EFFECT OF STATIC SHEAR ON RESISTANCE TO LIQUEFACTION

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ABSTRACT

The influence of static shear on undrained cyclic loading behaviour of Ottawa sand has been studied using triaxial samples anisotropically consolidated to various stress ratios. It is shown that the presence of static shear does not always lead to increased resistance to liquefaction or cyclic strain development. The resistance to liquefaction can increase or decrease with increasing static shear depending on the relative density, magnitude of the static shear and the specified level of strain development. It is also shown that flow deformation occurs during cyclic loading of loose sand much in the same manner as observed by Castro in monotonic tests, and is responsible for sudden strain development during cyclic loading.

Key words: cyclic loading, liquefaction, sand, static shear, triaxial test (IGC : D7)

INTRODUCTION

The liquefaction or cyclic straining potential of a level saturated sand deposit subjected to seismic load is evaluated commonly by undrained cyclic triaxial tests on isotropically consolidated samples or cyclic simple shear tests on one-dimensionally consolidated samples. These tests are designed to simulate stress conditions in soil elements beneath the level ground. On these elements, there is no initial static shear stress on horizontal planes prior to earthquake shaking. However, there are many cases of practical interest in which soil elements are subjected to initial static shear stress on horizontal plane. During earthquake shaking, these elements are subjected to additional cyclic shear stress due to shear wave propagating vertically upward from the bedrock. The presence of these initial static shear stresses can have a major effect on the response of the soil to superimposed cyclic loading.

The field conditions in which there are initial static shear stresses on the horizontal planes have been simulated in the laboratory by cyclic triaxial test on anisotropically consolidated sample with effective stress ratio, \( K_s = \sigma_{is}/\sigma_{uc} \) greater than 1.0 (Lee and Seed, 1967; Seed and Lee, 1966; Seed, Lee, Idriss and Makdisi, 1973). The results of these studies show that the response of the anisotropically consolidated samples under cyclic loading depends on the effective stress ratio.

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after consolidation and the amplitude of the cyclic stress applied. For the case of no shear stress reversal, the sample tends to deform progressively in each successive loading cycle, but porewater pressure generated does not increase sufficiently to cause a state of transient liquefaction ($\sigma' = 0$), which leads to a rapid build up of strains with further cycles of loading. However, for the case of partial or complete shear stress reversal, the porewater pressure may build up progressively to the value of initial confining stress, resulting in the attainment of the condition of transient liquefaction accompanied by a rapid build up of strains. The major conclusions from these studies have been that larger the initial static shear stress on the plane with a given normal stress, the larger is the maximum and cyclic deviator stress required to induce a certain amount of strain in a fixed number of cycles (Lee and Seed, 1967; Seed, Lee, Idriss and Makdisi, 1973).

It is considered that the simple shear test simulates field stress condition more closely. The cyclic loading behaviour of saturated sand subjected to initial static shear stress on the horizontal plane has been studied under such conditions by Yoshimi and Oh-o-ka (1975) using a ring torsional shear apparatus. The conclusions reached in this study regarding the influence of initial static shear stress on resistance to liquefaction were essentially opposite to those based on studies in the triaxial test by Seed and Lee (1967 and 1969). Resistance to liquefaction, measured by cyclic stress amplitude, was found to decrease or remain unchanged with increase in initial static shear stress level.

A study on the influence of initial static shear stress on the resistance to liquefaction has also been carried out in shaking table tests (Yoshimi and Tokimatsu, 1978). In such a study, a small scale soil-structure model was used and porewater pressures were monitored at various locations in sand during shaking. The authors drew conclusions similar to those of Yoshimi and Oh-o-ka (1975).

The effect of initial static shear stress on the resistance to liquefaction under plane strain condition using cyclic simple shear test was investigated by Vaid and Finn (1979). Constant volume cyclic simple shear tests were performed on one-dimensionally consolidated samples of sand with initial static shear stress on the horizontal plane. The study showed that the prevalent belief that the presence of initial static shear stress always increases the resistance to liquefaction as suggested by Seed and Lee (1967, 1969) was not always found to be valid. The resistance to liquefaction can either increase or decrease due to the presence of initial static shear stress depending on the relative density, magnitude of static shear stress and definition of resistance to liquefaction.

It is felt that most of the research on cyclic loading behaviour of saturated sands has been restricted to relating the resistance to liquefaction or cyclic straining to the number of cycles of loading. Few attempts have been made to look at the behaviour within cycles of loading, which is essential for a fundamental understanding of the process leading to liquefaction or cyclic strain development. Furthermore, a wide scatter is generally present in laboratory test results reported by various investigators. This scatter might be attributed to the nature of the testing methods, different sample preparation techniques, resulting in non-uniformities in sample density, premature loading of the sample before commencement of cyclic loading and the effect of system compliance. Also, most of the investigations were carried out in a limited range of density. Consequently, contradictory conclusions may have emerged with respect to the influence of initial static shear stress on the resistance to liquefaction.

The purpose of this study is to better understand the process of cyclic loading which leads to liquefaction or cyclic strain development. This will be attempted by looking at the undrained response of saturated samples not only at the end of loading cycles as conventionally done, but also within each cycle of loading. A further aim of this study is to generate basic and consistent data.
on the effects of initial static shear stress on the resistance to liquefaction and clarify the apparently contradictory conclusions reported in the previous studies. To achieve these objectives, cyclic loading triaxial tests were carried out under carefully controlled conditions. Specific innovations included improved sample preparation techniques to insure uniform density throughout the specimen, eliminating possible premature loading of sample prior to cyclic loading and testing larger size samples in order to minimize the effects of membrane penetration.

Even though the triaxial test does not simulate field stress condition as well as the simple shear test, it was used in the present investigation primarily because of its simplicity and its almost universal use in current seismic design. Furthermore, one of the important aims of the investigations is to study the mechanism of porewater pressure and strain development during cyclic loading. The choice of a particular type of test is not crucial for investigation of such fundamental questions. In any case suitable correlations between triaxial and simple shear behaviour can be established, as has been done in the past liquefaction studies.

EXPERIMENTAL PROGRAM

As discussed previously, cyclic triaxial tests were used in the present study. The triaxial specimens were 2.5 in. (6.4 cm) in diameter by 5 in. (12.8 cm) long. It is felt that the conventional method of sample preparation by sedimentation creates non-uniform density within the specimen, particularly in samples with high densities. In conventional sedimentation techniques, densification of the sample to the desired density is carried out prior to seating of the top loading cap. A loose layer tends to form at the top of the sample by such a procedure, partly as a result of seating the cap and partly due to the inability of vibrations to densify the unconfined top layer. In this test program, the sample was deposited loose, and then brought to the desired density by tapping on the base of the triaxial cell while maintaining a gentle pressure on the sample cap. It has been shown that this technique of sample preparation results in samples of uniform density throughout (Finn and Vaid, 1978; Vaid and Finn, 1979). Often the connection of the loading ram to the loading piston by conventional techniques results in premature axial loading or unloading of the sample before initiation of cyclic loading. This may affect the subsequent undrained response. To minimize any such loading of the sample, an eyed connecting ring was used. This technique permits a much better centering, and prevents premature axial loading or unloading of the sample.

All samples were initially consolidated isotropically under an effective stress of 2.0 kgf/cm² (200 kPa). Anisotropically consolidated samples were obtained by applying static deviator stress under drained conditions until the desired value of anisotropic stress ratio, $K_o$ was obtained.

A sinusoidal waveform was used for cyclic loading and tests were carried out at a frequency of 0.1 Hz. Low frequency loading was used in order to examine in detail the phenomenon of porewater pressure and strain development within each cycle of loading. During each test, cyclic load, porewater pressure and axial strain were continuously monitored by electronic transducers and records obtained on strip chart or oscillographic recorders.

Improved sample preparation techniques and testing methods used in these investigations are believed to result in improved sample uniformity and sample disturbance is minimized. Essentially no necking of samples was observed until extremely large axial extensional strains developed. This enabled the interpretation of results with confidence in the strain range of interest.

Tests were performed on Ottawa Sand, ASTM designation C-109. This is a natural Silica sand consisting of rounded particle with grain sizes between 0.15 mm and 0.59 mm and $D_{10}=0.40$ mm. The maximum and minimum void ratios, determined using the
procedure ASTM D2049, are 0.82 and 0.50, respectively.

Cyclic loading tests were performed on both isotropically and anisotropically consolidated samples. Two series of tests on anisotropically consolidated samples were carried out using $K_c = \sigma_{c}' / \sigma_{sc}'$ value of 1.19 and 1.48, respectively. The magnitudes of cyclic deviator stress $\sigma_{dev}$ relative to static deviator stress $\sigma_{sc}$ were chosen so that both shear stress reversal and non-reversal were simulated. In each series, cyclic loading tests were performed over a range of relative density varying from 33% to 76%.

Stress controlled monotonic loading undrained tests were also performed on loose and medium dense samples. This was done in order to establish the effective stress failure envelope of the sand and the characteristics of pore water pressure generation and strain development, and their possible interrelationship with undrained behaviour under cyclic loading.

**TEST RESULTS**

*Cyclic Loading Behaviour*

Typical results of cyclic loading behaviour of loose samples consolidated to different static stress ratios are shown in Fig. 1(a) and 1(b). The axial strain represents the maximum accumulated strain until the stress cycle under consideration. This strain can either be compressional or extensional with respect to the sample configuration at the end of consolidation. It may be seen that for all samples, the residual porewater pressure $\Delta u_r$ increased progressively with cycles of loading. This was later followed by a sudden increase in porewater pressure shortly before it reached a terminal value. For isotropically consolidated sample, the terminal value of the residual porewater pressure equals the initial effective confining pressure $\sigma_{sc}'$. However, its value is less than the confining pressure in the case of the anisotropically consolidated samples. The value of the terminal residual porewater pressure may be noted to decrease with increasing $K_c$ value.

From Fig.1(a) and 1(b), it may be seen that a sharp increase in residual porewater pressure is accompanied by a sudden development in axial strain in all cases. This phenomenon is associated with contractive flow deformation (Casagrande, 1976; Castro, 1969) developed in the sample, which will be discussed further in later sections. Sudden development in residual porewater pressure and axial strain did not occur until the maximum effective stress ratio during cyclic loading reached a certain critical value. The value of this critical stress ratio was found to be about 2.60 and was independent of the consolidation stress ratio $K_c$ and cyclic stress ratio $\sigma_{dev}/2 \sigma_{sc}'$. A more vivid illustration of this phenomenon will be given in a later section.

Typical results for medium dense samples are shown in Fig. 2. The development of residual porewater pressure with number of cycles is essentially similar to that for the loose samples, except in the case of the sample consolidated to high $K_c$ value. In this case no accelerated increase in porewater pressure is observed. The residual porewater pressure...
increased progressively and approached the terminal value asymptotically. However, for a given $K_c$ value, the terminal value of residual porewater pressure was the same as that for the loose sample and was independent of the cyclic stress ratio.

Similar to the behaviour of loose samples, significant amount of strain started to build up when accelerated increase in residual porewater pressure developed. The strain increased progressively, though at a slower rate when compared to that for loose sand. Once again an accelerated increase in residual porewater pressure and axial strain were observed only when the maximum effective stress ratio during cyclic loading reached a critical value of about 2.67.

Typical results of the cyclic loading behaviour of dense sand are shown in Fig. 3. It may be
Fig. 5. Effective stress paths in cyclic loading tests on isotropically and anisotropically consolidated medium dense sand.

Fig. 6. Effective stress paths in cyclic loading tests on isotropically and anisotropically consolidated dense sand.
seen that the behaviour of dense sand is essentially similar to that of the medium dense sand. However, the development of residual porewater pressure and axial strain are at a slower rate than that for the medium dense sand.

All test results show that the maximum residual porewater pressure reaches the value of initial effective confining pressure in samples with complete or significant amounts of shear stress reversal, and it always occurs at the instant when shear stress is equal to zero. This finding supports the results of a similar study in the simple shear test by Vaid and Finn (1979). Lee and Seed (1967), however, reported that even the slightest shear stress reversal during cyclic loading triaxial test gave rise to a condition of transient liquefaction ($\sigma_1'=0$).

**Mechanism of Liquefaction or Strain Development**

Typical effective stress paths during cyclic loading for loose, medium dense and dense sand consolidated both isotropically and anisotropically are shown in Figs. 4, 5 and 6. Irrespective of relative density, initial consolidation stress ratio or cyclic stress ratio, the effective stress paths moved toward the failure envelope progressively with cycles of loading. However, in loose samples (Fig. 4), before the stress state reached the failure envelope, a contractive flow deformation occurred. A sharp increase in porewater pressure accompanied by a sudden development in axial strain was observed. This flow deformation stopped when the sample strained sufficiently so as to cause dilation with further straining. This phenomenon is similar to the limited liquefaction observed by Castro (1969). After the sample developed flow deformation, it reached the failure envelope very quickly and the residual porewater pressure reached its terminal value. From the stress paths, it may be seen that the phenomenon of flow deformation was triggered when the sample reached a state of stress corresponding to an effective stress ratio of about 2.60, (shown by broken lines in Fig. 4) regardless of the initial $K_e$ value and the cyclic stress ratio.

For medium dense sand, the stress paths (Fig. 5) show no flow deformation. Instead of developing flow deformation, the stress path moved progressively toward the failure envelope. A careful study of the stress paths shows that there exists an effective stress ratio line, both in compression and extension regions (shown dotted in Fig. 5), beyond which the sample dilates and develops significant amounts of strain whenever it is loaded, and develops large positive porewater pressure whenever it is unloaded below this line. The value of this effective stress ratio was about 2.67 and was found to be approximately the same in both compression and extension regions. The accelerated increase in residual porewater pressure and the nature of progressive increase in axial strain is due to the repetition of this mechanism with further loading cycles. Mechanism of porewater pressure and axial strain development in medium dense sand is thus different from that for loose sand where flow deformation accounts for the sudden large porewater pressure and strain development.

The effective stress paths for dense sand (Fig. 6) are essentially similar to those for the medium dense sand, and so is the mechanism of strain development during cyclic loading. However, due to more dilatant characteristics of dense sand, the development of porewater pressure and axial strain are at a slower rate than that for the medium dense sand.

It was shown earlier that the terminal value of residual porewater pressure decreases with increasing $K_e$ value but is independent of the relative density of the sample and cyclic stress amplitude applied. An examination of the effective stress paths shows that ultimately all cyclic undrained stress paths stabilized along the failure envelope. This failure envelope was found to be essentially the same regardless of the relative density of the sand, initial $K_e$ value and cyclic stress amplitude applied. Hence for a given $K_e$ value, there exists a theoretical terminal
value of residual porewater pressure \((\Delta u_r)_{\text{term}}\) which can be expressed by the relation

\[
(\Delta u_r)_{\text{term}} = \sigma_{3c}' \left( 1 - \frac{K_e - 1}{2} \sin \phi' \right)
\]

\[(1a)\]

or

\[
(\Delta u_r)_{\text{term}} = \sigma_{3c}' \left( 1 - \frac{\tau_s}{\sigma_{3c}'} \sin \phi' \right)
\]

\[(1b)\]

in which \(\tau_s = \sigma_{3c}' / 2\) is the initial static shear stress on the plane 45° to the horizontal and \(\phi'\) is the angle of internal friction. Eq. (1) shows that \((\Delta u_r)_{\text{term}}/\sigma_{3c}'\) decreases linearly with increasing \(K_e\) value or initial static shear stress level. \((\Delta u_r)_{\text{term}}\) equals the initial confining pressure \(\sigma_{3c}'\) only in isotropically consolidated samples, which correspond to \(K_e = 1\). For \(K_e > 1\), \((\Delta u_r)_{\text{term}}\) is always less than the initial confining pressure. The measured values of \((\Delta u_r)_{\text{term}}\) for cyclic loading tests as a function of \(K_e\) value are shown by data points in Fig. 7 where the predicted relationships is also shown by a solid line. The predicted value is based on the average \(\phi'\) angle of 36.6°. Excellent agreement may be seen between the observed and predicted values.

From stress paths, it may also be seen that conventional initial liquefaction, \(\Delta u = a_{3c}'\), is a transient phenomenon during cyclic loading, which always occurs at the instant when shear stress is equal to zero. This phenomenon can occur in isotropically consolidated samples or in anisotropically consolidated samples with significant amount of shear stress reversal. It is clear that conventional initial liquefaction cannot be induced in case there is no shear stress reversal, because the stress path never crosses the zero shear stress line. It may also be noted that after initial liquefaction, sample regains its strength due to dilation when it is further sheared, thus limiting further deformation within the loading cycle.

Monotonic Loading Behaviour

Stress controlled monotonic loading undrained tests were performed on loose and

![Fig. 7. Relation between terminal residual porewater pressure and initial static shear stress level (number in parenthesis indicates the number of data points)](image)

![Fig. 8. Stress-strain response of loose and medium dense sand under monotonic compressive loading)](image)
medium dense samples in order to obtain the stress-strain curves and the characteristics of porewater pressure development. Typical results are shown in Fig.8. For two loose samples (samples are referred to as loose if they develop flow deformations), S-1 and S-2, the deviator stress and porewater pressure increased progressively with very small strain development and the effective stress path moving towards the failure envelope. This trend continued until a state of stress was reached at which the sample became unstable. A sudden decrease in deviator stress occurred accompanied by a sharp increase in porewater pressure and axial strain in a very short period of time. This flow deformation, which was also observed in cyclic loading tests, was stopped by dilation once the sample developed sufficient strain. Thereafter the sample reached the failure enveloped very quickly. The medium dense sample, S-3, on the other hand did not develop flow deformation. Instead the sample dilated and approached the failure envelope progressively with strain development at a much higher rate compared to that in the initial stage. The effective stress ratio at which the sample started to dilate was found to be approximately the same regardless of the relative density, but was slightly higher than the stress ratio at which loose sample started to develop flow deformation.

Comparing the results of cyclic and monotonic loading tests, there seems to exist a critical effective stress ratio which controls the onset of flow deformation of loose samples. Flow deformation is believed to be responsible for the sharp increase in porewater pressure and sudden development in axial strain, which is the characteristic difference in strain development between loose and dense samples in cyclic loading tests (Figs. 1, 2 and 3). This critical effective stress ratio is found to be independent of initial consolidation stress ratio and cyclic stress level.

Resistance to liquefaction or straining is expressed by the cyclic stress ratio $\frac{\tau_{cy}}{\sigma_{nc}'} (\tau_{cy} = \sigma_{c2y}/2$) required to develop a specified amount of axial strain from the initial sample configuration (i.e. single amplitude ±axial strain) in a given number of cycles. The cyclic loading resistance of both isotropically and anisotropically consolidated samples is shown in Figs. 9, 10 and 11 as cyclic stress ratio versus the number of stress cycles to develop 1 and 2-1/2% axial strain. These results are derived by cross plotting the basic test data which was generated in the form of contours of relative density versus number of cycles to develop a specified amount of strain when $\tau_{cy}$ and $K_s$ were held constant. For anisotropically consolidated samples, the cyclic stress has been normalized with respect to static consolidation stress $\sigma_{nc}'$ on the plane inclined at 45° to $\sigma_1'$ plane. This plane is subjected to the maximum amplitude of shear stress during cyclic loading and is considered to simulate the cyclic earthquake stress conditions on the horizontal planes in the ground.

The relationships shown in Figs. 9, 10 and

![Graph showing the effect of initial static shear stress on cyclic stress ratio required to cause specified amount of strain in loose sand.](image)

Fig. 9. Effect of initial static shear stress on cyclic stress ratio required to cause specified amount of strain in loose sand.
cyclic stress ratio required to develop 1% or 2-1/2% axial strain for sample with initial static shear stress can either be higher or lower than the case with $\tau_s=0$ depending on the level of $\tau_s$. For medium dense and dense states, however, (Figs. 10 and 11) the presence of static shear leads to a larger resistance to cyclic straining at each level of chosen cyclic strain in comparison to the case with no static shear. In medium dense sand, an increasing static shear does not necessarily lead to increased resistance to cyclic straining as is the case with dense sand.

The variation of cyclic stress ratio required to cause 1%, 2-1/2% and 5% axial strain in 10 stress cycles for each of the chosen relative densities is shown in Fig. 12. For loose sand (Fig. 12(a)), it may be noted that an increase in resistance to liquefaction or cyclic straining is observed at low levels of initial static shear stress. However, significant reduction in resistance to liquefaction occurs when $\tau_s/\sigma_{nl}$ is larger than about 0.1. This reduction in resistance to liquefaction is attributed to the fact that the initial stress state of the sample prior to cyclic loading is closer to the critical effective stress ratio line at which flow deformation is initiated, and only a few loading cycles are needed to reach this line. From the trend of the resistance curves, it appears that a very small cyclic stress ratio may be required to cause large deformations in loose sand if the initial static shear stress is high enough. This corresponds to the phenomenon of spontaneous liquefaction.

For medium dense sand (Fig. 12(b)) also the cyclic loading resistance first increases and then decreases as $\tau_s$ is increased in order to develop strain levels of either 1% and 2-1/2%. However, the resistance increases essentially monotonically with increasing $\tau_s$ in order to develop a larger, 5% level of axial strain.

In contrast to the behaviour of loose and medium dense sand, the resistance to liquefaction of dense sand (Fig. 12(c)) was found to increase with increasing initial static shear stress level, irrespective of the level

Fig. 10. Effect of initial static shear stress on cyclic stress ratio required to cause specified amount of strain in medium dense sand

Fig. 11. Effect of initial static shear stress on cyclic stress ratio required to cause specified amount of strain in dense sand

11 have been chosen to represent loose, medium dense and dense states of the sand. For loose sand, (Fig. 9), it may be seen that...
of strain development. The increase in cyclic stress ratio with \( \tau_s \), however, tends to level off at higher levels of \( \tau_s \) at all levels of strain considered.

In Fig. 12 it may also be noted that for medium dense sand there is a larger divergence between \( \tau_{cy}/\sigma_{nc}' \) versus \( \tau_s/\sigma_{nc}' \) relationships at different strain levels in the region below a 45° line through the origin. This region represents static shear levels which do not result in shear stress reversal during cyclic loading. For such cases of no stress reversal, strain accumulates very slowly with number of stress cycles. Consequently significantly higher \( \tau_{cy}/\sigma_{nc}' \) are needed for a fixed amount of additional strain development at a given \( \tau_s/\sigma_{nc}' \) level. For cases involving stress reversal (region above 45° line), because of the occurrence of transient liquefaction during each cycle after its first occurrence, the strain accumulates very rapidly with cycles of loading. Therefore, the relationships between \( \tau_{cy}/\sigma_{nc}' \) and \( \tau_s/\sigma_{nc}' \) at various strain levels are much closer in this region of stress reversal. A similar phenomenon may be seen to explain the closely spaced relationships (Fig. 12 (c)) for dense sand, since they too correspond to very large stress reversals. These observations are in general agreement with simple shear results (Vaid and Finn, 1979). However, direct comparison of results may not be appropriate due to differences in the stress conditions in the two types of tests.

Resistance to Liquefaction or Cyclic Straining Versus Relative Density

The influence of relative density on the cyclic stress ratio required to cause specified levels of strain (1, 2-1/2%, and 5%) in 10 cycles for samples with and without initial static shear stress is shown in Fig. 13. The results obtained by Finn and Vaid (1978) using cyclic constant volume simple shear tests on the same sand with no initial static shear stress on the horizontal plane are also shown in Fig. 13(c). Such relationships showing the influence of relative density on the resistance to liquefaction or cyclic straining for anisotropically consolidated samples have never been reported in literature.

For sand with no initial static shear stress, there is a gradual increase in resistance to liquefaction with increasing relative density up to about \( D_r \approx 60\% \). This resistance to liquefaction increases at a much faster rate for \( D_r \) in excess of about 60%. It may be noted that this relationship obtained using the triaxial test is very similar to that obtained under cyclic constant volume simple shear conditions (Finn and Vaid, 1978). Studies on large scale simple shear samples by De Alba, Seed and Chan (1976), however, show that resistance to liquefaction increases virtually linearly with relative density up to \( D_r \) of about 80%. The observed dramatic increase in resistance to liquefaction at higher relative densities is believed to be a consequence of the improved sample preparation techniques. This improved sample preparation technique aims at forming samples of uniform density throughout and minimizes any effects which tends to create a loose layer at the top of an otherwise dense
For sand with low level of $\tau_s$, the resistance to liquefaction or cyclic straining is higher than the case with $\tau_s=0$ over a wide range of relative density. However, the resistance could be less than that for sand with $\tau_s=0$ only in the very loose state. For higher levels of $\tau_s$, the relationship between resistance to liquefaction or cyclic straining with increasing $D_r$ is different from those with no or small $\tau_s$. In the case of loose sand, the resistance could be substantially less than that for sand with $\tau_s=0$. This is attributed to the fact that for large $K_e$ values, the initial state of stress of sand prior to cyclic loading is much closer to the critical effective stress ratio line at which flow deformation is induced. Due to the contractive nature of the loose sand, rather small cyclic stress amplitude is required to develop large deformation in a given number of cycles. For medium dense to dense states, however, no flow deformation occurs. Due to the dilatant nature of such sand, the dilation tendency is then responsible for a rapid increase in the resistance to liquefaction. The unusual shape of the cyclic resistance curve for dense sand appears to be related to regions of stress reversals and no stress reversals during cyclic loading. The rate of build-up of resistance with relative density shows temporary slowing down once $\tau_{cy}/\sigma_{oc}'$ exceeds the static shear stress level. No such discontinuity in relationship is present at low $\tau_s$ levels since the entire range of $\tau_{cy}$ represents cases of stress reversal.

CONCLUSIONS

Cyclic loading behaviour of Ottawa sand has been studied under triaxial conditions with and without initial static shear stress to simulate the stress conditions on the horizontal planes of soil elements beneath horizontal ground, sloping surface or adjacent to the structures.

The test results show that the prevalent belief that the presence of initial static shear stress always increases the resistance to liquefaction or cyclic strain development
when compared to the case of no static shear was not always found valid. The resistance to liquefaction for samples with initial static shear stress can either be higher or lower than those with no initial static shear stress, depending on the relative density of the sample and the level of initial static shear stress.

From the cyclic loading behaviour, it was found that for loose sand there exists a critical effective stress ratio line at which flow deformation is triggered. This effective stress ratio line was found independent of the initial consolidation stress ratio and the cyclic stress amplitude applied. Flow deformation is responsible for the sharp increase in porewater pressure and sudden development of axial strain during cyclic loading tests. The phenomenon of flow deformation is responsible for reduced resistance to straining in loose sample with higher initial static shear stress. The upper limit of relative density for which flow deformation is developed was found to be about 45%.

From the study of the effective stress paths during cyclic loading, it was observed that a state of transient liquefaction can only be induced in samples with complete or significant amount of shear stress reversal. This is, however, a momentary phenomenon and sample regains its strength due to dilatation whenever it is sheared further. The sand can sustain a high deviator stress without excessive deformation especially in the dense state.

From the effective stress paths, it was shown that only a limiting value of the residual porewater pressure can be developed due to cyclic loading, and this value can be predicted by Eq. (1). This is important in the post-cyclic redistribution of excess porewater pressure which may cause instability in slopes or foundations.

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NOTATION

- $D_r$: relative density
- $D_{50}$: 50% finer size
- $e$: void ratio
- $K_c$: effective consolidation stress ratio, $\sigma_{sc}'/\sigma_{oc}'$
- $N$: cycles of loading or blow count
- $\Delta u$: excess porewater pressure
- $\Delta u_r$: excess residual porewater pressure
- $(\Delta u_r)_{term}$: terminal value of excess residual porewater pressure
- $\varepsilon_a$: axial strain
- $\sigma_1', \sigma_3'$: major and minor effective principal stresses
- $\sigma_{sc}', \sigma_{sc}$: major and minor effective consolidation stresses
- $\sigma_d$: deviator stress
- $\sigma_{dev}$: cyclic deviator stress
- $\sigma_{st}$: static deviator stress
- $\sigma_{nc}'$: normal effective consolidation stress on plane inclined at 45° to $\sigma_{sc}'$ plane
- $\tau_{dev}$: cyclic shear stress $= \sigma_{dev}/2$
- $\tau_i$: initial static shear stress $= \sigma_{st}/2$
- $\phi'$: angle of internal friction

REFERENCES