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EFFECT OF CONFINING PRESSURE  
AND PARTICLE ANGULARITY  
ON RESISTANCE TO LIQUEFACTION

by

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## ABSTRACT

A study to investigate the effects of particle angularity and high confining stresses on liquefaction resistance of sands is presented. Two quartz sands of identical mineral composition and gradation but differing in particle angularity were used. The investigations were performed under cyclic simple shear condition which closely simulates field stress conditions.

Resistance to liquefaction is compared for angular and rounded sands over a range of relative densities and confining stresses. Confining stress of up to 2500 kPa were applied to represent the condition of granular materials in high dams. The change in liquefaction resistance with increase in confining stress is shown for each sand for a range of relative densities. The data indicates that little benefit is gained in dynamic resistance by initially densifying tailings sands which will later be subjected to high confining stresses.

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## NOTATIONS

$D_r$	Relative density after consolidation.
$D_{ri}$	Initial relative density before consolidation.
$e$	Void ratio after consolidation.
$e_i$	Initial void ratio before consolidation.
$N$	Number of loading cycles.
$\Delta u$	Excess porewater pressure.
$\gamma$	Shear strain.
$\sigma'_{vo}$	Vertical confining pressure.
$\tau_{cy}$	Cyclic shear stress.



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## 1. INTRODUCTION

Liquefaction is one of the problems associated with earthquake shaking of saturated cohesionless materials. It is the development of large strains in soil mass during cyclic undrained loading when the pore water pressure in the soil becomes close or equal to the effective confining stress. Sands and silts are the most susceptible materials to liquefaction phenomena. When these materials are subjected to earthquakes, no significant pore water pressure dissipation is expected to occur even in relatively permeable sands due to the short duration of the earthquake loading. Thus soils of this type can be considered undrained during earthquake shaking.

Liquefaction resistance of cohesionless soils can be determined in the laboratory mainly by using cyclic triaxial or cyclic simple shear tests. Cyclic torsional shear tests and shaking table tests are also used but less frequently. By conducting a series of undrained cyclic simple shear or cyclic triaxial tests, one can obtain a relationship between the cyclic stress ratio ( $\tau_{cy}/\sigma'_{vo}$ ) to cause liquefaction in a specified number of cycles and the sand relative density. This relationship forms the liquefaction resistance curve of the soil. It is felt that this relationship may be affected when the material is loaded under high confining stresses. However, no comprehensive study has been made to seek the influence of high confining stress on liquefaction potential of sands. These confining stresses in earth dams can go as high as 2500 kPa when the dam height approaches 200 m.

The past experience with the evaluation of the liquefaction

potential is confined mainly to natural sands which consist of rounded to subrounded particles. Tailings sands which are used to construct tailings dams are different from natural sands in that they consist of angular particles. Recently there is a growing tendency to build high tailings dams. It is felt that the performance of these tailings sands in high tailings dams could be different from that of conventional sands in their resistance to liquefaction. This research work is an attempt to investigate the effects of confining stress and particle angularity on liquefaction resistance of sands. The constant volume cyclic simple shear apparatus is used in these laboratory investigations. Simple shear conditions are considered most representative of the in-situ stress conditions during earthquakes.

The effect of particle angularity has been examined by testing two different materials, rounded Ottawa sand and angular tailings sand, having an identical mineral composition and gradation. The effect of confining stress on both sands has been investigated through testing each sand over a range of confining stresses up to a maximum of 2500 kPa.

## 2. REVIEW OF THE LITERATURE

To the author's knowledge, no comprehensive study has been made to seek the influence of large confining stresses on the liquefaction resistance of granular materials. The previous work carried out by few researchers was confined to a relatively low confining stress. Furthermore, no direct assessment of the effect of particle angularity on resistance to liquefaction has been attempted.

Early recommendations have been made regarding the density requirements to preclude liquefaction. Sherard (13) stated that sands with relative density of 50% or more probably cannot liquefy regardless of the gradation. A similar conclusion has been made by D'Appolonia (4) as he indicated that liquefaction might occur for soils having a relative density less than 50% during ground motions with accelerations in excess of approximately 0.1 g, and for relative densities greater than 75% liquefaction for most earthquake loading is unlikely. Casagrande (2) had recommended a relative density of 60% to be sufficient as far as the compaction of mine tailings dams is concerned. A minimum relative density of 60% was also recommended by the Department of Energy, Mines and Resources (5) as a requirement for the mine waste embankments.

However, the above recommendations were based on empirical criteria. It will be shown in a later chapter that sands can liquefy even at relative densities in excess of 75% if they are under high confining stresses and subjected to a moderate earthquake loading. Therefore, these recommendations are not always true, as they might have been based on performance of rounded sand under low confining

stresses.

Data on liquefaction resistance of several subangular to subrounded sands was presented by Castro and Poulos (3). A general reduction trend in cyclic stress ratio to cause liquefaction was observed as the confining stress increased from 50 to 600 kPa. The sands were tested in triaxial apparatus with isotropic consolidation. A similar reduction in liquefaction resistance of compacted tailings sand was reported by Volpe (15). The cyclic stress ratio to cause liquefaction was reduced by 25% when the confining stress had increased from 100 to 350 kPa. Volpe had used the triaxial apparatus in generating these data, using anisotropic consolidation stress ratio  $k_c$  of 2.

Later, as a step in the design procedure of dams, Seed (12) had suggested to reduce the cyclic stress ratio to cause liquefaction if the confining stress exceeds 150 kPa. The reduction increases to ~35% when the confining stress reaches 800 kPa. The reduction curve presented by Seed is shown on Fig. (1). However, no reference was made as to either the sand type or relative density level at which this correction was suggested. Anyhow, this reduction mode cannot be generalized and it may be valid only for one type of material at a certain relative density level. Dorey and Byrne (6), in dynamic stability analysis of tailings impoundment, had shown that as the height of tailings increases liquefaction resistance decreases for compacted tailings and increases for uncompacted tailings.

From the above limited investigations, one can realize that the effect of confining stress has been investigated over a relatively low range (maximum of 600 to 800 kPa). For dams of ~200 m height, the confining stress at the lower zone of the dam can be as high as 2500

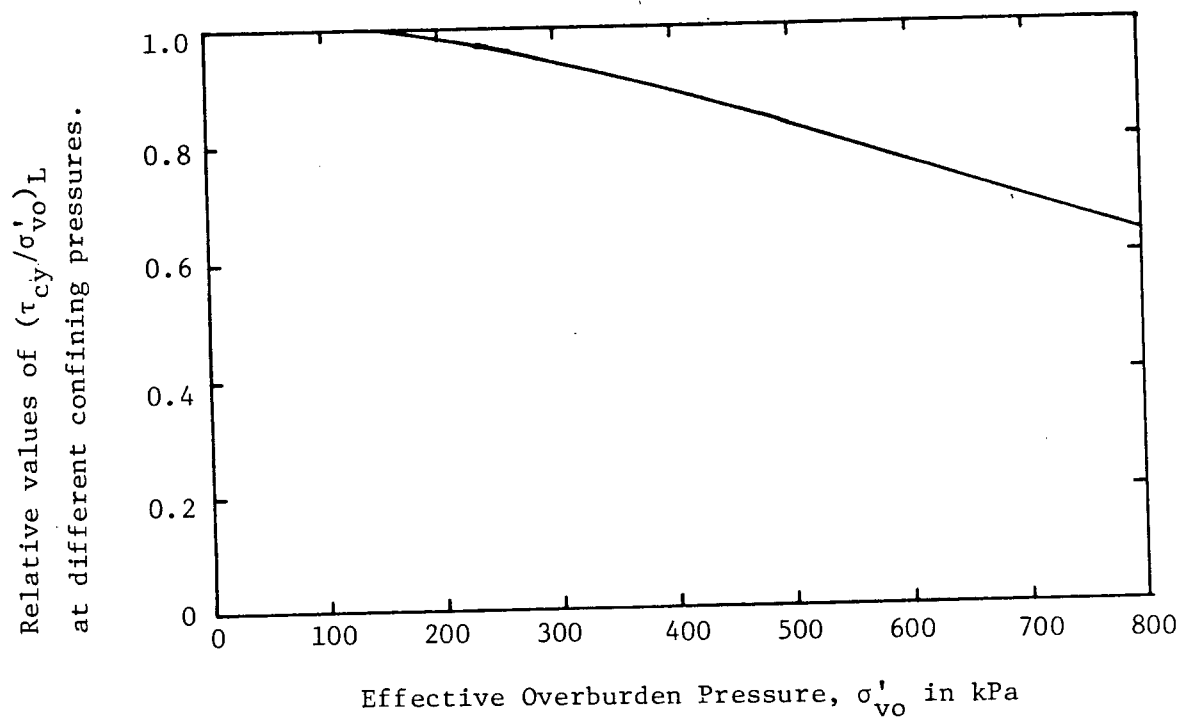


Fig. 1. Reduction in Cyclic Stress Ratio Causing Liquefaction With Increase in Confining Pressure Suggested by Seed H.B. (10).

kPa. Furthermore, a clear assessment of the effect of particle angularity on liquefaction resistance has not been made. This thesis is therefore an attempt to clarify the effects of particle angularity and confining stress on the liquefaction potential of sands.

### 3. TESTING PROGRAM

#### 3.1 Testing Apparatus

The constant volume cyclic simple shear apparatus described by Finn and Vaid (9) was used in this study. The apparatus is shown in Fig. (2). In the constant volume technique, the changes in the vertical stresses to maintain constant volume during the cyclic loading are equivalent to the changes in pore water pressures in the corresponding undrained tests. The constant volume of the simple shear specimen is achieved by clamping the loading head to a rigid loading plate which in turn is clamped to four vertical posts. These posts are threaded into the body of the simple shear apparatus. The vertical stress is applied by tightening the bolt nut on the underside of the loading plate until the desired value of the vertical stress is achieved. Then the bolt nut on the top of the loading plate is tightened. Only a very small volume change can be introduced due to the recovery of the elastic deformation of the loading plate as the vertical stress decreases during the constant volume tests. These small changes in the volume during the constant volume tests represents a very small percent of those associated with system compliance in the undrained tests (9). Hence more accurate and reliable cyclic loading results are expected from the constant volume tests, since they are free from the compliance effects which are common to all undrained tests.

The sample preparation technique described by Finn and Vaid (9) was used in preparing dry sand specimens. In this technique, the membrane is first stretched in the sample cavity in the simple shear apparatus. The sand is then deposited within the membrane in the



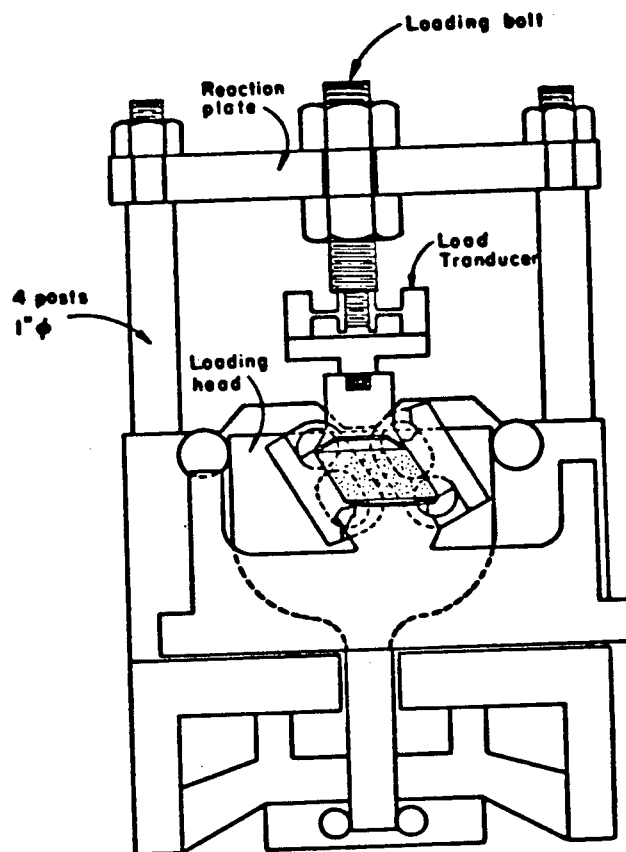


Fig. 2. Constant Volume Simple Shear Apparatus (after Finn & Vaid)

apparatus through a funnel tip permitting a free fall until the height of the sand in the sample cavity exceeds the required sample height. The excess sand over the final grade is then siphoned off using a small vacuum. The sample height is controlled by adjusting the vacuum tube length. The top ribbed plate is then placed on the top of the sample and the membrane closed over it. The sample is then sealed to the loading head. The desired density is achieved by vibrations using a soft hammer while the sample is kept under a seating effective stress of about  $0.20 \text{ kg/cm}^2$ .

The above sample preparation procedure results in a sample of uniform density throughout (9). This is very important especially while preparing dense samples in which the liquefaction resistance may be underestimated by the possible existence of loose surface layer during sample preparation (9).

There are advantages in using the constant volume cyclic simple shear apparatus. It permits the use of dry sand for cyclic undrained tests. It is easier and faster to handle dry sand than saturated sand. Furthermore, many problems associated with undrained testing are avoided. This, together with the improved sample preparation technique described by Finn and Vaid (9) leads to a more accurate estimate of the liquefaction potential in the laboratory.

The simple shear specimen had a square dimension with a horizontal cross-sectional area of  $\approx 25 \text{ cm}^2$  and a height of  $\approx 2.5 \text{ cm}$ .

The cyclic shear stress was applied by means of an electro-pneumatic loading system. A sinusoidal shape was used with a frequency of  $0.1 \text{ Hz}$ . This low frequency was used in order to overcome any deficiency in the response of the electropneumatic system or of the strip

chart recorder on which signal traces were recorded. It also enabled examination of the pore water pressures and strain development not only at the completion of the loading cycles but also during each loading cycle. Vertical and horizontal loads were measured by means of strain gauge type transducer whereas displacement was measured by a displacement transducer. The transducers were precisely calibrated. The friction in the linear bearings of the apparatus as well as the resistance due to membrane stretch during simple shear deformation were measured over the full working pressure and strain range using an air sample. A friction coefficient of 0.006 was recorded and considered in correcting the applied cyclic shear stress amplitude in each test.

Continuous records of the cyclic shear stress, pore water pressure, and strain as monitored by the transducers were obtained on a strip chart recorder.

### 3.2 Material Tested

Two different granular materials, Ottawa sand and Brenda mine tailings sand, were used in this study. Ottawa sand is a natural silica sand consisting of rounded particles. It is a medium sand and corresponds to ASTM designation C-109. Its maximum and minimum void ratios are 0.82 and 0.50 respectively, and its specific gravity is 2.67. Brenda mine tailings sand was the coarse fraction of a copper mine waste which is used in building the tailings dam. It was treated so that its grain size when tested was essentially the same as that of Ottawa sand. This was achieved by washing through #100 sieve together with removal of some of the coarse fraction. The grain size curves of the two sands are shown in Fig. (3). Tailings sand had maximum and

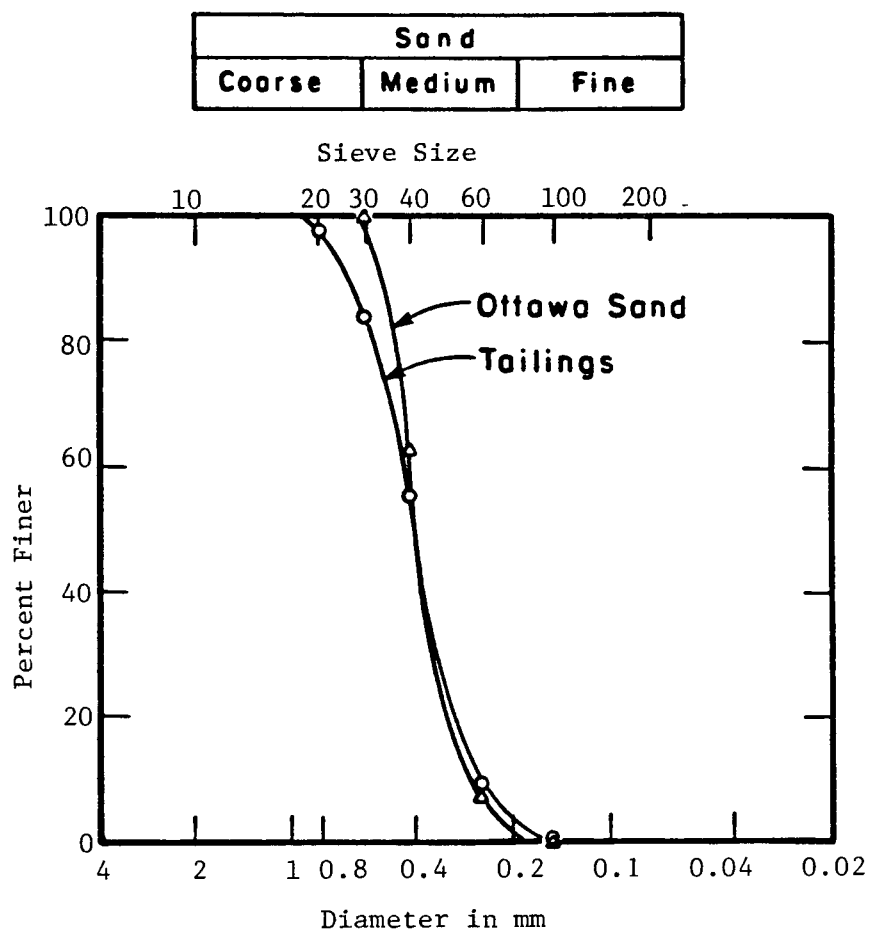


Fig. 3. Grain Size Distribution of Ottawa and Tailings Sands.

minimum void ratios of 1.06 and 0.688 respectively, and a specific gravity of 2.68. Tailings sand which is composed of angular particles is more compressible than Ottawa sand. The marked difference in their compressibilities may be noted from the results of one dimensional consolidation tests, Figs. (4) and (5).

The mineral composition of tailings was mainly quartz with occasional traces of mica and chalcopyrite. Since Ottawa sand is composed of quartz, the mineral composition of the two sands is identical. Thus any difference in behaviour of these sands can be attributed to grain shape.

### 3.3 Testing Program

Samples of both sands, prepared as described earlier, were subjected to vertical effective confining stresses of 200, 400, 800, 1600, and 2500 kPa. At each confining stress, samples were cyclically loaded using three or more different cyclic stress ratios ( $\tau_{cy}/\sigma'_{vo}$ ). The amplitudes of the cyclic stress ratios were selected in such a way that the sample liquefied in a reasonable number of cycles (preferably between 5 and 50 cycles). This was achieved by making a few initial trial tests at each confining stress. At every cyclic stress ratio level samples were prepared at different initial relative densities and then subjected to the cyclic loading until liquefaction.

Liquefaction is considered here to be the development of a certain shear strain amplitude. Up to this level of developed strain the electropneumatic loading system provided a satisfactory response and did not result in attenuation of the shear stress amplitude with large strain excursions.

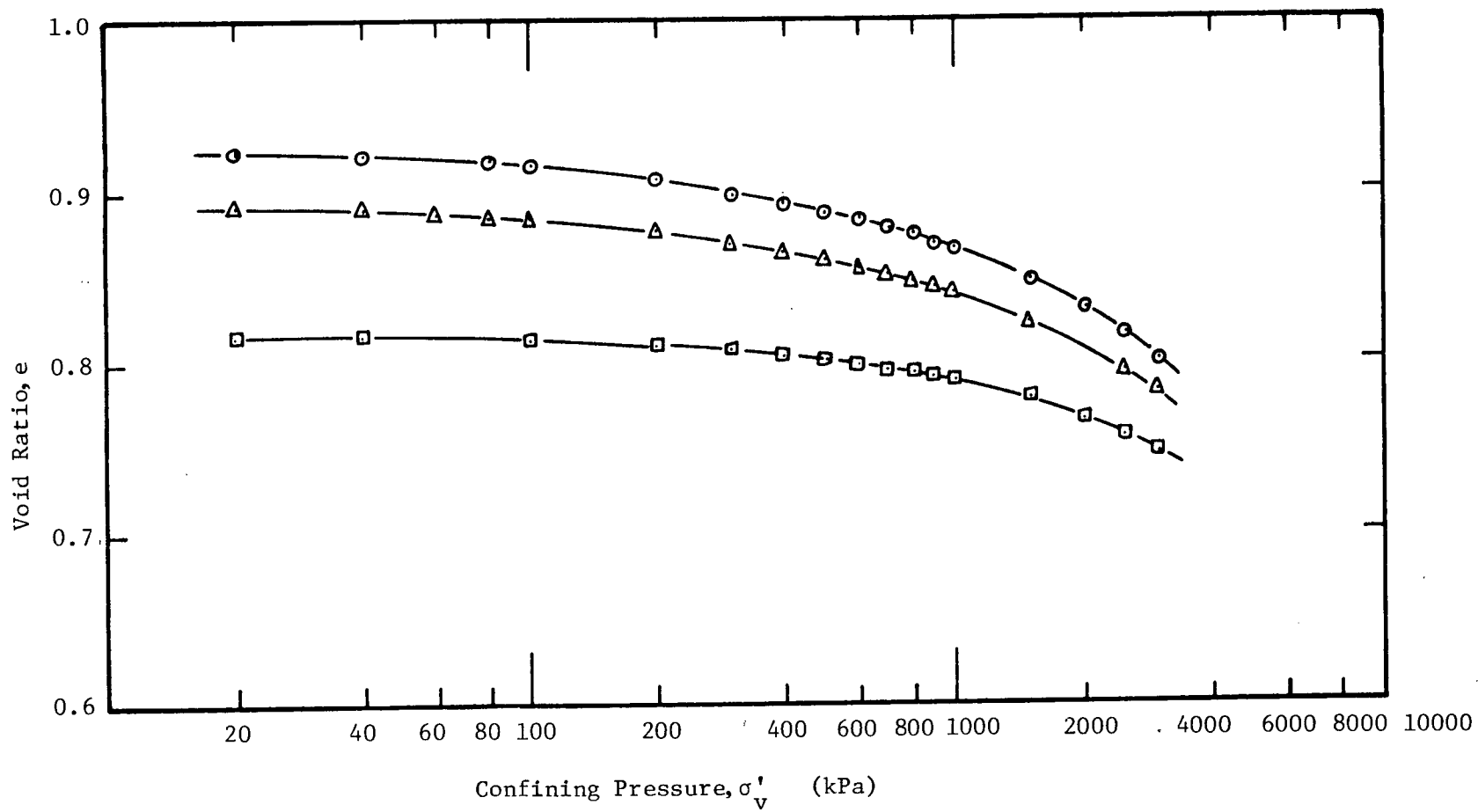


Fig. 4. One Dimensional Compressibility of Tailings Sand.

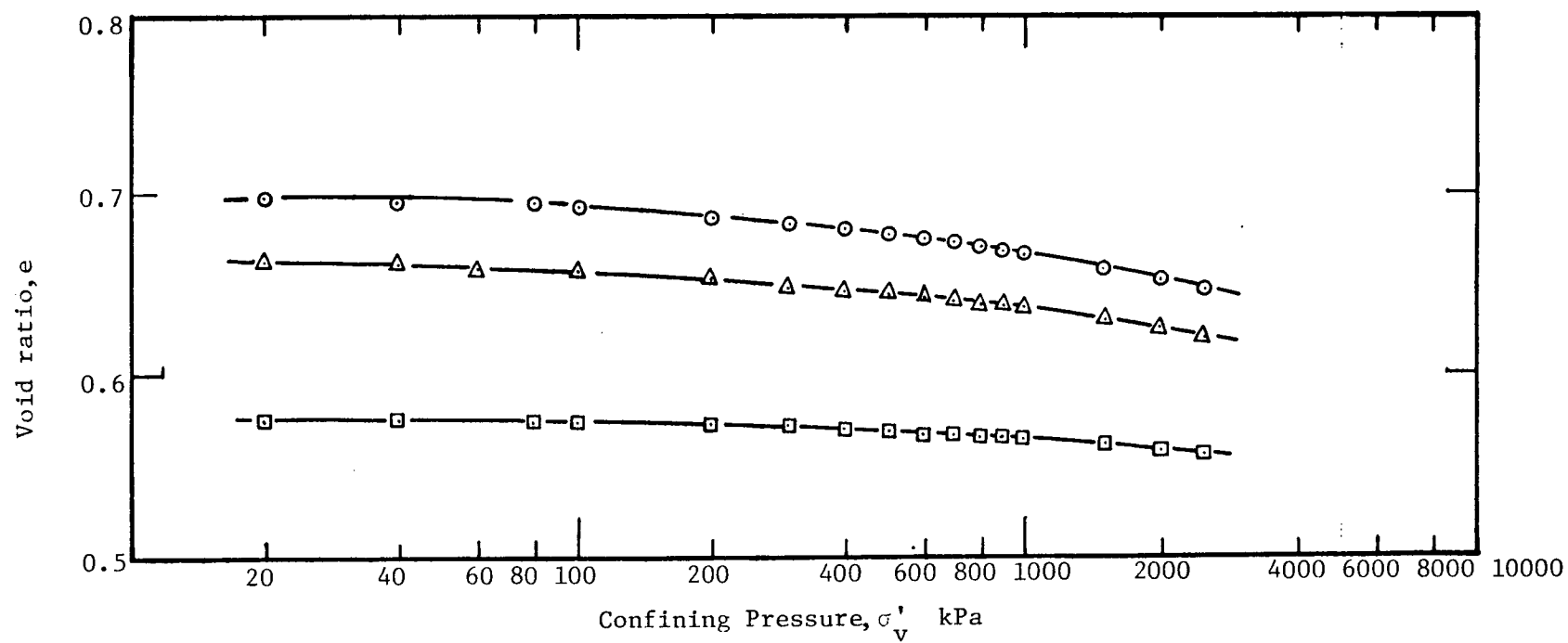


Fig. 5. One-Dimensional Compressibility of Ottawa Sand.

#### 4. TEST RESULTS

The basic data on cyclic loading behaviour was obtained in the form of number of cycles to cause a certain shear strain in the sample due to the applied cyclic shear stress for various initial relative densities. Several such relationships were obtained at each confining stress level and various levels of cyclic stress ratios ( $\tau_{cy}/\sigma'_{vo}$ ). The relationships between relative density and the cyclic stress ratio to cause liquefaction in a specific number of cycles were then achieved by cross plotting the data. The test data for both sands, tailings and Ottawa sand, showed extremely high degrees of reproducibility and little scatter.

##### 4.1 Cyclic Loading Behaviour

Typical relationships of residual pore water pressure ratio ( $\Delta u/\sigma'_{vo}$ ) as well as shear strain  $\gamma$  with the number of loading cycles are shown in Figures (6, 7, 8, 9). In these figures, the behaviour of both sands under low and high confining stresses is shown at loose and dense relative densities. At loose relative density, there was a large development of cyclic shear strain after a certain number of cycles regardless of the confining stress level and particle angularity. The strain increased suddenly from a very low value to more than 5% in one cycle. At high relative densities, however, a gradual increase in the cyclic shear strain was noted with cycles of loading. At such densities, it may take more than 10 additional cycles to bring up the shear strain level from 2.5% to 5% (Figure (6a)). This difference in the shear strain development between the loose and dense states would



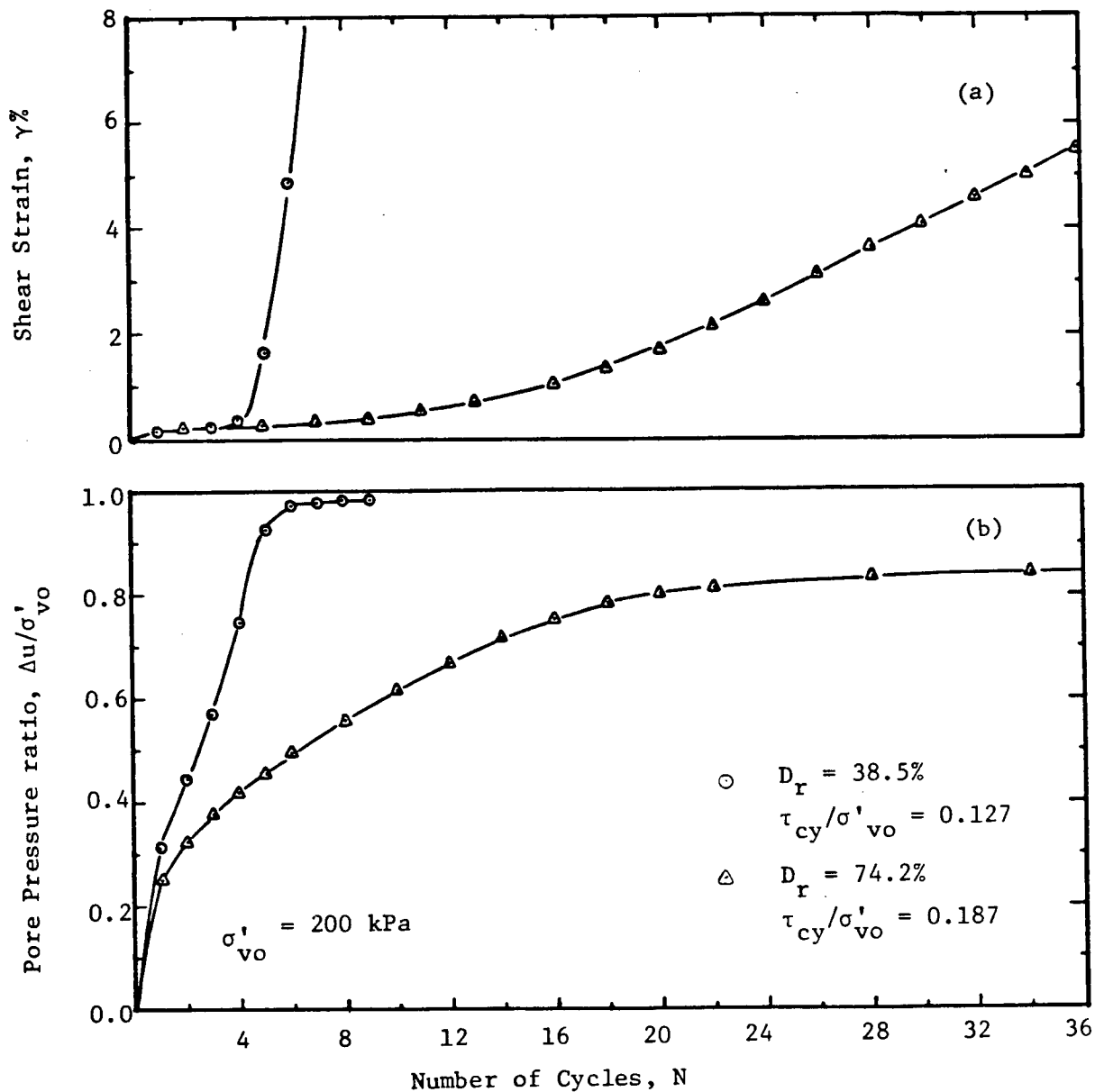


Fig. 6. Typical Cyclic Loading Behaviour of Tailings Sand at Low Confining Pressure. (a) Shear Strain Versus Number of Cycles. (b) Pore Pressure Ratio Versus Number of Cycles.

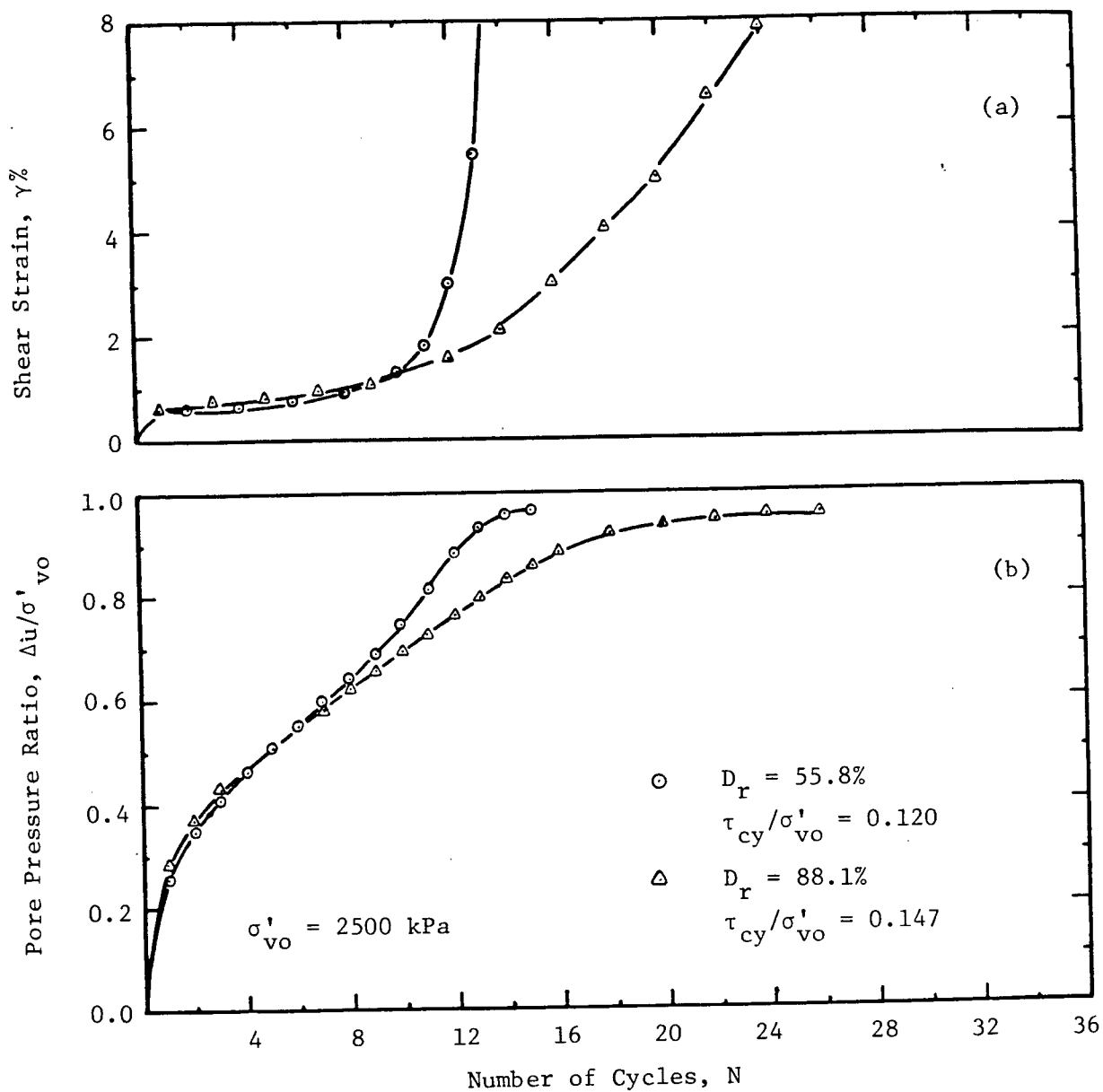


Fig. 7. Typical Cyclic Loading Behaviour of Tailings Sand at High Confining Pressure. (a) Shear Strain Versus Number of Cycles. (b) Pore Pressure Ratio Versus Number of Cycles.

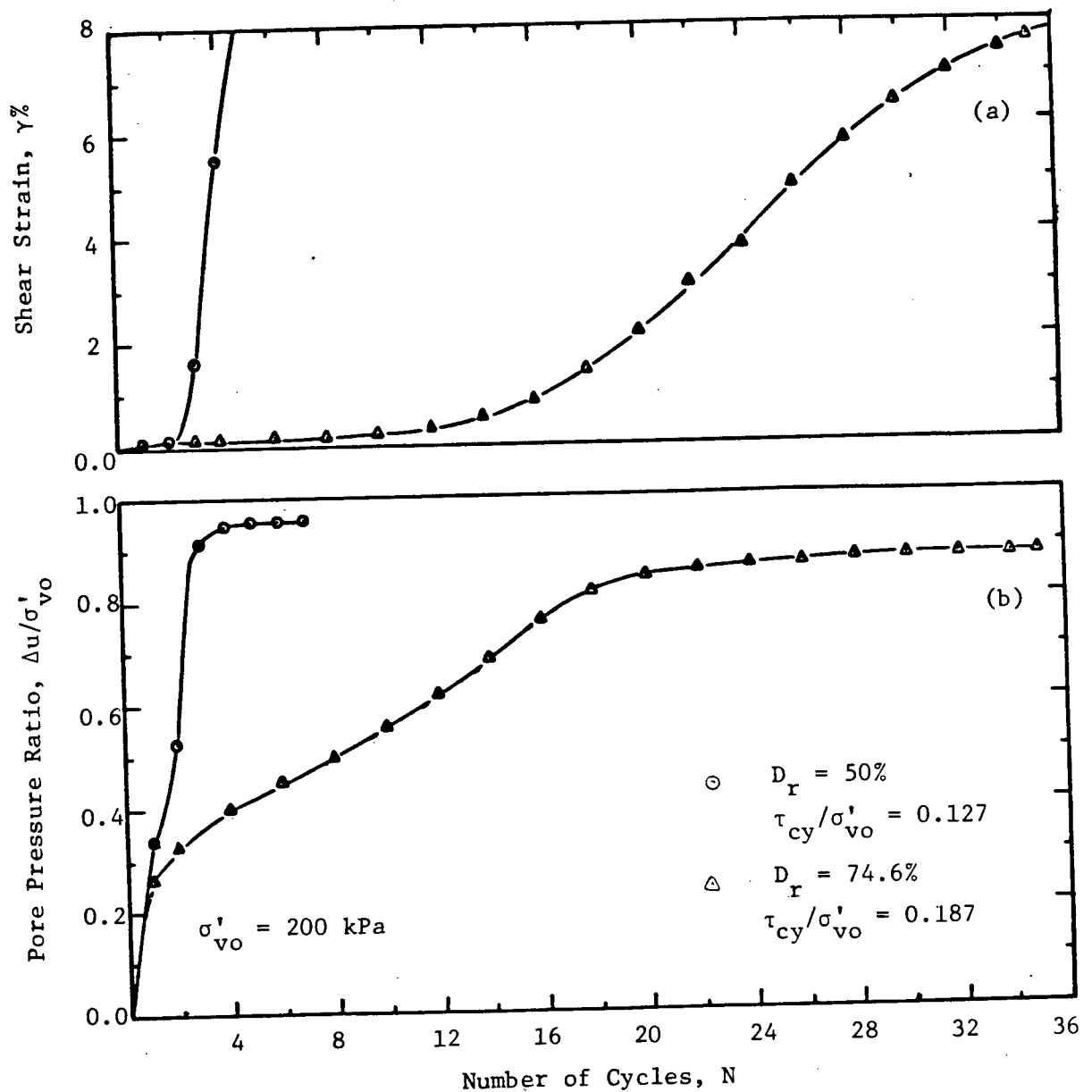


Fig. 8. Typical Cyclic Loading Behaviour of Ottawa Sand at Low Confining Pressure. (a) Shear Strain Versus Number of Cycles. (b) Pore Pressure Ratio Versus Number of Cycles.

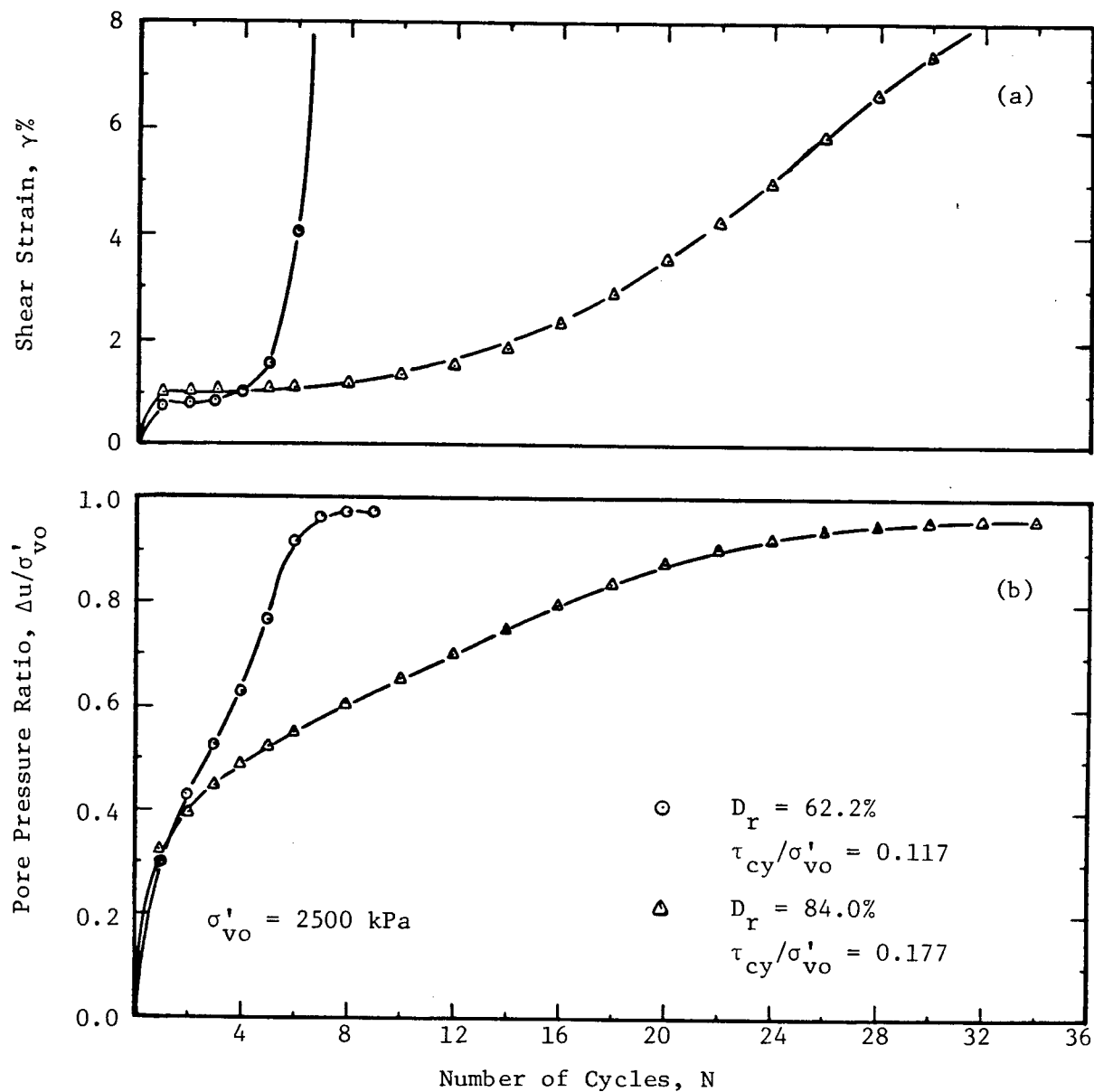


Fig. 9. Typical Cyclic Loading Behaviour of Ottawa Sand at High Confining Pressure. (a) Shear Strain Versus Number of Cycles, (b) Pore Pressure Ratio Versus Number of Cycles.

affect the cyclic stress ratio causing liquefaction, depending on what level of strain development is considered to define the occurrence of liquefaction. Such differences will be discussed later.

For both sands, at low confining stresses, the development of pore water pressures in loose samples was at a faster rate, which reflects the high potential volume contraction during cyclic loading. Dense samples at low confining stresses, however showed a gentle increase in pore water pressure ratio with the number of cycles.

At high confining stresses, loose samples of both sands showed a similar increase in pore pressure to that at low confining stresses. But, dense samples of tailings sand showed a faster rate of pore pressure generation with increase in number of cycles than similar samples of Ottawa sand. It may be noted in Figures (7 and 9) that although tailings sand was at higher relative density and subjected to lower cyclic stress ratio than Ottawa sand, the pore pressure development in tailings sand was at a faster rate than that in Ottawa sand. The breakage of sharp edges of tailings sand during cyclic loading at high confining stresses might be responsible for larger potential volumetric strain which could be the cause for this high pore pressure development rates in tailings sands.

#### 4.2 Liquefaction Resistance of Tailings Sand

In the following discussion, the cyclic stress required to develop  $\pm 5\%$  shear strain in 10 loading cycles is defined as the resistance to liquefaction. Results based on development of  $\pm 5\%$  shear strain in 15 cycles as well as  $\pm 2.5\%$  strain in 10 and 15 cycles will also be presented later.

The relationships between void ratio after consolidation and the number of cycles to cause liquefaction of tailings sand at various cyclic shear stress ratios and under confining stresses of 200, 400, 800, 1600, and 2500 kPa are shown in Figure (10). In these relationships, each contour was developed using a fixed level of cyclic shear stress ratio while the void ratio was varied. It may be seen that the number of cycles to liquefy the tailings sand increases very rapidly with decrease in void ratio at low confining stresses regardless of the level of cyclic shear stress ratio. However, at high confining stresses, a similar decrease in void ratio results in a much smaller increase in number of cycles to cause liquefaction. This is apparent in progressive steepening of the void ratio versus number of cycles contours in Figure (10) as the confining stress increased.

Figure (11) shows the liquefaction resistance of tailings sand as a function of relative density and confining stress. The liquefaction resistance is defined here as the cyclic stress ratio to cause  $\pm 5\%$  shear strain in 10 cycles. The liquefaction resistance, as expected, increases with increase in relative density. However, the rate of this increase depends on the confining stress level and relative density range considered. At low confining stresses ( $\sigma'_{vo} < 400$  kPa), the liquefaction resistance builds up very rapidly over a narrow range of relative density in excess of about 60%. A small increase in relative density at these confining stress levels results in a considerable increase in the resistance. The resistance curves at confining stresses  $< 400$  kPa are highly nonlinear in contrast to the generally assumed linear increase in resistance with the increase in relative density (1).

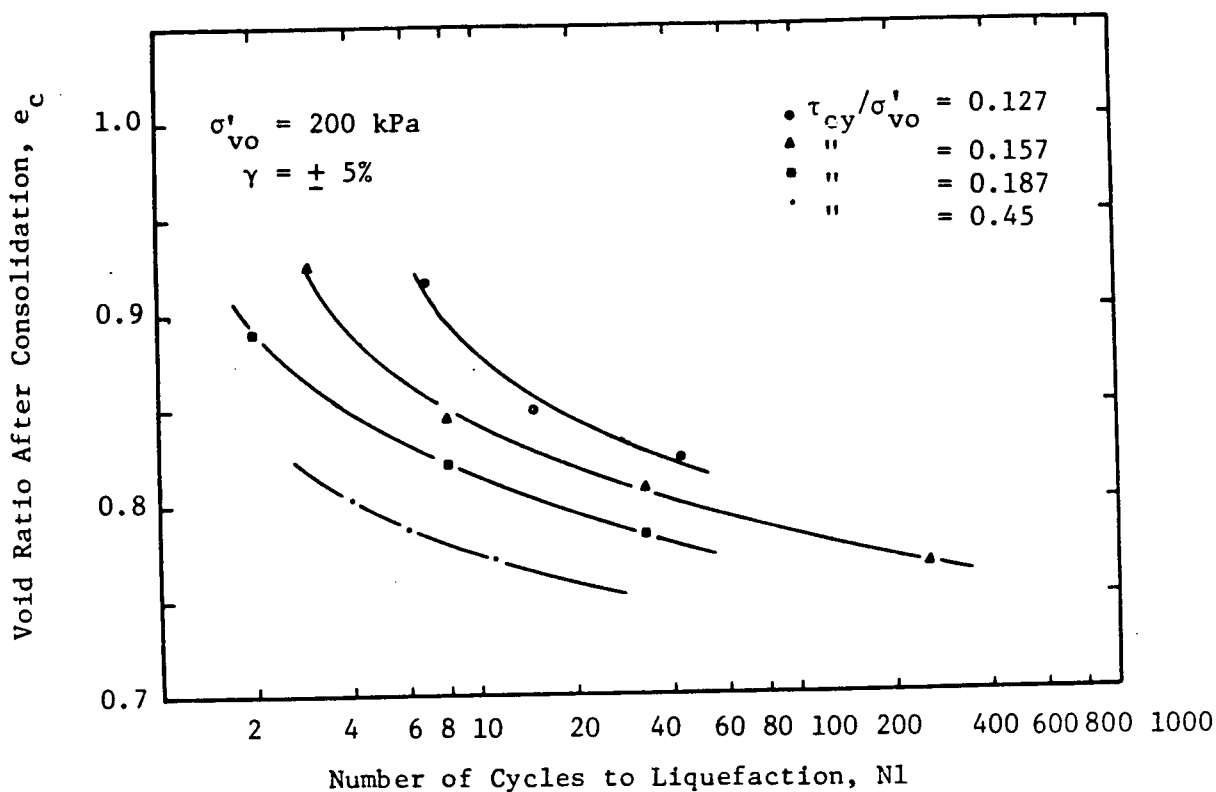


Fig. (10a). Number of Cycles to Liquefaction Versus Void Ratio for Tailings Sand at Confining Pressure of 200 kPa.

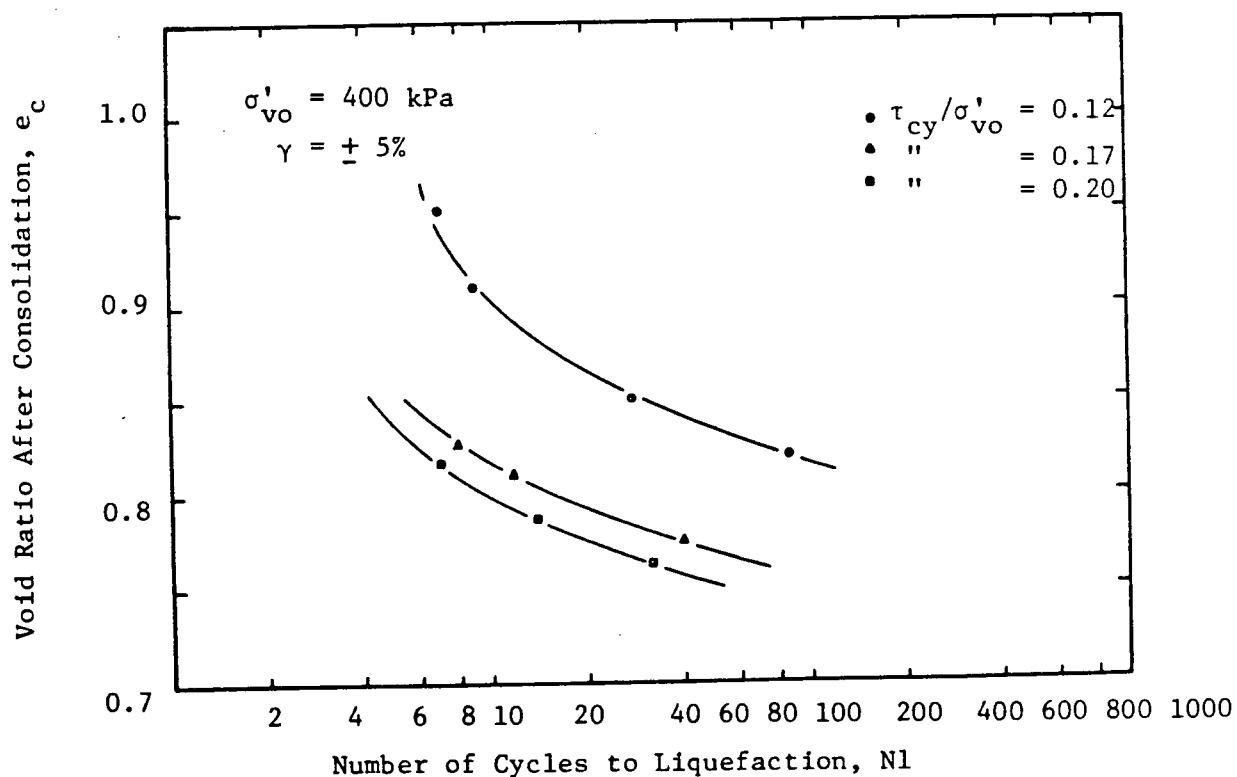


Fig. (10b). Number of Cycles to Liquefaction Versus Void Ratio for Tailings Sand at Confining Pressure of 400 kPa.

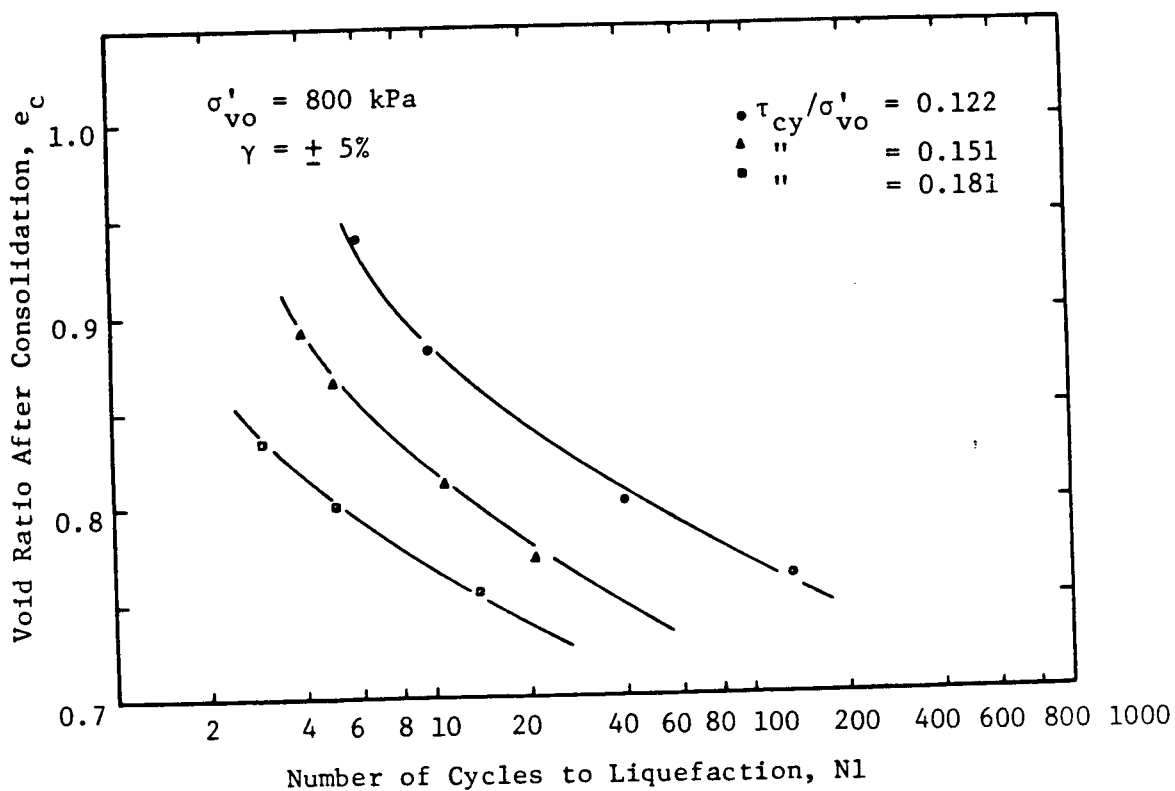


Fig. (10c). Number of Cycles to Liquefaction Versus Void Ratio For Tailings Sand at Confining Pressure of 800 kPa.

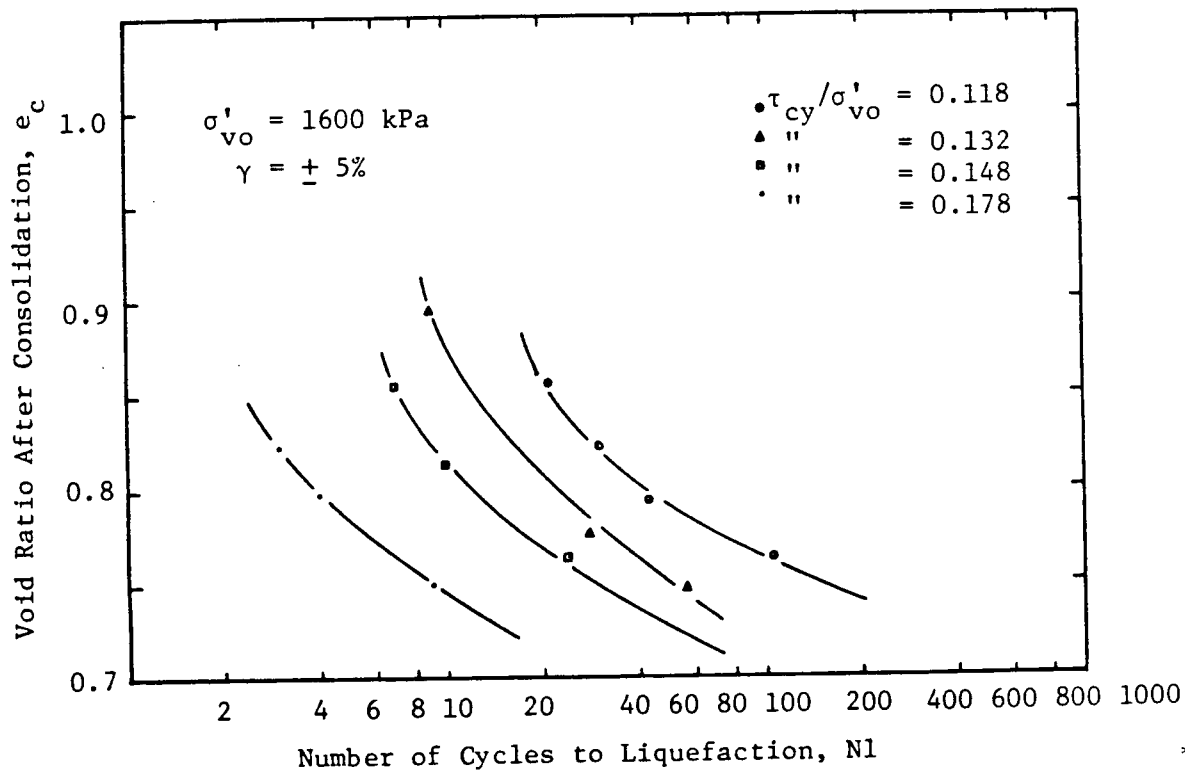


Fig. (10d). Number of Cycles to Liquefaction Versus Void Ratio For Tailings Sand at Confining Pressure of 1600 kPa.



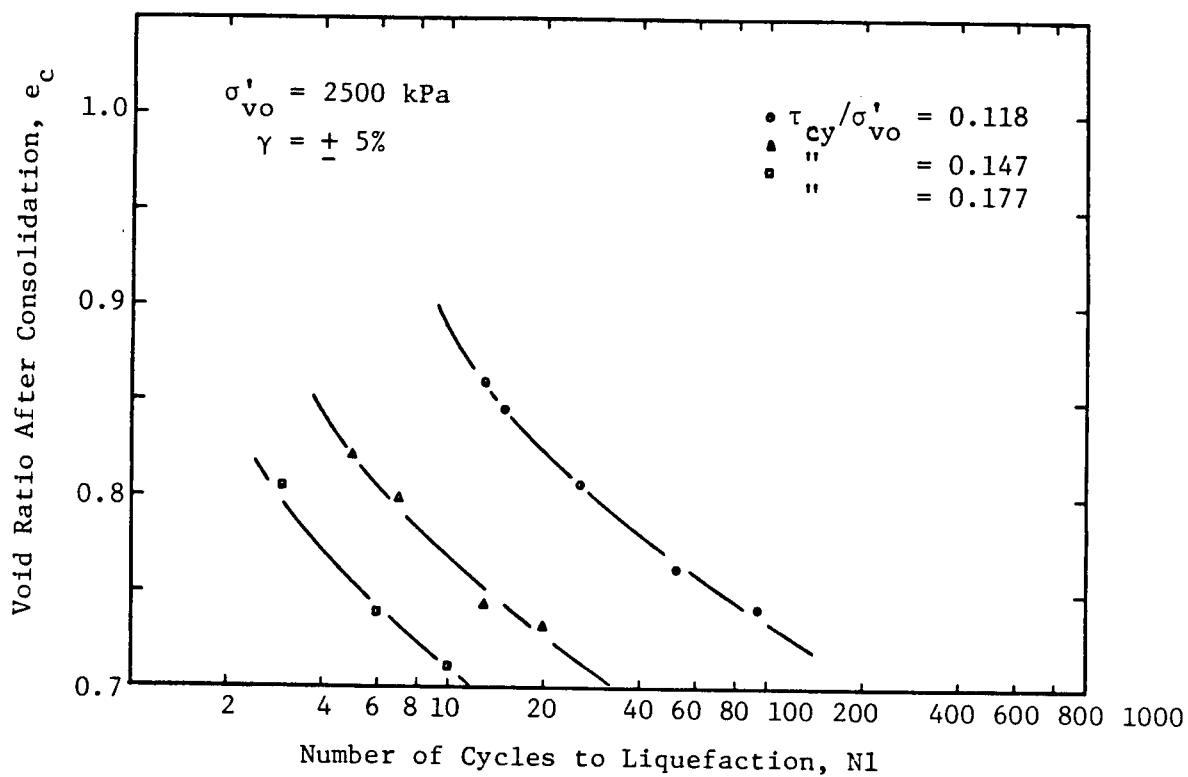


Fig. (10e). Number of Cycles to Liquefaction Versus Void Ratio For Tailings Sand at Confining Stress of 2500 kPa.

At high confining stress levels, the build up in liquefaction resistance with increase in relative density is much smaller than at lower confining stresses. The resistance curves become progressively flatter as the confining pressure increases. The liquefaction resistance, at a given relative density level, decreases with the increase in confining stress as it is apparent in Figure (11). This decrease in resistance with increase in confining stress seems to be confined to relative densities in excess of about 55%. As the relative density increases above this value, the reduction in resistance becomes progressively larger with increasing confining pressure. The most dramatic decrease in resistance seems to be associated with the increase of confining stress from 200 kPa to 800 kPa. At relative density of 77%, the reduction in liquefaction resistance as the confining stress increases from 200 kPa to 800 kPa is about 60%, while the total reduction in the resistance at the same relative density level as the confining stress increases from 200 kPa to 2500 kPa is 68%.

Samples at relative densities greater than about 77%, at a confining stress of 200 kPa could not be formed easily in the laboratory. On the other hand, the minimum achieved relative density at a confining stress of 2500 kPa was about 60%. This confining stress of 2500 kPa brought the relative density of samples prepared at initial relative density of about 20% to a relative density of about 60% after consolidation. These limitations in the relative densities under confining stresses of 200 kPa and 2500 kPa limits the comparison between the responses under the extreme values of confining stresses to the range of relative density between 60% and 77% only. Due to very high liquefaction resistance at confining stress of  $< 400$  kPa, tailings sand at

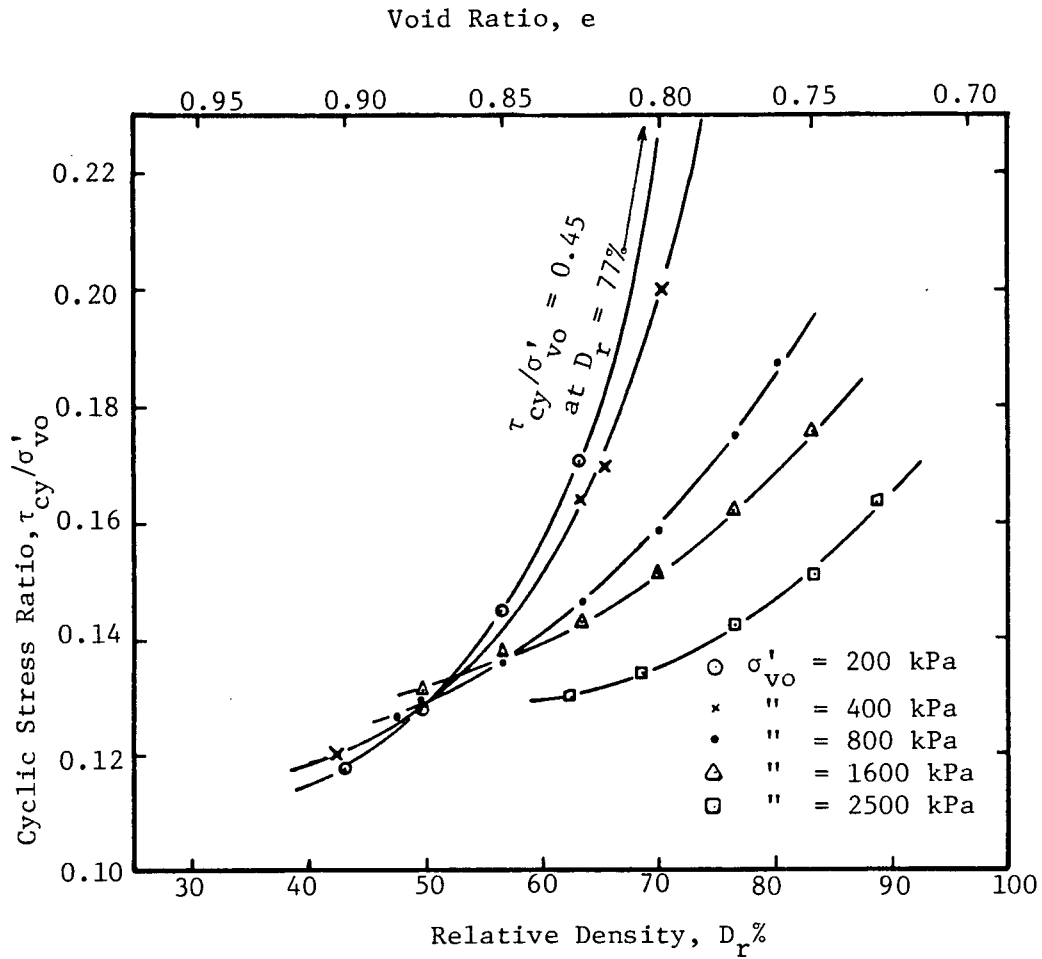


Fig. 11. Resistance to Liquefaction of Tailings Sand at Various Confining Pressures Based on Shear Strain Level of  $\pm 5\%$  in 10 Cycles.

relative densities in excess of 70% is unlikely to liquefy even under moderate to strong earthquakes, whereas at confining stress of 2500 kPa, the same sand may be susceptible to liquefaction even at relative densities approaching 90% under moderate earthquake shaking.

The reduction in liquefaction resistance with the increase in confining stress occurs at high relative densities rather than low ones. At relative densities of about 50% to 55%, all resistance curves tend to merge together, indicating liquefaction resistance relatively independent of confining stress. As the relative density drops below about 50%, the liquefaction resistance becomes higher at higher confining stresses, provided this relative density level is accessible at the confining pressure under consideration.

The variation of cyclic stress ratio to cause liquefaction with increase in confining stress at various relative density levels is shown in Figure (12) while the percent reduction in cyclic stress ratio to cause liquefaction with increase in confining stress at these relative density levels, when referred to a confining pressure of 200 kPa, are shown in Figure (13). It may again be noted from Figures (12) and (13) that the largest reduction in liquefaction resistance occurs as a consequence of confining stress increase from 200 kPa to 800 kPa. The higher the relative density, the more is the reduction. Not much change in liquefaction resistance occurs when the confining stress increases from 800 kPa to 1600 kPa, except at relative densities in excess of about 65%. However, a larger reduction occurs as the confining stress exceeds 1600 kPa.

It may also be noted from Figure (12) that the change in relative density at lower confining stresses has a much larger effect on the

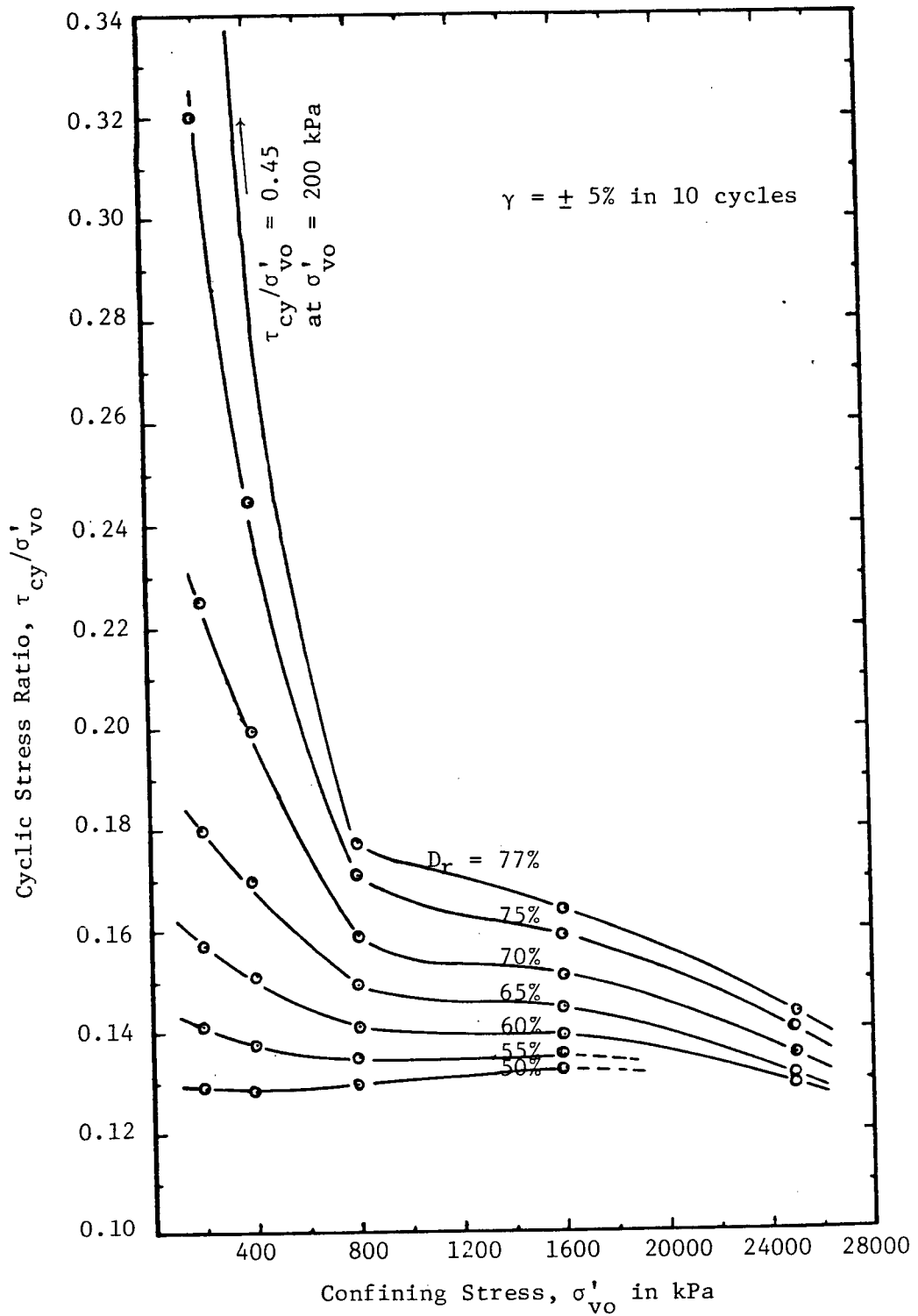


Fig. 12. Variation of Cyclic Stress Ratio to Cause Liquefaction of Tailings Sand With Confining Pressure at Various Relative Density Levels.

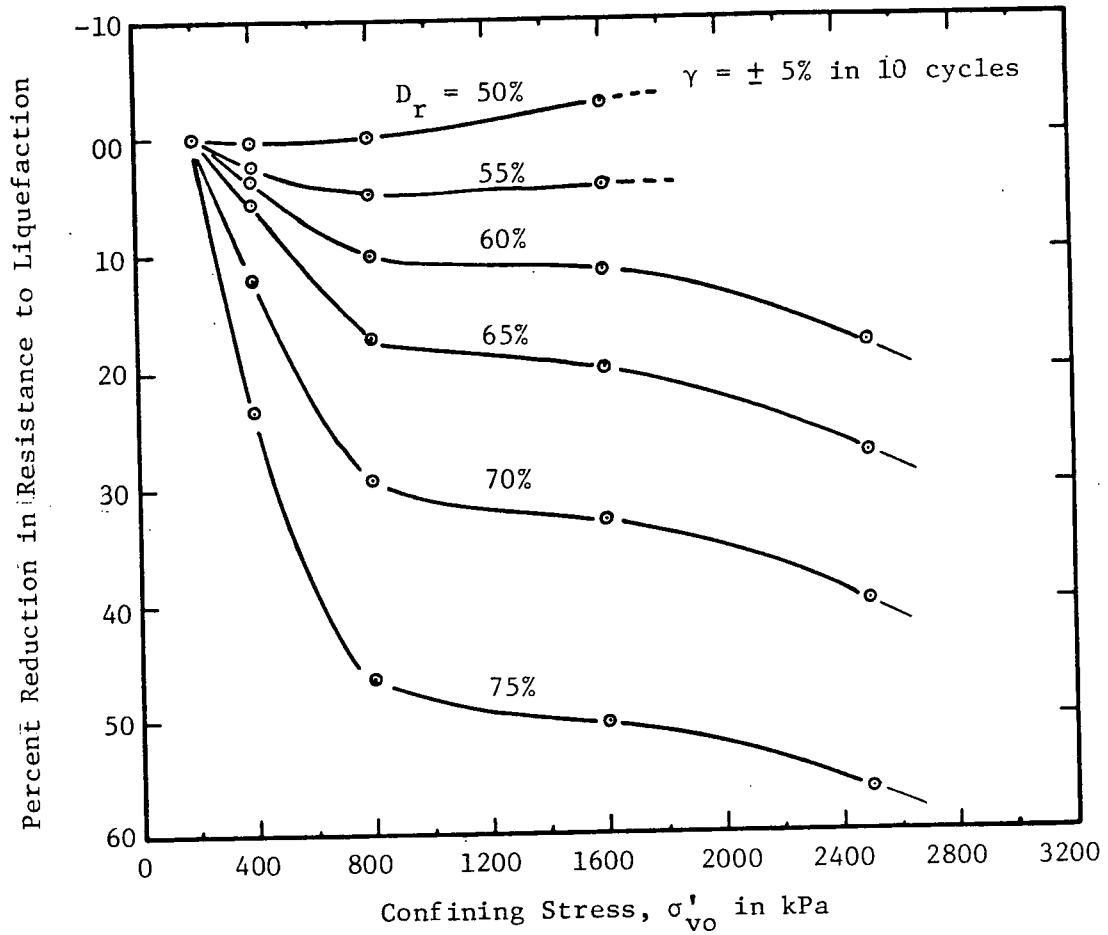


Fig. 13. Percent Reduction in Resistance to Liquefaction of Tailings Sand When Referred to the Resistance at 200 kPa.

liquefaction resistance of tailings sand. At a confining stress of 200 kPa, the cyclic stress ratio ( $\tau_{cy}/\sigma'_{vo}$ ) required to liquefy a sample at relative density of about 50% is only 0.13, whereas a cyclic stress ratio of about 0.45 is needed to liquefy samples at relative densities of 77% under the same confining stress. On the other hand, a change in relative density at a high confining stress has only a small effect on liquefaction resistance e.g., at a confining stress of 2500 kPa, the cyclic stress ratio ( $\tau_{cy}/\sigma'_{vo}$ ) to cause liquefaction increased only from 0.13 to 0.155 as the relative density increased from 60% to 85%.

The compressibility characteristics of tailings, as measured in one-dimensional consolidation tests and expressed as the relationship between void ratio  $e$  and  $\log \sigma'_v$  were shown in Figure (4). It may be noted that considerable volume compression occurs on application of large confining pressures. The effect of confining stress on relative density increase, however, decreases with increase in initial relative density. The substantial increase in relative density is the one associated with the application of high confining stresses on samples of initially low relative density.

Figure (14) shows the relationships between the initial void ratios and the void ratios after consolidation at confining stresses under consideration. It is interesting to note that at each selected confining stress, a linear relationship is obtained between initial void ratio  $e_i$  and the void ratio after consolidation,  $e_c$ . This observed linearity in the relationships between  $e_i$  and  $e_c$  helped in estimating the relative densities after consolidation at each confining stress level.

The variation in liquefaction resistance with increase in

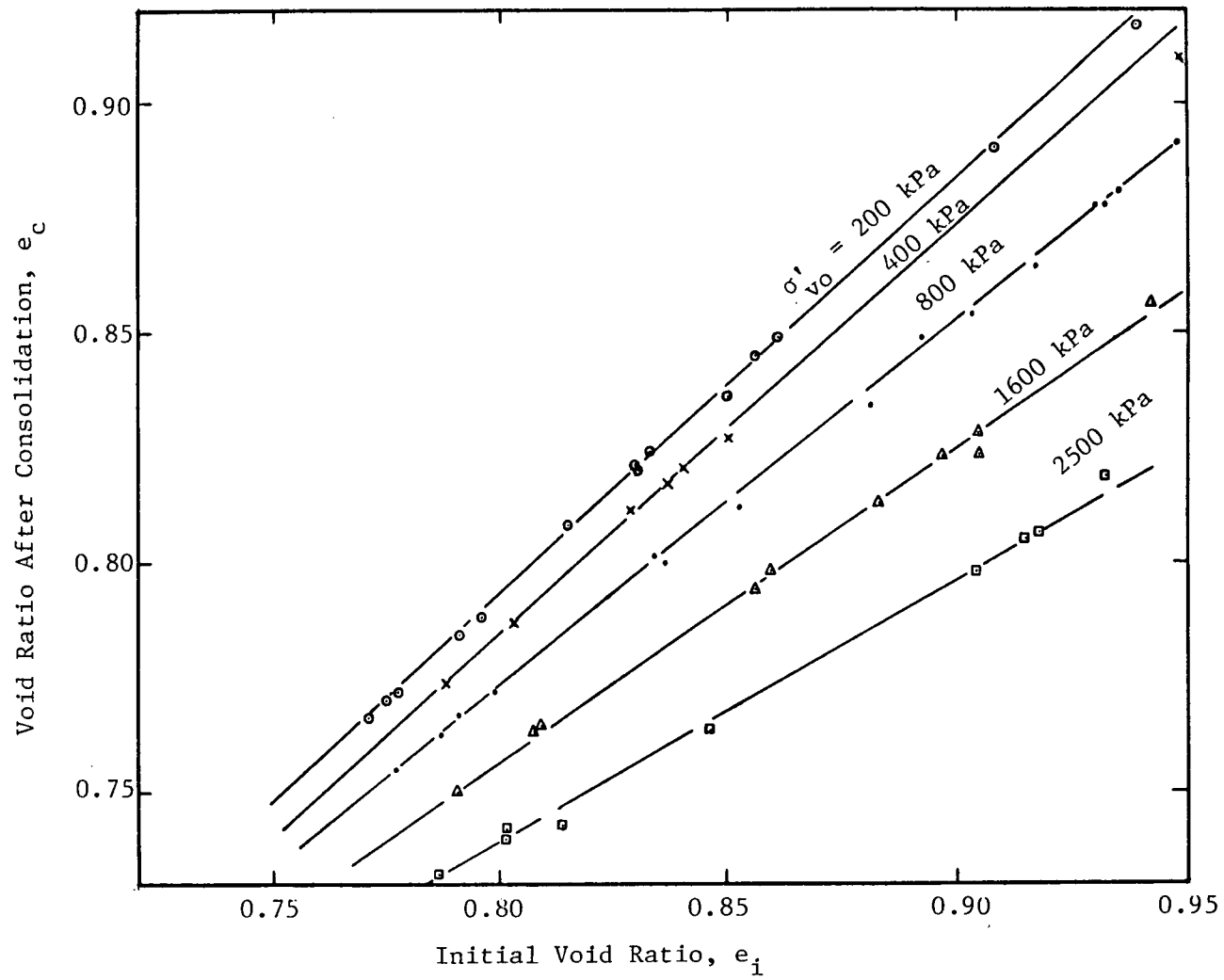


Fig. 14. Initial Void Ratio,  $e_i$ , With Void Ratio After Consolidation,  $e_c$ , Relationships of Tailings Sand at Various Confining Pressures.



confining stress at fixed values of initial relative densities ( $D_{ri}$ ) is shown in Figure (15). Each contour in Figure (15) represents the liquefaction resistance of samples consolidated along a typical consolidation curve in Figure (4). The confining stress has two effects on the liquefaction resistance, which are opposite to each other, 1. Increased confining stress reduces liquefaction resistance. 2. Increased confining stress increases the relative density which, in turn, increases the resistance. The resistance curves in Figure (15) show the net influence of these two factors. It may be seen that at low initial relative densities, the effect of densification far outweighs that of increasing confining stress up to  $\sigma'_{vo}$  of about 1600 kPa. At higher confining stresses, the effect of confining stress in reducing the cyclic resistance seems to be predominant. A general continuous decrease in resistance is obtained with increase in confining stress at higher initial relative densities. This indicates that at these high initial relative densities, the increase in relative density due to consolidation is too small to offset the reduction due to high confining stresses. That initial densification of tailings sand had a large effect on its liquefaction resistance at lower confining stresses ( $\sigma'_{vo} < 400$  kPa) may be noted from Figure (15). At confining stress of 200 kPa, for example, the resistance increased by 150%, if the sand had been initially densified to a relative density of 70% instead of 35%. At higher confining stresses ( $\sigma'_{vo} > 800$  kPa) initial densification had little benefit to the liquefaction resistance. At confining stress of 2500 kPa, only 19% increase in resistance was observed as the initial relative density increases from 35% to 70%. This has a considerable practical significance in deciding placement densities of tailings at

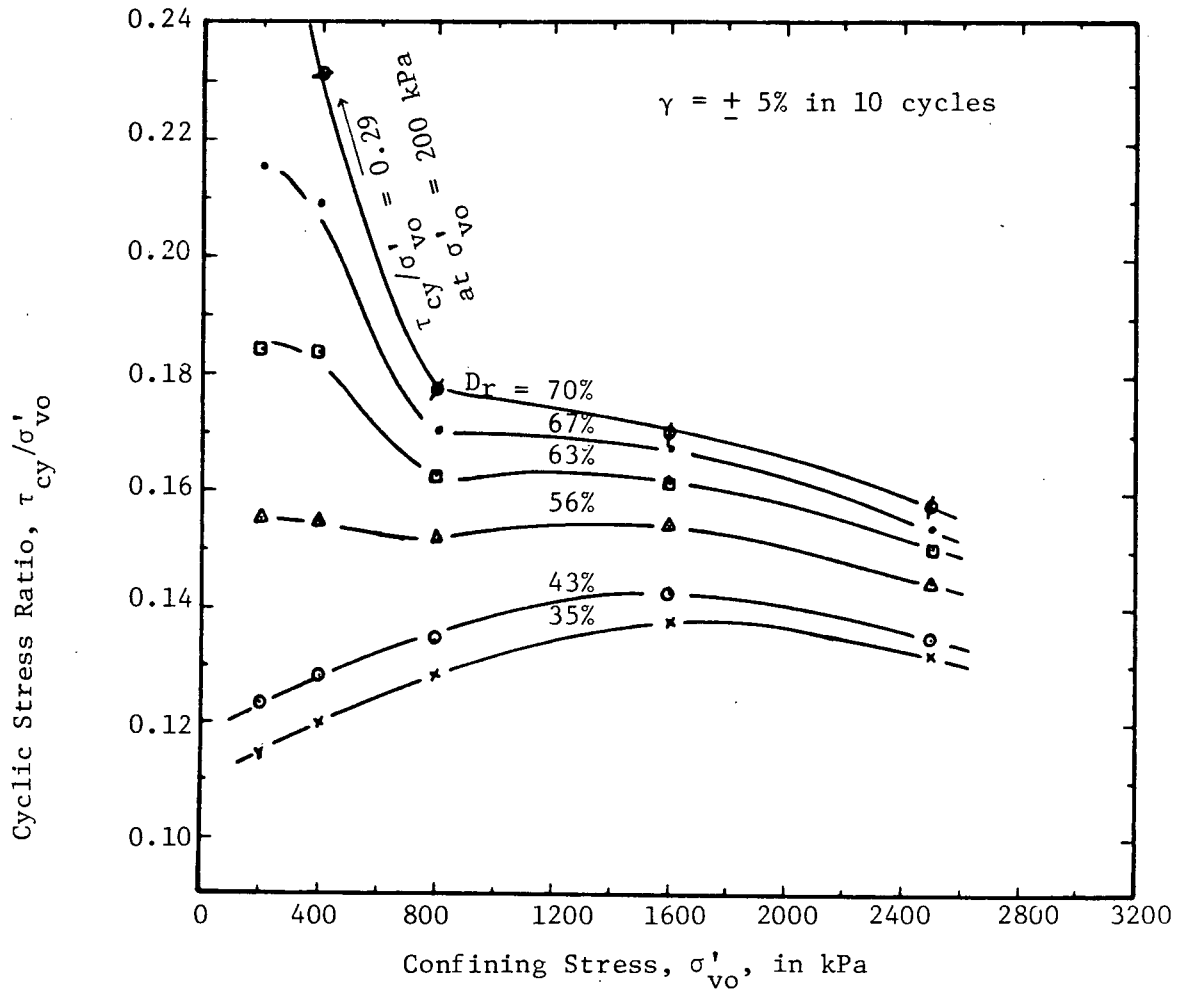


Fig. 15. Effect of Confining Pressure on the Resistance to Liquefaction of Tailings Sand Prepared at Various Initial Relative Densities.

various locations in tailings dams.

Liquefaction resistance of tailings sand based on the development of  $\pm 5\%$  shear strain in 15 stress cycles rather than 10 cycles is shown in Figure (16). The resistance curves look very similar to those previously discussed for 10 cycles. The relative positions of the curves at all confining stresses stay about the same. The values of the cyclic stress ratios to cause  $\pm 5\%$  strain in 15 cycles are as expected less than those for 10 cycles as shown in Figure (11). All the curves in Figure (16) are essentially horizontally shifted towards higher relative densities. This shift results in the resistance curves merging at slightly higher relative density levels than in the case of 10 cycles.

The liquefaction resistance of tailings sand based on the development of  $\pm 2.5\%$  shear strain in 10 cycles and 15 cycles is shown in Figures (17) and (18) respectively. Figure (17) shows the cyclic stress ratio required to cause  $\pm 2.5\%$  shear strain in 10 cycles with increase in relative density at various confining stresses. The resistance curves in Figure (17) are similar to those for  $\pm 5\%$  strain shown in Figure (11) except that they become slightly flatter in the region of higher relative densities. This is because, a relatively large number of cycles is needed for dense sand to bring up the shear strain from 2.5% to 5%. Such a difference is clearly shown in Figures (6, 7, 8, and 9), where the number of cycles needed to increase the shear strain from 2.5% to 5% could be up to 10 cycles or more in the case of dense sand. On the other hand the strain builds up from very low values to more than 5% occurs in only one cycle in loose sand.

Liquefaction resistance curves of tailings sand based on the

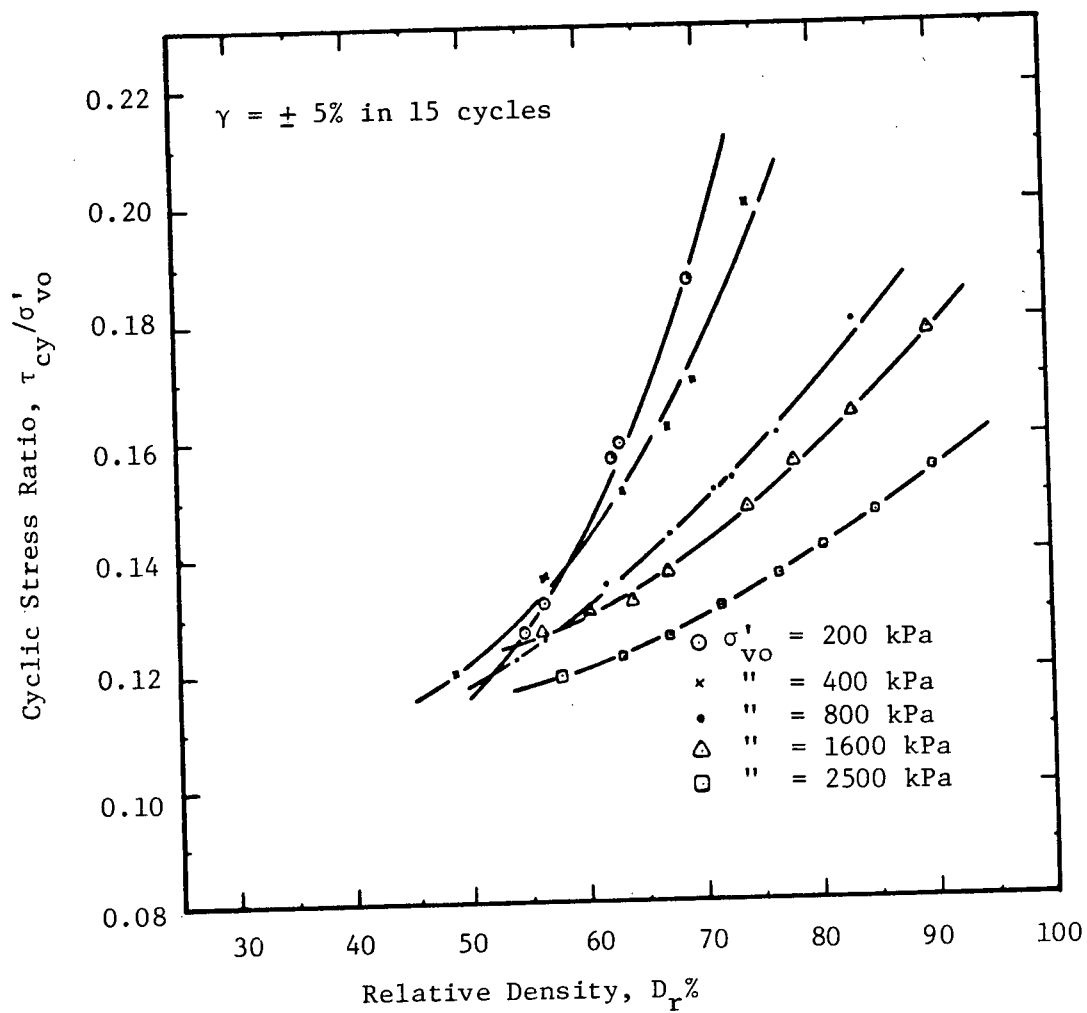


Fig. 16. Resistance to Liquefaction of Tailings Sand at Various Confining Pressures Based on Shear Strain Level of  $\pm 5\%$  in 15 Cycles.

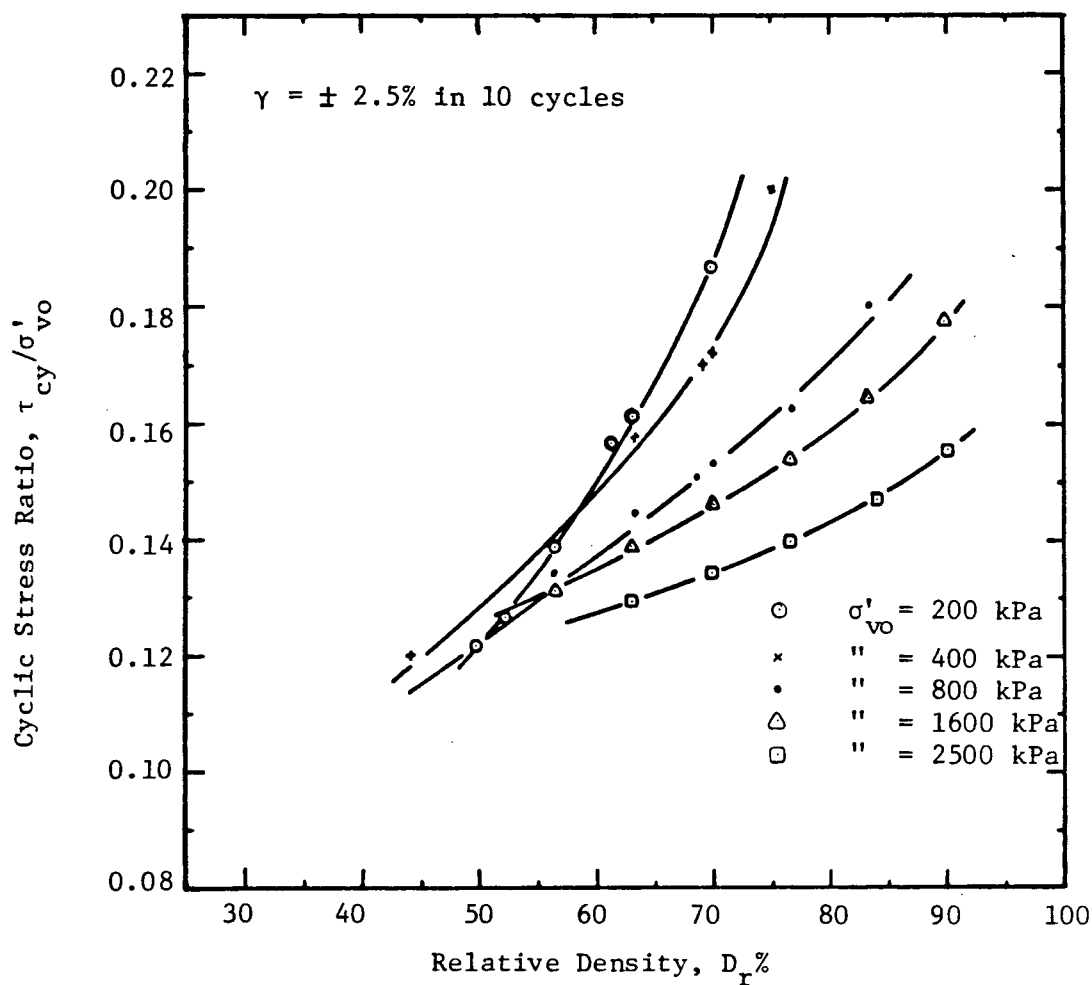


Fig. 17. Resistance to Liquefaction of Tailings Sand at Various Confining Pressures Based on Shear Strain Level of  $\pm 2.5\%$  in 10 Cycles.

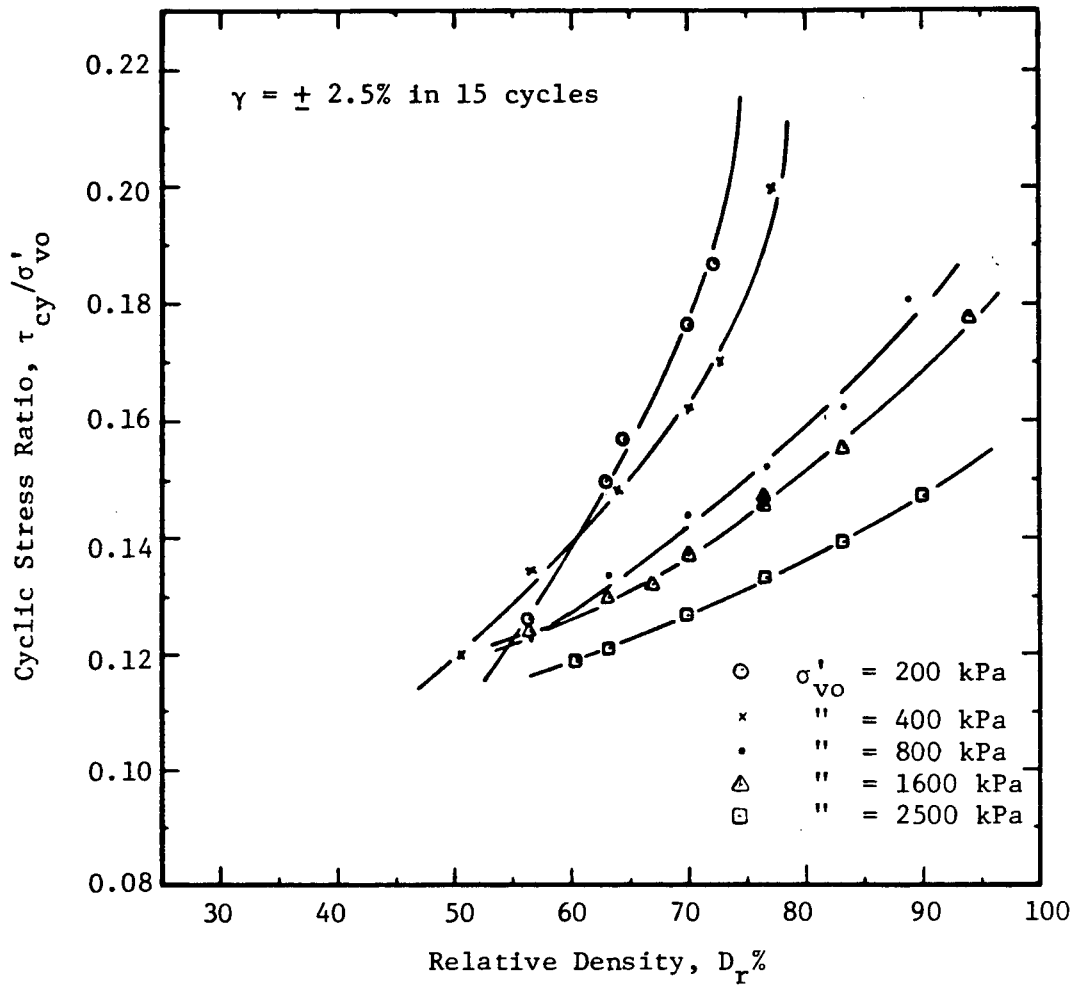


Fig. 18. Resistance to Liquefaction of Tailings Sand at Various Confining Pressures, Based on Shear Strain Level of  $\pm 2.5\%$  in 15 Cycles.

development of 2.5% strain in 15 cycles are shown in Figure (18). The resistance curves are similar to those in Figure (17) with a slight shift towards the higher relative densities. In both Figures (17 and 18), the relative position of the curves stays the same as in the case of 5% strain. This implies that similar reduction in liquefaction resistance occurs with increase in confining stress, regardless of the shear strain level to define the liquefaction.

#### 4.3 Liquefaction Resistance of Ottawa Sand

The resistance to liquefaction is first based on the development of  $\pm 5\%$  shear strain in 10 cycles. Data obtained at other levels of shear strain and different number of loading cycles will be discussed later.

The basic data on liquefaction resistance of Ottawa sand is shown in Figure (19). The increase in number of cycles to cause  $\pm 5\%$  shear strain with the decrease in void ratio at confining stress of 200 kPa was very rapid and similar to that for tailings at the same confining stress. At higher confining stress, even though the void ratio range is different from that at low confining stress, the increase in number of cycles to cause liquefaction as the void ratio decreases is still at a high rate. This is a distinctive characteristic of Ottawa sand when compared to the behaviour of tailings sand and implies a rapid buildup of resistance to liquefaction with relative density even at high confining stresses.

The liquefaction resistance of Ottawa sand as expressed by a relation between the cyclic stress ratio to cause  $\pm 5\%$  strain in 10 cycles and relative density at each confining stress level is shown in Figure

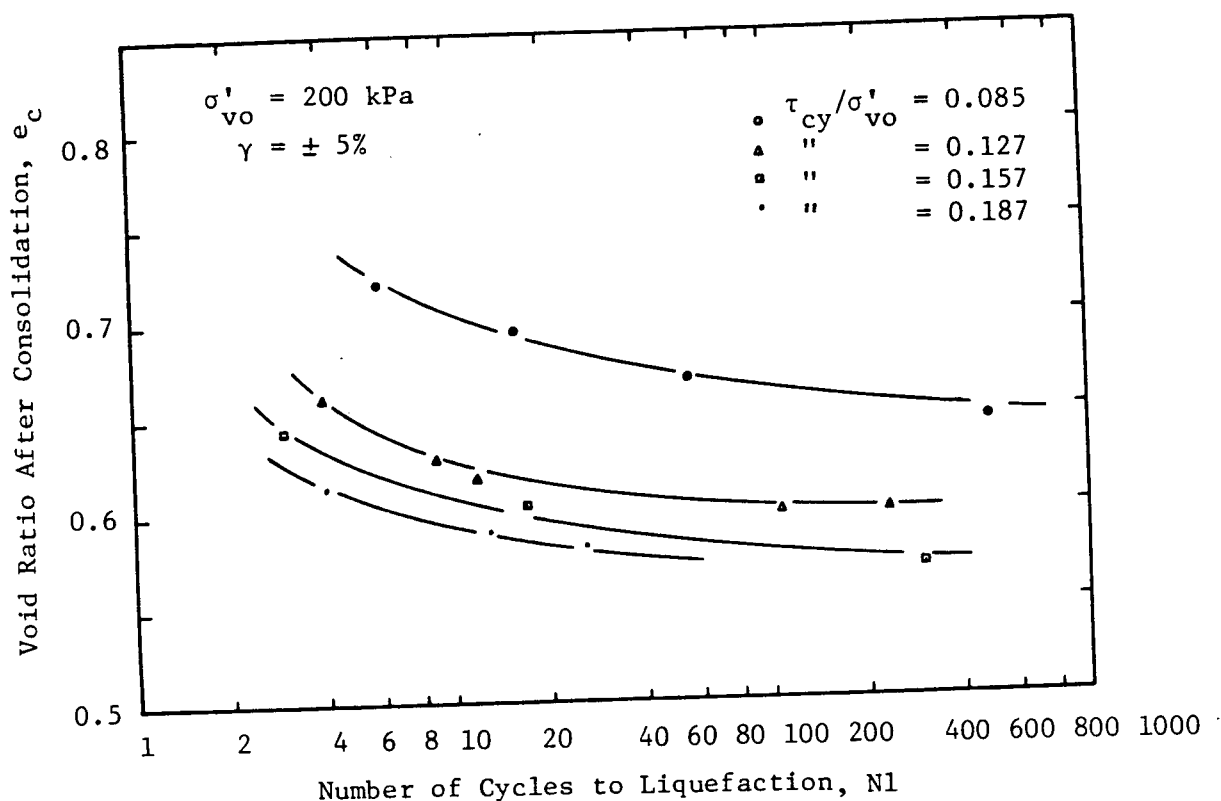


Fig. (19a). Number of Cycles to Liquefaction Versus Void Ratio for Ottawa Sand at Confining Pressure of 200 kPa.

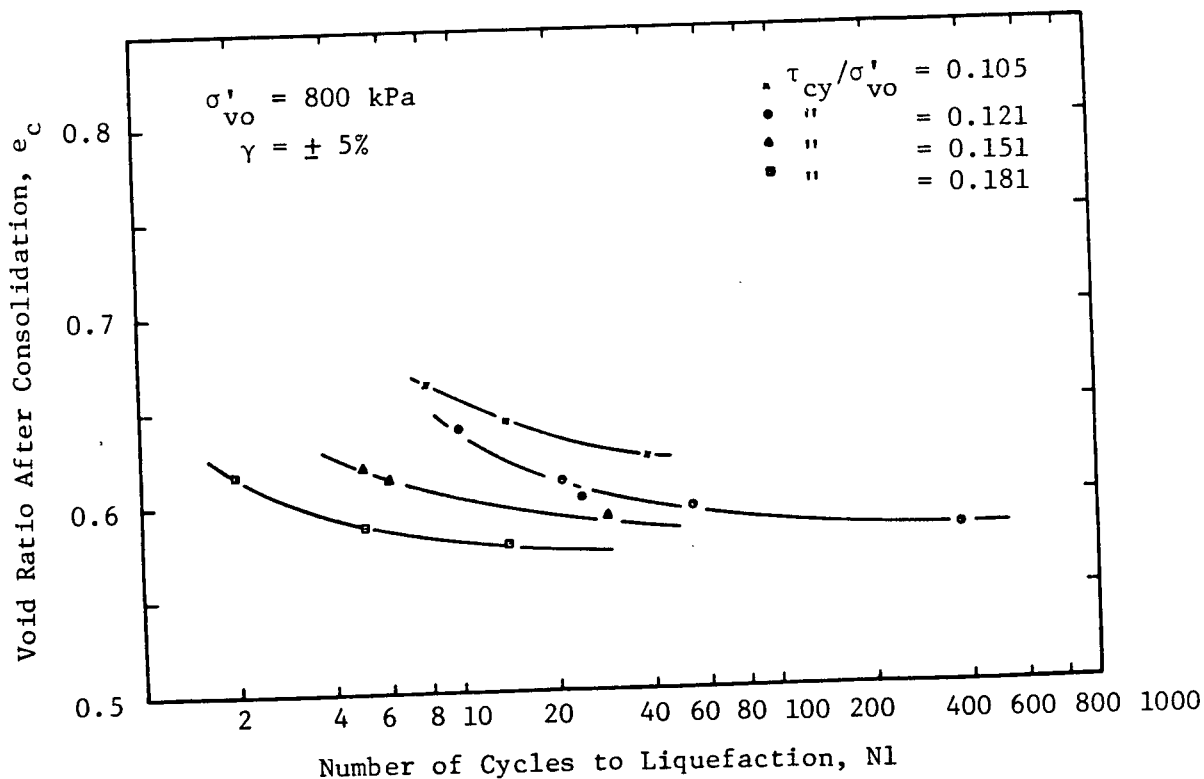


Fig. (19b). Number of Cycles to Liquefaction Versus Void Ratio for Ottawa Sand at Confining Pressure of 800 kPa.



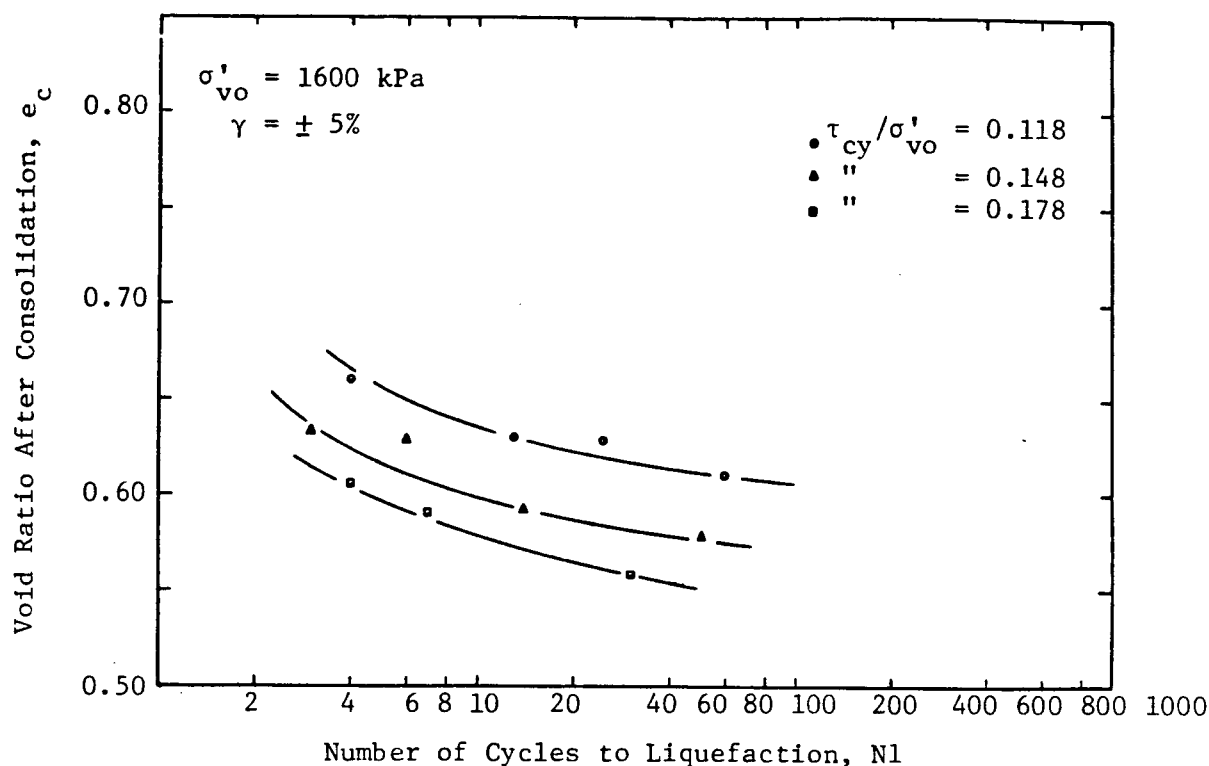


Fig. (19c). Number of Cycles to Liquefaction Versus Void Ratio For Ottawa Sand at Confining Pressure of 1600 kPa.

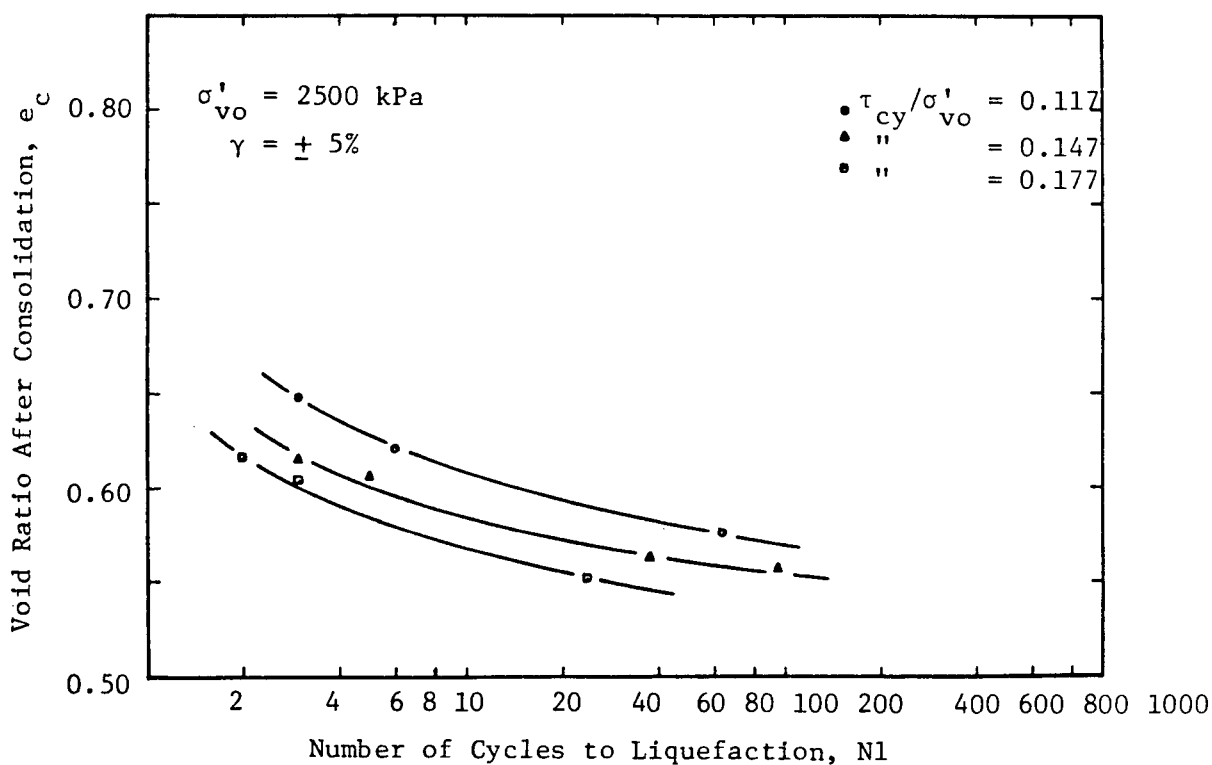


Fig. (19d). Number of Cycles to Liquefaction Versus Void Ratio For Ottawa Sand at Confining Pressure of 2500 kPa.

(20). A nonlinear increase in resistance as the relative density increases may be noted from Figure (20) over practically the full range of relative densities considered. The resistance curve at confining stress of 200 kPa has also been presented in earlier studies (see 8). No tests were performed at a confining stress of 400 kPa, however, earlier studies on this sand (8) have shown that its resistance to liquefaction was not affected by the increase of confining stress from 200 kPa to 400 kPa. It may be seen in Figure (20) that the liquefaction resistance builds up rapidly as the relative density increases, even at high confining stresses. This occurs despite the difference in the relative density range between low and high confining stresses at which samples can exist. The resistance to liquefaction at relative densities in excess of about 55% decreases with increase in confining stress level. The reduction in resistance is larger at higher relative densities. Again, as for tailings, the most significant reduction in resistance to liquefaction occurs as the confining stress increases from 200 kPa to 800 kPa. No change in resistance seems to occur when confining stress increases from 800 kPa to 1600 kPa. Then as the confining stress exceeds 1600 kPa, further reduction is noticed, regardless of the relative density level. At relative densities below about 55%, the shape of the resistance curve at  $\sigma'_{v0}$  of 1600 kPa seems to suggest a crossover with that at  $\sigma'_{v0}$  of 200 kPa, implying larger resistance at lower relative densities associated with higher confining stresses.

Ottawa sand is unlikely to exist at relative densities less than about 50% under confining stresses in excess of 800 kPa. At the same time, samples at relative densities of more than 75% were extremely

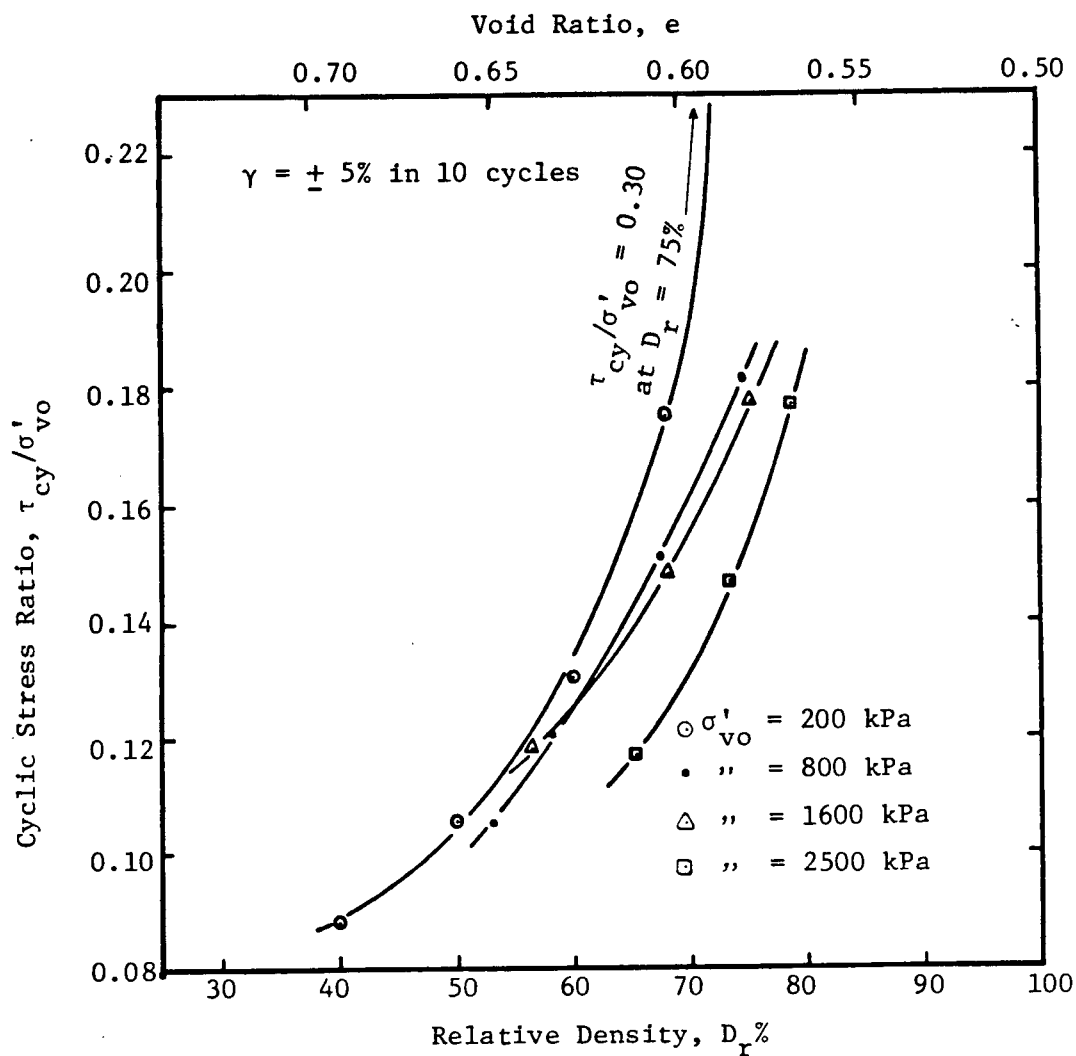


Fig. 20 . Resistance to Liquefaction of Ottawa Sand at Various Confining Pressures Based on Shear Strain Level of  $\pm 5\%$  in 10 Cycles.

difficult to prepare under a consolidation pressure of 200 kPa. Thus the variation of cyclic stress ratio with the increase in confining stress at various relative densities which is shown in Figure (21), spans a relative density range of only 55 to 75%. It may be noted from Figure (21) that the decrease in liquefaction resistance with increase in confining stress is larger at higher relative densities. The increase in resistance with increase in relative density is higher at lower confining stresses. At high confining stresses, even though the increase in resistance with increase in relative density is less than that at low confining stresses, Ottawa sand, unlike tailings, shows a marked increase in resistance with increase in relative density.

The percent reduction in resistance due to increase of confining stress as it is referred to a confining stress of 200 kPa is shown in Figure (22).

Unlike the behaviour of tailings, the application of high confining stress to Ottawa sand causes only a small change in relative density (Figure 5). A confining stress of 2500 kPa causes the relative density of the loose sample to increase by only 15% and dense sample by a mere 6%. Nevertheless, even these smaller increases in relative density are much more effective, in comparison with that for tailings, in increasing its resistance to liquefaction. This is so because of steepness of the resistance curves shown in Figure (20).

The void ratio of Ottawa sand after consolidation is again linearly related with the initial void ratio at all confining stress levels. This relationship, as for tailings sand, was useful in predicting the relative density after consolidation under a prescribed confining pressure when starting from a known initial density.

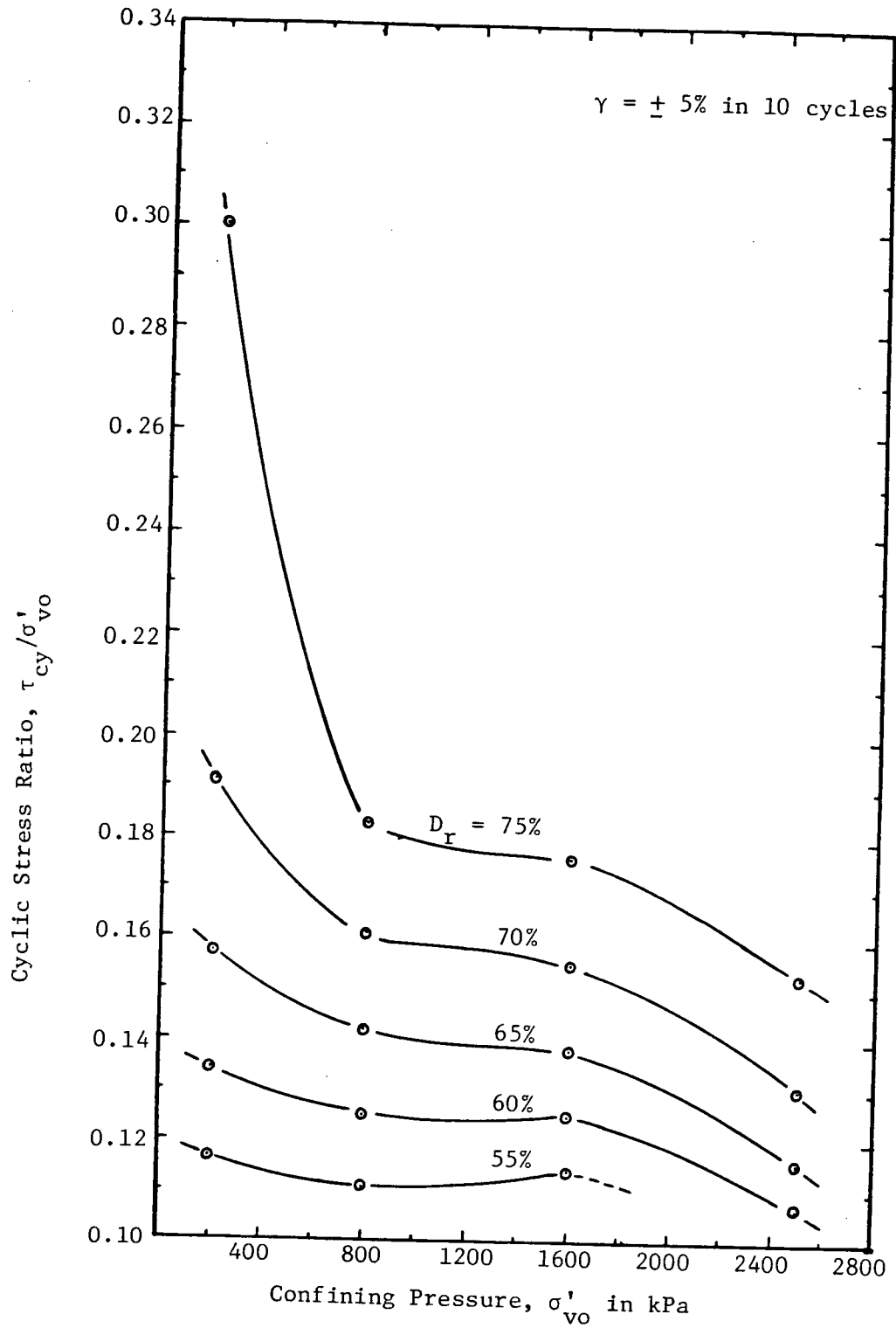


Fig. 21. Variation of Cyclic Stress Ratio to Cause Liquefaction For Ottawa Sand With Confining Pressure at Various Relative Density Levels.

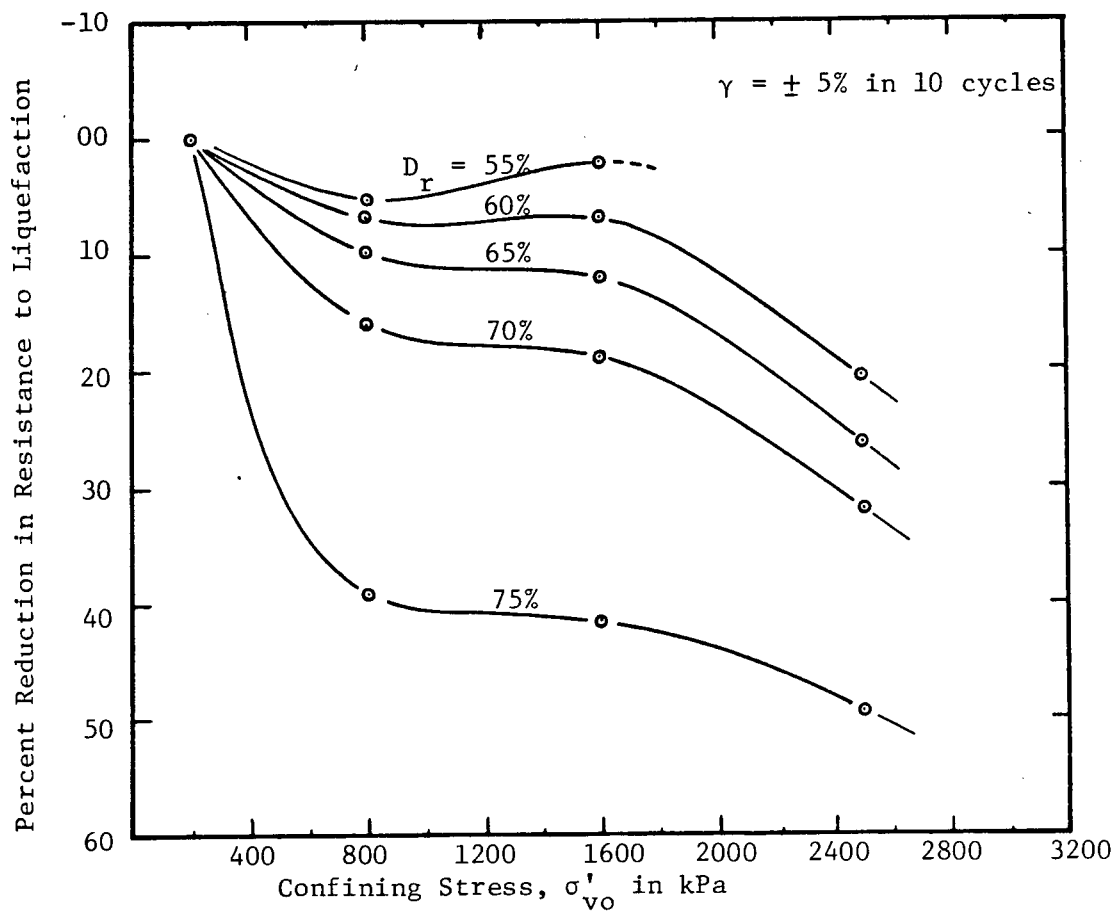


Fig. 22. Percent Reduction in Resistance to Liquefaction of Ottawa Sand When Referred to the Resistance at 200 kPa.

Figure (24) shows the relationship between cyclic stress ratio to cause liquefaction and confining stress at various initial relative densities. At initial densities up to about 62%, the cyclic resistance increases with increasing confining stress up to  $\sigma'_{v0}$  of ~1200 kPa, as the positive influence of densification exceeds the negative effect of confining stress increase. At initial relative density of about 62% and a confining stress range from 200 kPa to ~1600 kPa, the positive effect of densification of the sand with confining stress seems to compensate the negative effect due to the confining stress increase. A general reduction in cyclic resistance may be noted with confining stress increase at relative densities in excess of 62%. A very slight change in resistance occurs at all initial relative densities when the confining stress increases from 800 kPa to 1600 kPa. As the confining stress exceeds 1600 kPa, the liquefaction resistance decreases with increase in confining stress, regardless of the initial relative density level.

Initial densification of Ottawa sand is beneficial in increasing its liquefaction resistance over a broad range of confining stress as shown in Figure (24). Regarding this aspect, densification is much more effective at lower confining stresses. At a confining stress of 200 kPa, the liquefaction resistance is increased by 80% as a consequence of increase in initial relative density level from 53% to 69%. Whereas at confining stress of 2500 kPa, the gain in resistance for the same increase in initial relative density was only 32%.

Results of liquefaction resistance at  $\pm 5\%$  shear strain in 15 cycles are shown in Figure (25). The resistance curves, in this case, are similar to that for 10 cycles and their relative position stays

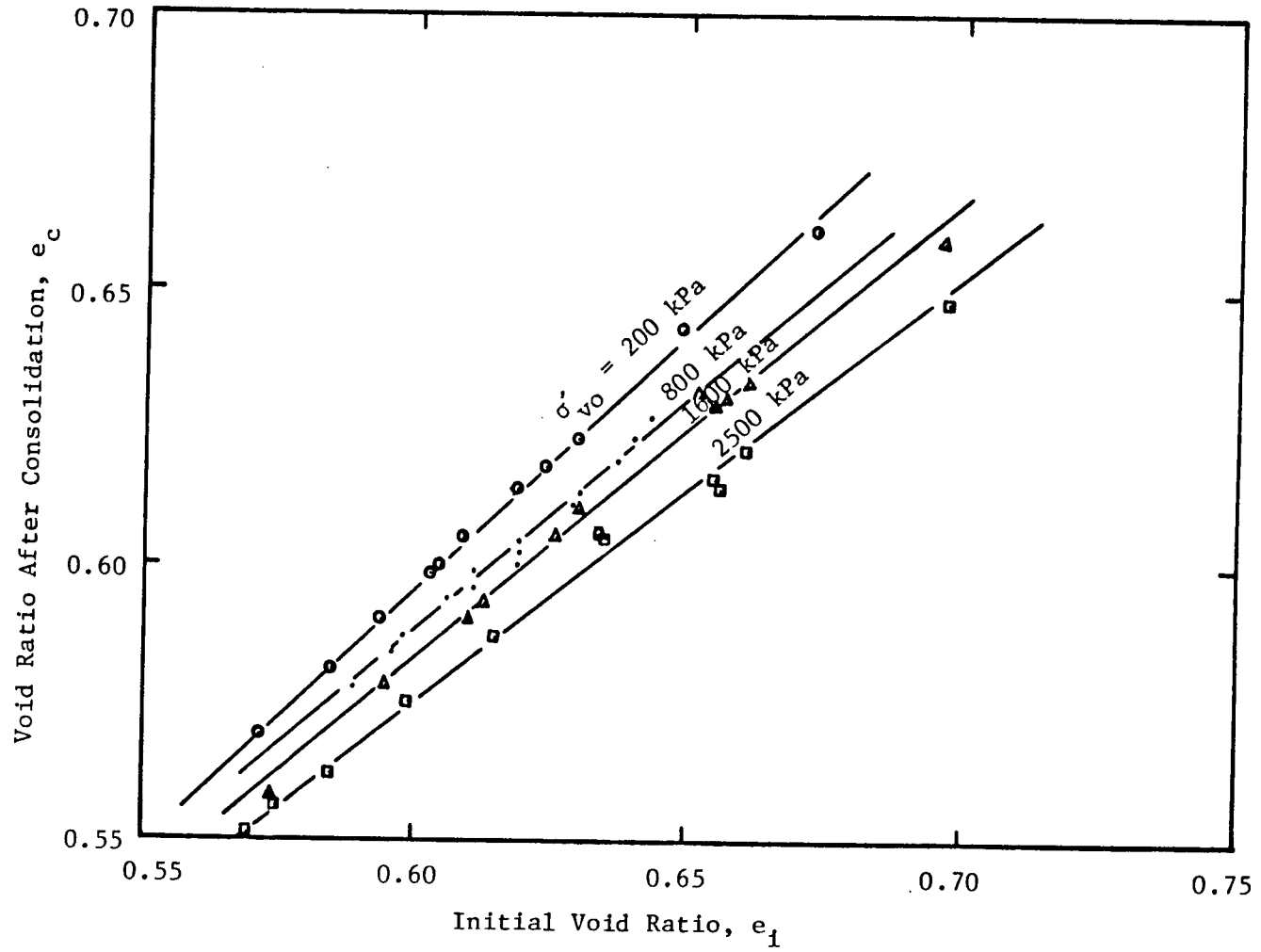


Fig. 23. Initial Void Ratio,  $e_i$ , With Void Ratio After Consolidation,  $e_c$ , Relationships of Ottawa Sand at Various Confining Pressures.



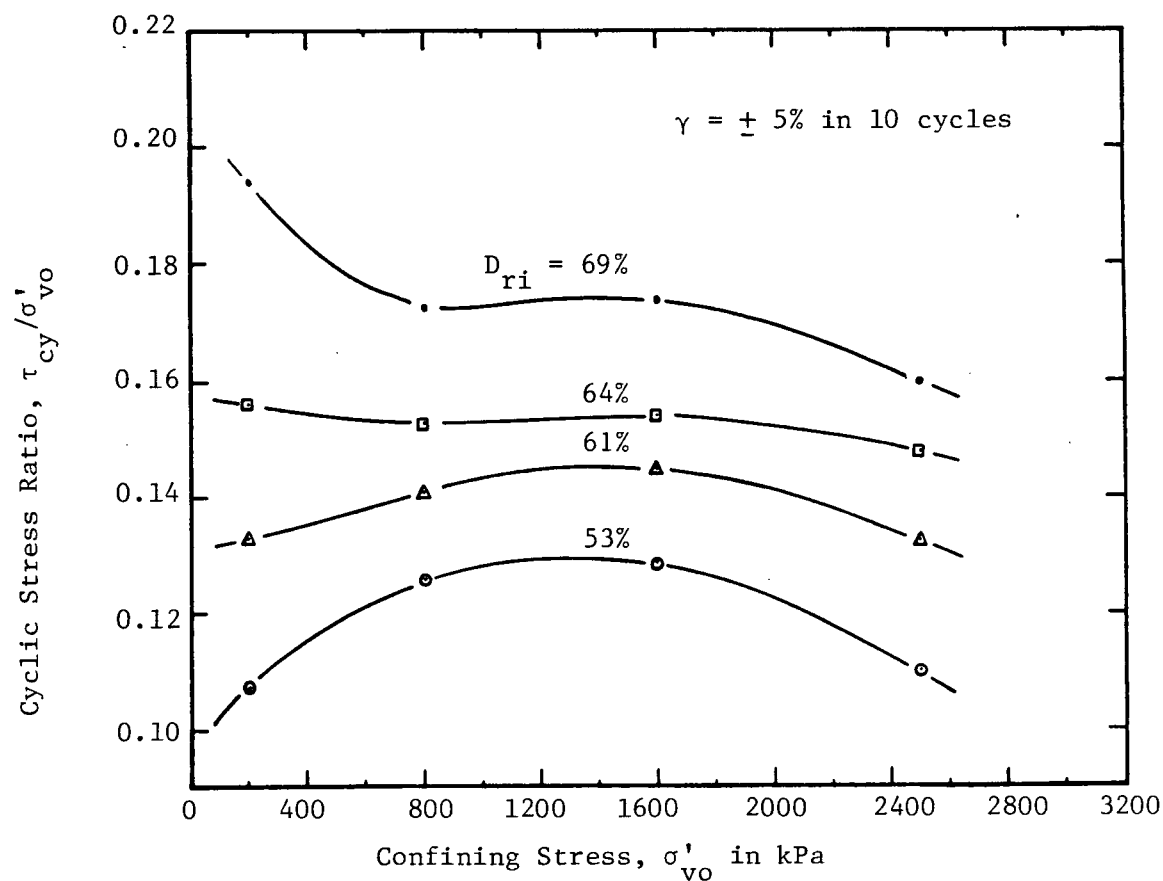


Fig. 24. Effect of Confining Pressure on the Resistance to Liquefaction of Ottawa Sand Prepared at Various Initial Relative Densities.

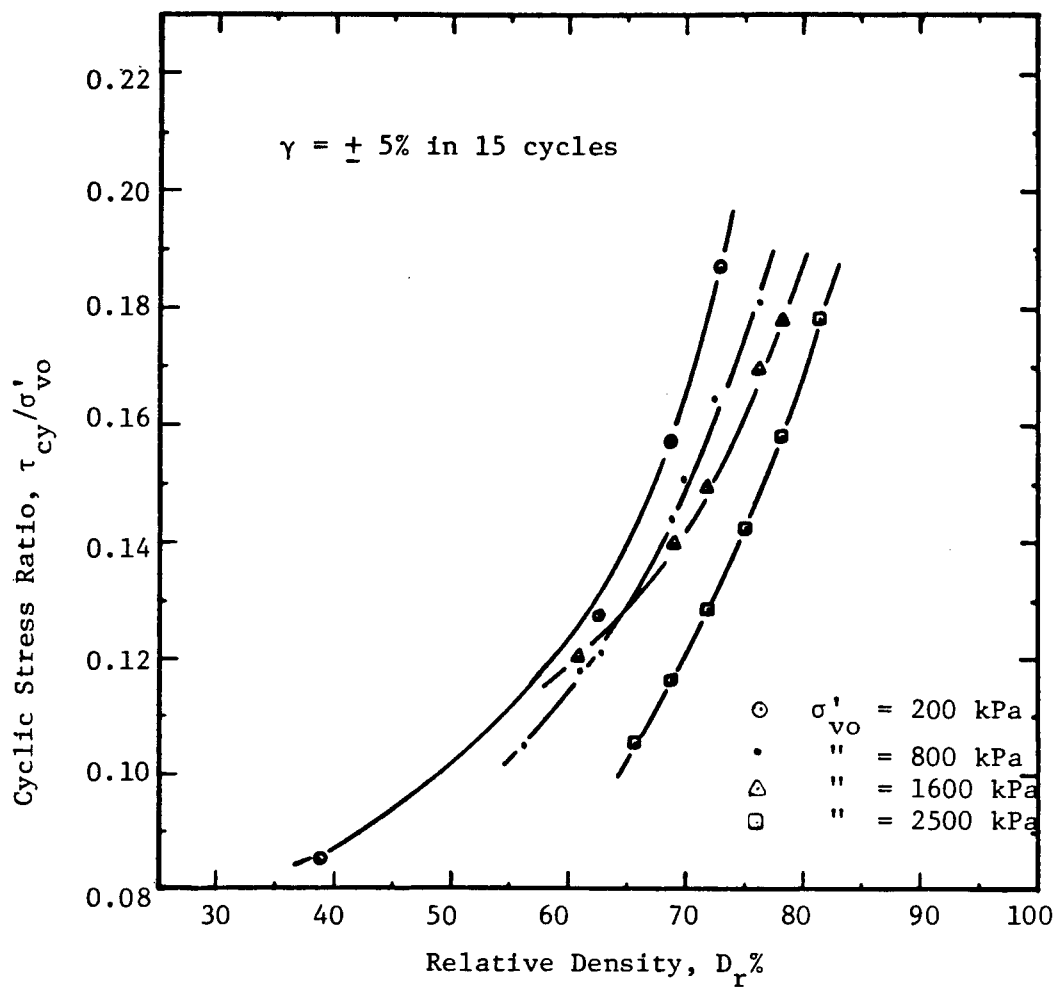


Fig. 25. Resistance to Liquefaction of Ottawa Sand at Various Confining Pressures Based on Shear Strain Level of  $\pm 5\%$  in 15 Cycles.

almost the same. As expected, a higher relative density is needed to withstand a certain cyclic shear stress level for 15 loading cycles than the relative density required for the same shear stress level in 10 cycles at all confining stress levels. The reduction in cyclic stress ratio to cause  $\pm 5\%$  strain in 15 cycles at fixed relative density levels is very similar to that for 10 cycles.

The liquefaction resistance of Ottawa sand based on shear strain level of  $\pm 2.5\%$  in 10 and 15 cycles is shown in Figures (26) and (27) respectively. A similar conclusion to that on liquefaction resistance of tailings sand at the same strain level can be applied here. The relative positions of the resistance curves at the various confining pressure levels stay very well the same as in the case of  $\pm 5\%$  shear strain. This implies a similar reduction in liquefaction resistance, with increase in confining pressure, to that at  $\pm 5\%$  shear strain regardless of the shear strain level to define the liquefaction.

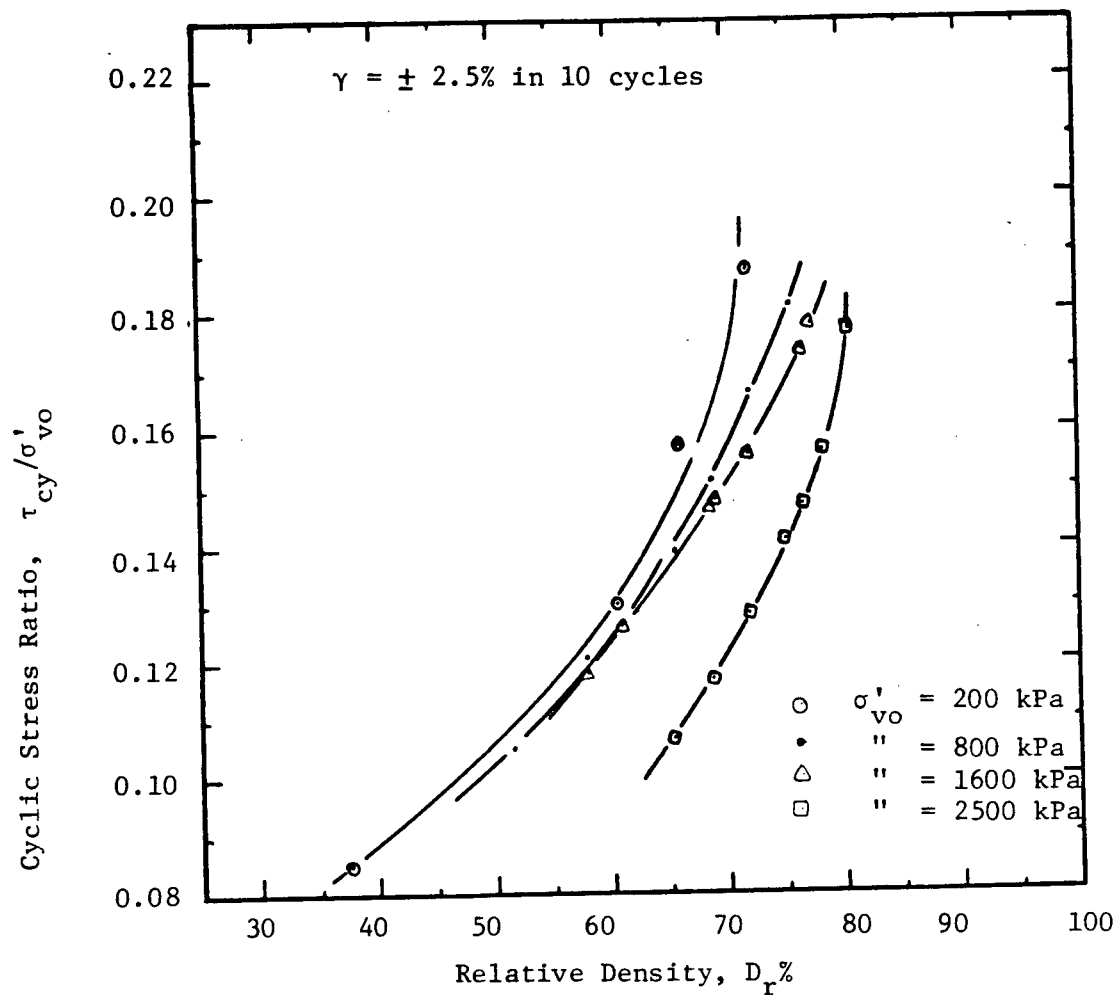


Fig. 26. Resistance to Liquefaction of Ottawa Sand at Various Confining Pressures, Based on Shear Strain Level of  $\pm 2.5\%$  in 10 Cycles.

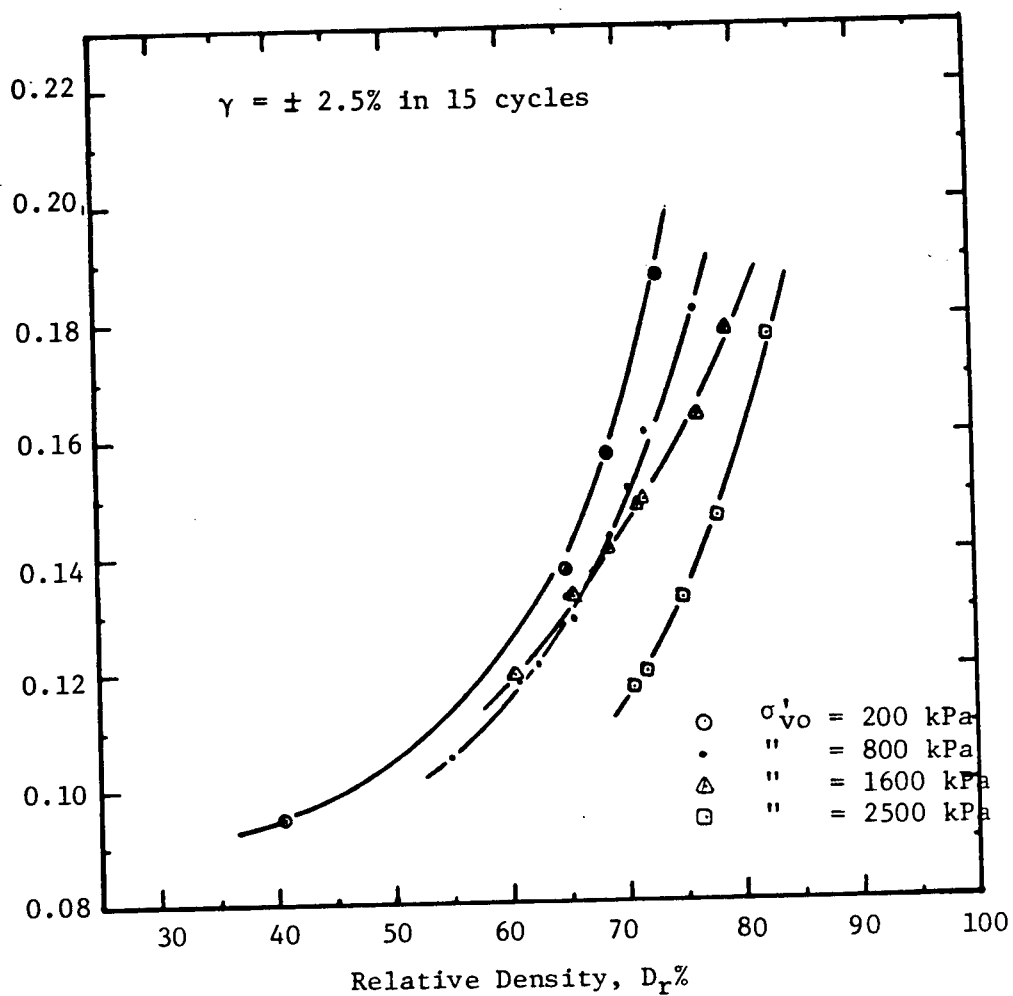


Fig. 27. Resistance to Liquefaction of Ottawa Sand at Various Confining Pressures Based on Shear Strain Level of  $\pm 2.5\%$  in 15 Cycles.

## 5. EFFECT OF CONFINING STRESS AND PARTICLE ANGULARITY ON LIQUEFACTION POTENTIAL

The main purpose of this research was to investigate the effect of confining stress and particle angularity on liquefaction potential. The effect of confining stress has been investigated and discussed in Chapter 4 by looking at the resistance of both angular and rounded sands at various confining stress levels. The effect of particle angularity will be considered by comparing the response of the two sands at fixed levels of confining stress and relative density. In the following discussion, development of  $\pm 5\%$  strain in 10 cycles is considered as the occurrence of liquefaction.

The resistance to cyclic loading of both tailings and Ottawa sand, as discussed earlier, clearly indicate a reduction with increase in confining stress. The variation of the cyclic stress ratio to liquefy both sands with confining stress increase is shown in Figures (12 and 19). Both figures show a general reduction in cyclic stress ratio to cause liquefaction with increase in confining stress, regardless of the sand type. The magnitude of reduction, however, depends on the sand type, confining stress level, and the relative density level at which this evaluation is made.

The percent reduction in liquefaction resistance with confining stress increase at various levels of relative density is shown in Figures (13 and 20) for tailings and Ottawa sand. In these figures, the resistance at confining stress of 200 kPa was taken as the reference. The liquefaction resistance of tailings sand, for example, reduces by as much as 56% due to an increase in confining stress from

200 kPa to 2500 kPa at relative density of 75%. Most of the reduction occurs as the confining stress increases from 200 kPa to 800 kPa. The same trend appears to be applicable for Ottawa sand but with relatively lower reductions. The amount of reduction decreases as the relative density decreases. Furthermore, there seems to be a certain upper limit of relative density, for both sands, below which the liquefaction resistance appears not to be negatively affected by the increase in confining stress. The value of this relative density is about 50 to 55% for both sands.

The effect of confining stress on the liquefaction potential, however, cannot be isolated from the effect of the particle shape. Very large confining stresses result in very large densification of angular sands and consequently may increase their cyclic resistance more by densification than the reduction due to increasing confining pressure.

The two sands used in the study had identical mineral composition and gradation. Therefore the difference in their response to cyclic loading can be attributed solely to the differences in angularity of their particles. Figure (28) shows a direct comparison of liquefaction resistance of the two sands at confining stresses of 200 kPa and 2500 kPa. It may be noted that at low confining stress (200 kPa), the angular sand is more resistant to liquefaction than the rounded sand over the entire range of relative densities investigated. At high confining stress (2500 kPa), the difference in their response depends on the relative density level under consideration. At relative densities less than about 70%, the angular sand is more resistant to liquefaction than the rounded sand. As the relative density exceeds about 70%, the

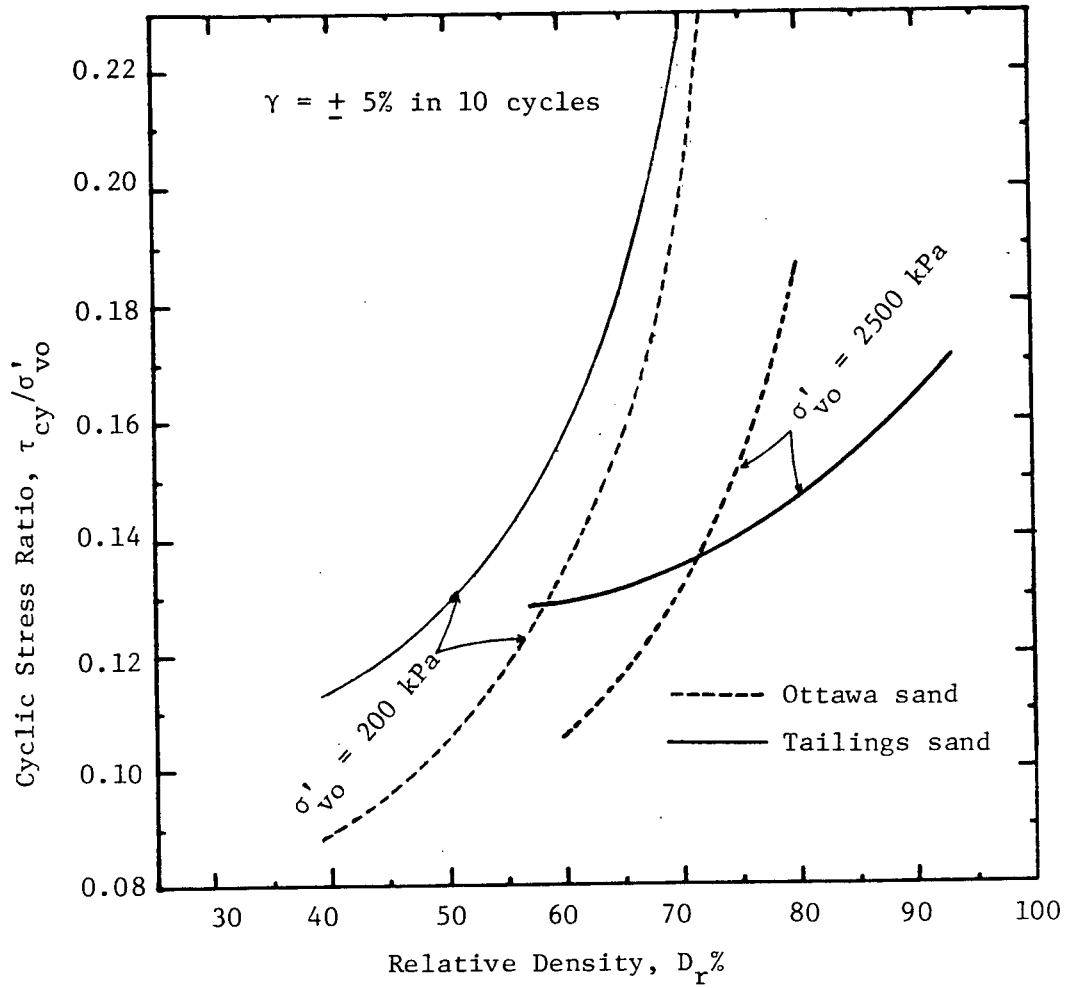


Fig. 28. Comparison of Resistance to Liquefaction of Angular and Rounded Sands at Low and High Confining Pressures.



rounded sand becomes more resistant than the angular sand. The difference between the resistance of the two sands beyond the relative density of 70% increases rapidly as the relative density increases. This may be due to the much faster rate of the resistance buildup of Ottawa sand at high confining stresses, whereas for angular sand, the resistance curve at high confining stress (2500 kPa) is much flatter. Comparison of liquefaction resistance at other confining pressures can be made in a similar manner, which would show a gradual transition between the behaviour at low (200 kPa) and high (2500 kPa) confining pressures.

Thus, the resistance of angular sand can be either larger or smaller than that of its rounded counterpart, depending upon the level of confining stress and the magnitude of relative density at which the comparison is made. At low confining stresses, both angular and rounded sands are unlikely to liquefy at relative densities in excess of about 70% even under strong earthquakes. This is apparent in Figure (28) which shows extremely high cyclic resistance for relative densities in excess of about 70%. At high confining stresses, tailings sand may be susceptible to liquefaction even at relative densities approaching 100% under moderate earthquake shaking. Ottawa sand at high confining stresses is more resistant than tailings sand and seems unlikely to liquefy at relative densities in excess of about 80% even under strong earthquakes.

The low resistance of tailings at higher confining stresses may be due to the breakage of sharp edges of tailings sand particles under cyclic shear strains. The consequence of particle breakage during cyclic loading is analogous to increased particle compressibility,

which would result in an accelerated pore water pressure rise in undrained tests. The resistance to liquefaction of such a sand, under confining stress high enough to cause particle breakage during cyclic shearing, will be of course less than that in the case where no particle breakage would occur.

Results from monotonic undrained triaxial tests on both sands indicate that gradation curve of Ottawa sand after being tested at confining stress of 2500 kPa is virtually identical to that for the untested sand. For tailings sand, however, about 0.5% increase in fines content was observed during consolidation under the confining stress of 2500 kPa and an additional increase of about 1.5% during monotonic undrained testing. However, larger increase in fines may be expected from cyclic loading of tailings. This implies that both consolidation and shearing of angular sands results in breakage of the shape edges of the particle under high confining stresses. No detectable increase in fines content was noted for tests at confining stresses less than 400 kPa and consequently liquefaction resistance of tailings at these confining stress levels would not be reduced by breakage of particle edges during cyclic shearing.

## 6. CONCLUSIONS

The effects of high confining pressure and particle angularity on liquefaction resistance of sands have been investigated under the constant volume cyclic simple shear condition. Two quartz sands of identical mineral composition and gradation but varying in particle angularity were used in the study.

The results show that a decrease in liquefaction resistance of sands occurs with increase in confining stress regardless of particle shapes constituting the sand. The magnitude of reduction in resistance to liquefaction with increase in confining stress, however, depends on the relative density level, particle shape of the sand, and the range of confining stresses of interest.

Liquefaction resistance of both angular and rounded sands at low confining stress of 200 kPa increased very rapidly with increase in relative density. At this low confining stress level, angular sand was more resistant to cyclic loading than rounded sand. At high confining stresses, by contrast, the buildup in liquefaction resistance of angular sand with increase in relative density is very slow compared to that of rounded sand, which maintained a rapid rate of increase in resistance with increase in relative density. This makes rounded sand under high confining stresses more resistant to cyclic loading than angular sand at higher relative densities.

The decrease in resistance to liquefaction with increase in confining stress, for both sands, increases with increase in relative density. However, such decrease seems to be more significant for angular sand. Very little increase in resistance occurs with large

increase in relative density at high confining stresses in such a sand.

The most dramatic decrease in resistance to liquefaction, for both sands, was that associated with increase in confining stress from 200 kPa to 800 kPa.

A certain relative density level appeared to exist, for both angular and rounded sands, below which the resistance to liquefaction was not affected by the negative effect of confining stress, provided such relative density states were accessible under confining stress considered. At low confining stresses ( $\sigma'_{vo} < 400$  kPa), both sands at relative density in excess of about 70% are unlikely to liquefy even under strong earthquakes because of their extremely large resistance to liquefaction ( $D_r$  of 75%,  $\tau_{cy}/\sigma'_{vo} > 0.3$ ).

At high confining stresses, cyclic shearing tends to cause breakage of sharp edges of angular sand particles, which induces more potential volumetric contraction and consequently an accelerated pore water pressure increase. This makes angular sand more susceptible to liquefaction under high confining stresses than rounded sand. Angular sand could liquefy under high confining pressure during even moderate earthquakes, despite relative densities approaching 100%. Furthermore, initial densification of angular sand was found to be of little benefit in increasing its liquefaction resistance if it was to perform eventually under high confining stresses.

Rounded sand at relative densities in excess of about 80% seemed to be non-susceptible to liquefaction even at confining stresses of up to 2500 kPa under strong earthquake shaking.

Because of the differences in the behaviour of angular and rounded

sands discussed above, extreme caution must be exercised in trying to predict cyclic resistance of tailing sand at high confining pressures from results of comparable studies on natural rounded sands or from studies on tailings sands at low confining stresses.

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