Influence of fines content on liquefaction resistance of fine-coarse-grained soil mixtures

Influence de la fine teneur sur la résistance de liquéfaction des mélanges de sols à grain fin

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ABSTRACT

In order to investigate liquefaction resistance *CRR* of fine-coarse-grained soil mixtures, a series of undrained cyclic triaxial tests were performed on fine-coarse-grained soil mixtures with different fines content *FC* and relative density D_r. According to the theory of intergrain contact state, the fine-coarse-grained soil mixtures are categorized as coarse-like soil, fines-like soil and in-translation soil. Skeleton void ratio e_{sk} was used as a contact density index to describe the intergrain contact state which compose the skeleton of fine-coarse-grained soil mixtures, and the parameters *b* and *m* were used to characterize the contribution of the fines and coarse grains fraction to the transition between coarse-like and fines-like behavior in fine-coarse-grained soil mixtures. The test results show that as *FC* increasing, the *CRR* of fine-coarse-grained soil mixtures with the same D_r decreased first, thereafter, it remained constant; in addition, the *CRR* of fine-coarse-grained soil mixtures with different *FC* and D_r decreased with the increase of the e_{sk}; the parameters *b* and *m* for fine-coarse-grained soil mixtures tested in this study are 0.15 and 0.80. Moreover, the test data obtained in this study revealed that e_{sk} can used as an index to uniquely evaluate the *CRR* of fine-coarse-grained soil mixtures, and a power relationship between a decrease in *CRR* and an increase in e_{sk} was then obtained

RÉSUMÉ

Pour étudier la résistance de liquéfaction *CRR* des mélanges de sols à grain fin, une série d'essais triaxiaux cycliques non drainés ont été réalisés sur des mélanges de sols à grain fin, à teneur en particules fines *FC* et densité relative D_r. Selon la théorie de l'état de contact entre grains, les mélanges de sols de grain fin et grossier sont classés comme des sols de type grossier, des sols fins et des sols en translation. On a utilisé l'e_{sk} de rapport de vide de squelette comme indice de densité de contact pour décrire l'état de contact entre grains qui composent le squelette de mélanges de sol à grain fin, et les paramètres *b* et *m* ont été utilisés pour caractériser la contribution de la fraction des fines et des grains secondaires à la transition entre le comportement de type grossier et fin dans les mélanges de sols à grain fin. Les résultats des essais montrent que lorsque le *FC* augmente, le *CRR* des mélanges de sols à grain fin grossier avec le même D_r diminue d'abord, puis il reste constant; En outre, le *CRR* des mélanges de sols à grain fin grossier avec différents *FC* et D_r a diminué avec l'augmentation de l'e_{sk}; Les paramètres *b* et m pour les mélanges de sols à grain fin et grossier testés dans cette étude sont de 0,15 et 0,80. De plus, les données d'essai obtenues dans cette étude ont révélé que l'e_{sk} peut être utilisé comme un indice pour évaluer de manière unique le *CRR* des mélanges de sol à grain fin, et une relation de pouvoir entre une diminution du *CRR* et une augmentation de l'e_{sk} a puis été obtenue.

KEYWORDS: fines-coarse-grained soil mixtures; liquefaction resistance; intergrain contact state; fines content

1 INTRODUCTION

Recent earthquake case histories indicate that natural soils and man-made sandy deposits that contain a significant amount of finer-grains (silty sands or clayed sands) and/or gravel do liquefy and cause lateral spreads (Ishihara, 1985; Munenori et al, 1997; Chu et al, 2000). Experience grained from past literatures on clean sands does not always directly translate to such broadly graded soils. Recognition of this has lead to a lot of laboratory and field studies to evaluate the effect of increasing fines content on: (a) liquefaction resistance, (b) collapse potential, (c) steady state strength, (d) shear wave velocity, etc. Results from laboratory studies on clean sands mixed with fines content show that, there is no uniformly correlation between liquefaction resistance and fines content. Polito and Martin (2001) found that the liquefaction resistance of fines-coarse-grained soil mixtures with the same void ratio first decreases with increasing fines content, as the fines content continues to increase, the liquefaction resistance begins to increase; but for the mixtures with the same relative density, the liquefaction resistance keeps almost constant with the increase of fines content, and then decreases as long as fines content more than 30%. Hsiao et al (2015) assumed that the liquefaction resistance of fines-coarse-grained soil mixtures with the same relative density decreases with the increasing fines content. Therefore, it is necessary to investigate the effect of different particle compositions and density state on the liquefaction resistance of fines-coarse-grained soil mixtures systemically.

This paper presents the results of an investigation into the effects of fines content on the liquefaction resistance of fine-coarse-grained soil mixtures. Nearly 123 cyclic triaxial tests were performed on mixtures with different fines content ranging from 0 to 100%. The liquefaction resistance was evaluated using the fines content and skeleton void ratio of the specimen.

2 THEORY OF INTERGRAIN CONTACT STATE

In order to describe the effect of fines content *FC* on the mechanical properties and responses of fines-coarse-grained soil mixtures, the theory of intergrain contact state was proposed by Thevanayagam (2007). With the increase of *FC*, the intergrain contact state of fines-coarse-grained soil mixtures can be constituted by infinite different ways. Each one of them leads to a different internal force chain network among grains and hence each exhibits a different stress-strain response during cyclic loading, among infinite variations, a few extreme limiting contact state of microstructure and the relevant roles of coarser and finer grains are as follows:

case 1: the contact state is when the finer grains are fully confined within the void spaces between the coarser-grains with no contribution whatsoever in supporting the coarser grain skeleton. They may largely play the role of "filler" of intergranular voids. The mechanical behavior is affected primarily by the coarser grain contacts.

case 2: a part of fines grains act as a load transfer vehicle between "some" of the coarse-grain particles in the soil matrix while the remainder of the fines play the role of "filler" of voids.

case 3: fines grains play an active role of "separator" between a significant number of coarse grains contacts and therefore begin to dominate the strength characteristics, while the coarse grains may act as reinforcing elements embedded within the fines grain matrix.

Case 4: the fines grains carry the contact and shear forces while the coarse grains are fully dispersed.

In order to distinguish this four different intergrain contact states, minimum in-transition fines content ($FC_{\text{in-min}}$), threshold fines content (FC_{th}) and maximum in-transition fines content ($FC_{\text{in-max}}$) were employed, $FC_{\text{in-min}}$, FC_{th} and $FC_{\text{in-max}}$ can be calculated as follows (Thevanayagam, 2007):

$$FC_{\text{in-min}} = (e_{\text{c-max}} - e)/(e_{\text{c-max}} + 1) \tag{1}$$

$$FC_{\text{th}} = e/e_{\text{f-max}} \tag{2}$$

$$FC_{\text{in-max}} = 1 - \pi(1+e)/6s^3 \tag{3}$$

Where e is the global void ratio of fines-coarse-grained soil mixtures, $e_{\text{c-max}}$ and $e_{\text{f-max}}$ are the maximum void ratio of pure fines grained soil and pure coarse grained soil, and s = 1+a/R_{d}, a = 10, R_{d} = D_{50}/d_{50}, D_{50} and d_{50} are mean grain size of pure fines-grained soil and pure coarse-grained soil.

In the theory of intergrain contact state, skeleton void ratio (e_{sk}) was used to describe the idealized packing conditions of the dominant grains fraction. For mixtures with distinct coarse and fines grains, e_{sk} is defined as the volumetric ratio between the voids formed by the soil skeleton and the volume of grains that make up the skeleton. While, according to the study of Thevanayagam (2007), when $FC < FC_{\text{in-min}}$, the contact state of mixtures is case 1, and e_{sk} can be described as:

$$e_{\text{sk}} = (e + FC)/(1 - FC) \tag{4}$$

when $FC_{\text{in-min}} < FC < FC_{\text{th}}$, the contact state of mixtures is case 2, e_{sk} can be calculated as follows:

$$e_{\text{sk}} = [e + (1-b)\cdot FC]/[1-(1-b)\cdot FC] \tag{5}$$

when $FC_{\text{th}} < FC < FC_{\text{in-max}}$, the contact state of mixtures is case 3, e_{sk} can be shown as:

$$e_{\text{sk}} = e/[FC + (1-FC)/R_{\text{d}}^{\text{m}}] \tag{6}$$

when $FC_{\text{in-max}} < FC$, the contact state of mixtures is case 4, e_{sk} can be described as:

$$e_{\text{sk}} = e/FC \tag{7}$$

where $0 < b, m < 1$, b and m denote the portion of the fines grains and coarse grains that contributes to the active intergrain contact.

3 UNDRAINED CYCLIC TRIAXIAL TESTS

The fines-coarse-grained soi mixtures used in this study with fines content (FC) of 0%, 10%, 20%, 25%, 30%, 35%, 40% 50%, 60%, 70%, 85% and 100% was man-made, silt grains with a sub-angular shape and a mean particle size of 0.051 mm was used as the finer fraction. The gravelly soil with a sub-angular shape and a particle size of 10 - 0.075 mm were used as the coarse fraction. The physical properties of the testing materials used in this study are given in Table 1. The specimens were prepared by adding fines in various percentages (by weight of total specimens) to the gravelly soil without fines grains. The grain size distribution of fines-coarse-grained soil mixtures with different FC are presented in Figure 1.

Table 1 Index properties of fines grain and coarse grain of fine-coarse-grained soil mixtures

	Coarse grain	Fines grain
Soil type	Gravel soil	silty
Mean grain size D_{50}/mm	1.849	0.056
Effective grain size d_{10}/mm	0.567	0.014
Uniformity coefficient C_{u}	4.306	4.130
Specific gravity G	2.680	2.720
Maximum index density ρ_{max}/(g·cm^{-3})	1.740	1.679
Minimum index density ρ_{min}/(g·cm^{-3})	1.437	1.271
Maximum void ratio e_{max}	0.865	1.140
Minimum void ratio e_{min}	0.540	0.620

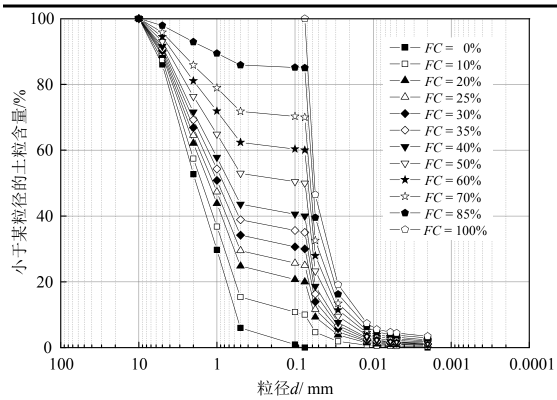
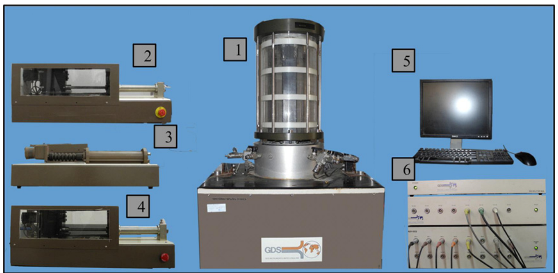


Fig. 1 Grain size distribution of the fine-coarse-grained soil mixtures

Specimens used in this study were 100 mm in diameter and 200 mm in height. The specimens were formed using waist tamping method in a split mold. Once the preparation of the specimen was completed, initial saturation of the specimen was done by passing carbon dioxide through the specimen for 1 h. After that The confining pressure and the backpressure maintain a difference of 20 kPa for 10 min, then, The specimen is then saturated by increasing the cell pressure and back pressure by 50 kPa every 10 min until cell pressure up to 400 kPa. At the end of this process the cyclic machine was switched on. The machine is capable of applying sufficient back pressure till it was ensured that Skempton's B parameter is higher than 0.95. The specimen were then isotropically consolidated to 100 kPa initial effective confining stress (σ_{3c}').

The testing apparatus used in the current study is English GDS hollow cylinder torsional shear apparatus (HCA), as shown in fig .2. All tests were conducted at a cyclic loading frequency (f) of 1 Hz. The excess pore pressure was measured at the top of each specimen. The specimens were then loaded with a sinusoidal axial stress at the appropriate cyclic stress ratio ($CSR = \sigma_{\text{d}}/2\sigma_{3c}$') until they liquefied. Experimental program are shown in Table 2.



1 Cyclinder triaxial cell	2 Inner cell pressure controller
3 Back pressure controller	4 Cell pressure controller
5 Computer	6 Digital servo controller and acquisition system

Fig. 2 GDS Hollow Cylinder Apparatus test system

Table 2 Cases of undrained cyclic triaxial tests for fine-coarse-grained soil mixtures

Sample ID	Fines content FC/%	Relative density D_r/%	Void ratio e	Contact state	Sample ID	Fines content FC/%	Relative density D_r/%	Void ratio e	Contact state	Sample ID	Fines content FC/%	Relative density D_r/%	Void ratio e	Contact state
S1	0	30	0.77	Case 1	S15	30	15	0.39	Case 2	S29	50	70	0.40	Case 3
S2	0	50	0.70	Case 1	S16	30	22	0.38	Case 2	S30	60	30	0.60	Case 3
S3	0	70	0.64	Case 1	S17	30	30	0.36	Case 2	S31	60	50	0.54	Case 3
S4	10	30	0.59	Case 1	S18	30	50	0.32	Case 3	S32	60	70	0.47	Case 3
S5	10	50	0.54	Case 1	S19	30	70	0.28	Case 3	S33	70	30	0.69	Case 4
S6	10	70	0.48	Case 1	S20	35	15	0.41	Case 2	S34	70	50	0.62	Case 4
S7	20	30	0.43	Case 1	S21	35	30	0.38	Case 3	S35	70	70	0.55	Case 4
S8	20	50	0.38	Case 1	S22	35	50	0.34	Case 3	S36	85	30	0.84	Case 4
S9	20	70	0.33	Case 1	S23	35	70	0.30	Case 3	S37	85	50	0.75	Case 4
S10	25	15	0.41	Case 2	S24	40	30	0.41	Case 3	S38	85	70	0.66	Case 4
S11	25	22	0.40	Case 2	S25	40	50	0.37	Case 3	S39	100	30	0.98	Case 4
S12	25	30	0.38	Case 1	S26	40	70	0.33	Case 3	S40	100	50	0.88	Case 4
S13	25	50	0.34	Case 1	S27	50	30	0.50	Case 3	S41	100	70	0.78	Case 4
S14	25	70	0.30	Case 1	S28	50	50	0.45	Case 3					

4 TEST RESULTS AND DISCUSSION

The typical undrained cyclic triaxial testing results for fines-coarse-grained soil mixtures with FC = 10%, 30%, 50%, and 85% are shown in Figure 3, respectively. As shown in Fig. 3(a), when the intergrain contact state of mixtures is case 1, the fines-coarse-grained soil mixtures is coarse-like soil, excess pore pressure ratio R_u developed fast at first and then became stable, showing a "fast-steady" development model, the experimental results show that the double-axial strain ε_{DA} of the specimen is more than 2.5% when R_u = 1, which is basically consistent with the experimental results of sand-gravel mixtures. As shown in Fig. 3(b) and (c), when intergrain the contact state is case 2 or 3, the fines-coarse-grained soil mixtures is in-transition soil, R_u developed linearly as number of cycles (N) increasing, and in the early stage, ε_{DA} remained almost unchanged, when $R_u > 0.7$, ε_{DA} increased gradually, and when $R_u = 1.0$, ε_{DA} could reach 5%. As shown in Fig. 3(d), when the intergrain contact state is case 4, the fines-coarse-grained soil mixtures is fines-like soil, as N increasing, R_u grown fast at the beginning and then grown at a steady rate, and finally developed sharply, showing a "fast-steady-rapid" development model, when $R_u < 0.8$, ε_{DA} remained constant and close to 0, and when $R_u > 0.8$, ε_{DA} increased rapidly with few N, when $R_u = 1$, ε_{DA} approached 7.5%, this results were basically the same with silty. In conclusion, with the action of cyclic axial loading, the initial liquefaction ($R_u = 1$) can be reached, although the ε_{DA} of fines-coarse-grained soil mixtures varies from 2.5% to 7.5%, at this point, the skeleton of mixtures shown a flow failure, and the mixtures no longer have the shear strength. Therefore, "$R_u = 1$" was used as the liquefaction criterion for fines-coarse-grained soil mixtures.

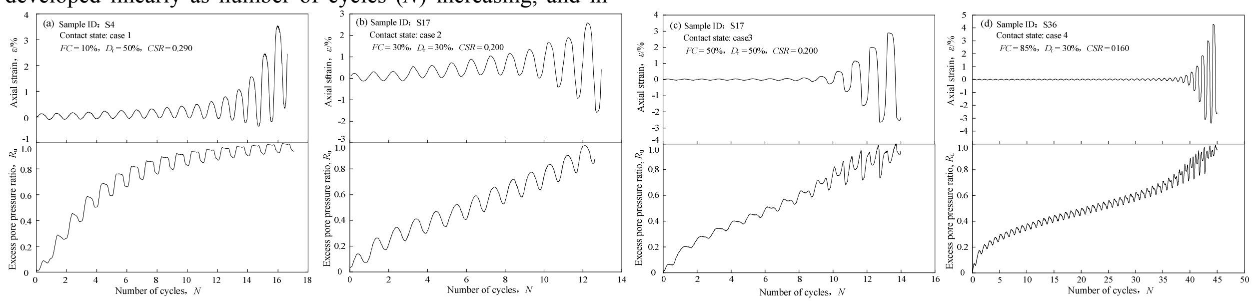


Fig. 3 Undrained cyclic triaxial test results of fines-coarse-grained soil mixtures with different intergrain contact state

In order to determine the cyclic shear strength or liquefaction resistance ratio (CRR) of specimens with desired FC corresponding to the concerned approach, a series of undrained cyclic triaxial tests were carried out at specimens with different CSR till the 100% pore pressure ratio which was reached as discussed earlier. Thereafter these CSR were plotted against the corresponding cycles to 100% pore pressure ratio as shown in Figure 4.

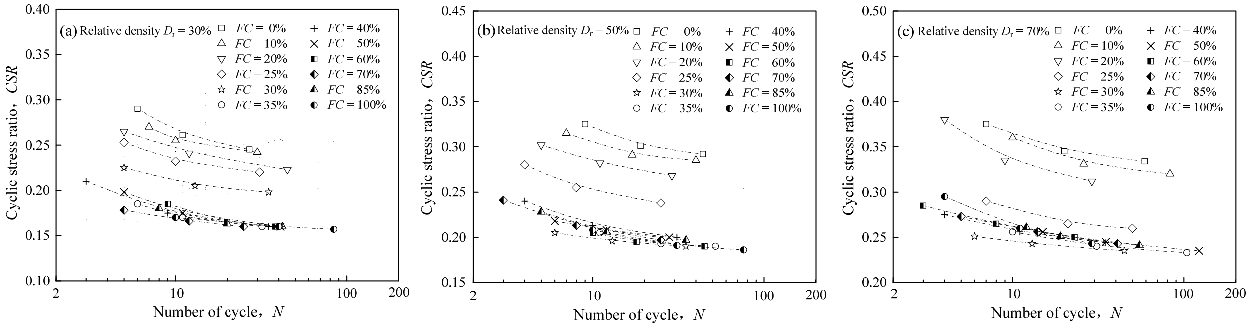


Fig. 4 The relationship between the cyclic stress ratio CSR and number of cycles N to liquefaciton criterion of fine-coarse-grained soil mixtures with different fines content FC

Liquefaction resistance ratio (*CRR*) of fines-coarse-grained soil mixtures of desired fines content was determined as *CSR* at which initial liquefaction occurred (R_u = 1) for 15 cycles of loading. Figure 5 shows the influence of *FC* on the *CRR* of fines-coarse-grained soil mixtures with the same relative density D_r. It can be seen from the figure that the *CRR* of mixtures deceases with the increase of *FC*, and then remains constant regarding whether the dense state at loose (D_r = 30%), medium (D_r = 50%) or dense (D_r = 70%), this is consistent with the effect of *FC* on the *CRR* of the mixtures from the experimental results of Karim and Alam (2014). It is noteworthy that, when D_r = 30%, as long as *FC* is greater than 35%, the *CRR* of mixtures keep basically unchanged; and when D_r = 50% or 70%, once *FC* more than 30%, the *CRR* of mixtures will remain constant. This difference may be due to the fact that, as D_r difference, the transition process of intergrain contact state of fines-coarse-grained soil mixtures is different as *FC* increasing.

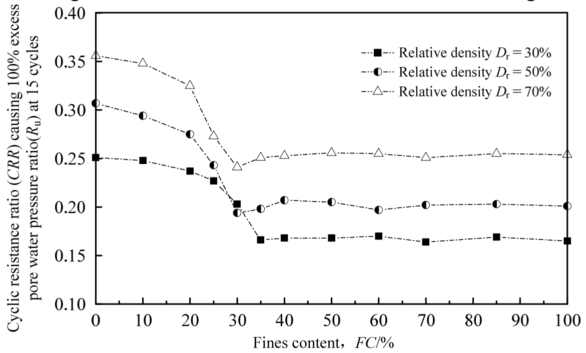


Fig. 5 The cyclic resistance of fine-coarse-grained soil mixtures with different fines content

According to the theory of intergrain contact state, the contact state of fines-coarse-grained soil mixtures with the same void ratio *e* varies with the change of *FC*, thus leading to the change of mechanical properties and responses of the fines-coarse-grained soil mixtures, which indicates that *e* can't reasonably describe the *CRR* of mixtures. Polito and Martin II (2001) found that there is no clear correlation between *e* and *CRR* for Monterey sand-silt-grained soil mixtures, at the same time, within each *FC* a decrease in *CRR* with an increase in e was observed. The test results of Hsiao et al (2015) demonstrate that the *CRR* of sand-silt-grained soil mixtures is not correlated with *e*, regardless of whether the mixtures have the same D_r or undrained shear strength. This indicates that *e* does not describe the effect of *FC* on the *CRR* of the mixtures well.

Fig. 6 shows the relationship between liquefaction resistance *CRR* and skeleton void ratio e_{sk} of fines-coarse-grained soil mixtures. From the figure we can see, when b = 0.15 and m = 0.80, the *CRR* of fines-coarse-grained soil mixtures with different e_{sk} are distributed in a narrow band, regardless of *FC* and D_r, and the *CRR* of mixtures decreases rapidly with increasing e_{sk}, which is consistent with the relationship between *CRR* and e_{sk} presented by Polito and Martin II (2001) or Papadopoulou and Tika (2008). However, the test results of Polito and Martin II (2001) or Papadopoulou and Tika (2008) showed that the distribution of *CRR* of sand-silt-grained soil mixtures for $FC > 50\%$ was no consistent with the distribution of *CRR* for $FC < 50\%$. A unified relationship between *CRR* and e_{sk} of sand-silt-grained soil mixtures can't be established, this is because Polito and Martin II (2001) or Papadopoulou and Tika (2008) do not take into account the effect of fines grain or coarse grain on e_{sk} when the grain contact state is case 2 or case 3, thus overestimating the e_{sk} of in-translation soil. While the e_{sk} based on the theory of intergrain contact state of fines-coarse-grained soil mixtures can describe the *CRR* with different intergrain contact state uniformly, and *CRR* can be reasonably expressed as a power function form of e_{sk}:

$$CRR = 0.158 \times e_{sk}^{-1.768},\ R^2 = 0.972 \quad (8)$$

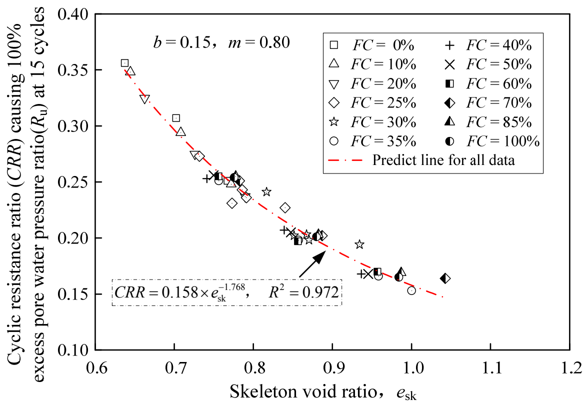


Fig. 6 Liquefaction resistance *CRR* versus skeleton void ratio e_{sk} of fine-coarse-grained soil mixtures

5 SUMMARY

A series of undrained cyclic triaxial tests were performed on the fines-coarse-grained soil mixtures with 12 different fines contents *FC* in the range of 0% to 100%. The testing results and findings are summarized as following:

(1) As *FC* increasing, intergrain contact state of mixtures can be divided into 4 cases, and according to the theory of intergrain contact state, fines-coarse-grained soil mixtures can be classified as fines-like soil, in-translation soil and coarse-like soil.

(2) Liquefaction resistance *CRR* of fine-coarse-grained soil mixtures with the same D_r decreased first, thereafter, it remained constant, as *FC* increasing.

(3) *CRR* decreases with the increase of e_{sk}, *CRR* and e_{sk} show a good power function relationship, which means e_{sk} based on the theory of intergrain contact state can characterize *CRR* of fines-coarse-grained soil mixtures reasonably.

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