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A CRR-based calibration method for pore pressure models

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ABSTRACT

In a recent study, a calibration method for pore pressure models was proposed based on well-known triggering liquefaction curves to consider the various aspects that affect the liquefaction of sand. The previous calibration method considered the behavior of clean sand, the effect of critical stress ratio, earthquake magnitude, and initial stress level. However, the proposed calibration factors were clearly biased towards a specific set of cyclic resistance ratios (CRR) for clean sand. To remove such limitation, a CRR-based calibration approach is introduced in this study so that the pore pressure model can be readily applied for various soils. Factors affecting the CRR including fines content, static bias, K_0, and others are already readily available in the literature, and using the CRR as an input parameter widens the application of the pore pressure model. Results showed that for the same CRR and D_r, the calibration factor increases as N_{liq} decreases while CF increases for the same N_{liq} and CRR as D_r increases. Relationships of D_r, N_{liq}, and CRR with CF were very scattered. It was concluded that finding relationships between the above variables can be difficult.

1. INTRODUCTION

To increase global trade and to develop residential and commercial areas in South Korea, land reclamation projects such as the Songdo international business district

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project and Saemangeum development project have been initiated in the country. However, reclaimed lands are known to be vulnerable to liquefaction especially if the reclaimed deposits are not properly treated. Reclamation projects require geotechnical analysis, and liquefaction assessment of these natural and artificially placed soils have not been widely investigated in the country.

Pore pressure models can be a valuable tool in understanding the liquefaction mechanism of soils because they can relate major factors that affect liquefaction resistance based on direct measurement of pore pressure data (Kim et al. 2023). One of the earliest pore pressure models was developed by Seed et al. (1975). The model was formulated based on the equivalent number of uniform cycles and the number of cycles to cause liquefaction. Ishibashi et al. (1977) and Sherif et al. (1978) also proposed a pore pressure model that predicts the pore pressure rise under uniform and non-uniform dynamic shear stresses based on undrained cyclic shear experiments conducted on saturated Ottawa sand. Kim et al. (2023) reported that there was a discrepancy between Ottawa sand and clean sand. Based on the experiments conducted by Sherif et al. (1978), Ottawa sand is more resistant to liquefaction at lower densities. In addition, the trend of their experiments tended to favor lower CRR at higher $(N_1)_{60}$ values for Ottawa sand as compared to the clean sand. As a result of the above-mentioned discrepancies, a method in adjusting the incremental pore pressure by use of calibration factors was introduced by Kim et al. (2023) so that the pore pressure model can be calibrated based on the effect of the peak stress ratio, earthquake magnitude, and initial stress levels.

However, the calibrated model proposed by Kim et al. (2023) has some limitations, and requires additional aspects to be considered to be able to closely replicate the actual behavior of various soils. Numerous factors including fines content, static bias, K_0, and others affect the liquefaction resistance of soils. Basically, the calibration factors obtained by Kim et al. (2023) were based on the behavior of the clean sand from chosen research, which can result in biases. Varying behaviors of pore pressure rise are to be expected from different soils in various test devices, and recalibrating the pore pressure model can be tedious. In this study, a calibration approach based on the cyclic resistance ratio (CRR) is introduced so that the pore pressure model can be readily applied for various types soils. The main objective of this study is to generate a database of calibration factors for various CRRs, relative densities, and number of cycles to liquefaction.

2. THEORETICAL BACKGROUND

The governing equation of the density-based pore pressure model proposed by Kim et al. (2023), which is based on the model proposed by Ishibashi et al. (1977) and Sherif et al. (1978), is given in Eq. (1). In Eq. (1), N is the cycle number, ΔU_N is the normalized incremental excess pore water pressure at the current stress cycle, U_{N-1} is the normalized total excess pore water pressure at the previous stress cycle, τ_N is the shear stress during the current stress cycle, σ'_{N-1} is the effective pressure from the previous stress cycle, α is the power of the stress ratio (τ_N/σ'_{N-1}), and D_r is the relative density.

$$\Delta U_N = (1 - U_{N-1})\left(\frac{\tau_N}{\sigma'_{N-1}}\right)^{\alpha} \cdot \frac{\left(0.025 \cdot D_r{}^{-3.49} + 1.97\right) \cdot N}{N^{\left(2.07 \cdot D_r{}^{4.47} + 1.77\right) - [1.6 \cdot sin(0.37 \cdot D_r + 2.8) + 0.07 \cdot sin(8.1 \cdot D_r - 0.6)]}} \tag{1}$$

Calibration factors CF and CF_{crit} are introduced to adjust the original predicted curve of the pore pressure model (pre-calibrated curve), as shown in Eq. (2). CF is applied to each of the incremental pore pressure rise per half-cycle throughout the duration of cyclic loading while CF_{crit} is only applied when ($\tau_N/\sigma'_{N\text{-}1}$) is greater than or equal to the critical stress ratio $(\tau/\sigma')_{crit}$. In this study, $(\tau/\sigma')_{crit}$ is defined as the stress ratio at the start of the stage wherein the rate of excess pore water pressure accumulation starts to increase and goes off course from the nearly constant rate of pore pressure buildup from the previous stage (Sherif et al. 1977; Konstadinou and Georgiannou 2014). The critical stress ratio $(\tau/\sigma')_{crit}$ is determined by drawing a line on the graph that intersects with the portion where the rate of pore pressure buildup is constant. The stress ratio that last intersects the line is determined as the critical stress ratio.

$$\Delta U_{N,calib} = CF \cdot CF_{crit} \cdot \Delta U_N \tag{2}$$

Once ($\tau_N/\sigma'_{N\text{-}1}$) exceeds $(\tau/\sigma')_{crit}$, the values of two parameters in the pore pressure model, namely α and CF_{crit}, are changed. Konstadinou and Georgiannou (2014) deduced that the value of α increases by about 2.83 times the initial value of α when ($\tau_N/\sigma'_{N\text{-}1}$) is greater than $(\tau/\sigma')_{crit}$. The initial value of α is denoted as α_i and has a value equal to (2.63-D_r) while α_i multiplied by 2.83 is denoted as α_{crit}, as shown in Eq. (3). This change in α allows for the rate of pore pressure rise to slowly transition into a rapid rate after $(\tau/\sigma')_{crit}$ is achieved. For CF_{crit}, its value is 1.0 when ($\tau_N/\sigma'_{N\text{-}1}$) is less than $(\tau/\sigma')_{crit}$ and increases to a value greater than 1.0 when ($\tau_N/\sigma'_{N\text{-}1}$) is greater than or equal to $(\tau/\sigma')_{crit}$. The value of CF_{crit} is related to relative density as given by Eq. (4). $(\tau/\sigma')_{crit}$ can be determined based on D_r and $(\tau/\sigma')_{peak}$, as given by Eq. (5). For the values of ϕ_{cv} and parameter n^b in Eq. (5), Boulanger and Ziotopoulou (2017) suggested that the default value of ϕ_{cv} for clean sand is 33° while the default value of n^b is 0.5 when the relative state parameter index (ξ_r) < 0 and 0.125 when $\xi_r > 0$.

$$\alpha_{crit} = 2.83 \cdot \alpha_i \tag{3}$$

$$CF_{crit} = 5.121 \cdot D_r{}^{-6.34} + 18.27 \tag{4}$$

$$\begin{aligned}(\tau/\sigma')_{crit} &= \left(2.729 \cdot D_r{}^{5.105} + 0.2678\right) \cdot (\tau/\sigma')_{peak} \\ &= \left(2.729 \cdot D_r{}^{5.105} + 0.2678\right)[0.5 \cdot \sin(\phi_{cv}) \cdot \exp(-n^b \cdot \xi_r)]\end{aligned} \tag{5}$$

The values of CF are to be determined by trial and error based on the CRR, which can be a tedious method. To accelerate the determination of CF, the pore pressure model was coded in Matlab such that CF increases from a value of 0 until the value of the normalized total excess pore pressure (U) at a chosen CRR or applied stress ratio (τ/σ'_0) and number of cycles to liquefaction (N_liq) is equal to or greater than 0.99. In other terms, when the predicted U after N_liq is less than 0.99, the previous value of CF is increased incrementally, and the pore pressure rise from N = 1 to N_liq is calculated again until the failure criterion is satisfied. To ensure that the obtained value of *CF* is satisfactory, it is necessary to use smaller increments, however, very small increments could result in longer calculation times. There have been numerous equations proposed in the literature to determine the value of CRR, as well as the factors that affect them. They can be found in the research by Youd et al. (2001), Cetin et al. (2004), Idriss and Boulanger (2008), and many others.

3. CALIBRATION DATA

In this study, the three important variables for calibration are relative density (D_r), number of cycles to liquefaction (N_{liq}), and the cyclic resistance ratio (CRR). The value of these variables are given in Table 1, and combinations of these variables resulted in the determination of 1540 calibration factors. Relationships between the CF, D_r, N_{liq}, and CRR are shown in Figs. 1 and 2. In Fig. 1, it can be seen that for the same CRR and D_r, the calibration factor increases as N_{liq} decreases while in Fig. 2, it can be seen that CF increases for the same N_{liq} and CRR as D_r increases. Histogram plots of various variables are show in Fig. 3. Looking at Fig. 3d, it can be seen that a considerable amount of CF data are in the zone of values less than 25 while higher values of CF are scarce. This is because CF values greater than 100 are mostly related to CRR values lower than 0.05. It should be noted that CRR values lower than 0.05 are typically rare.

Table 1. Values of variables used in obtaining calibration factors (*CF*)

Variable	Values	Total number of calibration factors (CFs) obtained
D_r	0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.75	1540
N_{liq}	2 , 4, 8 , 12, 20, 30, 50, 75,125, 200	
CRR	0.01 to 0.65	

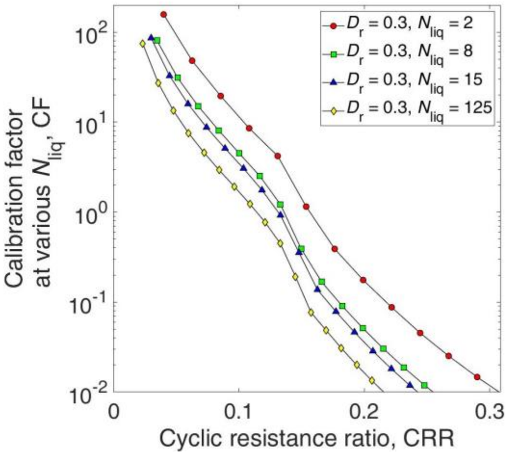


Fig. 2. Relationship between CRR, N_{liq},

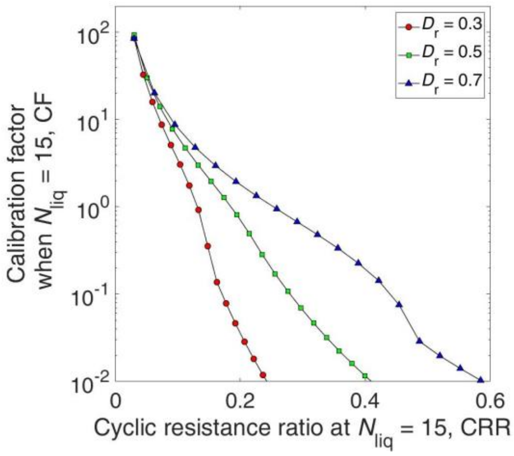
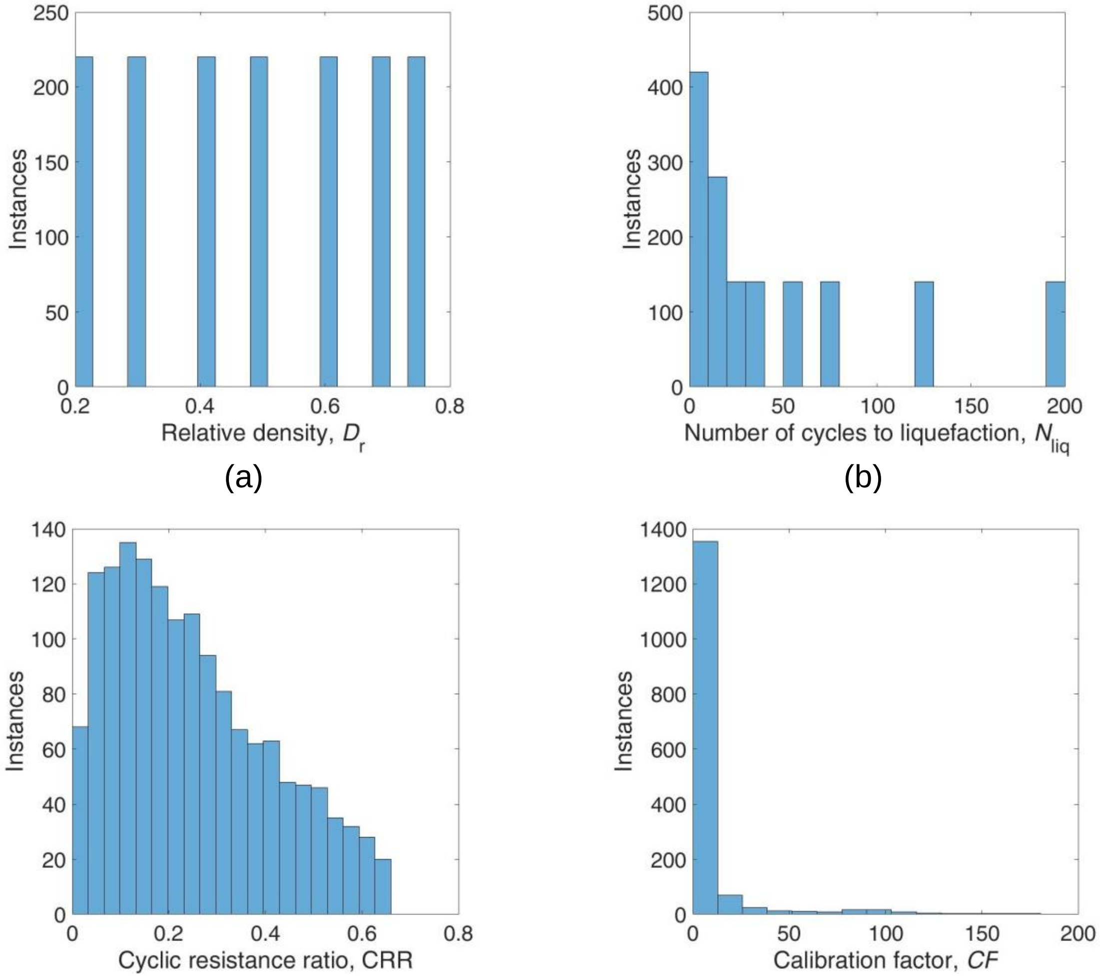


Fig. 3. Relationship between CRR, D_r,

and *CF* and *CF*



(a) (b)

(c) (d)

Fig.4. Histogram plot of various variables: a) D_r, b) N_{liq}, c) CRR, and d) *CF*

4. APPLICATION OF MACHINE LEARNING METHODS FOR PORE PRESSURE MODEL CALIBRATION

A summary of the data obtained by calibration of the pore pressure model and the relationships between variables is shown in Fig. 5. Based on Fig. 5, it can be seen that there are no clear trends between D_r, N_{liq}, and CRR. In addition, relationships of D_r, N_{liq}, and CRR with *CF* are very scattered. It can be concluded that finding relationships between these variables can be difficult. Due to the innumerable calibration factors (CFs) obtained from datasets of relative density, CRR, and number of cycles to liquefaction, it may be necessary to use machine learning (ML) methods such as artificial neural networks (ANN) and regression learning methods. The previous calibration method introduced by Kim et al. (2023) used numerous combinations of nonlinear equations.

With the numerous amounts of data obtained in this study, finding relationships between these variables can result in high inaccuracy. ML can be used to train the data obtained in this study to easily obtain the CF for various D_r, CRR, and N_{liq}, which allows for the pore pressure model to be easily applied for any type soil.

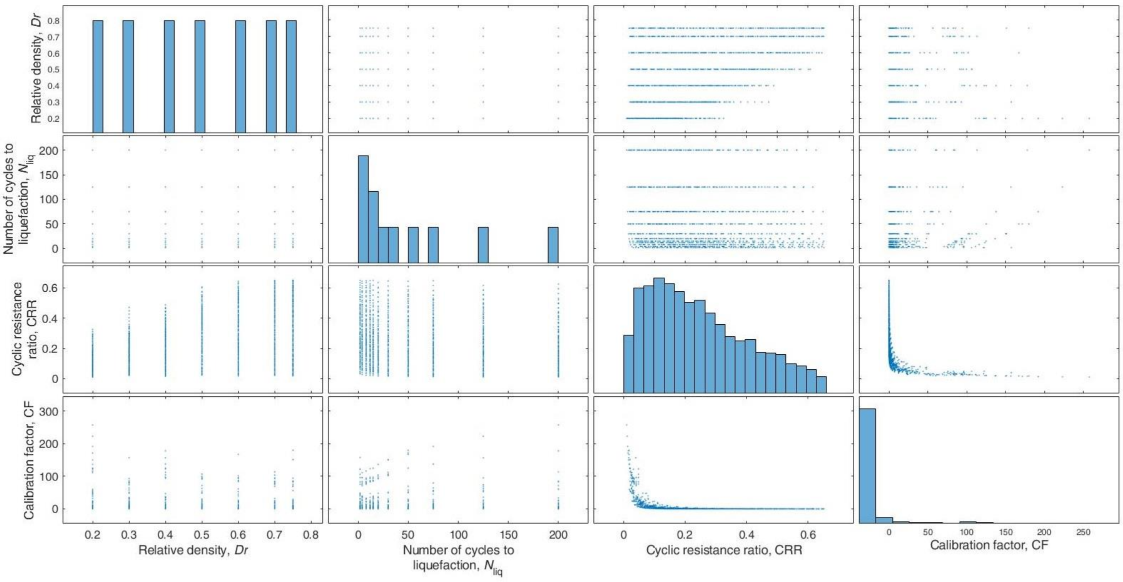


Fig. 5. Summary of the data obtained by calibration of the pore pressure model and the relationships between variables

5. CONCLUSIONS

In a recent study, a calibration method for pore pressure models was proposed based on well-known triggering liquefaction curves to consider the various aspects that affect the liquefaction of sand. However, the proposed calibration factors were clearly biased towards a specific set of cyclic resistance ratios (CRR) for clean sand. In this study, a calibration approach based on the cyclic resistance ratio (CRR) is introduced so that the pore pressure model can be readily applied for various soils. The main objective of this study is to generate a database of calibration factors for various CRRs, relative densities, and number of cycles to liquefaction. Results showed that for the same CRR and D_r, the calibration factor increases as N_{liq} decreases while CF increases for the same N_{liq} and CRR as D_r increases. Relationships of D_r, N_{liq}, and CRR with *CF* were very scattered. It was concluded that finding relationships between the above variables can be difficult. Due to the innumerable calibration factors (CFs) obtained from datasets of relative density, CRR, and number of cycles to liquefaction, it may be necessary to use machine learning (ML) methods such as artificial neural networks (ANN) and regression learning methods.

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