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Research Article

Evaluation of Pore Water Pressure Generation in Sands Containing Kaolin

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ABSTRACT

Accurately predicting pore-water pressure is essential for comprehending soil behavior under seismic loads and for estimating effective stresses. In recent years, various models have been proposed to estimate pore pressure development for clean sands, silts, and clays. However, in nature, soils often consist of mixed formations. Considering the nature of soil formations, in this study the pore pressure development of clayey sand was investigated. The excess pore water pressure development of clayey sand under dynamic loads using three different models from the literature is analyzed. For this purpose, stress-controlled dynamic triaxial test were performed on specimens prepared poorly graded sands with three different kaolin clay contents (FC=5-15) to measure excess pore water pressure generation at four cyclic stress ratios. Specimens were prepared by using wet tamping method to be ensure homogeneity. The tests were conducted under an effective confining pressure of 100 kPa. The results were used to obtain excess pore water pressure development of clayey sands under undrained dynamic conditions. Then, the results were compared with three different pore water pressure generation models. The model coefficients of three models were updated for clayey sand. Although it was proposed for clean sands, the model presented by Seed et al. [23] has also proven to be quite suitable for clayey sands.

Introduction

Liquefaction is a significant hazard associated with earthquakes. Liquefaction happens when relatively loose saturated soils lose its strength due to increased pore water pressure during seismic loading. During seismic effect, as the drainage rate decreases, the excess pore pressure does not have sufficient time to dissipate, resulting in an increase in excess pore pressure [1, 2]. Thus, in order to comprehensively examine liquefaction behavior, it is necessary to understand the development of excess pore water pressure under cyclic loading. Generally, pore water pressure distribution phenomenon has been searched within various frameworks including plasticity-based, stress-based, deformation-based and energy-based approaches. Moreover, since the excess pore water pressure accumulation is the main mechanism leading to liquefaction, various models have been suggested to predict excess pore water pressure distribution [3-5]. One of the first method for calculation the pore water pressure distribution which marks a significant initial step towards quantitatively formulating liquefaction is suggested by Martin et al. [6]. However, through Martin et al.'s [6] investigation, it was assumed that the volume-change characteristics of dry sand under cyclic loading were related with the pore water pressure increment of saturated sand subjected to undrained cyclic experiments. Then, Ishibashi et al. [7] proposed another model based on the undrained cyclic tests performed on Ottawa sand to address this uncertainty of Martin et al.'s [6] approach and it is still one of the most commonly used model for pore water pressure prediction. In the establishment phase of the model, Ishibashi et al. [7] considered various parameters which were the stress history, the number of cycles and the applied shear stress. Later, Ishibashi et al. [7] and Sherif et al. [8] updated the model by considering additional parameters such density, mean grain size, the coefficient of uniformity and curvature.

Nemat-Nasser and Shokooh [9], focuses on energy dissipation rather than the number of cycles to liquefaction. Subsequently, some researchers have worked on models that obtain pore water pressure generation based on energy [10-13]. Besides, many other earliest models were proposed by Seed et al. [14] and Booker et al. [15] using a stress-based approach. Later, Dobry et al. [16] established strain-based pore water pressure build-up model by considering threshold shear strain. Additionally, Çetin et al. [17] described probabilistic models for evaluating the cyclic large strain and the resulting pore water pressure responses of saturated pure sands. Green et al. [18] and Jafarian et al.

[19], on the other hand, have used an energy-based method approach to determine excess pore water pressure development for cohesionless soils. Besides, Baziar et al. [20] examines the effectiveness of a simple model to estimate pore water pressure development in non-plastic silty sand. Although many models have been proposed for the development of pore water pressure under dynamic loads through a time, these models have generally focused on clean sands and sands with non-plastic silts. It should be noted that in clayey sand, differences in pore water pressure development are observed depending on the plasticity and clay content. Karakan et al. [21-22] updated model parameters suggested by Booker at al. [15], Seed et al. [23] and Polito et. al. [24] for non-plastic silts. Moreover, Chiaradonna et al. [25] updated a simplified model for predicting pore pressure development and proposed new coefficient values for Adapazari silt, Scortichino sandy silt, Monterey sand and Messina sandy gravel considering fine content, relative density and cyclic stress ratio. Porcino and Diano [26] found that for a sand-silt mixture with fines content (FC) below 20%, the β value ranged between 0.6 and 1.0 in the model proposed by Booker et al. [15]. However, considering the fines content between 20 and 35%, the β value showed significant variation, ranging from 0.69 to 1.41. El Hosri et al. [27] conducted cyclic triaxial tests on clean sand and silty clay soils and found that the pore water pressure (PWP) generation behavior in non-plastic sandy soils was different from that in plastic silty clay soils.

Generally, in literature fines have been classified into three categories: non-plastic fines, low-plasticity fines, and high-plasticity fines. The studies mentioned above mostly focus on soils containing non-plastic and low-plasticity fines. In this study, for fines inclusion, kaolin clay with a high plasticity (with a liquid limit of 56) has been chosen to investigate the effect of fines on pore water pressure development. The proposed pore water pressure models have been suggested for sand and silty sands, and the aim of this study is to modify the model and model coefficients for clayey sands with high plasticity. The primary objective of this study is to examine the current cyclic pore water pressure models on clayey sand. For this purpose, kaolin type of clay is selected at three clay inclusion levels (5, 10 and 15%). The pore water pressure buildup of these clayey sands is investigated at different CSR (cyclic stress ratio) levels. The compatibility of the models for clayey sand has been examined and new coefficients were obtained.

Materials and Methods

Materials

The experimental program utilized on fine sand with a mean grain size (D_{50}) of 0.21 mm, characterized by a coefficient of uniformity (C_u) of 1.56 and a coefficient of curvature (C_c) of 0.56. According to the Unified Soil Classification System (USCS), this sand was classified as poorly graded sand (SP). The maximum and minimum void ratios of sand were obtained as 0.98 and 0.63 in accordance with ASTM 4254, ASTM 4253, respectively. In addition, specific gravity of sand was determined as 2.52. Additionally, kaolin type of clay with a plasticity index of 25 was selected to investigate influence of clay content on pore water distribution. The maximum void ratio of kaolin was obtained as 1.43, while the minimum void ratio was achieved as 0.87. The clayey specimens were prepared at 5%, 10%, and 15% clay content. Furthermore, the maximum (e_{max}) and minimum (e_{min}) void ratios for each sand-clay mixture were found according to ASTM D4254 and ASTM D4253 standards and were provided in Table 1.

Table 1. The maximum and minimum void ratio values of clay-sand mixtures

Clay content (%)	Kaolin	
	e_{max}	e_{min}
5	0.87	0.58
10	0.85	0.55
15	0.79	0.49

Specimen Preparation and Experimental Procedure

The experiments were conducted using a cyclic triaxial device manufactured by Seiken company in accordance with JGS 0541-2000 standards, with sinusoidal loading frequencies between 0.001 and 10 Hz (Fig. 1).

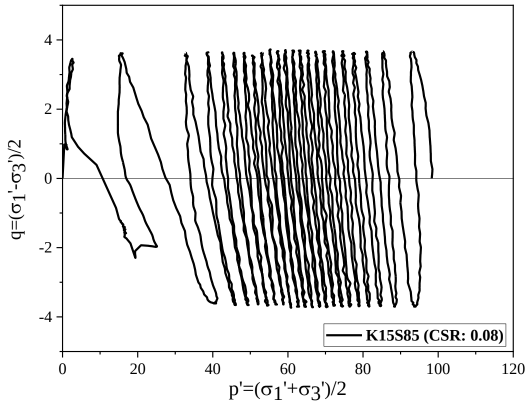
Figure 1. Cyclic triaxial device used in study

The specimens were prepared using the wet tamping method, achieving a moisture content of 5% at a relative density of 50%. Specimen preparation procedure begins with blending sand and clay in dry states in the correct proportions. Then, necessary amount of water is added to this mixture to reach 5% water content, and the mixture is stirred again to obtain homogeneous mixture. Then, the prepared mixture is stored in a humidity room for at least 12 hours to allow the fines to fully saturate. The experimental setup involves placing a membrane and a split mold, followed by applying a -20 kPa vacuum to the mold. The weight of the material required for each layer is measured. The sand or sand-clay mixture is then poured into the mold and compacted at five layers using a wooden tamper. Afterwards, the cell was filled with water and, before releasing the vacuum, a confining pressure of 20 kPa was applied to ensure the specimen remained self-standing. According to the standards, the saturation phase of the specimen generally consists of CO_2 flushing, de-aired water flushing, and back pressure stages. In this case that specimens prepared by using wet tamping method, the voids of the specimens partially filled with water which causes a disturbance of specimens during CO_2 flushing. Consequently, the saturation process is completed by water flushing for a minimum 12 hours and back pressure increment. The specimen is considered saturated when the B value exceeds 0.96.

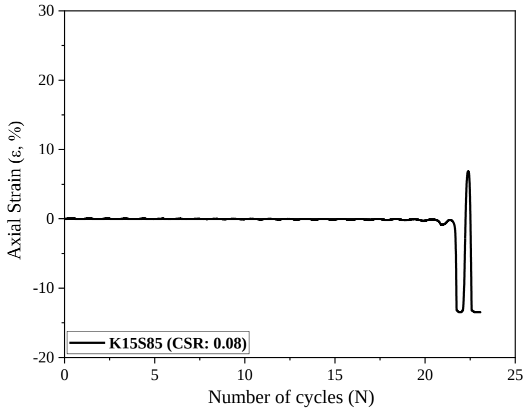
After completing the saturation stage, the specimens consolidated at 100 kPa effective pressure for 2 hours. During this stage, volume change and axial strain were measured and recorded to calculate actual volume and cross section of specimen (Fig. 2).

Figure 2. Consolidated specimen inside the cell before the loading stage.

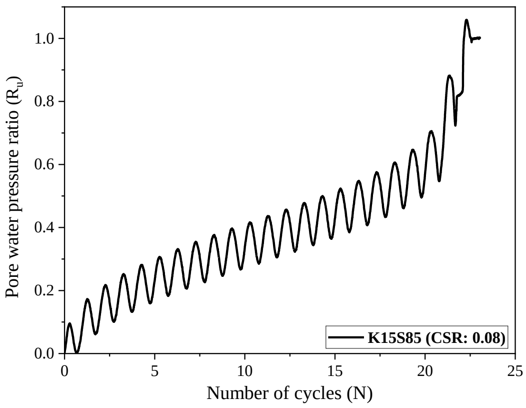
Once consolidation process is completed, specimen is subjected sinusoidal type of cyclic loading with a frequency of 0.1 Hz. According to the JGS 0541-2000 standards, liquefaction happened if either of the following conditions are occurred within 200 cycles; the double amplitude strain is reached 5% or the excess pore water pressure ratio exceeds 0.95. Typical test results obtained from a dynamic triaxial test on clayey sand are shown in the Fig. 3.



(a)



(b)



(c)

Figure 3. Relationship between (a) q and p' (b) axial strain and number of cycles (c) pore water pressure ratio and number of cycles (d)

Pore water pressure generation models

As it is mentioned before, for prediction of excess pore water pressure, various excess pore models have been established for sands. Seed et al. [23] formulated a model from the undrained stress-controlled experiments on clean sand and proposed a relationship between excess pore pressure ratio-the cyclic ratio which is given in Equation 1.

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

Here, α is an empirical constant depending on test conditions and soil properties, also N is number of uniform cyclic loading cycles. According to the test data, Seed et al. [23] recommended a value of 0.70 for parameter "α". Then, this value (α) is revised by Polito et al. [24] regarding to various factors, such as relative density, fine content and CSR.

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

In this equation, FC, D_r and CSR indicate fine content, relative density and cyclic stress ratio. The equation (2) is applicable mostly coarse-grained soils that have a fine content lower than 35%. It should be noted that for clean sands, the main influencing factor is relative density (D_r) and cyclic stress ratio (CSR) is almost negligible. Futhermore, Booker et al. [15] revised to simplify the model established by Seed et al. [23] and presented in Equation (3).

$$r_u = \frac{2}{\pi} sin^{-1}\left[\left(\frac{N}{N_{liq}}\right)^{\frac{1}{2\alpha}}\right] \tag{3}$$

As mentioned before, α is an empirical constant and N_{liq} specify number of cycles to liquefaction. After several stress-controlled undrained cyclic triaxial experiments on silty sands, Baziar et al. [20] modified Equation (3) to adjust the formula for silty soils by using statistical software.

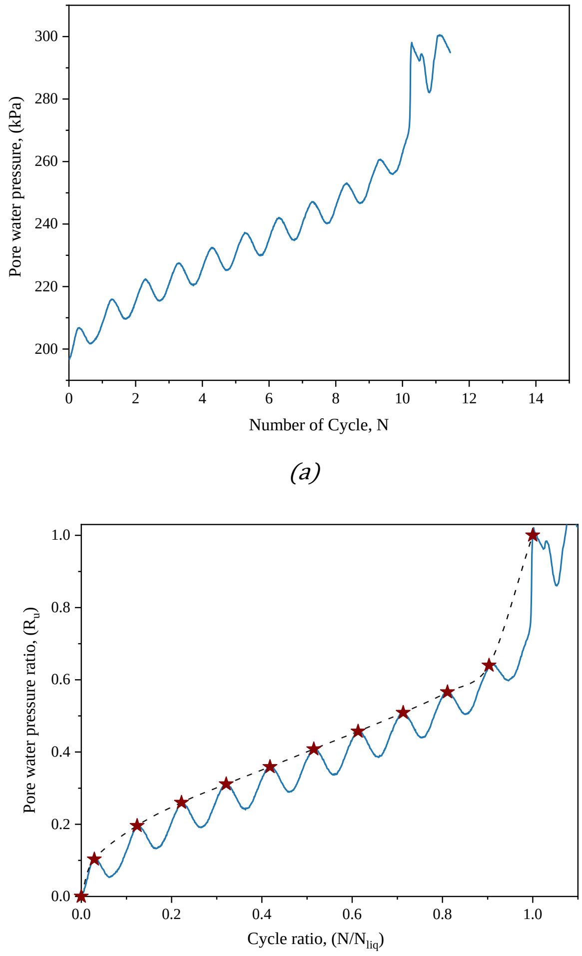
$$r_u = \frac{u_g}{\sigma} = \frac{2}{\pi} sin^{-1}\left(\frac{N}{N_{liq}}\right)^{\frac{1}{2\alpha}} + \beta\sqrt{\left(1 - \left(2\frac{N}{N_l} - 1\right)^2\right)} \tag{4}$$

Although the Seed et al. [23] model closely aligns the measured build-up of pore pressure, model has several limitations. The primary drawback is that it requires N and N_L to be defined a priori, making it unsuitable for coupled numerical analysis. Additionally, the model cannot be applied to non-liquefiable soils, for which N_L cannot be defined. On the other hand, the approach suggested by Seed et al. [23] is relatively simple and widely used model for generating pore water pressure build-up.

Methodology

In this study, excess pore water pressure models proposed by Seed et al. [23], Broker et al. [15] and Polito et al. [24] were used. The "α" value for each model has been calculated for clayey sand with using non-linear least squares fitting.

Firstly, the relationship between the number of cycles and excess pore water pressure was obtained from the dynamic triaxial test results, as shown in Fig. 4a. Since the experiments were conducted under an effective stress of 100 kPa, when the pore water pressure increased by 100 kPa, the effective stress value decreased to zero, resulting in liquefaction. Subsequently, the pore water pressure and the number of cycles in Figure 4a were normalized to apply the models (Fig. 4b). Then, the peak points in each cycle were identified, and the pore water pressure ratio and cycle ratio curve were obtained (Fig. 4b). After obtaining peak values of pore water pressure each cycle, "α" values of for each model were calculated by using non-linear least squares fitting for each experiment. Then, using the models and calculated "α" value, pore water ratio versus cycle ratio curve was drawn and compared with actual experiment curve (Fig. 5).



(b)

Figure 4. a) Pore water pressure and number of cycles b) Pore water pressure ratio and cycle ratio curves

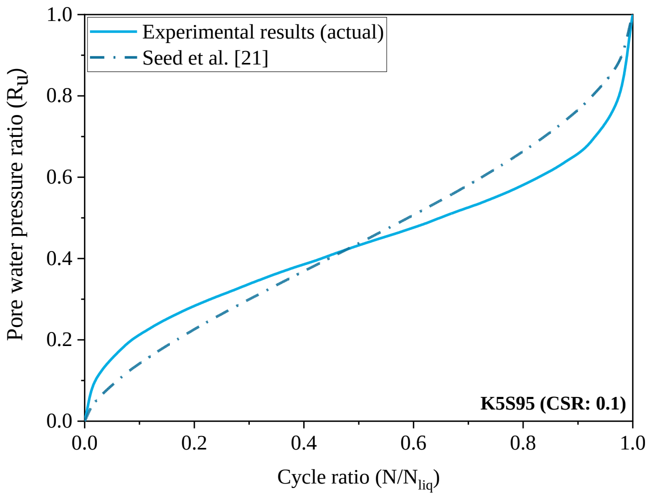


Figure 5. Comparison of the pore water pressure ratio-cycle ratio relationship obtained from experiment with the model obtained by Seed et al. [23]

Results And Discussion

As mentioned before, for clean sands, Seed et al. [23] suggested an "α" value of 0.7 for Equation 1. Upon reevaluation, it was observed that in Seed et al.'s [23] approach, the "α" value was determined to be very close to the original "α" value. However, in Equation 3 established by Booker et al. [15], the "α" value calculated very similar to the Seed et al. [23] approach, despite minimal differences. In light of the data obtained in the laboratory, the "a" values for all three models are presented in Table 2. It was observed that the minimum value of the "a" coefficient is 0.63 and the maximum value is 0.92 for Equation 1. The mean value was calculated as 0.75, which is very close to the value proposed by Seed et al. [23]. Moreover, MSE values varied between 0.001 and 0.009.

In the Booker et al.'s [15] approach, the minimum and maximum values were obtained as 0.65 and 0.92, respectively, with MSE values ranging from 0.0008 to 0.009. Similar to this study, Porcino and Diano [26] found the α value to be between 0.6 and 1 in silty sands with fines content below 20% in soils containing sand and silt. Polito et al. [24] recommended various "α" coefficients based on relative density, fines content, and cyclic stress ratio, for a model originally proposed by Seed et al. [23]. However, the equation can be applied to soils with a fines content of less than 35% (FC <35%). In this study, "α" coefficients suggested by Polito et al. [24] were updated by using experimental results. When the updated equation was examined, it was observed that the CSR value and fines content were more effective than relative density. Comparing the coefficients obtained with the "α" coefficients proposed by Polito et al. [24], it was determined that, specifically for sands containing kaolin clay, the effect of CSR was greater. It was also determined that relative density did not show a significant difference. However, it can be said that as the plasticity of fines increases, their percentage also has a greater impact on the α parameter.

In Fig. 6a, the relationship between pore water pressure ratio (R_u) and cycle ratio of experimental results were presented. Then, pore water pressure ratio (R_u) and cycle ratio relationship obtained by using non-linear least squares fitting was shown in Fig. 6b. Considering Fig. 6b, it was observed that the pore water pressure formed in a narrower range when comparing with experimental results, which was also emphasized by Karakan et al. [22]. This situation was observed more distinctly in the Polito et al. [24] and Booker et al. [15] models.

Table 2. Limit state functions and updated coefficients of models

Model	Limit State Functions		α_1	α_2	α_3	α_4
Seed et al. [23]	$r_u = \left\{\frac{1}{2} + \frac{1}{\pi}\sin^{-1}\left[2 * \left(\frac{N}{N_{liq}}\right)^{\frac{1}{\alpha}} - 1\right]\right\}$	Maximum	0.92	-	-	-
		Mean	0.75	-	-	-
		Minimum	0.63	-	-	-
		Original value	0.70			
Booker et al. [15]	$r_u = \frac{2}{\pi}\sin^{-1}\left[\left(\frac{N}{N_{liq}}\right)^{\frac{1}{2\alpha}}\right]$	Maximum	0.92	-	-	-
		Mean	0.77	-	-	-
		Minimum	0.65	-	-	-
		Original value	Ranged according to soil type			
Polito et al. [24]	$r_u = \left\{\frac{1}{2} + \frac{1}{\pi}\sin^{-1}\left[2 * \left(\frac{N}{N_{liq}}\right)^{\frac{1}{\alpha}} - 1\right]\right\}$ $\alpha = \alpha_1 * FC + \alpha_2 * D_r + \alpha_3 * CSR + \alpha_4$		0.0935	0.00826	0.111	0.7617
		Original value	0.01166	0.007397	0.01034	0.5058

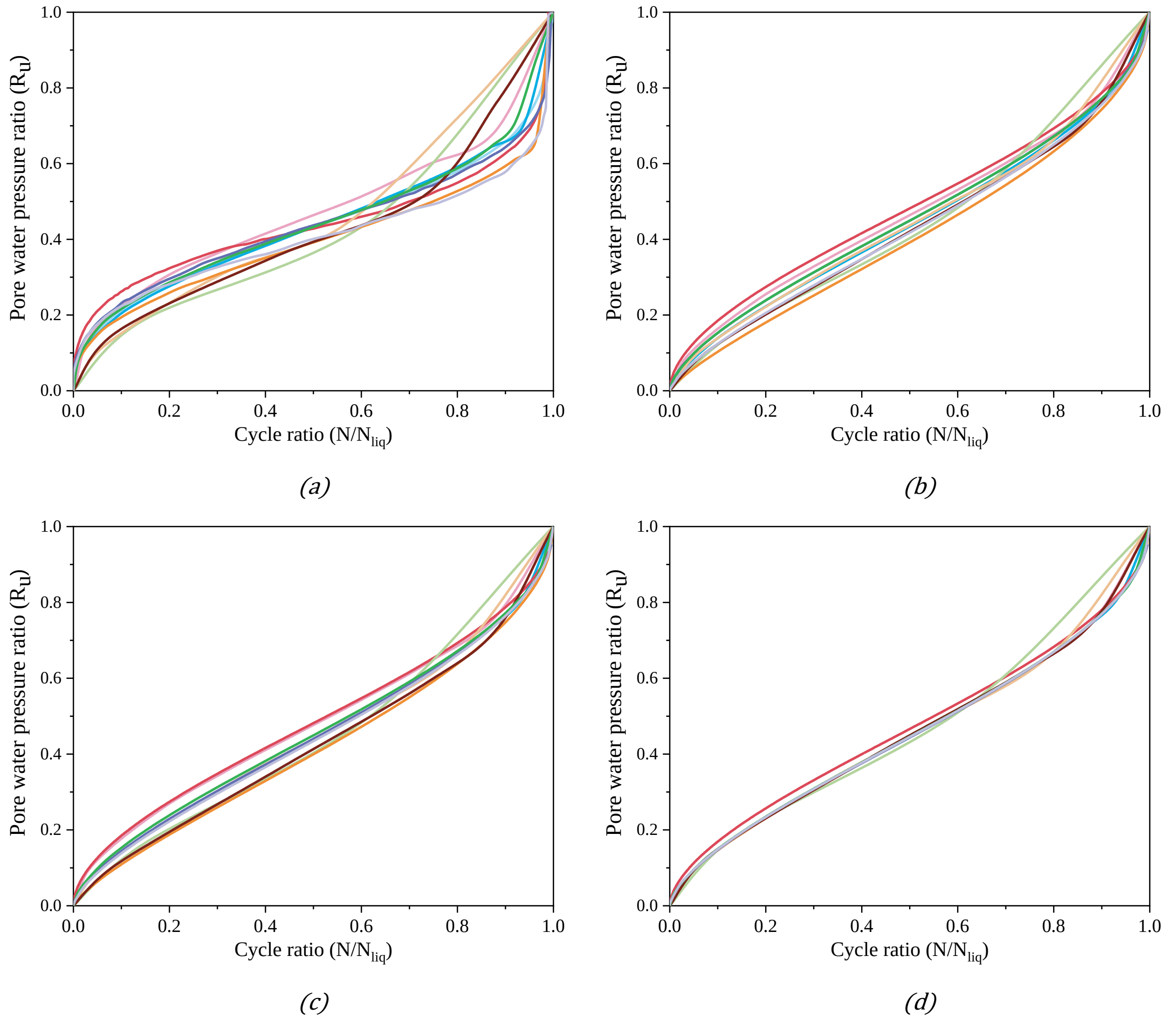


Figure 6. Pore pressure response -cycle ratio relationship obtained (a) from experiments (b) from method suggested by Seed et al. [23] (c) from method suggested by Booker et al. [15] (d) from method suggested by Polito et al. [24]

Conclusion

In this study, pore water pressure build-up under undrained cyclic triaxial experiments on clayey sand was investigated. Moreover, empirical models for pore water pressure generation by considering pore water pressure ratio-cycle ratio response of clayey sand are discussed from the literature. Suggested coefficients were updated according to experimental results. Three different pore water pressure generation models were examined, and the new coefficients were proposed for sand with kaolin clay. Considering the models and coefficients proposed by Seed et al. [23], Booker et al. [15], and Polito et al. [24], it was determined that the existing coefficients were quite close to the obtained coefficients, and the model proposed by Seed showed higher performance compared to the other models in sandy soils containing kaolin. Considering the coefficients in the model proposed by Polito [24], it has been observed that for the modified model (for sand containing kaolin), the fine-grained content is more effective compared to the original model. Moreover; it has been determined that the pore water pressure models proposed for sand and silty sands can also be used for clayey sands with minor modifications.

Ethics committee approval and conflict of interest statement

There is no need to obtain permission from the ethics committee for the article prepared. There is no conflict of interest with any person / institution in the article prepared.

Authors' Contributions

Bozyigit I: Study conception and design, acquisition of data, analysis and interpretation of data, drafting of manuscript

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