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Research Article

The Effect of the Nonplastic Fines on the Cyclic Resistance of the Saturated Sand-Fines Mixtures

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A series of undrained cyclic triaxial tests were carried out to study the nonplastic fines on the cyclic behaviour of saturated sand-fines mixtures. The influences of the fines content (FC), global void ratio (e), and relative density (D_r) were considered. The results show that the cyclic resistance ratio (CRR) of the mixtures firstly decreases and then increases, finally stabilizing with increasing FC when the samples are prepared at a constant D_r. The CRR reaches its minimum when the FC is 20%. However, the CRR decreases and then increases with increasing FC when the samples are prepared at a constant e. The CRR reaches its minimum when the FC is at 30%. The CRR of the mixtures increases with increasing D_r when the FC is given. A single D_r or e cannot describe the dense state of the mixture effectively. A new index, D_r/e, is proposed in this study to describe the dense state of the mixtures. A semiempirical model is proposed to evaluate the CRR of the mixtures using the parameters of D_r/e and FC of the mixture based on the back analysis method. The applicability of the model is verified by the test data from this study and other scholars. In addition, the parameters of D_r/e and FC of the mixture can be obtained from basic geotechnical tests, which is convenient for the application of the model.

1. Introduction

Liquefaction is a special phenomenon wherein the excess pore pressure of a mass of soil increases and the shear resistance decreases when subjected to a monotonic, cyclic, or dynamic load. The mass undergoes very large unidirectional shear strains; it appears to flow until the shear stress is as low as or lower than the reduced shear resistance [1]. Such a phenomenon leads to the lateral spreading of gently sloping ground, densification and vertical ground settlements, and slope instability. The loss of life and damage to facilities and infrastructure due to liquefaction were very significant in past earthquakes, such as those in Kobe, Wenchuan, and east Japan [2–4]. For these reasons, soil liquefaction is one of the most important and complex issues studied in geotechnical earthquake engineering. Scholars have devoted themselves to the phenomenon's investigations, and many significant results have been achieved [5–11]. For many years, the phenomenon of liquefaction was thought to be limited to sand. Finer-grained soils were considered incapable of generating high pore pressures, which were commonly associated with soil liquefaction. Therefore, most of the previous research work on soil liquefaction has been focused on relatively clean sands [12–14]. However, natural sandy soils, though, contain fines (passing sieve no. 200, particle size less than 0.074 mm) more or less. Natural sands are always mixed with fines. Such combinations are called silty sands or sand-fines mixtures. Historically, many cases of earthquake-induced liquefaction were observed to occur in silty sands. Field performance data during earthquakes indicated that liquefaction-related failures had also occurred at sites with silty sands and sandy silts. For example, liquefaction occurred in the sands induced by the Chi-Chi earthquake was with very high fines content (FC) [15]. Therefore, the effect of FC on the liquefaction behavior of sand-fines mixtures has elicited particular interest from scholars in the past few decades, and plenty of test data are available in the technical literature.

However, many data points and conclusions in the technical literature are seemingly contradictory, and the subject of the effect of FC on the liquefaction behavior of sand-fines mixtures seems to be associated with confusion.

For the laboratory test, Amini and Qi [16], and Chang et al. [17], among others, found that the cyclic resistance ratio (CRR) of the sand-fines mixtures increased with the increase of the FC, which meant the FC exerts a positive effect on the liquefaction resistance of the mixtures. However, Troncoso and Verdugo [18], Vaid [19], Chien et al. [20], and Papadopoulou and Tika [21], among others, found that the CRR decreased with the increase of the FC, which meant the FC exerts a negative effect on the liquefaction resistance of the mixtures. In addition, Dash et al. [22], Polito and Martin [23], Xenaki and Athanasopoulos [24], and Thevanayagam [25, 26], among others, held the view that the CRR decreased firstly and then increased with the FC increasing from low to high, which meant the FC exerts a negative effect on the liquefaction resistance of the mixtures in the low FC but exerts a positive effect in the high FC. It is believed that the FC plays an important role in determining the sand structure and the consequent extreme void ratios. These, in turn, have significant influences on the compressibility and liquefaction potential of a sand deposit [27]. There exists a threshold value of fines content, FC_{th}, which is not unique but it may depend on the characteristics of the coarse and fine grains, as well as on the value of the global void ratio (e) of the mixtures. Cabalar et al. [28] studied the compressional behavior of gravel and clay mixture and believed that the FC_{th} is the boundary between fine-domination and coarse-domination of a mixture. Thevanayagam [26] proposed a conceptual framework by introducing intergranular and interfine void ratio to describe the contact state of the mixtures rather than e. Rahman et al. [29, 30] proposed a semiempirical formula to calculate FC_{th}. Cabalar and Hasan [31] and Monkul and Ozden [32] studied the compressional behavior of a sand and clay mixture. The intergranular void ratio was used to express the compressive response of the mixture. Wei and Yang [33, 34] proposed a critical state constitutive model for the silty sands to describe the mechanical behavior and studied the cyclic behavior and liquefaction resistance of silty sands with the presence of initial static shear stress. Furthermore, Yang et al. [35] believed that e was a better parameter to describe the contact and mechanical behavior of the sand-fines mixtures than the skeleton void ratio. It was logically inconsistent with the assumption underlying the concept of the skeleton void ratio that fines make no contribution to the force transfer.

With respect to the conflicting conclusions in the technical literature and the confusion about the effect of the FC on the liquefaction behaviour of sand-fines mixtures, a series of undrained cyclic triaxial test investigations were carried out to understand the cyclic behaviours of saturated sand-fines mixtures, especially the CRR. The influences of FC, e, and D_r were considered. A new index, D_r/e, is proposed in this study for the dense state of the sand-fines mixtures. A semiempirical model is proposed to evaluate the CRR of the sand-fines mixtures using the parameters of D_r/e and FC of the fines based on the back analysis method. The test results and proposed model are good references for engineering practice.

2. Undrained Cyclic Triaxial Tests

2.1. Testing Materials. Fujian sand was used as the host sand material. Fujian sand is one type of clean sand in China, which has been widely used in recent studies. Stone powder was used as nonplastic fines. The mixtures of Fujian sand and stone powder are called FS for convenience. The FC of FS mixtures are 10%, 20%, 30%, 40%, and 50%. The particle size distribution curves of FS mixtures under various FC are schematically illustrated in Figure 1. The basic properties of the sand and fines are listed in Table 1.

2.2. Testing Apparatus and Method. The undrained cyclic triaxial tests were carried out using a DYNTTS-type cyclic triaxial test system manufactured by GDS Instruments, UK. The full view of the apparatus is shown in Figure 2. The axial force, displacement, confining pressure, and back pressure of the test system can be independently controlled by the equipment, and monotonic or cyclic loads can be applied according to the test requirements. The maximum dynamic load that can be applied in the test system is 10 kN and the frequency is 2 Hz. The axial force and displacement are controlled by a servo motor in the base, which can apply sine, cosine, and other forms of loads or displacements with an accuracy of 0.1 kPa and 0.001 mm. The confining pressure is applied using water. The volume precision of the confining pressure and back pressure controller can reach 1 mm^3 and the pressure precision can reach 0.1 kPa (maximum value of 2 MPa). The overall accuracy of the test system is high enough to meet the accuracy requirements of the tests.

The cylindrical specimen has a diameter of 50 mm and height of 100 mm. The specimen was prepared using a dry tamping method, which has previously been used by several scholars to test granular material [36, 37]. The well-mixed sand and fines were tamped into a cylindrical specimen preparation device for four layers in the dynamic triaxial apparatus using the dry tamping method. The presaturation was conducted after the specimen preparation. The presaturation consists of 3 steps: (1) permeating the specimen with CO_2 for 30 minutes; (2) flushing with deaired water for 60 minutes; (3) and flushing all water lines. After the presaturation, the back pressure saturation was initiated. Back pressure was gradually applied and the Skempton B-value was checked until it was greater than 0.95, which guaranteed the saturation of the tested sample. The saturated sample was consolidated under an effective target confining pressure until the variable quantity of the back pressure volume was smaller than 5 mm^3 every 5 minutes. The sample was tested thereafter. The undrained cyclic triaxial tests were performed in accordance with the ASTM D5311D/5311M standard [38].

The influences of the FC, e, and D_r were considered to study the cyclic behaviours of saturated sand-fines mixtures, especially the CRR. The undrained cyclic triaxial tests were

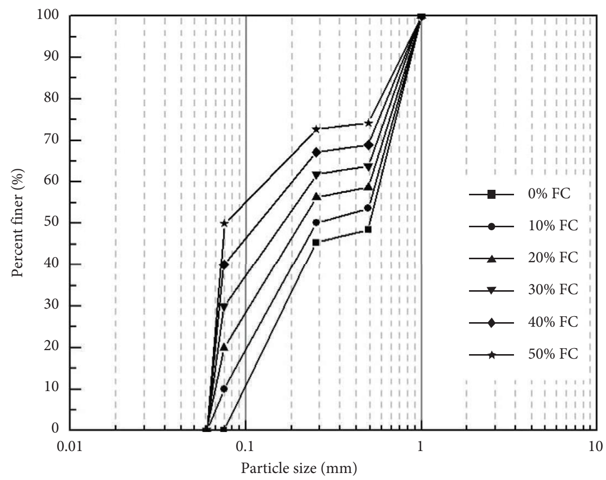

Figure 1: Grain size distribution curves of the sand and soil mixtures.

Table 1: Basic properties of the sand and fines used in the test.

Type	G_s	ρ_{max} (g/cm^3)	ρ_{min} (g/cm^3)	e_{max}	e_{min}	C_u	C_c
Fujian sand	2.64	1.888	1.616	0.634	0.398	5.368	0.523
Stone powder	2.65	1.626	1.215	1.181	0.630	—	—

Note. G_s means specific gravity; C_u means coefficients of uniformity; C_c means coefficients of curvature; e_{max} and e_{min} mean maximum and minimum global void ratio, respectively. ρ_{max} and ρ_{min} mean maximum and minimum dry density, respectively.

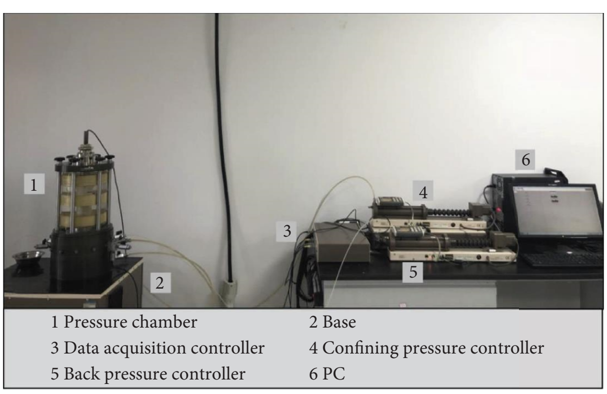

Figure 2: GDS dynamic triaxial apparatus.

conducted at various cyclic stress ratios (CSRs). The CSR of the sample in an isotropic consolidation state is defined in equation (1) [39]

$$\mathrm{CSR} = \frac{\sigma_d}{2\sigma_0'}, \tag{1}$$

where σ_d is the applied sinusoidal cyclic axial stress amplitude.

The maximum and minimum global void ratios of FS with various FCs are shown in Figure 3. The values were determined according to the ASTM D4253 and D4254 standards [40, 41].

A series of undrained cyclic triaxial test investigations were carried out to understand the cyclic behaviours of saturated sand-fines mixtures, especially the CRR. The influences of the FC, e, and D_r were considered. The detailed

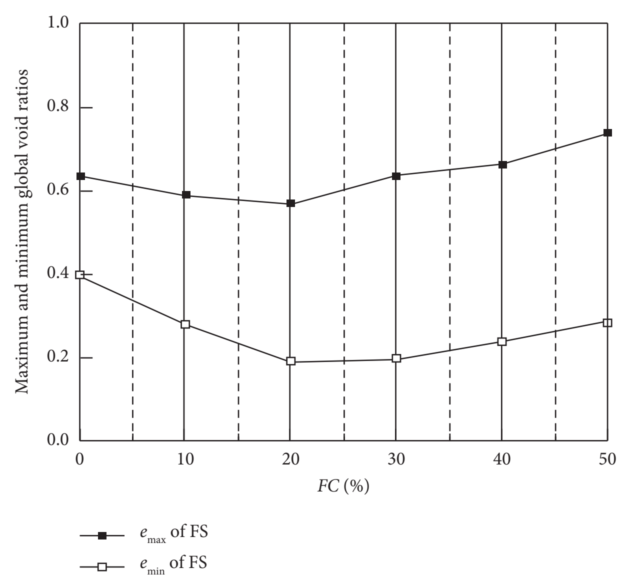

Figure 3: Maximum and minimum global void ratios of FS with various FCs.

undrained cyclic triaxial test conditions are shown in Table 2. The effective confining pressure (σ_0') and loading frequency (f) of the test are 100 kPa and 0.1 Hz, respectively.

3. Test Results and Analysis

3.1. Liquefaction Criterion. With respect to the liquefaction failure of the soil mass under cyclic load, Seed and Lee [5] deemed that the effective stress and shear strength of the soil

Table 2: Detailed undrained cyclic triaxial test conditions.

Mixture	Sand	Fines	FC (%)	D_r (%)	e	σ_0' (kPa)	f (Hz)
FS	Fujian sand	Stone powder	0/10/20/30/40/50	50	—	100	0.1
FS	Fujian sand	Stone powder	10/20/30/40/50	—	0.474	100	0.1
FS	Fujian sand	Stone powder	20	40/50/60	—	100	0.1

mass were 0 when liquefaction occur. However, Casagrande [42] focused on the flow characteristics of liquefied soil and suggested that liquefied soil had a steady-state shear strength and that damage was mainly manifested as excessive deformation, displacement, or strain. For the undrained cyclic triaxial laboratory test, the liquefaction criteria of clean sand in an isotropic consolidation state are divided into two types. The first type is the pore pressure criterion. The pore pressure increment (Δu) of the sample is equal to σ_0', which means that the excess pore pressure ratio ($R_u = \Delta u/\sigma_0{}'$) under cyclic load is 1. The second type is the deformation criterion. The single amplitude strain (ε_{SA}) of the sample reaches 2%~3%, and the double amplitude strain (ε_{DA}) reaches 5% under cyclic load. Considering that the specimen cannot be completely saturated and the excess pore pressure ratio cannot be 1, $\varepsilon_{DA} = 5\%$ was selected as the initial liquefaction criteria in this study.

3.2. Cyclic Resistance Ratio Analysis. The correlations between the CSRs of the FS mixtures with various FCs and the number of initial liquefaction cycles (N_L) are shown in Figure 4. The N_L is defined as the number of cycles required to lead to the initial liquefaction of the sample under a certain CSR. All samples were prepared at a D_r of 50%. As shown in Figure 4, *FC* has significant effects on the CSR of the mixtures. The CSR curves significantly differ with increasing FC. The N_L of a mixed sample with a certain FC increases with decreasing CSR. The results show that the relationship between the CSR and N_L of sandy soil can be described using the following equation [43]:

$$\mathrm{CSR} = \alpha N_L^{\beta}. \tag{2}$$

The test data for the CSR and N_L of various mixtures were fitted using this equation. The fitting curves are shown in Figure 4.

The CRR is defined as the CSR that leads to the initial liquefaction of the soil at a certain N_L. The N_L was selected to be 15 in this study. Therefore, the CRR of various sand-fines mixtures is represented by CRR_{15} in this study. The correlations between the CRR_{15} and FC of FS mixtures prepared at a constant D_r are shown in Figure 5.

Figure 5 shows that the CRR_{15}s of FS mixtures nonlinearly change with increasing FC. The CRR_{15}s firstly decrease and then increase, finally stabilizing with increasing FC.

FC_{th}, the threshold fines content, is 20% when the samples are prepared at a constant D_r.

The correlations between the CSR of samples prepared at a constant e with various FCs and the N_L are shown in Figure 6. The e of the FS mixtures is 0.474. The curves fitted

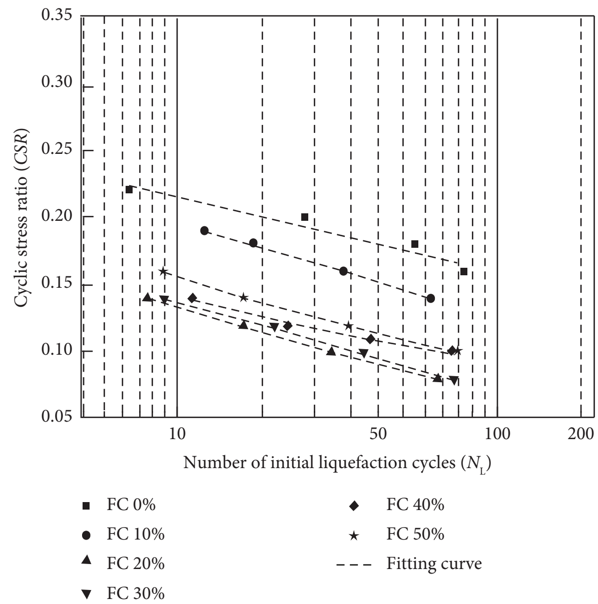

Figure 4: Correlations between the CSR and N_L of FS mixtures at a constant D_r.

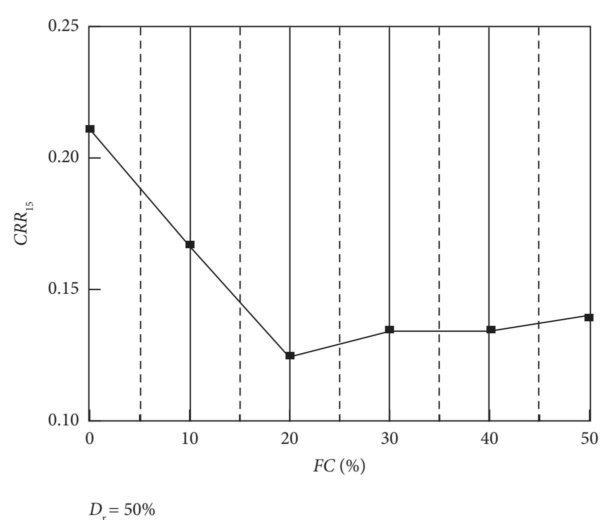

Figure 5: Correlations between the CRR_{15} and FC of various mixtures at a constant D_r.

using equation (2) are also shown in Figure 6. The correlations between the CRR_{15} and FC of FS mixtures prepared at a constant e are shown in Figure 7.

As shown in Figure 7, the CRR_{15}s of the FS mixtures nonlinearly change with increasing FC. The CRR_{15} values decrease and then increase with increasing FC. The FC_{th} of FS mixtures prepared at a constant e is 30%.

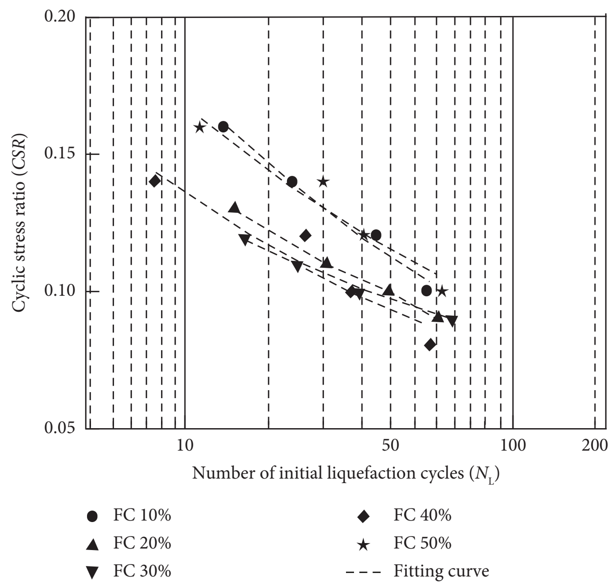

Figure 6: Correlations between the CSR and N_L of FS mixtures at a constant e.

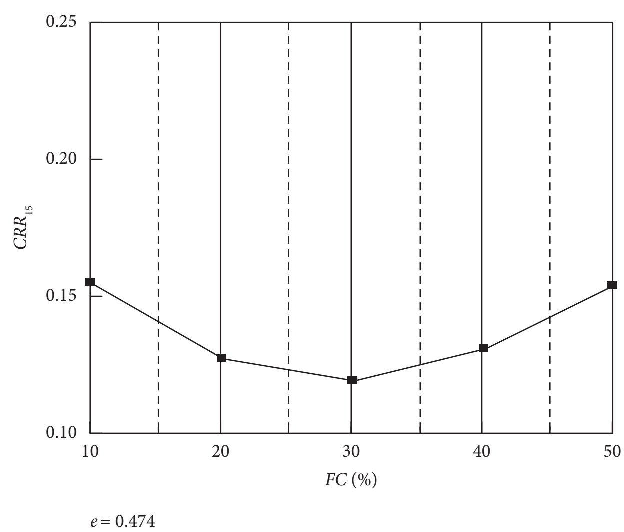

Figure 7: Correlations between the CRR_{15} and FC of various mixtures at a constant e.

It can be noted that the CRR_{15} change trend of the mixture samples prepared at a constant e has both similarities and differences compared with that of the samples prepared at a constant D_r. The CRR_{15} of the two groups of samples first decreases with increasing FC. The reason for this decrease is that the fines occupy the voids between the coarser particles, smoothen the roughness, and reduce the interlocking shear strength of the coarser particles with a low FC. Therefore, the CRR_{15} first decreases. The CRR_{15} increases with increasing FC when the samples are prepared at a constant e. The reason is that the fines become the skeleton to bear the load and the sands suspend in the fines. The fines impede the relative movement of the coarser particles and lead to an increase in the CRR_{15}. However, the e of the samples prepared at a constant D_r increases with increasing FC, which leads to a decrease in the CRR_{15}. The CRR_{15} of the samples prepared at a constant D_r is stable under increasing e and FC. In addition, the FC_{th} of FS mixtures prepared at a constant D_r is 20%. However, the FC_{th} of FS mixtures prepared at a constant e is 30%. The FC_{th} varies with the sample preparation standard. In a word, the correlations between the CRR_{15} and FC of mixtures prepared at a constant D_r differ from those of samples prepared at a constant e. It is significant to define a constant D_r or e before the test.

The correlations between the *CSR* values of the FS mixture with an FC of 20% under various D_r values and the N_L are shown in Figure 8. The curves fitted using equation (2) are also shown in Figure 8. As shown in Figure 8, the D_r affects the CSR of the mixtures. The CSR-N_L curves shift upwards with the increase in the D_r from 40% to 60%, which means that the CRR of the mixtures increases with increasing D_r.

As shown in Figure 9, the CRR_{15}s of FS mixtures increases almost linearly with the increasing D_r. The e of the

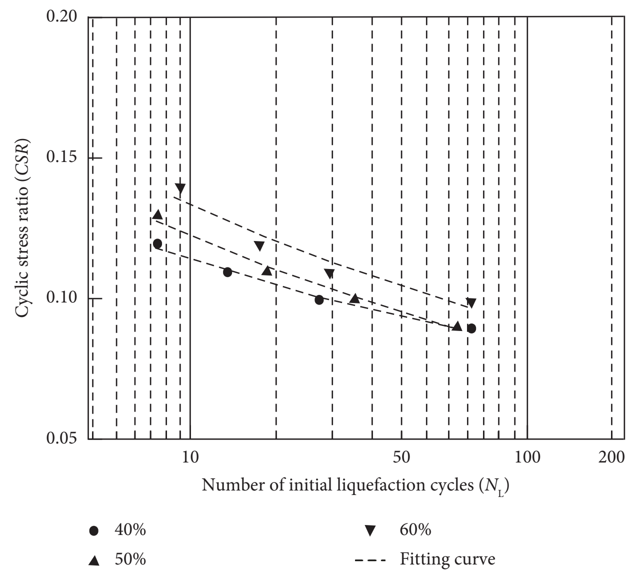

Figure 8: Correlations between the CSR and N_L of various mixtures for various D_r values.

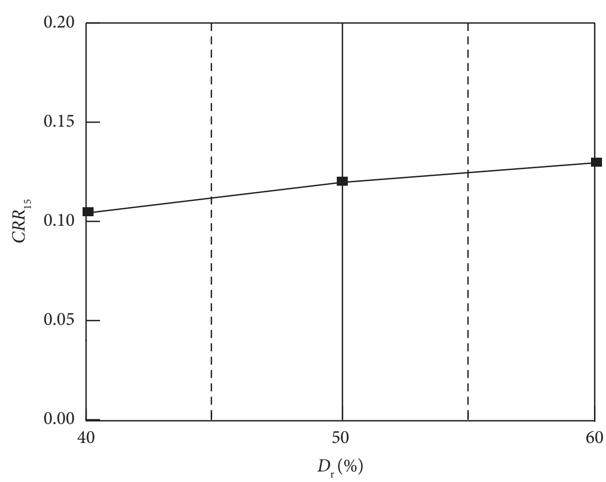

Figure 9: Correlations between the CRR_{15} and D_r of various mixtures at a constant FC.

mixtures decreases with increasing D_r, which is not conducive to the development of excess pore pressure. Therefore, the CRR of the mixtures increases with increasing D_r.

3.3. Semiempirical Evaluation Model for the CRR. The test results show that the correlations between the CRR_{15} and FC of sand-fines samples prepared at a constant D_r differ from those of samples prepared at a constant e. The FC_{th} of FS mixtures prepared at a constant D_r is 20%. However, the FC_{th} of FS mixtures prepared at a constant e is 30%. The findings mean a single D_r or e cannot describe the contact state of the mixture effectively. In addition, the CRR_{15} of the mixture under a certain FC increases with the increasing D_r and decreases with the increasing e. As a result, a new index, D_r/e, is proposed in this study to describe the dense state of the sand-fines mixtures. A semiempirical model is proposed to evaluate the CRR of the sand-fines mixtures using the parameters of D_r/e and FC based on the back analysis method. The model can be described using equation (3), where a, b, c, d, h, and g are the fitting parameters.

$$\mathrm{CRR} = a \times \left(\frac{D_r}{e}\right) + b \times (\mathrm{FC}) + c \times \left(\frac{D_r}{e}\right)^2 + d \times (\mathrm{FC})^2 + h \times \left(\frac{D_r}{e}\right) \times (\mathrm{FC}) + g. \quad (3)$$

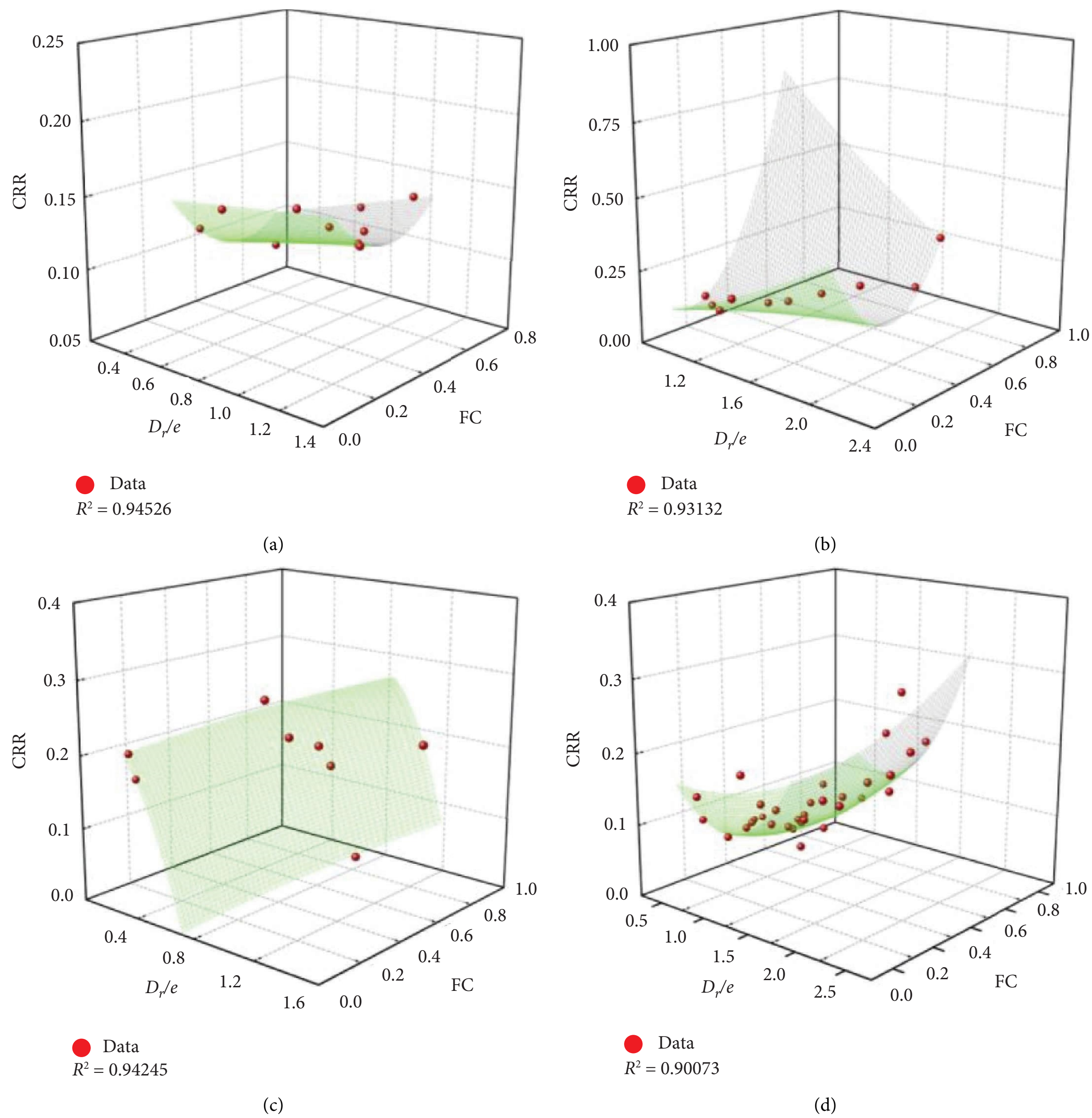

Figure 10: Fitting results based on the semiempirical model. (a) FS. (b) Dash et al. (c) Polito et al. (d) Sitharam et al.

Table 3: Fitting parameters for the test data.

Data origin	a	b	c	d	h	g	Goodness of fit (R^2)
FS	0.01441	−0.47054	−0.0015	0.59764	0.06797	0.18254	0.94256
Dash et al.	0.12892	0.44739	0.06984	3.19421	−1.27473	−0.02852	0.93132
Polito et al.	0.09642	−0.38099	−0.01038	−1.74485	0.21685	0.23737	0.94245
Sitharam et al.	−0.03493	−0.78730	0.03086	1.00981	0.12429	0.20793	0.90073

The test data obtained in this study were fitted using equation (3). The fitting results are shown in Figure 10. The data obtained from the study of Dash et al. [22], Polito and Martin [23], and Sitharam et al. [44] are also fitted using the model to verify its applicability. The fit results of the data from other studies are shown in Figure 10. The fitted parameters for the test data of the study and other references are listed in Table 3.

It can be seen from Table 3 that the goodness of fit for the test data of FS, Dash et al., Polito et al., and Sitharam et al. are 0.94256, 0.93132, 0.94245, and 0.90073, respectively. All the values of the goodness of fit are larger than 0.9, which means the proposed model is applicable for the CRR evaluation of sand-fines mixtures with nonplastic fines. In addition, the parameters of D_r/e and FC of the mixture can be obtained from basic geotechnical tests, which is convenient for the application of the model.

4. Conclusions

A series of undrained cyclic triaxial test investigations were carried out to understand the cyclic behaviours of saturated sand-fines mixtures, especially the CRR. The influences of the FC, e, and D_r were considered. A new index, D_r/e, is proposed in this study to describe the dense state of the sand-fines mixtures. A semiempirical model was proposed to evaluate the CRR of saturated sand-fines mixtures based on the test results of this study and other references. The following conclusions can be drawn:

(1) Both the FC and D_r (or e) affect the CRR of the sand-fines mixtures when the effect of the FC on the CRR is considered. It is important to define a constant D_r or e before the test. The CRR of the sand-fines mixtures firstly decreases and then increases, finally stabilizing with increasing FC when the samples are prepared at a constant D_r. The CRR reaches its minimum when the FC is 20%. However, the CRR decreases and then increases with increasing FC when the samples are prepared at a constant e. The CRR reaches its minimum when the FC is at 30%. The CRR of the sand-fines mixtures increases with increasing D_r.

(2) A single D_r or e cannot describe the dense state of the mixture effectively. A new index, D_r/e, is proposed in this study to describe the dense state of the sand-fines mixtures. A semiempirical model is proposed to evaluate the CRR of the sand-fines mixtures using the parameters of D_r/e and FC of the mixture based on the back analysis method. The applicability of the model is verified by the test data from this study and other scholars.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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