Undrained Cyclic Behavior of Loose Sand under Anisotropic Consolidation

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ABSTRACT

This paper presents an experimental study of the liquefaction behavior of sand under initial shear conditions. The emphasis of the study was placed on loose sand by using cyclically loaded triaxial tests, where sand specimens were subjected to anisotropic consolidation to arrive at different levels of static shear stresses before the application of cyclic loading. The study reveals that a small static shear applied in compression is beneficial to liquefaction resistance but high levels of initial shear stress may become a detrimental factor. It is proposed that a threshold initial shear stress level above which cyclic resistance starts to drop exists in loose sand. Compared with an initial shear applied in compression, an initial shear stress applied in extension is found to impose a contrasting behavior such that increasing the initial shear stress level always reduces the cyclic resistance. This behavior is considered to be the result of the enhanced contractiveness of sand in extension.

KEYWORDS: soil liquefaction, initial static shear, laboratory testing, dilatancy, sand

1. INTRODUCTION

Significant efforts have been made over the past decades to understand soil liquefaction behavior. The current practice in the evaluation of soil liquefaction resistance relies on the "simplified procedure" developed by Seed & Idriss (1971), which was applicable only to level or gently sloping free field ground with shallow depth. In many major projects involving slopes, earth dams and buildings, soils are subjected to additional initial static shear stresses in the horizontal plane before earthquake loading. Seed (1983) proposed two empirical correction factors K_σ and K_α to extrapolate the simplified procedure to higher overburden pressure σ_{vo}' and higher initial static shear stress τ_s , respectively, such that the normalized cyclic shear resistance termed as cyclic resistance ratio CRR under any σ_{vo}' and τ_s is

$$CRR_{\sigma,\alpha} = CRR_{100,0} \times K_\sigma \times K_\alpha \tag{1.1}$$

where $CRR_{100,0}$ is the cyclic resistance ratio at $\sigma_{vo}' = 100$kPa and $\tau_s = 0$; and α is a measure of initial static shear stress level, which is defined as

$$\alpha = \frac{\tau_s}{\sigma_{vo}'} \tag{1.2}$$

While the use of K_σ to account for the overburden pressure effect is generally accepted (Youd & Idriss, 2001), the use of K_α correlations in routine engineering practice is however not recommended. This is due mainly to the lack of convergence and consistency in the current experimental data. While several studies produced new data enriching our understanding to some extent (Hyodo et al., 1994; Vaid et al., 2001; Sivathayalan & Ha, 2004), cyclic tests studying the effects of initial shear so far were mostly focused on rather dense sand with relative density above 40%, and the levels of initial shear tested were narrowly ranged with α often in between 0 and 0.2. Moreover, the importance of applying initial shear in compression and extension in triaxial tests was largely neglected.

In this study, a series of cyclic triaxial tests on *loose* sand that is particularly susceptible to liquefaction has been conducted under a wide range of initial static shear stress levels and initial confining pressures. The objective of this experimental study is to investigate the effect of initial shear stress on the liquefaction behavior of loose sand and how the confining stress levels affect the impact brought about by the initial shear. Furthermore, the importance of having initial shear applied in compression and in extension is also brought into focus.

2. EXPERIMENTS

All cyclic triaxial tests presented here were carried out using an automated triaxial testing system – CKC Triaxial System. The system is capable of performing various functions including isotropic and anisotropic consolidation and different modes of shear loading under either stress- or strain-controlled conditions. Toyoura sand, the Japanese standard sand was tested. It is uniform fine silica sand consisting of angular to sub-angular grains composed of over 90% quartz. The sand has an average particle size D_{50} of 0.175mm and uniformity coefficient C_u of 1.5 with 0% fines. The maximum and minimum void ratio e_{max} and e_{min} were found to be 0.977 and 0.605, respectively. The specific gravity G_s is 2.64. Moist tamping technique was employed to prepare sand samples, and in all tests, the specimens were fully saturated with B-value > 0.98.

The initial confining pressure and initial static shear stress were arrived at by anisotropic consolidation as the normal effective stress σ_{nc}' and initial static shear stress τ_s on the plane of maximum shear, i.e. the 45^o plane in the specimen respectively. By simply rotating principal stress directions by 90^o, compression initial shear can be reversed as extension. Their levels were controlled by the major and minor principal consolidation pressures σ_{1c}' and σ_{3c}' as

$$\alpha = \frac{\sigma'_{1c} - \sigma'_{3c}}{\sigma'_{1c} + \sigma'_{3c}} \tag{2.1}$$

$$\sigma'_{nc} = \frac{\sigma'_{1c} + \sigma'_{3c}}{2} \tag{2.2}$$

The major part of this test program involved subjecting sand with relative density after consolidation D_{rc} = 20% to three levels of initial confining pressure σ_{nc}' = 100, 300 and 500kPa and for each confining stress level seven levels of initial shear α = 0, 0.05, 0.1, 0.25, 0.4, -0.1 and -0.2. Here positive α value refers to compression initial shear and negative for extension. Our intension was to investigate the effects of both levels and directions of initial shear on the cyclic liquefaction behavior of loose sand under various levels of confining stresses. Sand samples with D_{rc} = 10% and 35% were also tested under similar stress conditions but to a lesser extent so as to investigate the influence of density as well. The unique features of this test program include, firstly, testing very loose sand with relative density after consolidation as low as 10%. Secondly, α was largely ranged up to 0.4 allowing for more thorough understanding on the impact brought about by varying the levels of initial shear. Thirdly, tests were repeated at identical initial conditions but reversing the initial shear direction to ensure the effects of compression α and extension α on loose sand to be compared. Moreover, the entire range of initial shear stress was repeatedly tested under three levels of confining stress up to 500kPa allowing the effects of confining pressure to be studied.

3. RESULTS AND DISCUSSION

3.1 Cyclic Behavior of Loose Sand

Loose sand undergoes complete liquefaction as a result of strain softening when subjected to sufficient number of undrained loading cycles. Unlike the strain accumulation and transient softening experienced by dense sand, once liquefaction is triggered in loose sand, a complete loss of shear strength is resulted with sudden and excessive deformation. Indeed, how liquefaction is brought about depends on the initial state and the cyclic stress amplitude. The initial density and confining stress level together control the contraction/dilation of sand while the relative amplitude of initial static shear stress and cyclic shear stress determines the occurrence of stress reversal; both are responsible for the different mechanisms leading to liquefaction (Yang & Sze, 2008).

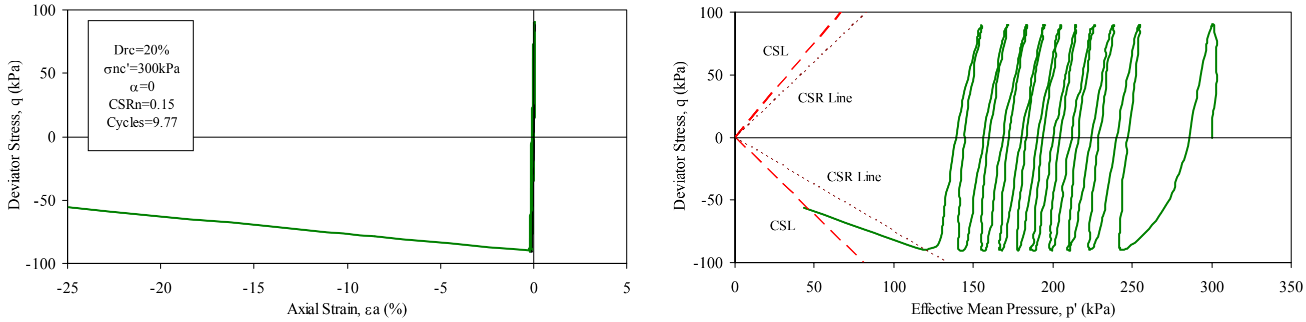

Figure 1 Cyclic behavior of sand (D_{rc}=20%, σ_{nc}'=300kPa, α=0)

Figure 1 shows the cyclic behavior of loose sand at D_{rc} = 20% and σ_{nc}' = 300kPa without initial shear. Stress reversal was expected. In the stress space, the effective stress state of sand was brought progressively towards the critical stress ratio (CSR) line, which defines the state of triggering of strain softening. Until the 9th cycle, strain accumulation did take place in both compression and extension but was not obvious. Once the stress state reached the extension CSR line, 100% pore water pressure buildup with a complete loss of effective stress was resulted. Concurrently, excessive axial strain was developed suddenly in extension from almost 0 to over 25%. Complete liquefaction was said to have occurred and the sand exhibited no shear strength and shear stiffness.

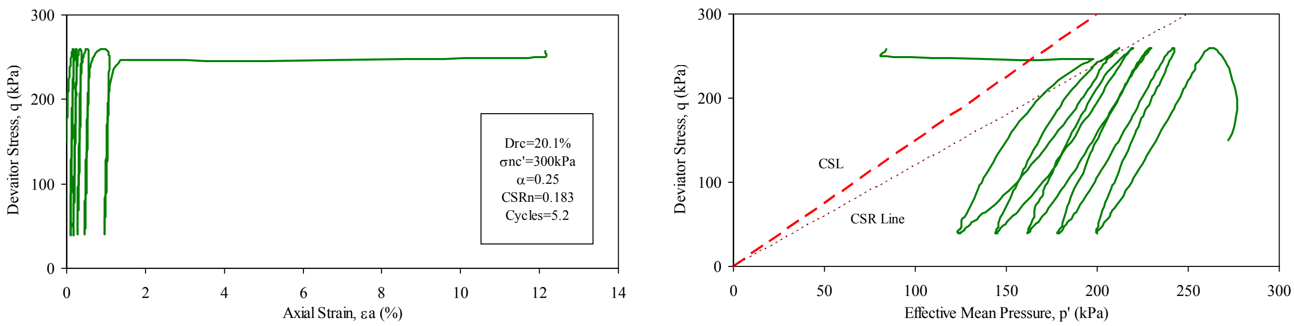

Figure 2 Cyclic behavior of sand (D_{rc}=20%, σ_{nc}'=300kPa, α=0.25)

Under the same initial conditions but with initial shear in compression at α = 0.25, the cyclic behavior is shown in Figure 2. Anisotropic consolidation brought the initial stress state above the p' axis in the stress space. Since loading was applied without stress reversal, the entire loading cycles lie on the compression side. Notable strain accumulation occurred in early cycles but in compression only. Again, strain softening was triggered when the stress state was brought to the CSR line but on the compression side in this case, being associated with sudden and excessive axial deformation. It seems that while the occurrence of stress reversal affects the mechanism of strain development, it does not significantly affect when liquefaction is brought about which, however, is likely to be controlled by the relative position of the initial stress state and the CSR lines. Therefore, it can be expected that if initial shear is applied in extension to a similar level, triggering of strain softening would be resulted in extension when the state reached the extension CSR line. This is indeed evidenced in Figure 3 with α = -0.2.

3.2 Characterization of Cyclic Liquefaction Resistance

Certain liquefaction criteria are required to define the cyclic liquefaction resistance of sand under different initial conditions on a common basis. Cyclic strength or cyclic resistance is often expressed as cyclic resistance ratio CRR which is the cyclic shear stress τ_{cyc} required to initiate liquefaction normalized by the overburden pressure. In this study for triaxial tests, it is expressed as

$$CRR_n = \frac{q_{cyc}}{2\sigma_{nc}^{'}} \qquad (3.1)$$

where q_{cyc} is the cyclic deviator stress. Note that the above equation *is* different from the customary use of σ_{3c}'. This is because that the conventional use of σ_{3c}' is only true in the absence of initial shear (i.e. σ_{nc}' = σ_{3c}' = σ_{vo}'). With the presence of initial shear, σ_{3c}' < σ_{nc}' if it is applied in compression but σ_{3c}' > σ_{nc}' in the case of extension.

The onset of liquefaction in loose sand can uniquely be defined as the triggering of strain softening, i.e. when the effective stress state reaches the CSR line in the stress space. It is also necessary to specify the number of uniform loading cycles required to reach this point. It has been customary to consider 10 or 20 cycles since they are the number of significant cycles in the actual time histories of accelerations recorded in past earthquakes. In this regard, the liquefaction resistance of sand is defined here as the cyclic shear stress required to trigger strain softening in 10 uniform loading cycles. CRR_n of loose sand so computed was found to be highly dependent on the levels of initial static shear stress and initial confining stress. Depending on how loose the sand is, CRR_n would also differ. Therefore, the cyclic resistance is very sensitive to D_{rc}, σ_{nc}' and α and that the effects of each factor are interrelated.

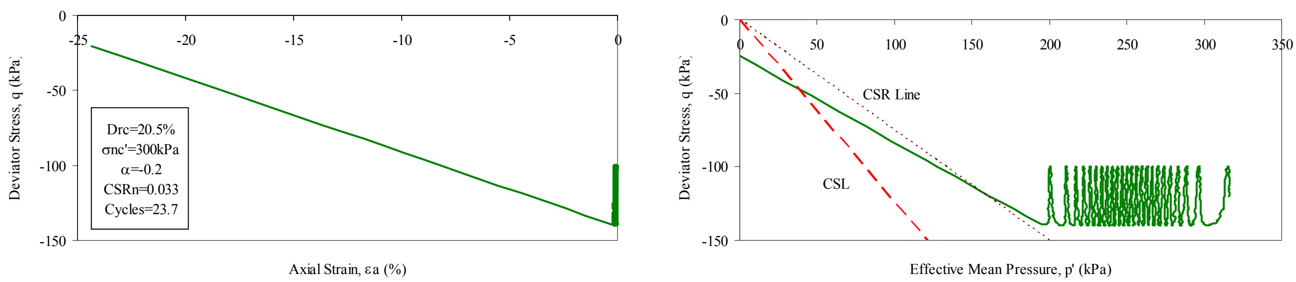

Figure 3 Cyclic behavior of sand (D_{rc}=20%, σ_{nc}'=300kPa, α=-0.2)

3.3 Effects of Initial Static Shear Stress Levels

The effects of levels of both compression and extension initial shear can be singled out by plotting CRR_n against α at different initial states, as done in Figure 4(a). Focusing on compression α at the moment, CRR_n of loose sand always increases and then decreases with increasing α regardless of σ_{nc}'. Having CRR_n increased with the presence of initial shear is of course beneficial compared with the absence of initial shear. However, this beneficial effect only takes place within a small range of α. As α increases to a higher level, CRR_n starts to drop and soon becomes less than that at α = 0. The effect of initial shear then becomes detrimental since the sand is now more prone to liquefaction. Eventually, a peak CRR_n is always reached at a certain level of α, termed the threshold α, which is likely to depend on D_{rc} and σ_{nc}'. Once the drop of CRR_n commences at the threshold α, there is no sign of regain. It can thus be expected that loose sand would lose all its cyclic strength once the initial shear reaches a certain high level. This is evidenced in 20% sand at σ_{nc}' = 100kPa such that when α increases to 0.6, it bears no cyclic resistance at all.

Increasing α in compression adds static compressive deviator stress q_s to the specimen before loading. Cyclic loading then superimposes a periodically changing q_{cyc} on q_s. At a small level of initial shear, q_s is small in compression. Compared with the absence of initial shear, q_{cyc} needs to be higher to ensure firstly loading is applied with stress reversal and secondly there exists certain extension stress comparable to that at α = 0 to ensure that liquefaction can be rapid enough to take place in 10 cycles. This response is the result of higher contractiveness of sand in extension. This leads to a temporary gain of CRR_n with increasing α at a small level. However, if α keeps increasing, the increasing q_s would make loose sand whose structure is already less stable more unstable. As a result, only very small q_{cyc} is sufficient to destroy its structure causing liquefaction. Furthermore, sufficiently high pure compression stress could be enough to achieve the same effect of having extension stress to cause liquefaction, especially in loose sand which is contractive in nature. Therefore, the higher q_s is, the lower q_{cyc} would be. That's why CRR_n drops sharply as α keeps increasing.

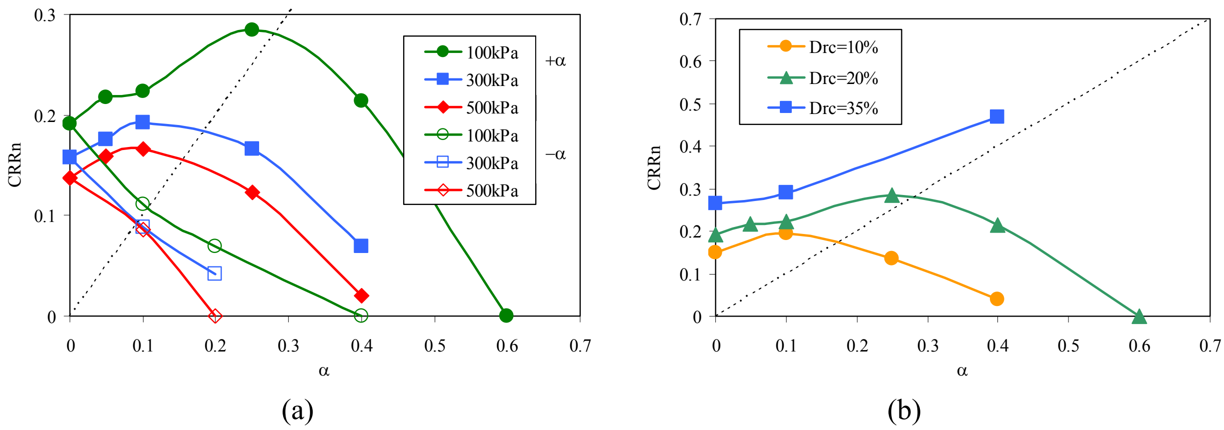

Figure 4 CRR_n versus α at various σ_{nc}' and D_{rc} values

More theoretically in the stress space, without initial shear liquefaction is triggered in extension since compression CSR line is steeper than the extension one. If α increases slightly such that the initial state is still closer to extension CSR line, q_{cyc} has to be increased to ensure that the state eventually reaches the extension line to initiate strain softening. If α keeps increasing such that the state becomes closer to compression CSR line, q_{cyc} needs not to be increased further to reach the extension line since it can reach the compression one first with a smaller q_{cyc}. This gives the increasing and decreasing trend of cyclic resistance with α in loose sand a more theoretical-based explanation.

Since loose sand cannot withstand too high level of initial shear or it would become more susceptible to liquefaction, it is important to understand more about the threshold α. From Figure 4(a), the threshold α increases with decreasing σ_{nc}', i.e. when sand becomes more dilative. It shows that the threshold α is around 0.25 when σ_{nc}' = 100kPa but it drops to less than 0.1 when σ_{nc}' rises to 500kPa. Also plotted in Figure 4 is a line on which $CRR_n = \alpha$, termed the zero reversal line. On its left, CRR_n is applied with stress reversal and on the right it is without reversal. It can be observed that whenever the $CRR_n - \alpha$ trend line touches the zero reversal line, CRR_n starts to or has just started to drop with α. It means that whether a drop of CRR_n would commence is associated with whether stress reversal takes place.

The zero reversal line thus determines the level of threshold α. The correspondence between the occurrence of stress reversal and the commencement of cyclic resistance drop follows the explanation above. At a higher confining pressure, the trend line touches the zero reversal line at a lower level of α due to the reduction of CRR_n as shown in Figure 4(a). At a higher density, however, the notable gain of CRR_n in denser sand increases the threshold α as shown in Figure 4(b). CRR_n of the 35% sand does not experience any drop up to α = 0.4 since its trend line does not reach the zero reversal line. If α increases further, a drop is still likely. Therefore, the zero reversal line can effectively estimate the behavior of CRR_n under the influences of D_{rc}, σ_{nc}' and α.

Figure 4 also shows that extension α always reduces CRR_n of loose sand. The drop becomes more substantial under higher confining pressures. Since sand behaves more contractively in extension, it will be liquefied more rapidly in cyclic loading with larger proportion of stress in extension compared with the same level of stress but in compression, i.e. CRR_n under extension α is always lower than that under corresponding compression α.

The variations of CRR_n with α are apparently dependent on the levels of σ_{nc}' such that increasing confining pressure always reduces CRR_n as shown in Figure 4. Both commencement of CRR_n drop and complete loss of CRR_n take place at lower levels of α when σ_{nc}' increases. It seems that the presence of higher confining pressure magnifies the destructive effects brought about by initial shear on loose sand. Indeed, this happens only at high levels of α and σ_{nc}'.

3.4 K_α Correction Factor for Initial Static Shear Stress Levels

The relationship between K_α and α established based on the experimental data is shown in Figure 5. The increase and decrease of K_α with α exactly follow that of CRR_n. It indicates that the threshold α above which CRR_n drops is exactly the same as the threshold α leading to the drop of K_α. Indeed, K_α does not tell exactly what cyclic resistance the sand bears but how great the change is due to the presence of initial shear compared with the absence of any. With varying the level of α, K_α varies around 1. $K_\alpha > 1$ certainly shows that the presence of initial shear at such level is beneficial; $K_\alpha < 1$ means that it experiences a reduction of resistance. Due to the correspondence between K_α and CRR_n, the above discussion on how CRR_n is influenced by D_{rc}, σ_{nc}' and α applies on K_α.

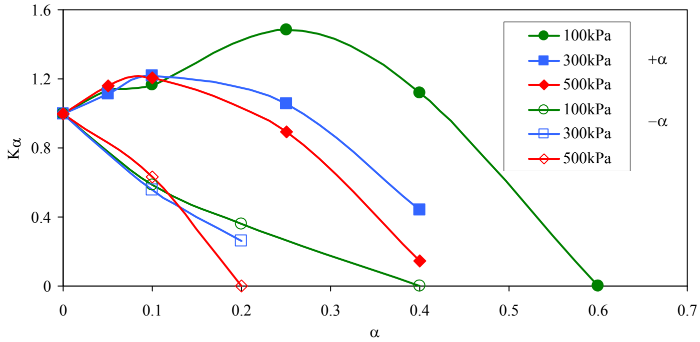

Figure 5 K_α versus α

4. CONCLUSIONS

An experimental investigation into the liquefaction behavior of loose sand has been presented, with focus on the effects of initial static shear that exist in many practical applications. The significant findings of the investigation can be summarized as follows: (1) strain softening is the unique cause of liquefaction in loose sand regardless of the levels and directions of initial shear; (2) increasing α in compression at small levels is beneficial since it enhances the cyclic resistance of sand but further increasing it becomes detrimental such that the cyclic resistance drops substantially; (3) a threshold α above which cyclic resistance starts to drop exists in loose sand and is dependent on the levels of density and confining stress; (4) an initial shear applied in extension imposes a contrasting behavior in loose sand such that increasing α always reduces its cyclic resistance due to the enhanced contractiveness of sand; (5) increasing confining pressure is always beneficial except above a certain level of α.

ACKNOWLEDGEMENTS

The work presented in this paper was supported by the Research Grants Council of Hong Kong under the grant number 712705. This support is gratefully acknowledged.

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