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Influence of particle-size disparity on cyclic liquefaction resistance of silty sands

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Liquefaction of silty sands remains puzzling due to the complexity involved in the interaction between coarse and fine particles during loading. This paper presents first-hand experimental data from a series of cyclic triaxial tests under controlled particle characteristics, with the aim to elucidate the influence of particle-size disparity on the liquefaction resistance of sand–fines mixtures. A detailed analysis of the test results and an experimental database compiled from the literature reveal that the particle-size disparity, defined as the ratio between the characteristic sizes of the base sand and the fines, is a major and rational factor controlling the reduction of cyclic resistance of sand–fines mixtures as compared with factors such as the grading and shape of the base sand. A simple, explicit expression is further proposed to properly account for the reduction of cyclic resistance of sand due to fines.

KEYWORDS: laboratory tests; liquefaction; particle-scale behaviour

NOTATION

A, a, B, b	fitting parameters
a_f	gradient of K_{fc}–FC relationship
C_u	coefficient of uniformity
D, d	particle size
D_X, d_X	particle size with X% finer particles
e_c	void ratio after consolidation
K_{fc}	correction factor for fines content
M_w	moment magnitude of earthquake
N_l	number of cycles to liquefaction
q_{cyc}	amplitude of cyclic deviatoric stress
σ'_{1c}, σ'_{3c}	effective axial and lateral stress, respectively
σ'_{nc}	effective normal confining pressure on maximum shear stress plane
χ	particle-size disparity ratio

INTRODUCTION

While soil liquefaction has been extensively investigated since the 1964 Niigata earthquake, recent earthquakes in Japan and New Zealand (Cubrinovski *et al.*, 2011; Yasuda *et al.*, 2012) indicate that a proper evaluation of liquefaction potential of silty sands remains puzzling. Previous studies mainly focused on the effects of fines content (FC) on the cyclic behaviour and resistance of silty sands (Shen *et al.*, 1977; Chang, 1987; Kuerbis *et al.*, 1988; Chien *et al.*, 2002; Carraro *et al.*, 2003; Papadopoulou & Tika, 2008; Dash & Sitharam, 2009; Kokusho *et al.*, 2012), and diverse observations and conclusions were reported. This divergence is probably due to different density parameters (e.g. void ratio, skeleton void ratio, relative density etc.) were chosen for comparison. Yang *et al.* (2015) examined the rationale of these different state variables and showed that the conventional void ratio remains a rational one that is particularly suited for the framework of critical state soil mechanics. When compared at the same void ratio, a consistent trend can be observed such that for a given sand–fines mixture the cyclic liquefaction resistance is reduced with increasing FC up to a threshold value (Stamatopoulos, 2010; Wei & Yang, 2015). Nevertheless, the amount of reduction was found to vary significantly for different sand–fines mixtures. For instance, Polito (1999) reported a reduction of cyclic resistance of Yatesville sand mixed with Yatesville silt by as much as about 27% for FC = 12%, whereas a more significant reduction of cyclic resistance of Monterey sand mixed with Yatesville silt (44% at FC = 10%) was observed. What is the reason behind the diverse results and how to properly account for the reduction of cyclic liquefaction resistance due to fines, therefore, became critical questions that needed action.

This paper presents an attempt to address the above questions along the line of micromechanical considerations (Yang & Wei, 2012; Wei & Yang, 2014), with focus on the role of particle-size disparity in undrained cyclic resistance of sand–fines mixtures. In doing so, test materials were carefully prepared to minimise the effects of particle grading and particle shape before conducting undrained cyclic tests. Also, a great amount of effort was invested to compile a quality database from the literature to allow for a more comprehensive analysis. The first-hand data and interpretations presented here provide an insight into the complicated effects of fines on cyclic liquefaction resistance of sands.

EXPERIMENTAL PROGRAMME

Test materials

Four quartz sands, namely Toyoura sand, Fujian sand, Ottawa sand (50–70) and Ottawa sand (20–30), were used as the base sands in the laboratory tests. Table 1 summarises their basic physical properties, and their particle-size distribution (PSD) curves are presented in Fig. 1. The four types of sand can be categorised into two groups – that is, Toyoura sand and Fujian sand as one group while the two types of Ottawa sand as the other group. Each group has

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Table 1. Properties of the tested materials

Name	C_u	D_{50}: mm	e_{max}	e_{min}	Particle shape/plasticity
Toyoura sand	1·37	0·197	0·977	0·605	Sub-angular to sub-rounded
Fujiand sand	1·61	0·398	0·879	0·555	Sub-angular to sub-rounded
Ottawa sand (50–70)	1·20	0·252	0·879	0·592	Sub-rounded to rounded
Ottawa sand (20–30)	1·20	0·713	0·753	0·490	Rounded
Crushed silica silt	2·32	0·053	NA	NA	Non-plastic

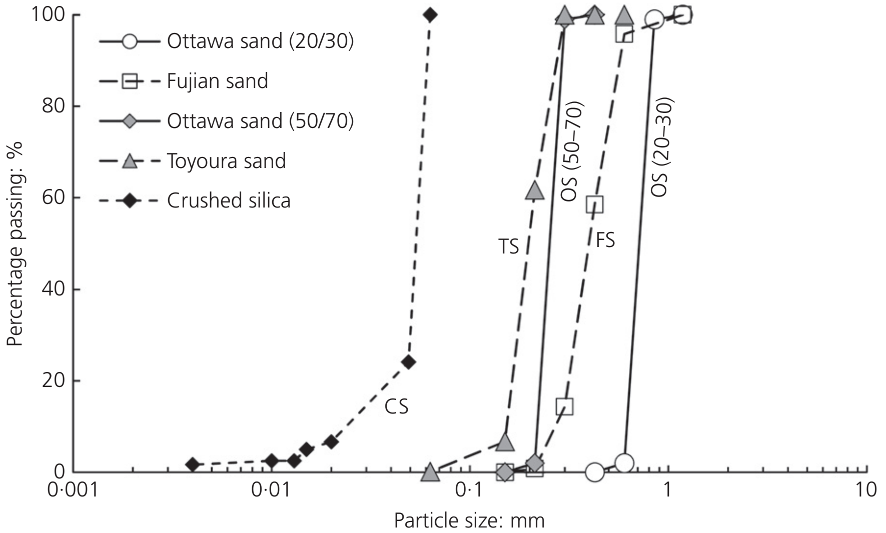


Fig. 1. PSD curves of the tested materials

parallel PSD curves (i.e. nearly the same coefficient of uniformity, C_u) and similar particle shape. Toyoura sand and Fujian sand mainly consist of sub-angular to sub-rounded particles, while the two Ottawa sands mainly consist of sub-rounded to rounded particles. In this connection, the influences on cyclic resistance due to the differences of particle grading (Kokusho, 2007) and of particle shape (Wei *et al.*, 2017) were minimised within each group.

To produce a sequence of sand dominant mixtures, crushed silica fines (<63 μm) were added to each base sand at varying percentages (0–20%) by mass. Abbreviations were adopted for each series of mixture in the analysis; for example, TSS stands for mixtures with Toyoura sand as the base sand while OSS (20–30) stands for mixtures with Ottawa sand (20–30) as the base sand. FC is represented by the number directly following the letters.

Test procedures

A series of undrained cyclic triaxial tests was performed on specimens reconstituted by the moist tamping method. Details of the method were described in Sze & Yang (2014). All reconstituted specimens were saturated by percolation of carbon dioxide and de-aired water, and then by applying back pressure. The condition of full saturation was assumed when the *B*-value was greater than 0·98. The specimens were isotropically consolidated to the effective confining pressure of 100 kPa and then loaded under uniform deviatoric stress cycles. The loading magnitude is represented by the cyclic stress ratio (CSR), which is defined as follows

$$\mathrm{CSR} = \frac{q_{\mathrm{cyc}}}{2\sigma'_{\mathrm{nc}}} = \frac{q_{\mathrm{cyc}}}{\sigma'_{1\mathrm{c}} + \sigma'_{3\mathrm{c}}} \qquad (1)$$

where q_{cyc} is the amplitude of the cyclic deviatoric stress; σ'_{nc} is the normal effective stress on the maximum shear stress plane; $\sigma'_{1\mathrm{c}}$ and $\sigma'_{3\mathrm{c}}$ are the axial and lateral effective stress after consolidation, respectively. The initial void ratio prior to cyclic loading (i.e. the post-consolidation void ratio e_c) was carefully determined by measuring the water content after testing (Yang & Wei, 2012).

Determination of cyclic resistance

Flow-type failure and cyclic mobility are two common failure patterns for the moist-tamped specimens (Yang & Sze, 2011), which were also observed in this study. The cause of different failure patterns is the result of combined effects of void ratio, confining pressure, degree of stress reversal and sample preparation method (Sze & Yang, 2014). Adding fines may also lead to a change in failure pattern under otherwise identical conditions. For specimens exhibiting flow-type failure, it is logical to define the onset of flow as failure, whereas for specimens exhibiting cyclic mobility, failure is conventionally defined by attaining 5% double amplitude (DA) of axial strain.

Different CSRs were applied to replicated specimens (the void ratio difference of the specimens was <0·006) and thus different numbers of cycles to failure/liquefaction (N_l) were obtained. The results show that N_l increases with decreasing CSR in a power relation

$$\mathrm{CSR} = a(N_l)^b \qquad (2)$$

The cyclic resistance ratio (CRR), is defined as the CSR causing liquefaction in a given number of cycles (e.g. $N_l = 10$ or 15) and corresponds to the moment magnitude (M_w) of an earthquake. Generally, the mean number of equivalent uniform cycles of ten corresponds to an earthquake with $M_w = 7$ while the number of 15 is for an earthquake of $M_w = 7{\cdot}5$ (Idriss, 1999).

TEST RESULTS

Effects of FC

When compared with the same void ratio, the cyclic resistance of sands decreases with increasing FC for all the four series, as shown in Fig. 2. In this figure, CRR_{10} means that $N_l = 10$ is used to define CRR. FSS series and OSS (20–30) series exhibit more decrease than their counterparts – that is, TSS and OSS (50–70) series, respectively. A correction factor, K_{fc}, can be defined as follows to characterise the reduction of CRR due to addition of fines

$$K_{\mathrm{fc}} = \frac{\mathrm{CRR}_{\mathrm{fc}\neq 0}}{\mathrm{CRR}_{\mathrm{fc}=0}} \tag{3}$$

where $\mathrm{CRR}_{\mathrm{fc}\neq 0}$ and $\mathrm{CRR}_{\mathrm{fc}=0}$ are CRR of specimens at the same void ratio and confining pressure when FC≠ and =0, respectively. Polito & Martin (2003) suggested that K_{fc} can serve as a standardised basis to compare the data from different studies. For the silty sands tested in this study (Fig. 3), $K_{\mathrm{fc}} = 1$ for FC = 0 and $K_{\mathrm{fc}} < 1$ for FC > 0, indicating that the effect of fines is detrimental. In addition, different N_l to define CRR has been found to have little influence on K_{fc} based on the test results.

For each series of mixtures, the K_{fc}–FC relation exhibits a certain degree of scatter, which is mainly due to the testing error other than the effects of void ratio because no consistent dependence of K_{fc} on void ratio is found. A linear trend line can be applied to characterise K_{fc}–FC relationship (Bouckovalas *et al.*, 2003)

$$K_{\mathrm{fc}} = 1 - a_{\mathrm{f}}\mathrm{FC}(\%) \tag{4}$$

where a_{f} is the gradient of the trend line reflecting the degree of detrimental effects due to fines. Obviously, the a_{f} of FSS is larger than that of TSS and the a_{f} of OSS (20–30) is larger than that of OSS (50–70). In each group of the materials, the base sand is the only variable as the same fines were used. While the differences in particle shape and grading are minimised for the base sands of each group, the particle-size disparity between the base sand and the fines is the remaining major variable that may cause such difference. Under otherwise identical conditions, adding the fines into base sand with coarser size will form larger voids than adding the same fines into a base sand with finer size. Larger voids tend to allow more fine particles to reside in the voids and less fine particles in the force transfer. This will lead to a less stable structure and thus a more reduction of cyclic resistance for the mixtures with a larger size disparity.

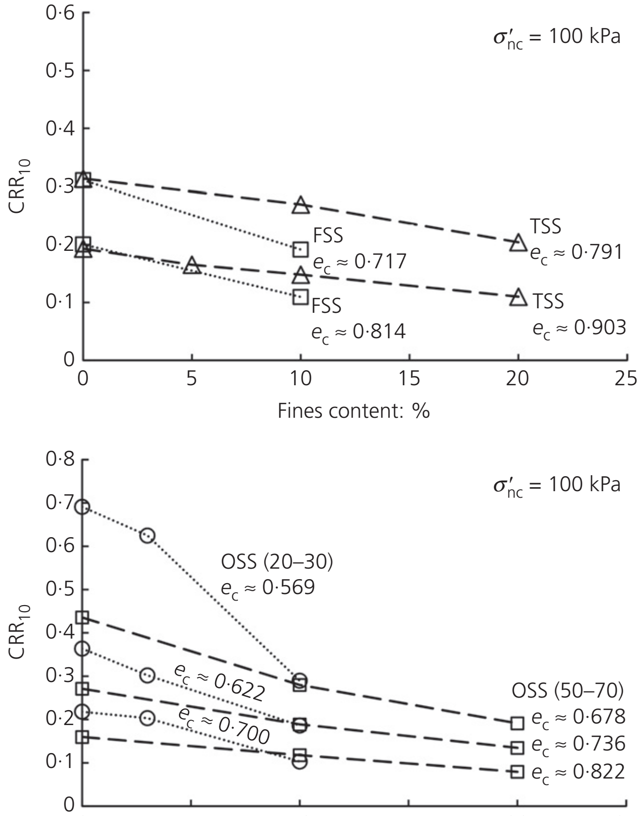


Fig. 2. Effect of FC on the cyclic resistance of tested silty sands

Effects of particle-size disparity

The particle-size disparity, reflecting the size difference between the coarse fraction and the fine fraction, can be characterised by particle-size disparity ratio (χ) defined as follows

$$\chi = \frac{D}{d} \tag{5}$$

where D and d are the characteristic particle size of the base sand and that of the fines. Several different particle-size disparity ratios defined by different characteristic particle sizes are commonly used, namely, $\chi_{50\text{–}50} = D_{50}/d_{50}$ (e.g. Monkul & Yamamuro, 2011; Liu & Yang, 2018), $\chi_{10\text{–}50} = D_{10}/d_{50}$ (e.g. Ni *et al.*, 2004; Yang *et al.*, 2015) and $\chi_{15\text{–}85} = D_{15}/d_{85}$ (e.g. Terzaghi *et al.*, 1996), where D_X and d_X are particle sizes with X% finer particles. As shown in Fig. 4, a_{f} increases with χ, indicating that larger particle-size disparity ratio leads to more reduction of CRR due to addition of fines. Although different trend lines can be found for each of the two groups, which may be due to the effects of different gradings and particle shapes of the base sands, a unique trend can give a fairly good characterisation using the following equation

$$a_{\mathrm{f}} = A\ln(\chi) - B \tag{6}$$

where A and B are fitting parameters. All the three particle-size disparity ratios can be used to capture the trend, and $\chi_{50\text{–}50}$ appears to result in a trend line with the highest R^2 for the mixtures tested.

LITERATURE DATABASE

The relationship of a_{f}–χ was established for mixtures of uniformly graded sand and silt. It is of interest to investigate whether or not the particle gradation affects this relationship. In doing that, a database was collected from the literature, as summarised in Table 2. The base sands in the database have various C_{u} and particle shape, while the confining pressure is mainly at 100 kPa. The K_{fc}–FC relationships of the literature data are plotted in Fig. 5, showing diverse gradients.

Furthermore, Fig. 6 shows that a_{f} increases with increasing χ. The a_{f}–χ data are scattered along the trend line to some extent, but there is no clear effect due to varying particle grading and particle shape. The scatter is possibly due to different degrees of data quality and is also partly associated with the extraction and conversion of the original cyclic resistance data to a_{f}. Overall, the function in equation (6) can give a reasonable description of the trend that a_{f} increases monotonically with increasing size disparity ratio. Among the three disparity ratios, $\chi_{10\text{–}50}$ leads to the best a_{f}–χ correlation whereas $\chi_{50\text{–}50}$ appears to give the poorest correlation. This observation implies that $\chi_{10\text{–}50}$ may be a

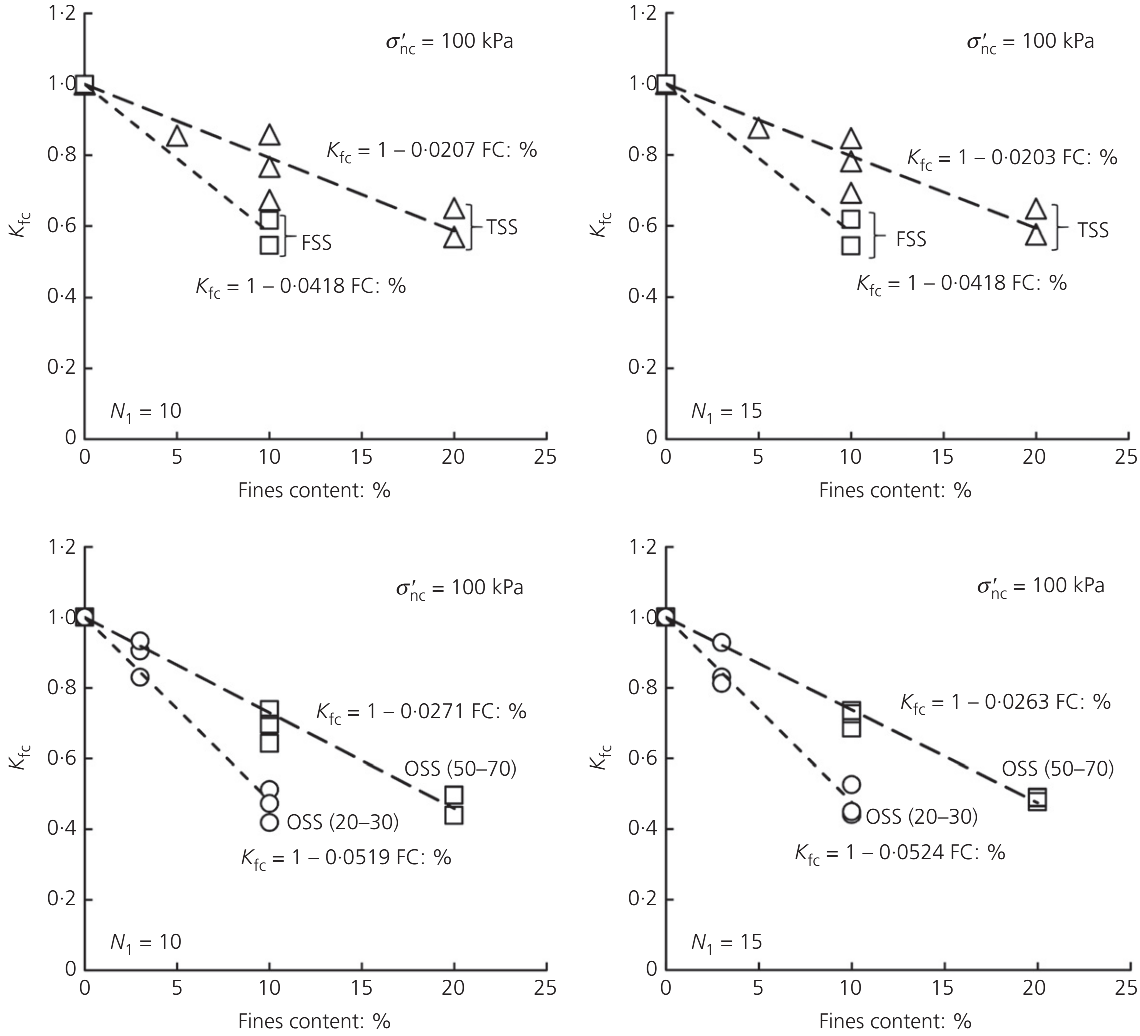
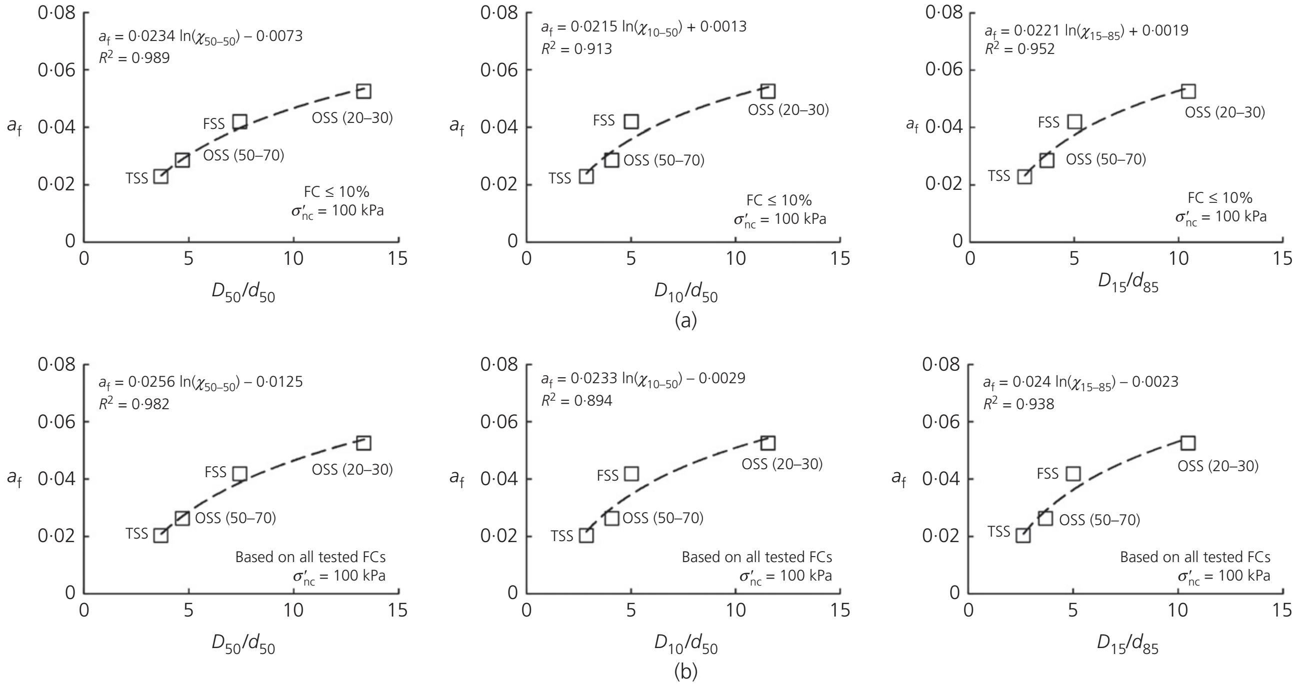


Fig. 3. Effect of FC on the correction factor, K_{fc}



(a)

(b)

Fig. 4. Effect of particle-size disparity on the reduction of cyclic resistance due to fines

Table 2. Information of the database

Reference	Sand				Silt				FC: %	Void ratio	Confining pressure	Failure criteria
	Name	C_u	D_{50}: mm	Particle shape	Name	C_u	D_{50}: mm	Plasticity				
Vaid (1994)*	Brenda sand 20/200	3·33	0·25	Angular	Kamloops silt†	2·96	0·01	Non-cohesive	0–13·5	0·47–0·75	350 kPa	2·5% Single amplitude, $N_l = 10$
Carraro *et al.* (2003)	C778 Ottawa sand	1·54	0·37	Rounded to sub-rounded	106 ground silica	6·10	0·02	Non-plastic	0–15	0·5–0·55	100 kPa	5% DA, $N_l = 20$
Polito (1999)	Monterey sand	1·58	0·46	Sub-angular to sub-rounded	Yatesville silt	4·62	0·03	Non-plastic	0–20	0·68	100 kPa	Initial liquefaction, $N_l = 10$
Polito (1999)	Yatesville sand	2·45	0·17	Sub-angular to sub-rounded	Yatesville silt	4·62	0·03	Non-plastic	0–26	0·76	100 kPa	Initial liquefaction, $N_l = 10$
Huang *et al.* (2004)	Mailiao sand	1·68	0·12	Angular	Mailiao silt	3·00	0·05	Low plastic	0–30	0·73–0·85	100 kPa	5% DA, $N_l = 20$

*Data compiled by Bouckovalas *et al.* (2003).
†Properties of silt extracted from Kuerbis *et al.* (1988) and Vaid (1994).

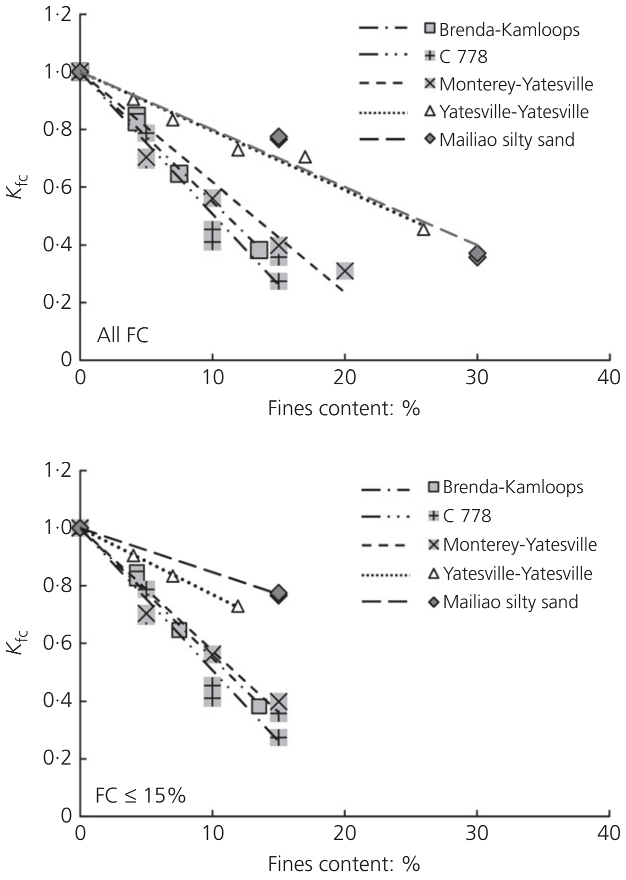


Fig. 5. Effect of FC on the correction factor (K_{fc}) interpreted from literature data

more universal parameter for size disparity, whereas χ_{50-50} may be only suitable for mixtures with uniformly graded sands and silts. More experimental data in future studies are desired to validate this finding.

DISCUSSION

The coefficient of uniformity is widely recognised as an important factor controlling the liquefaction resistance of sands (Kuerbis *et al.*, 1988; Kokusho, 2007), and has been taken into account in empirical methods to predict the liquefaction resistance of sands (e.g. Kim & Kim, 2006; Jafarian *et al.*, 2013). When a gap-graded soil is encountered, the application of C_u may be problematic. One of the problems is that the coefficient of uniformity may change significantly without leading to dramatically different liquefaction behaviour when FC (or the finer-fraction content) crosses 10%. The other problem is the difficulty in determining the coefficient of uniformity when FC is exactly equal to 10%. In addition, a_f is neither a simple function of C_u of the base sands nor of the fines, as shown in Fig. 7. For these reasons, the commonly used predicting models involving C_u may not be applicable for gap-graded silty sands.

The proposed a_f–χ relationship is mostly suitable for non/low-plastic silty sands, and caution should be used when it is applied to sands containing plastic fines. For lower χ, the relationship may be applicable for FC as high as more than 20% (e.g. TSS and Mailiao silty sand), but no more than the transitional FC. For higher χ, the relationship may be applied for FC less than 15%. This is because that the same void ratio cannot be achieved for specimens with higher FC.

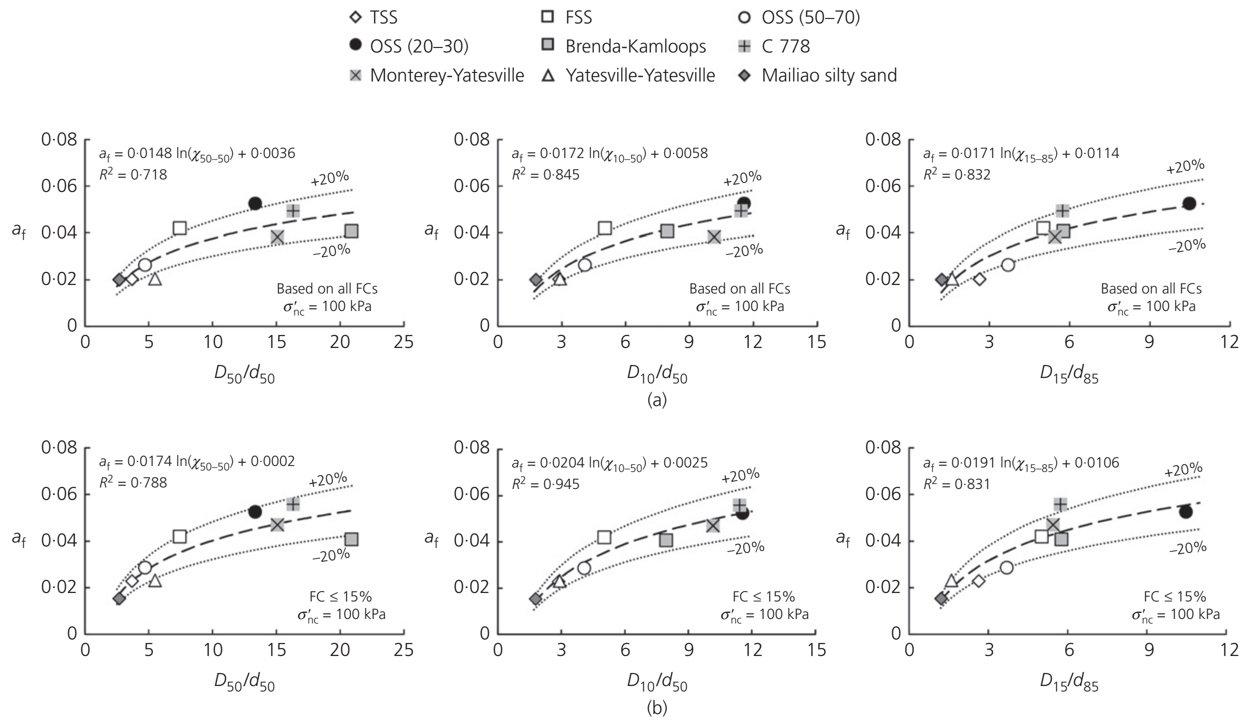


Fig. 6. Effect of particle-size disparity on the reduction of cyclic resistance of various types of sand–fines mixtures

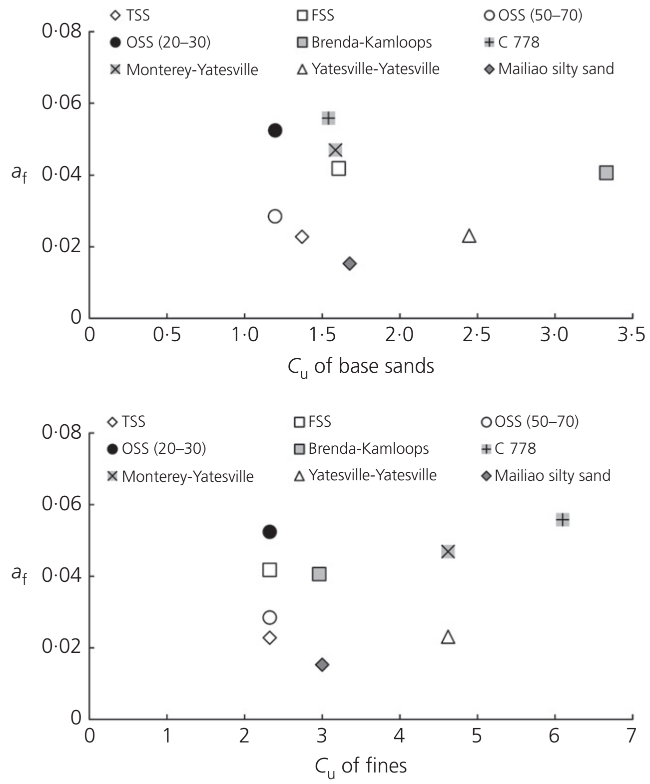


Fig. 7. Effect of the uniformity coefficient on the reduction of cyclic resistance of various types of sand–fines mixtures (for FC ≤ 15%)

In addition, this study ignores the effects of confining pressure based on the experimental observation so that the K_{fc}–FC relation is not affected by confining pressure (Wei & Yang, 2015). The implication is that a_f may not be dependent on confining pressure.

CONCLUSIONS

This study aims to elucidate the effects of particle-size disparity and FC on the cyclic resistance of silty sands through a specifically designed experimental programme along with literature data analysis. It is shown that the cyclic resistance decreases with increasing FC when compared at the same void ratio and under otherwise similar conditions. The reduction of cyclic resistance can be reasonably quantified by a factor, K_{fc}, which is linearly related to FC. The gradient of the linear relationship, a_f, is found to be highly dependent on particle-size disparity, χ_{10-50}. In general, a_f increases with increasing this size disparity ratio, meaning a more reduction in cyclic resistance at the same FC. However, no clear trend can be found between a_f and the grading and shape of the base sand. Further validation of these interesting findings using experimental data on different sand–fines mixtures is worthwhile.

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REFERENCES

Bouckovalas, G. D., Andrianopoulos, K. I. & Papadimitriou, A. G. (2003). A critical state interpretation for the cyclic liquefaction resistance of silty sands. *Soil Dynam. Earthquake Engng* **23**, No. 2, 115–125.

Carraro, J. A. H., Bandini, P. & Salgado, R. (2003). Liquefaction resistance of clean and nonplastic silty sands based on cone penetration resistance. *J. Geotech. Geoenviron. Engng* **129**, No. 11, 965–976.

Chang, N. Y. (1987). *Liquefaction susceptibility of fine-grained soils, preliminary study report*. Denver, CO, USA: US Army Corps of Engineers.

Chien, L. K., Oh, Y. N. & Chang, C. H. (2002). Effects of fines content on liquefaction strength and dynamic settlement of reclaimed soil. *Can. Geotech. J.* **39**, No. 1, 254–265.

Cubrinovski, M., Bray, J. D., Taylor, M., Giorgini, S., Bradley, B., Wotherspoon, L. & Zupan, J. (2011). Soil liquefaction effects in the central business district during the February 2011 Christchurch earthquake. *Seismol. Res. Lett.* **82**, No. 6, 893–904.

Dash, H. K. & Sitharam, T. G. (2009). Undrained cyclic pore pressure response of sand–silt mixtures: effect of nonplastic fines and other parameters. *Geotech. Geol. Engng* **27**, No. 4, 501–517.

Huang, Y. T., Huang, A. B., Kuo, Y. C. & Tsai, M. D. (2004). A laboratory study on the undrained strength of a silty sand from Central Western Taiwan. *Soil Dynam. Earthquake Engng* **24**, No. 9–10, 733–743.

Idriss, I. M. (1999). *An update to the Seed-Idriss simplified procedure for evaluating liquefaction potential. TRB workshop on new approaches to liquefaction*. Washington, DC, USA: Federal Highway Administration.

Jafarian, Y., Vakili, R. & Sadeghi Abdollahi, A. (2013). Prediction of cyclic resistance ratio for silty sands and its applications in the simplified liquefaction analysis. *Comput. Geotech.* **52**, 54–62.

Kim, Y. S. & Kim, B. T. (2006). Use of artificial neural networks in the prediction of liquefaction resistance of sands. *J. Geotech. Geoenviron. Engng* **132**, No. 11, 1502–1504.

Kokusho, T. (2007). Liquefaction strengths of poorly-graded and well-graded granular soils investigated by lab tests. In *Proceedings of the 4th international conference on earthquake geotechnical engineering-invited lectures, Thessaloniki, Greece* (ed. K. D. Pitilakis), pp. 159–184. Dordrecht, the Netherlands: Springer.

Kokusho, T., Ito, F., Nagao, Y. & Green, A. (2012). Influence of non/low-plastic fines and associated aging effects on liquefaction resistance. *J. Geotech. Geoenviron. Engng* **138**, No. 6, 747–756.

Kuerbis, R. H., Negussey, D. & Vaid, Y. P. (1988). Effect of gradation and fines content on the undrained response of sand. In *Hydraulic fill structures* (ed. D. J. A. Van Zyl), Geotechnical Special Publication No. 21, pp. 330–345. Reston, VA, USA: American Society of Civil Engineers.

Liu, X. & Yang, J. (2018). Influence of size disparity on small-strain shear modulus of sand-fines mixtures. *Soil Dynam. Earthquake Engng* **115**, 217–224.

Monkul, M. M. & Yamamuro, J. A. (2011). Influence of silt size and content on liquefaction behavior of sands. *Can. Geotech. J.* **48**, No. 6, 931–942.

Ni, Q., Tan, T. S., Dasari, G. R. & Hight, D. W. (2004). Contribution of fines to the compressive strength of mixed soils. *Géotechnique* **54**, No. 9, 561–569, https://doi.org/10.1680/geot.2004.54.9.561.

Papadopoulou, A. & Tika, T. (2008). The effect of fines on critical state and liquefaction resistance characteristics of non-plastic silty sands. *Soils Found.* **48**, No. 5, 713–725.

Polito, C. P. (1999). *The effects of non-plastic and plastic fines on the liquefaction of sandy soils*. PhD thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA, USA.

Polito, C. P. & Martin, J. R. (2003). A reconciliation of the effects of non-plastic fines on the liquefaction resistance of sands reported in the literature. *Earthq. Spectra* **19** No. 3, 635–651.

Shen, C. K., Vrymoed, J. L. & Uyeno, C. K. (1977). The effects of fines on liquefaction of sands. In *Proceedings of the 9th international conference on soil mechanics and foundation engineering* (ed. Y. Koizumi *et al.*), pp. 381–386. Tokyo, Japan: Japanese Society of Soil Mechanics and Foundation Engineering.

Stamatopoulos, C. A. (2010). An experimental study of the liquefaction strength of silty sands in terms of the state parameter. *Soil Dynam. Earthquake Engng* **30**, No. 8, 662–678.

Sze, H. Y. & Yang, J. (2014). Failure modes of sand in undrained cyclic loading: impact of sample preparation. *J. Geotech. Geoenviron. Engng* **140**, No. 1, 152–169.

Terzaghi, K., Peck, R. B. & Mesri, G. (1996). *Soil mechanics in engineering practice*, 3rd edn. New York, NY, USA: John Wiley & Sons, Ltd.

Vaid, Y. P. (1994). Liquefaction of silty soils. In *Ground failures under seismic conditions* (eds S. Prakash and P. Dakoulas), pp. 1–16. Atlanta, Georgia, USA: ASCE.

Wei, L. M. & Yang, J. (2014). On the role of grain shape in static liquefaction of sand-fines mixtures. *Géotechnique* **64**, No. 9, 740–745, https://doi.org/10.1680/geot.14.T.013.

Wei, X. & Yang, J. (2015). The effects of initial static shear stress on liquefaction resistance of silty sand. In *Proceedings of the 6th international conference on earthquake geotechnical engineering*, No. 145. Christchurch, New Zealand: Conference organizing committee.

Wei, X., Yang, J. & Guo, Y. (2017). Investigating the effects of particle shape on liquefaction resistance of sands from critical state perspective. In *Proceedings of 6th international young geotechnical engineers' conference, Seoul, Republic of Korea*, Seoul, Reblic of Korea: Conference organizing committee.

Yang, J. & Sze, H. Y. (2011). Cyclic behaviour and resistance of saturated sand under non-symmetrical loading conditions. *Géotechnique* **61**, No. 1, 59–73, https://doi.org/10.1680/geot.9.P.019.

Yang, J. & Wei, L. M. (2012). Collapse of loose sand with the addition of fines: the role of particle shape. *Géotechnique* **62**, No. 12, 1111–1125, https://doi.org/10.1680/geot.11.P.062.

Yang, J., Wei, L. M. & Dai, B. B. (2015). State variables for silty sands: global void ratio or skeleton void ratio? *Soils Found.* **55**, No. 1, 99–111.

Yasuda, S., Harada, K., Ishikawa, K. & Kanemaru, Y. (2012). Characteristics of liquefaction in Tokyo Bay area by the 2011 Great East Japan earthquake. *Soils Found.* **52**, No. 5, 793–810.

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