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TECHNICAL NOTE

On the role of grain shape in static liquefaction of sand–fines mixtures

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This technical note presents new experimental evidence for the role of grain shape in the static liquefaction behaviour of sand–fines mixtures. The laboratory experiments comprise a series of strain-controlled triaxial tests on several types of sand–fines mixtures that are intended to clarify a concern remaining in a previous study by the same authors: whether the observed effect of grain shape was due to the differences in hardness of the added fines. The comparison of new test results with the previous ones confirms that it is grain shape rather than grain hardness that is responsible for the observed differences in overall behaviour. Adding fines of rounded shape into a clean sand indeed results in a marked increase of liquefaction potential compared with adding fines of more angular shape into the same sand. It is also shown that the concept of the combined roundness is effective and useful for quantifying in an integrated manner the influence of grain shape and fines content on the overall friction angle of sand–fines mixtures at critical state.

KEYWORDS: laboratory tests; liquefaction; sands; silts

INTRODUCTION

Static liquefaction of saturated sand, characterised by a dramatic loss of strength and a rapid development of large deformation in undrained monotonic shearing, can cause catastrophic consequences for geotechnical applications. Over the past decades, a fundamental understanding of this shear behaviour has been established through well-controlled laboratory experiments on clean sands (e.g. Castro & Poulos, 1977; Alarcon-Guzman *et al.*, 1988; Ishihara, 1993; Yang, 2002; Wanatowski & Chu, 2007; and the references therein). Often natural sands are not clean, but contain some amount of fine particles of silt or clay size (i.e. fines). What the effect of fines is, therefore, is a matter of great concern. Existing views on whether the effect of fines is beneficial or detrimental for liquefaction resistance of sand are diverse and even contradictory, underlining the need for a better understanding of the role of grain characteristics (Yang & Wei, 2012). Based on undrained triaxial tests on four types of sand–fines mixtures, formed by adding non-plastic glass beads and crushed silica (<63 μm) respectively into two clean quartz sands (Toyoura sand and Fujian sand), Yang & Wei (2012) obtained several interesting findings on the role of grain shape. One of the findings, as shown in Fig. 1, is that a clean sand mixed with some percentage of rounded fines (glass beads) exhibits higher susceptibility to static liquefaction than the sand mixed with angular fines (crushed silica) of the same percentage.

While this finding was confirmed by repeated tests and was explained from a micromechanical perspective in that paper, there remains a concern that the two types of fines used in the experiments differ to some extent in hardness

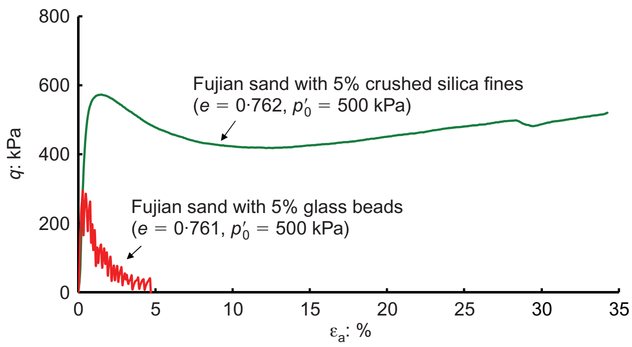

Fig. 1. Undrained shear behaviour of Fujian sand with addition of fines of distinct shapes (adapted from Yang & Wei (2012))

associated with their mineralogy. In other words, the marked reduction of strength observed on sand samples mixed with glass beads might be caused by lower hardness of the glass beads as compared with the crushed silica fines. According to Hagerty *et al.* (1993), Moh's hardness for typical glass is about 5·5 whereas for quartz it is around 7. One may speculate that the difference in hardness may influence the contacts between grains and thereby the vanishing of surface roughness of the grains (Greenwood & Wu, 2001; Cavarretta, 2009), leading to differences in the overall mechanical response.

To address this fundamental concern, crushed glass beads have been made as an additional type of fines and a series of strain-controlled undrained triaxial tests have been conducted to provide supplementary data. The crushed glass beads have their mean size and gradation similar to that of the spherical glass beads used in the study by Yang & Wei (2012), but have a much more angular shape (Fig. 2). This means that, for a given base sand, any observed differences in overall mechanical response can be attributed mainly to the influence of grain shape of the added fines. In this technical note, selected results from this new testing series are presented along with comparisons with the previous experimental data.

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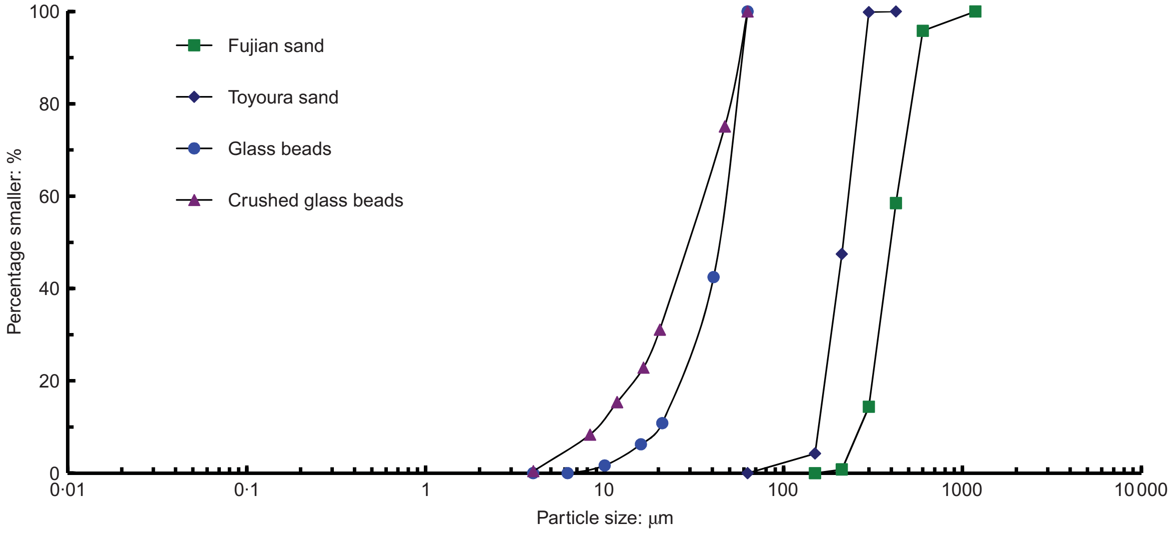

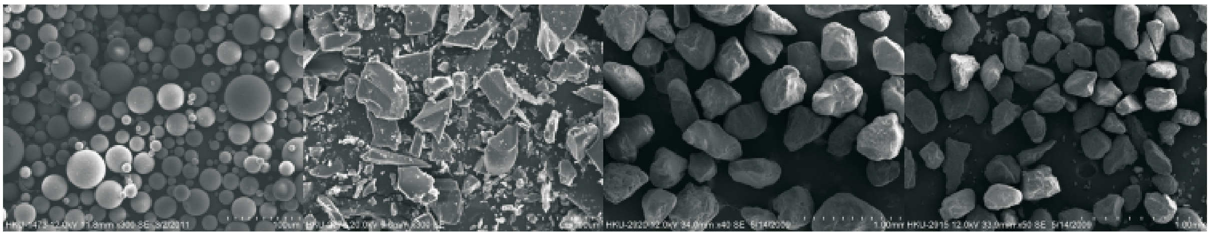

Fig. 2. Particle size distribution curves and scanning electron microscope images of test materials

RESULTS AND DISCUSSION

Stress–strain relation and stress path

In Fig. 3 the shearing response of Fujian sand mixed with 5% crushed glass beads is compared with that of Fujian sand mixed with 5% glass beads in the q–ε_a and q–p' planes. Here q is the deviatoric stress, p' is the mean effective stress and ε_a is the axial strain. Both specimens were prepared using the moist tamping method and were isotropically consolidated to the same effective stress (500 kPa), and they had similar values of post-consolidation void ratio. Clearly, the specimen containing 5% glass beads was highly contractive, showing a dramatic loss of strength after the peak response at a small strain (~0·3%), and the test ended with zero strength at a strain level of 5%. In contrast, the specimen containing 5% crushed glass beads exhibited a strongly dilative response, showing no signs of strength reduction in the entire loading process, and, remarkably, its strength was able to climb to as high as 1000 kPa at the end of the test. These observed discrepancies provide solid evidence for the important role of grain shape in modifying the shear behaviour of sand–fines mixtures.

It is worth noting that the specimen with 5% glass beads underwent complete liquefaction in undrained shearing. To have a better view of this feature, the recorded pore water pressures in this specimen are shown in Fig. 4. It is seen that, upon loading, pore water pressure quickly built up and soon reached the initial confining stress level at an axial strain of about 5%, resulting in total loss of effective stresses. By comparison, the maximum pore water pressure generated in the specimen with 5% crushed glass beads was only half of the initial confining stress, occurring at a strain level of 1·2%; further loading beyond this strain level led to a continuous drop of pore water pressure because of the onset of dilation. At the end of the test, the pore water pressure was recorded to be less than 10% of the initial confining stress.

Also, it is noteworthy that the significant saw-tooth fluctuations in the stress–strain curve and stress path of the specimen mixed with glass beads did not occur in the specimen containing crushed glass beads. Such fluctuations were not observed in shearing Fujian sand samples mixed with crushed silica fines either. This observation suggests that the unstable stick–slip response exhibited by Fujian sand mixed with glass beads should be attributed to the spherical shape of glass beads, not to low hardness of the fines.

Consistent observations on the role of grain shape were also obtained from another set of tests on Fujian sand and its mixtures, as shown in Fig. 5. The three specimens were consolidated to the same effective stress of 100 kPa and then subjected to undrained shearing. The results indicate that the addition of fines, either crushed glass beads or spherical glass beads, always led to an increased strain-softening response as compared with the base sand on its own at a similar void ratio. This implies that liquefaction resistance of clean sand can be reduced by the presence of fines. Furthermore, compared with spherical glass beads, adding the same percentage of crushed glass beads resulted in a much reduced strain-softening response, highlighting the importance of grain shape in altering the overall behaviour.

To further verify the role of grain shape, a series of strain-controlled triaxial tests were also conducted on Toyoura sand and its mixtures. Selected results are shown in Fig. 6, where the initial confining stress for all three tests was 100 kPa. Again, it is observed that adding either type of fines into Toyoura sand always led to an increase in contractiveness and strain softening as compared with the base sand on its own. This observation, along with the earlier one, is consistent with the finding that addition of fines lowers the critical state locus in the e–p' plot (e.g. Thevanayagam *et al.*, 2002; Murthy *et al.*, 2007; Yang & Wei, 2012) and consequently makes sand with fines more contractive than clean sand at the same void ratio.

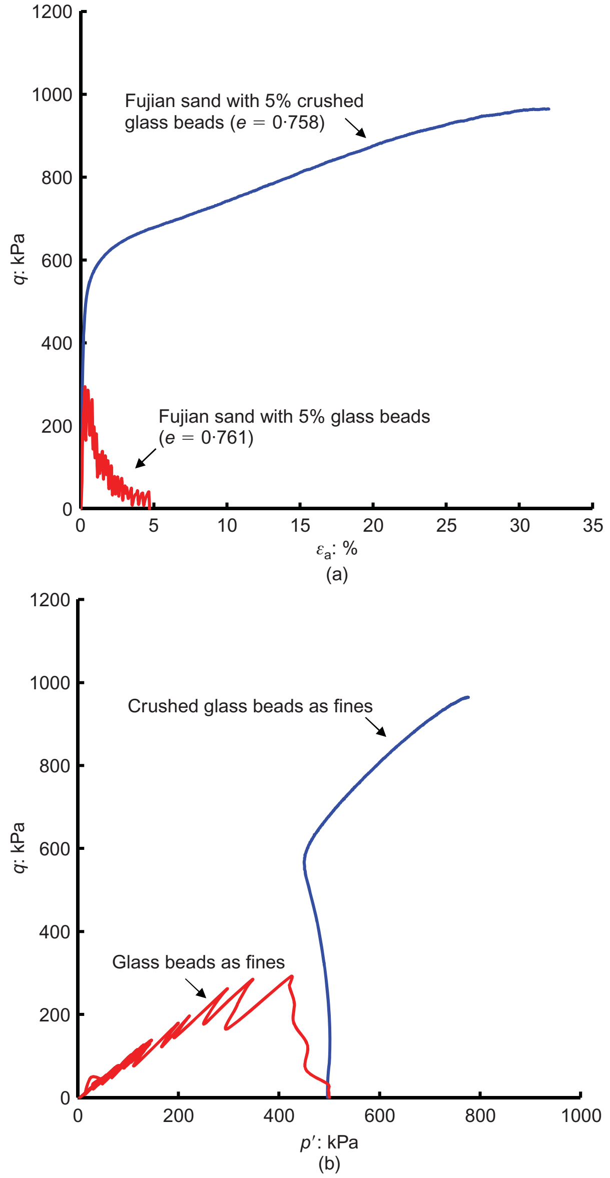

Fig. 3. Undrained shear behaviour of Fujian sand with the addition of fines of distinct shapes: (a) stress–strain relation; (b) stress path

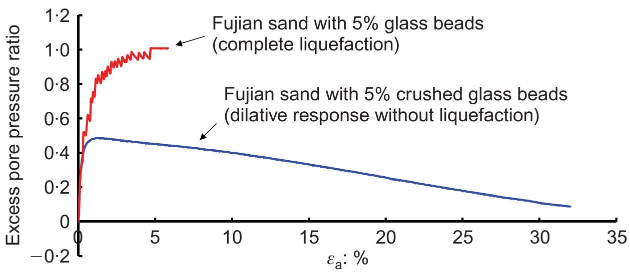

Fig. 4. Excess pore water pressure build-up in Fujian sand affected by shape of fines

Of particular interest here are the differences in the shear responses of the two mixed soil specimens as they are a direct reflection of the effect of grain shape. By comparison, the sample of Toyoura sand containing 5% glass beads appears to be more contractive than the sample of Toyoura sand containing 5% crushed glass beads: the former achieved a peak strength of ~175 kPa at an axial strain of 0·57%, whereas the peak strength of the latter was 45%

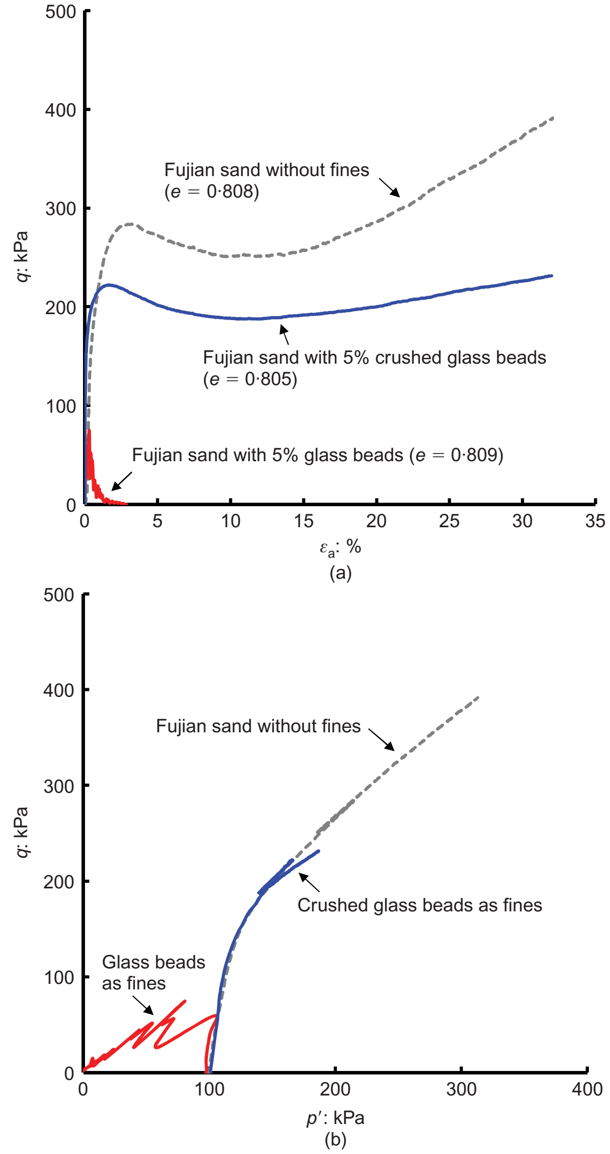

Fig. 5. Undrained shear behaviour of Fujian sand modified by addition of fines of distinct shapes: (a) stress–strain relation; (b) stress path

higher and it occurred at a relatively larger strain level (1·96%). For both specimens the exceedance of peak strength was followed by a limited period of strain-softening response, which ended with the onset of dilation. The transition state between the contraction and dilation is known as the quasi-steady state, at which the strength takes a local minimum. For more detailed discussion on this state, one may refer to Yang & Dai (2011).

It should be noted, by comparing the results in Fig. 6 with those shown in Figs 5 and 3, that the fluctuation or stick–slip response observed in shearing samples of Fujian sand mixed with spherical glass beads was not observed in samples of Toyoura sand mixed with glass beads. This observation suggests that the characteristics of sand grains also play a role in the overall behaviour of mixed soils. According to the grain-scale measurements made by Yang & Wei (2012), the grains of Fujian sand are more rounded and coarser than the grains of Toyoura sand. It can be postulated that in a binary mixture composed of fine and coarse grains that are both rounded, the grains favour rolling, thus yielding a microstructure that is unstable, and this feature may further be enhanced if the size difference between coarse and fine grains becomes larger.

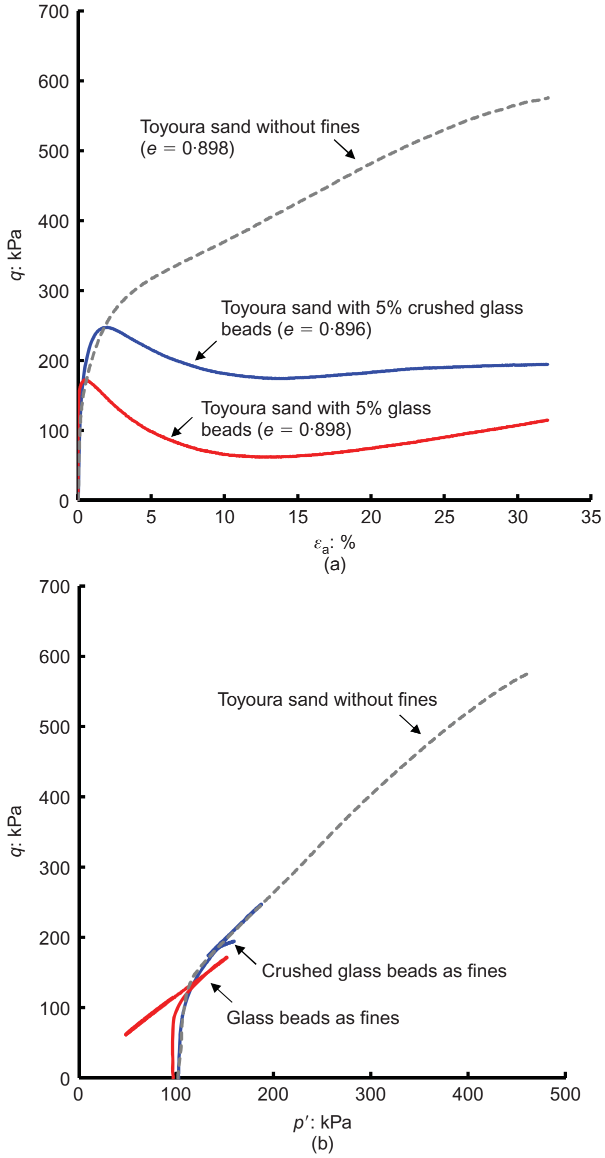

Fig. 6. Undrained shear behaviour of Toyoura sand modified by addition of fines of distinct shapes: (a) stress–strain relation; (b) stress path

Onset of static liquefaction

The onset of strain softening and liquefaction is an important consideration in geotechnical applications and it can be characterised by the stress ratio (q/p') at the peak point (or known as instability state) on the stress path (Kramer, 1996). The lower this stress ratio is, the higher is the susceptibility to liquefaction of the soil. To further examine the impact of grain shape on liquefaction susceptibility, values of this stress ratio were determined for the two clean sands and their mixtures, and are shown as a function of the post-consolidation void ratio in Fig. 7. All tests included here were sheared from the effective stress of 500 kPa.

There are several points that are noteworthy from the plot.

(*a*) For a given host sand (Toyoura sand or Fujian sand), the (q/p')–e trend line tends to shift to the left when either crushed or spherical glass beads are present, implying that at a given void ratio, strain softening is to be triggered at a lower stress ratio for sand containing fines.
(*b*) The shift is more remarkable for sand containing rounded fines (glass beads) than the same sand containing angular fines (crushed glass beads).
(*c*) The shift caused by the presence of glass beads is more significant for Fujian sand than for Toyoura sand.

Evidently these observations back up the hypothesis made by Yang & Wei (2012) that a clean sand mixed with rounded fines tends to form a less stable structure than the same sand mixed with angular fines and this tendency may become more evident if the host sand is also composed of rounded grains. These observations also indicate that it is grain shape, not grain hardness, that contributes to the significant variation of liquefaction susceptibility of sand.

In addition, it should be mentioned that for either clean sand or sand containing fines, there is a clear trend that the stress ratio (q/p') decreases with increasing void ratio in an exponential form. This means the idea derived from test data on clean sand (Yang, 2002; Wanatowski & Chu, 2007) that the flow liquefaction line for loose sand is not unique but state dependent can be extended to sand–fines mixtures.

Critical state friction angle

The experiments by Yang & Wei (2012) showed that the addition of glass beads to either Toyoura sand or Fujian sand

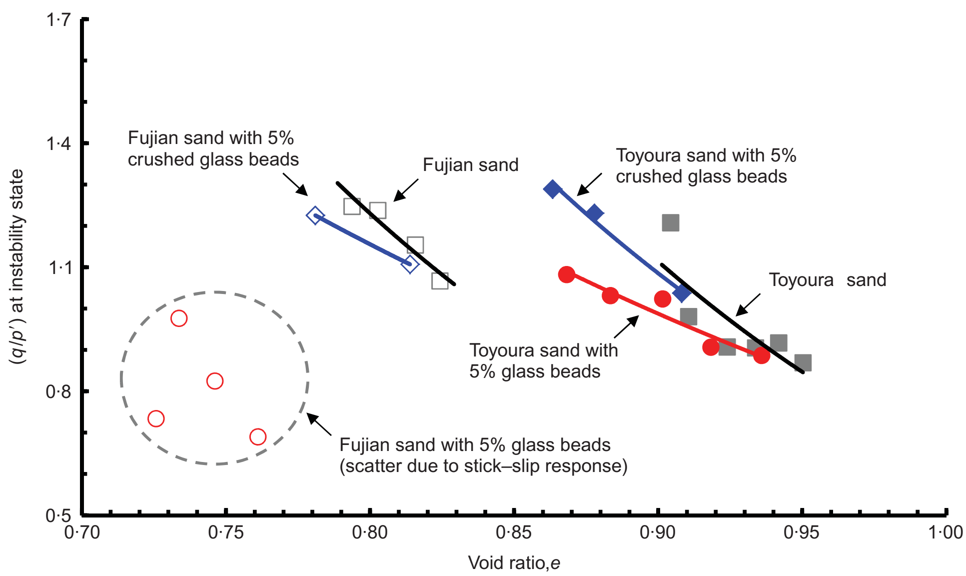

Fig. 7. Variation of stress ratio at instability with void ratio

results in a marked reduction of the overall friction angle at critical state (ϕ_{cs}). For example, the value of ϕ_{cs} was determined to be 30·77° for Fujian sand but it was reduced to 28·54° when the sand was mixed with 5% glass beads. In contrast, the addition of 5% crushed silica fines into Fujian sand was found to result in a slight increase in ϕ_{cs}, giving a value of 31·28°. The slight increase of ϕ_{cs} due to the addition of crushed silica fines was also observed by several researchers; for example, Murthy *et al.* (2007) reported that the addition of 5% non-plastic silt into Ottawa sand led to an increase in ϕ_{cs} by 1%. But whether the notable reduction of ϕ_{cs} for Fujian sand mixed with glass beads was due to low hardness of the fines remains a matter of concern.

The new testing series on sand samples mixed with crushed glass beads provides an excellent opportunity to address this concern. In the same way as Yang & Wei (2012), the values of the stress ratio (q/p') at critical state (denoted as M_{cs}) were determined and the values of ϕ_{cs} were then calculated as

$$\sin\phi_{cs} = \frac{3M_{cs}}{6+M_{cs}} \tag{1}$$

For the purpose of comparison, Table 1 lists these values together with those for the two clean sands and their mixtures with crushed silica fines and glass beads. It is encouraging to note that Fujian sand mixed with 5% crushed glass beads has a ϕ_{cs} value of 31·16°, which is close to that for Fujian sand mixed with 5% crushed silica fines, but is 9% higher than that for Fujian sand mixed with glass beads. Similarly, the ϕ_{cs} value for Toyoura sand mixed with 5% crushed glass beads is also notably larger than that for Toyoura sand mixed with 5% glass beads. These new data confirm that the notable reduction of ϕ_{cs} values observed in sand samples mixed with glass beads can be attributed to the spherical shape of the fines, not to low hardness of the fines.

Furthermore, it is desirable to examine whether the combined-roundness concept (Yang & Wei, 2012) works for the new data. According to this concept, the effect of grain shape on the critical state friction angle is coupled with the effect of fines content and this coupled effect can be accounted for using an index termed combined roundness R_{com}

$$R_{com} = R_{HS}(1-F_c) + R_F F_c \tag{2}$$

where R_{HS} is the roundness of the base sand, F_c is the fines content and R_F is the roundness of fines. A linear relationship has been established between ϕ_{cs} and R_{com} by Yang & Wei (2012)

$$\phi_{cs} = -65{\cdot}2R_{com} + 63 \tag{3}$$

(Toyoura sand and its mixtures)

$$\phi_{cs} = -94{\cdot}1R_{com} + 82{\cdot}27 \tag{4}$$

(Fujian sand and mixtures)

Table 1. Critical state friction angles of tested soils

Mixtures	M_{cs}	ϕ_{cs}: deg
Fujian sand (FS)	1·234	30·77
Fujian sand with 5% crushed silica (FSS)	1·256	31·28
Fujian sand with 5% glass beads (FG)	1·137	28·54
Fujian sand with 5% crushed glass beads (FCG)	1·251	31·16
Toyoura sand (TS)	1·257	31·30
Toyoura sand with 5% crushed silica (TSS)	1·261	31·40
Toyoura sand with 5% glass beads (TG)	1·162	29·11
Toyoura sand with 5% crushed glass beads (TCG)	1·235	30·80

Using the same method as described in Yang & Wei (2012), the roundness of crushed glass beads was determined to be 0·431, the aspect ratio 3·704 and the flatness 1·257. By superimposing new data points onto the ϕ_{cs}–R_{com} plane given in Yang & Wei (2012), it is striking that they fit well with the trend (Fig. 8), suggesting a wider applicability of the combined-roundness concept.

CONCLUSIONS

The purpose of this technical note is to address a fundamental question remaining in the previous study of Yang & Wei (2012): whether the observed effect of grain shape was caused by the differences in hardness of the added fines. A series of specifically designed tests has been conducted to provide supplementary data, and it has been confirmed that it is grain shape rather than grain hardness that is responsible for the observed differences in overall shear behaviour. Adding fines of rounded shape into clean sand can result in a marked increase of collapsibility or liquefaction susceptibility compared with adding fines of more angular shape into the same base sand. It has also been confirmed that the notable reduction of critical state friction angle observed on sand samples mixed with glass beads – as compared with their base sand – was caused by the spherical shape rather than low hardness of the fines. The new test series indicates that the combined roundness is an effective and useful index for quantifying in an integrated manner the effects of grain shape and fines content on the critical state friction angle of sand–fines mixtures.

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NOTATION

e void ratio after consolidation
F_c fines content (%)
M_{cs} effective stress ratio at critical state
p' mean effective stress
p'_0 initial mean effective stress (i.e. effective consolidation pressure)
q deviatoric stress
R_{com} combined roundness
R_F roundness of fines
R_{HS} roundness of host sand
ε_a axial strain
ϕ_{cs} critical state friction angle

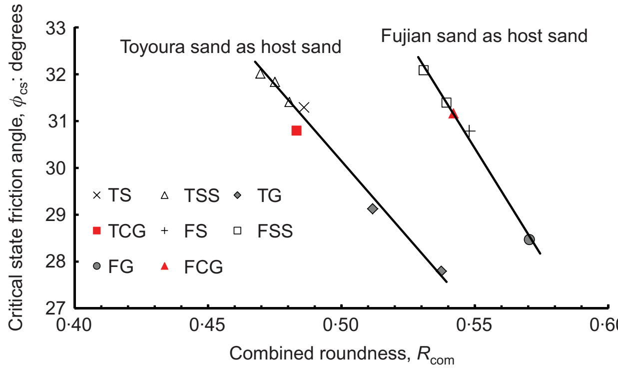

Fig. 8. Variation of critical state friction angle with combined roundness of sand–fines mixtures

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