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The Effects of Initial Static Shear Stress on Liquefaction Resistance of Silty Sand

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ABSTRACT

Understanding the cyclic behavior and liquefaction resistance of sand has been a subject of great interest over the years. Among various factors affecting the liquefaction resistance of sand, the effect of initial static shear stress plays an important role in the liquefaction analysis involving dams, embankments and slopes. Yet this effect remains poorly understood due partly to a lack of systematic experimental data. In this paper, selected results from an experimental study that was aimed to examine the effect of initial shear stress on the liquefaction resistance of silty sand are presented. Silty sand samples were produced by adding crushed silica fines of different percentages to Toyoura sand, and the liquefaction resistance was evaluated by conducting undrained cyclic triaxial tests for a range of initial states in terms of void ratio, effective confining stress and static shear stress. One of the significant findings is that while the liquefaction resistance of silty sand is lower than that of clean sand due to the presence of fines, the concept of the threshold static shear stress level proposed earlier based on laboratory tests on clean sand is valid for silty sand as well.

Introduction

Recent examples of liquefaction hazards (Yasuda et al. 2012; Cubrinovski et al. 2011) indicate that soil liquefaction remains a subject area of uncertainty and difficulty in earthquake geotechnical engineering. For large projects involving earth and tailings dams, embankments, and slopes, the initial static shear stress is an important factor in liquefaction analysis (Hyodo et al. 2012; Yang and Sze 2011a; Vaid et al. 2001; Harder and Boulanger 1997). The magnitude of initial static shear stress can be represented by a parameter α, which is defined as the ratio between the initial static shear stress and the normal effective stress on the maximum shear stress plane (Figure 1 (a) and Equation 1) for triaxial condition as follows:

$$\alpha = \frac{q_s}{2\sigma'_{nc}} = \frac{\sigma'_{1c}-\sigma'_{3c}}{\sigma'_{1c}+\sigma'_{3c}} \tag{1}$$

The above equation indicates that the level of initial static shear stress is increased with increasing α values and the limiting case of α=0 represents the level ground conditions without initial static shear stress. Depending on the density of soil and the initial effective stress level, the presence of initial static shear stress may have either beneficial or detrimental influence on the liquefaction resistance. Yang and Sze (2011a, b), based on a systematic testing program and in the framework of critical state soil mechanics, have found α-dependent correlations between cyclic liquefaction resistance (CRR) and the state parameter of Been and Jefferies (1985) and

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proposed the concept of threshold α, α_{th}, which can be approximately determined by using the no-stress-reversal line in the CRR – α plane (Figure 1 (b)). Following this concept, the liquefaction resistance will firstly increase with α until the α_{th} is reached, and then decrease with further increase in α.

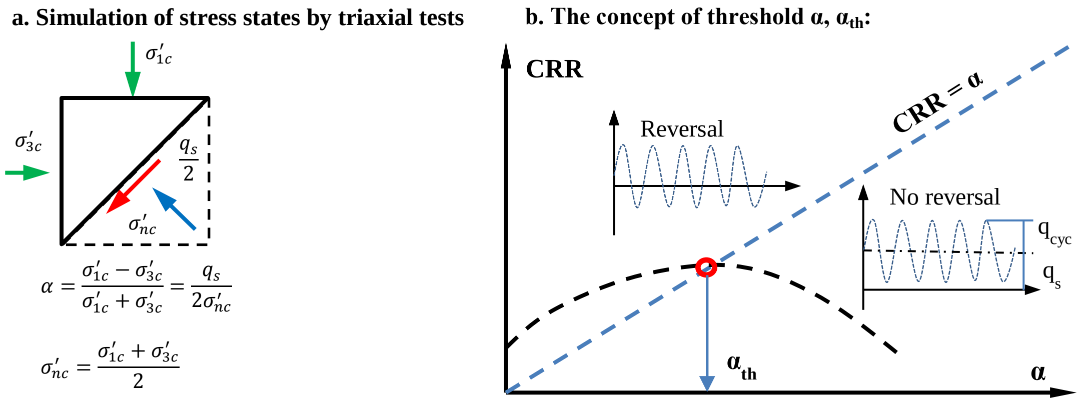


Figure 1. (a) Simulation of initial static shear stress by triaxial tests, and (b) the concept of threshold α (α_{th}) proposed by Yang and Sze (2011a, b)

Most of the experimental data considering initial static shear stress were based on test results for clean sand, whereas natural sand usually contains a certain amount of fines (referred to as silty sand in practice). Compared with clean sand, the mechanical behavior of silty sand under either monotonic or cyclic loading is less well understood (Yang and Wei 2012; Polito and Martin 2003). Addition of non-plastic fines into clean sand was found to cause either an increase or a decrease in liquefaction resistance of sands, depending on the density parameters used for comparison such as void ratio (Dash and Sitharam 2009; Xenaki and Athanasopoulos 2003), relative density (Carraro et al. 2003; Chien et al. 2002), and skeleton void ratio (Dash and Sitharam 2009; Carraro et al. 2003; Kuerbis et al. 1988). These studies, however, did not take into account the effect of initial static shear stress on CRR of silty sand.

This paper presents selected results from an experimental study that was aimed to investigate the combined effects of initial static shear stress and fines content on cyclic loading behavior and liquefaction resistance of sand. More specifically, the study was designed to explore how the liquefaction resistance of sand varies with the addition of non-plastic fines under different initial static shear stress levels and whether the framework of analysis developed by Yang and Sze (2011a, b) based on test data for clean sand works for silty sand.

Materials and testing program

Materials

Toyoura sand is a uniform and sub-rounded to sub-angular silica sand and has been widely used in liquefaction research. Non-plastic crushed silica fines were added into Toyoura sand at various fines contents (FC) to create silty sand samples. Figure 2 presents the particle size distribution curves of the sand, the silt, and their mixture at FC=10% (TSS10). The basic properties of the tested materials are summarized in Table 1.

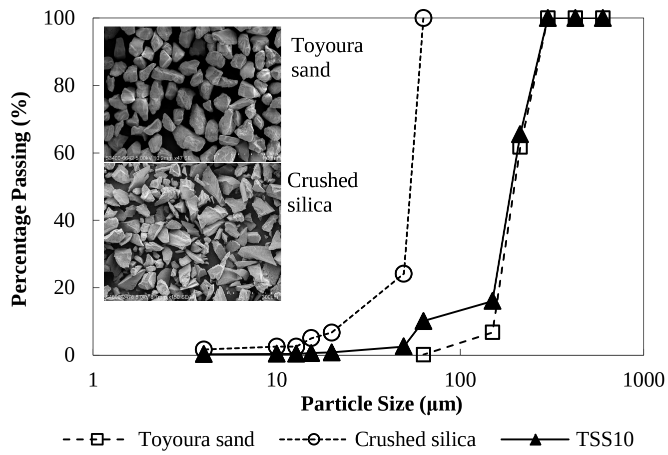


Figure 2. Particle size distribution curves of the tested materials

Table 1. Physical properties of the tested materials.

Material	Mean particle size (D_{50}, mm)	Coefficient of uniformity (C_u)	Coefficient of curvature (C_c)	Specific gravity (G_s)
Toyoura sand	0.198	1.367	0.962	2.64
Crushed silica	0.053	2.182	1.776	2.65
TSS10	0.192	3.266	2.178	2.64

Testing program

A series of undrained cyclic triaxial tests was performed under various initial states. Moist tamping method was adopted to reconstitute the specimens, and all specimens were saturated by percolation of CO_2 and de-aired water and then by applying back pressures. Given that liquefaction resistance is sensitive to the degree of saturation (Yang 2002), the condition of full saturation was considered to be achieved at B-values greater than 0.98. The specimens were anisotropically consolidated to different α levels and then loaded under cyclic deviatoric stresses. The loading magnitude is represented by the cyclic stress ratio, CSR, defined by Equation 2,

$$CSR = \frac{q_{cyc}}{2\sigma'_{nc}} \quad (2)$$

where q_{cyc} is the amplitude of the cyclic deviatoric stress. The post-consolidation void ratio, e_c was determined by measuring the water content after testing. Table 2 summarizes the testing conditions for different specimens. In this paper, test results for silty sand samples at two void ratios (e_c = 0.903 and 0.791) are presented, along with the results for clean sand taken from Yang and Sze (2011a) for the purpose of comparison.

Table 2. Testing series and conditions.

Material[1]	Void Ratio	Initial static shear stress ratio	Initial effective normal stress	Initial static deviatoric stress	Initial mean effective stress
	e_c[2]	α	σ'_{nc} (kPa)	q_s (kPa)	p' (kPa)
TSS10	0.903	0	100	0	100
	0.903	0.1	100	20	96.7
	0.903	0.15	100	30	95
	0.903	0.2	100	40	93.3
	0.903	0.25	100	50	91.7
	0.903	0.4	100	80	86.7
TSS10	0.791	0	100	0	100
	0.791	0.1	100	20	96.7
	0.791	0.25	100	50	91.7
	0.791	0.4	100	80	86.7

[1]: Clean Toyoura sand is denoted by TS; sand-silt mixtures are denoted by TSS with the subsequent number indicating their FC (%).
[2]: The target values of post-consolidation void ratio (e_c) were given in the table, whereas the actual values range from 0.903 to 0.908, and 0.791 to 0.796, respectively.

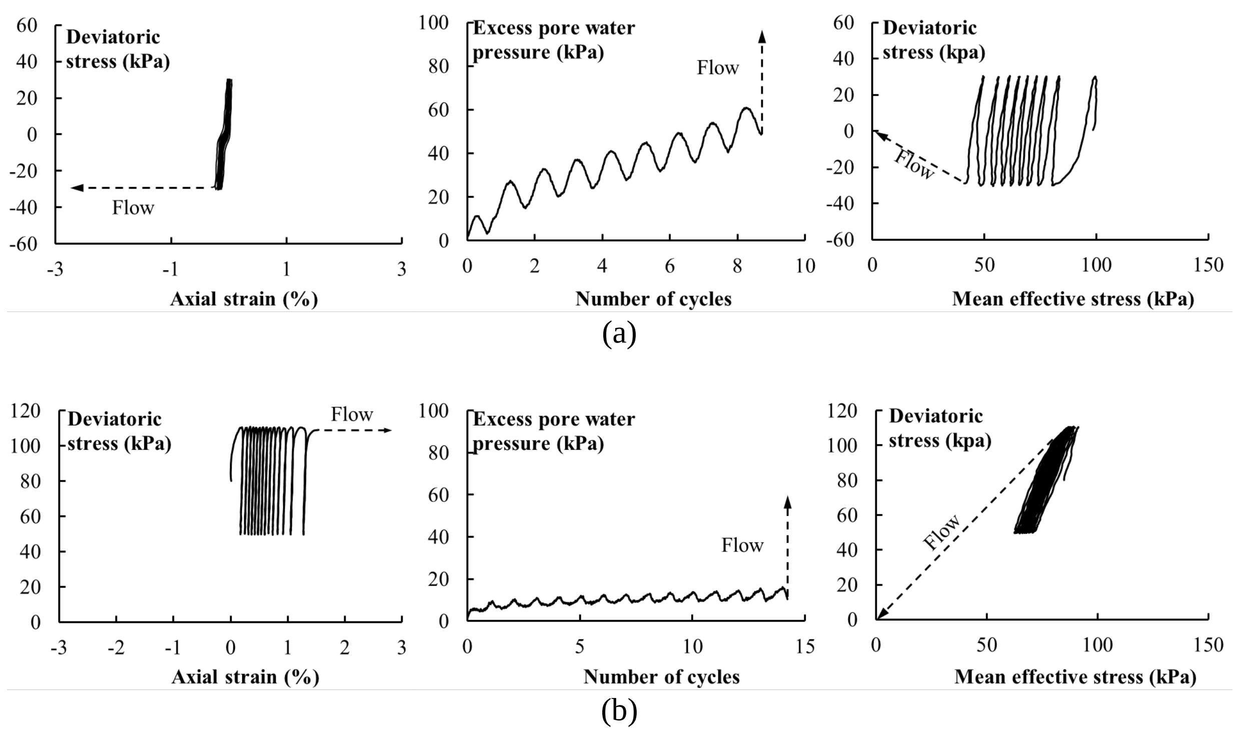
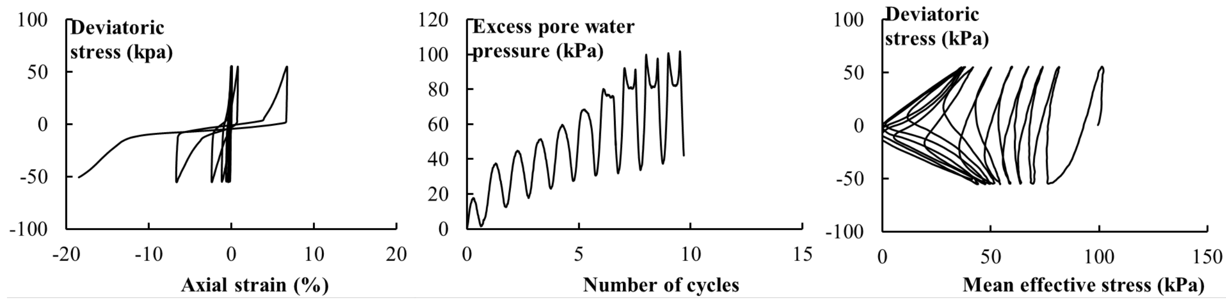


Figure 3. Cyclic response of TSS10, e = 0.903, σ'_{nc} = 100 kPa, under (a) α = 0, and (b) α = 0.4

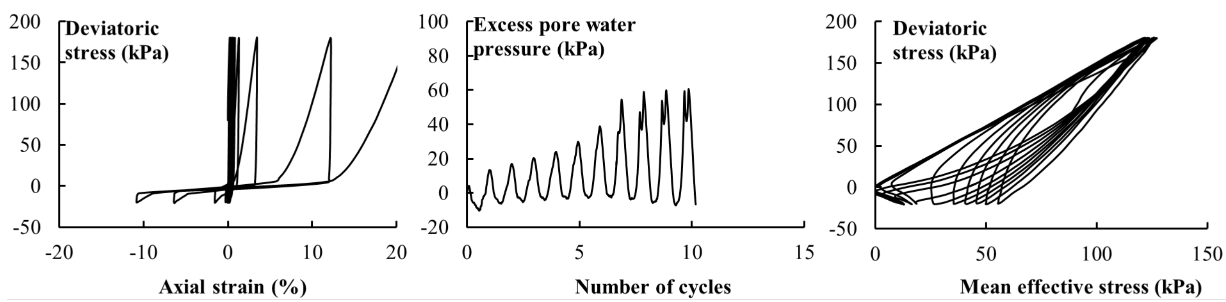
Test results

Failure patterns

The failure patterns of tested specimens were in agreement with the findings by Sze and Yang (2014) on clean sand that they would depend on such factors as density, initial effective confining pressure, α, CSR, and reconstitution method. For loose specimens, the specimens failed in the pattern of flow failure regardless of α, which is characterized by abrupt development of large deformations without significant pre-failure axial strain accumulation (Figure 3). The dense specimens failed in the pattern of cyclic mobility with the attainment of transient zero effective stress (Figure 4). The failure was defined as the onset of flow for loose specimens and as the attainment of 5% double amplitude (D.A.) axial strain for dense ones. The CRR was defined as the CSR leading to failure in the 10th cycle.



(a)



(b)

Figure 4. Cyclic response of TSS10, e = 0.791, σ'_{nc} = 100 kPa, under (a) α = 0, and (b) α = 0.4

Effect of initial static shear stress

The effect of initial static shear stress on CRR of silty sand was found similar to that for clean sand (Figure 5(a)). The CRR of loose specimens first increased with α until the no-stress-reversal line was crossed, and then decreased with further increase in α. A parabola may be used to depict the CRR – α relationship. The maximum point and the intersection with the no-stress-reversal line are so close to each other that the correspondence between α_{th} and the no-stress-reversal line can be confirmed. The CRR of dense specimens, however, increased almost linearly with α. Since the no-stress-reversal line was not exceeded, the CRR exhibited no tendency to decrease with increasing α. If the threshold α is derived by intersecting with the no-stress-reversal line, its dependence on the state parameter can be plotted in Figure 5(b), which is in good agreement with the data points given by Sze (2010) for clean sand. Note that in the determination of the state parameters for samples TSS10, the critical state locus determined by Yang and Wei (2012) from a series of monotonic tests was used.

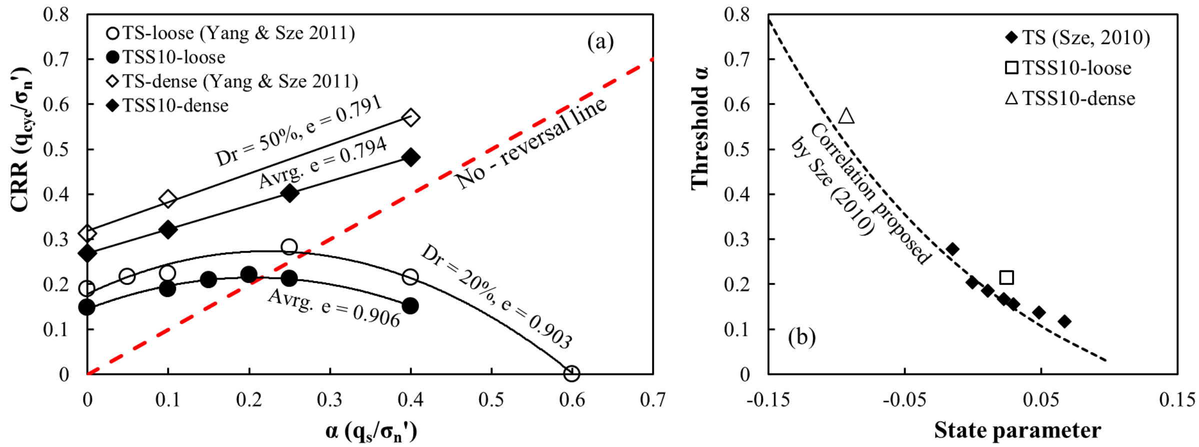


Figure 5. (a) Effect of initial static shear stress on the liquefaction resistance; (b) dependence of α_{th} on the state parameter

Effect of non-plastic fines

For a given confining pressure, relative density appears to provide a reasonable measure about how loose or dense the specimen is as compared with other density parameters. However, problems may be encountered regarding the applicability and repeatability of testing methods for the determination of maximum and minimum void ratios for silty sand samples. A most recent study by Yang et al. (2015) suggests that void ratio remains a useful state variable for critical state analysis of silty sand behavior. Therefore, the void ratio was adopted for comparison.

The threshold FC (Yang and Wei 2012), also known as the transitional fines content, which separates the sand-dominant and fines-dominant soils. From the results shown in Figure 5(a), the CRR of silty sand was lower than that of clean sand. Since the FC of the silty sand is lower than the threshold FC (~40%, see Yang and Wei 2012), the decrease in CRR with increasing FC can be anticipated when compared at the same void ratio. To quantify how much the strength lost due to increasing FC, a reduction factor, K_{fc}, defined by Equation 3 (Bouckovalas et al. 2003; Polito and Martin 2003) can be used:

$$K_{fc} = \frac{CRR_{fc\neq 0}}{CRR_{fc=0}} \tag{3}$$

where $CRR_{fc\neq 0}$ and $CRR_{fc=0}$ are liquefaction resistance ratios when FC ≠ and = 0, respectively. Note that in previous studies K_{fc} was obtained from tests in the absence of the initial shear stress. The series of tests presented here provides a good opportunity to examine K_{fc} under a range of α.

As shown in Figure 6, there appears a single relationship between K_{fc} and FC for dense specimens, regardless of α, whereas the relationship may vary in a modest way with α for loose specimens. Further test series is ongoing and more data will be included in future analysis.

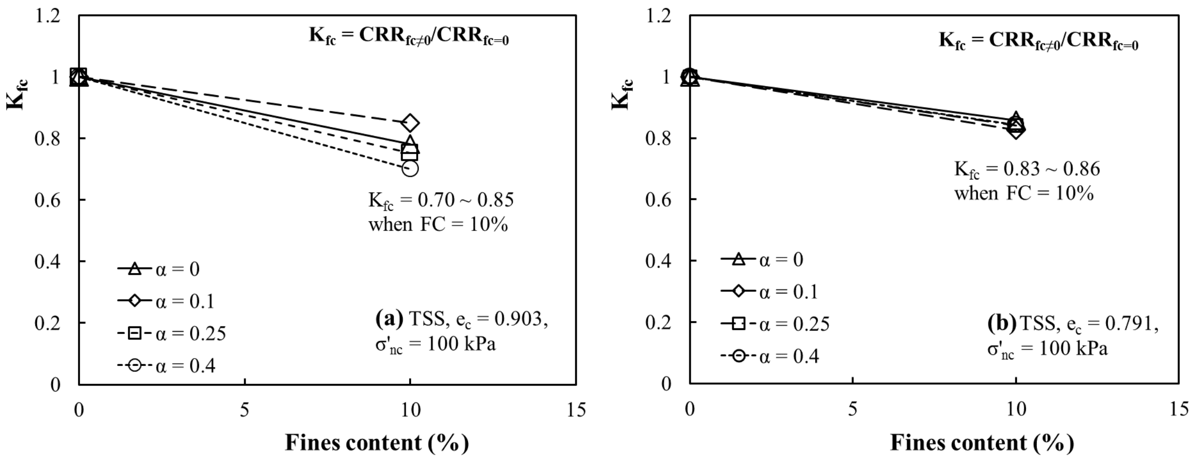


Figure 6. The relationship between K_{fc} and FC for (a) loose specimens, and (b) dense specimens

Conclusions

This paper presents selected results from an experimental program investigating the combined effects of initial static shear stress and fines content on liquefaction behavior of sand. The main findings are summarized as follows:

(a) The threshold α concept, proposed earlier based on test data for clean sand, can be extended to silty sand. This means that the effect of initial static shear stress on the liquefaction resistance of silty sand can be beneficial or detrimental, depending on the initial state of sand samples and the degree of stress reversal.

(b) There is a reasonably good correlation between the threshold α and the state parameter that collectively accounts for the initial effective confining pressure and void ratio. The threshold α tends to decrease with increasing state parameter.

(c) Under otherwise similar conditions, the addition of 10% non-plastic fines into Toyoura sand causes a decrease in liquefaction resistance (CRR) which ranges from about 30% to 15%.

(d) The reduction of liquefaction resistance can be characterized by the factor K_{fc} and the factor seems to be independent of α for dense specimens but varies with α in a modest way for loose specimens.

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