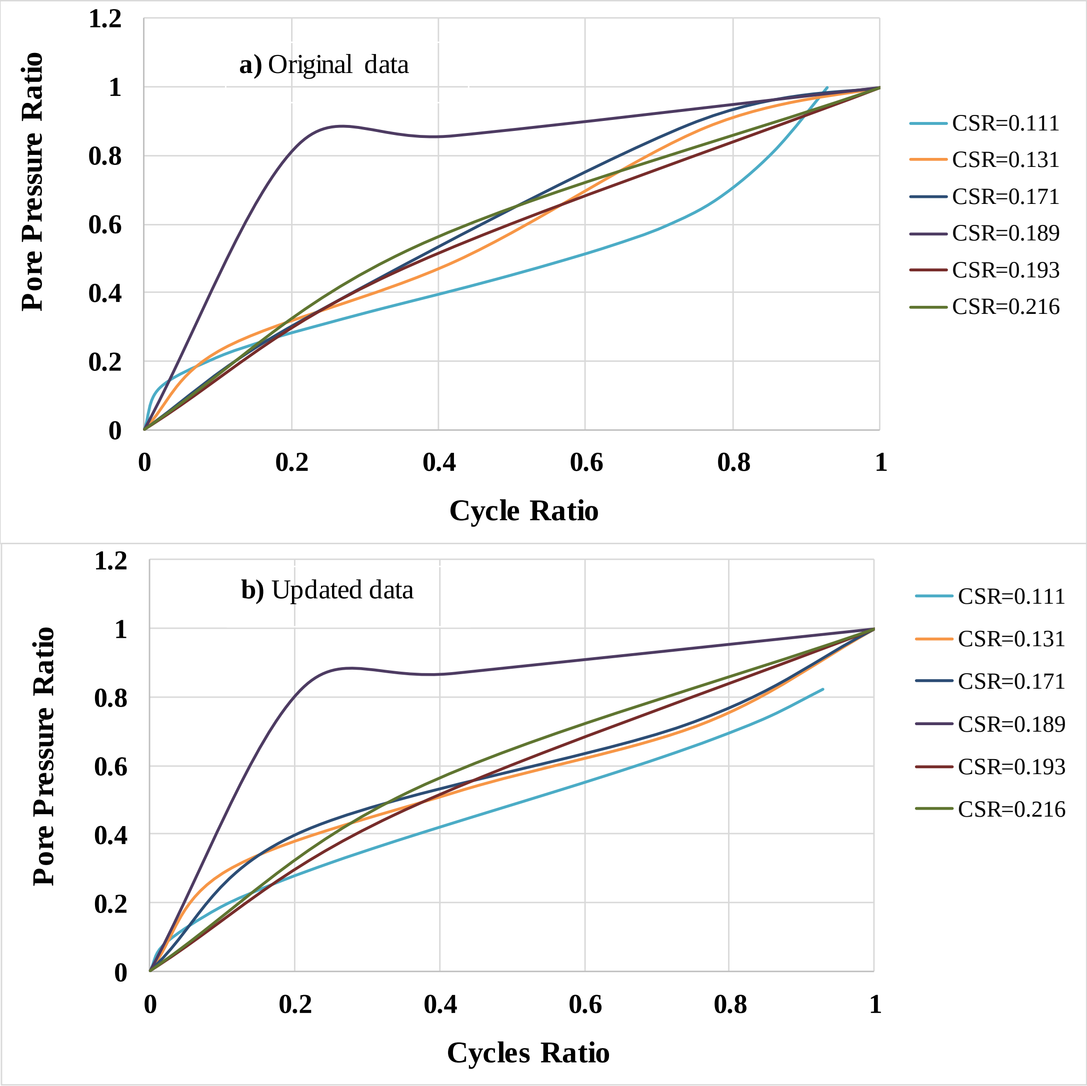

Figure 5. *Pore pressure response - cycle ratio relationship using method suggested by Seed et al. (1975)*

Behavior of pore water pressure build-up leading to liquefaction depends on CSR and relative density of soil. Several empirical methods are available in literature for evaluation and prediction of pore water pressure build-up behavior in fully saturated clean sands. In this way, Marcuson et al. [31] utilized pore water pressure ratio for estimation of degradation of soil stiffness during seismic action. Oda et al. [32] revealed a coherence among the PWP increment at the end of the first loading cycle and the number of cycles necessary to obtain a 5% double-amplitude axial strain in cyclic triaxial tests, irrespective of D_r and *CSR*. Dobry [15] recommended upper and lower boundaries of pore water pressure ratio - shear strain relationship based on strain-controlled cyclic test results on poorly graded sands. Besides, variations in number of cycles corresponding to a pore water ratio of 100% were compared with results obtained in previous research [12]. Lee and Albaisa [12] determined upper and lower boundaries for residual pore pressure ratio in Sacramento sand. Similar relationships for silty clays are proposed by El Hosri et al. [33]. An empirical method for prediction of PWP in clean sands is developed by Seed et al. [26], proposed method provides relationships among above-mentioned parameters: number of cycles to liquefaction increases with increasing relative density and decreases with stress increase. Boundaries determined by use of our data is plotted in accordance with these methods in Fig. 6. As can be seen from Fig. 6a, rate of PWP build-up is markedly faster at early stages of loading until a level of 80%, corresponding to a cycle number ratio of 0.4. Beyond a PWP of 80%, rate of PWP increase diminishes.

Test results also show that liquefaction was not observed below a CSR of 0.168. PWP development is constrained (Fig. 6b).

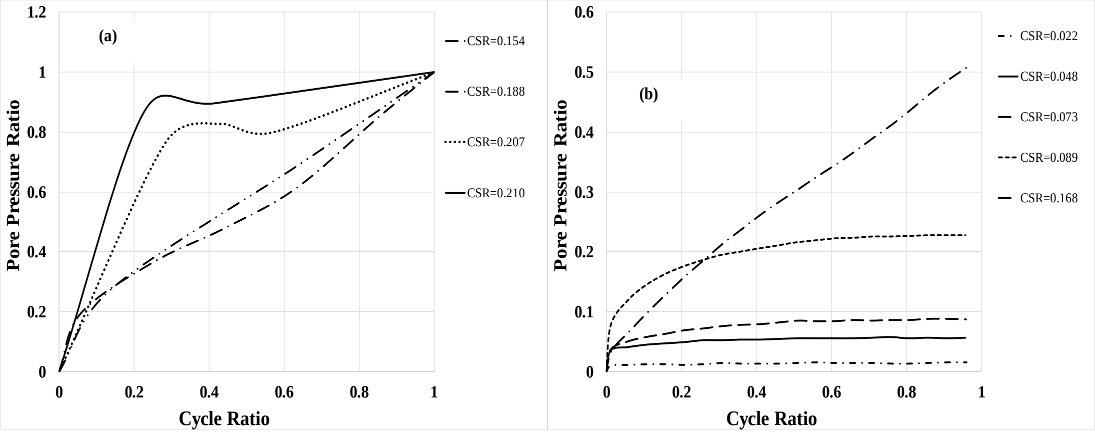

***Figure 6**. Pore water pressure generation behavior for silt (D_r = 70%, σ_0' = 100 kPa).*

IV. CONCLUSION

In this study, undrained cyclic behavior of silt is investigated through laboratory cyclic triaxial tests performed on reconstituted specimens consolidated under effective stress of 100 kPa. In this scope, pore water pressure ratio and cycle ratio of nonplastic silt specimens at relative densities of 60% and 70% were obtained for different cyclic stress ratio values. These values were compared with those of two widely used stress-based models existing in literature. It was observed that, increases in CSR values markedly influence pore water pressure build-up behavior of nonplastic silt. Therefore, liquefaction susceptibility is more pronounced after a certain threshold value of 0.111. Consequently, model parameters were updated for nonplastic silts. This study also proves that liquefaction potential of silt is significantly affected from CSR and pore water pressure increase substantially changes number of cycles leading to liquefaction.

In addition to results obtained, a comparison of the modified model parameters obtained in this study were compared with those obtained by models in literature (D_r=60%~70%). Results revealed that the modified model parameters is capable of predicting pore water pressure build-up behavior of a non-plastic silt. Pore water pressure ratio builds up steadily and levels off at initially applied confining pressure, depending upon the magnitude of cyclic stress ratio. At higher cyclic stress ratios, pore water pressure builds up faster. As a consequence, it is understood that liquefaction in dense silt was triggered at lower number of cycles. It is also concluded that dissipation of pore water pressure for silt will be much slower compared to that of sand due to its low permeability.

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