EFFECT OF CONFINING PRESSURE AND PARTICLE ANGULARITY ON RESISTANCE TO LIQUEFACTION

By

Y.P. Vaid, J.C. Chern and H. Tumi
Department of Civil Engineering, University of British Columbia
Vancouver, B.C., Canada

ABSTRACT

A study under simple shear conditions on the resistance to liquefaction of two quartz sands of identical mineral composition and gradation but varying in particle angularity is presented. Effect of confining pressures up to 2500 kPa is also investigated for its influence on the cyclic stress ratio causing liquefaction. High confining pressure chosen are representative of the conditions in high tailings dams which use angular tailigns in the embankment construction. Resistance to liquefaction is compared for the angular and rounded sands over a range of relative densities and confining pressures. Evidence in support of little benefit gained in dynamic resistance by initially densifying tailings sands under high confining pressures is presented.

INTRODUCTION

In the seismic design of tailings dams one of the major concerns is the susceptibility of saturated tailings to liquefaction due to earthquake shaking. Tailings are the ground up particles of rock which remain after the minerals have been extracted from the ore. They generally comprise of sand and silt size particles which are angular in shape in contrast to the natural sands which are generally rounded or subrounded. It is common practice in conventional tailings impoundments to separate the tailings into a coarse and a fine fraction and to use the coarse fraction to build the embankment. Cyclic loading laboratory tests on tailings material show that they behave in the same manner as natural sands; i.e. they are susceptible to liquefaction when saturated and relative density is the most important parameter controlling their resistance to liquefaction. Specifically, at a given relative density, particle angularity has been implicitly assumed not to influence the resistance to liquefaction. However, these observations on the resistance to liquefaction of tailings have been based primarily on studies conducted on natural sands at relatively low confining pressures. There is, however, a growing trend toward building tailings dams of increasing height, and thus the danger of liquefaction of tailings subjected to high confining pressures in these dams is of considerable concern. The angular tailings sands are inherently more compressible, especially under high confining pressures, than the subrounded and rounded natural sands. Under high confining pressures, they are also likely to possess compressibility on cyclic loading different from their rounded counterparts. This potential compressibility will under undrained conditions influence the rate of pore pressure generation and hence the resistance to liquefaction. It would, therefore, be of equal importance to investigate not only the effect of confining pressure but also that of particle angularity on the resistance to liquefaction of granular materials.

Although there is a general feeling that the resistance to liquefaction at high confining pressures is less than at low confining pressures on account of the supressed dilatancy of the granular materials, yet research on this important subject has been extremely limited. Seed (4) suggested a reduction of up to 35% in cyclic stress ratio, τ_{cy}/σ'_{vo}, to cause liquefaction when the effective confining pressure σ'_{vo} increases from 150 to 800 kPa. No reference was, however, made as to the sand type or the relative density state at which such reduction would apply. Data on the liquefaction resistance of several subangular to subrounded sands over a confining pressure range of 50 and 600 kPa by Castro and Poulos (2) also shows a general reduction in cyclic stress ratio to cause liquefaction with increasing confining pressure. The magnitude of reduction depended very much of the sand type and relative density. A similar reduction in liquefaction resistance of up to 25% was noted by Volpe (6) for compacted tailings over a confining pressure range of 100 to 350 kPa.

To the writers' knowledge no study has been made to seek the influence of large confining pressures on the resistance to liquefaction of granular materials. Confining pressures up to 2500 kPa could be encountered in tailings dams of 200 m height. Tailings dams approaching these heights are either being constructed or considered a real possibility in the future. Similarly, little is known regarding the influence of particle angularlity on liquefaction resistance under high confining pressures. This paper presents a study aimed at seeking the influence of high confining pressure and particle angularity on resistance to liquefaction. The experimental study was carried out using the simple shear apparatus, in order to simulate the most representative in-situ stress conditions during earthquake shaking.

EXPERIMENTATION

Soil Description

Ottawa sand, a natural silica sand and Brenda Mine tailings sand from a copper mine in British Columbia were used in the study. Ottawa sand was ASTM designated C-109, which is a medium sand with rounded particles had maximum and minimum void ratios of 0.82 and 0.50 respectively. Brenda Mine tailings were the coarse fraction used in building the embankment for tailings impoundment. They were first washed through #100 sieve in order to remove some fines present. Removal of these fines together with some coarse fraction brought its gradation curve almost identical to that of Ottawa sand C-109, and thus permitted the influence of particle angularity to be isolated without introducing a possible additional variable in the form of gradation. The grain size distibution curves for the two sands used are shown in Figure 1. Brenda Mine tailings sand consisted of almost all quartz with occasional traces of mica and chalcopyrite. Thus the mineral composition also of the two sands was identical and the only difference between the two being particle angularity. The maximum and minimum void ratios of tailings sand were found to be 1.06 and 0.688 respectively.

Test Program

Cyclic loading tests were performed using the constant volume cyclic simple shear apparatus (3). This apparatus permits the use of dry sand samples for evaluating undrained response. In these tests, changes in vertical confining pressure in order to maintain constant volume are equivalent to changes in porewater pressure in the corresponding undrained tests. The simple shear specimen size was 5 cm square x 2.5 cm high.

The constant volume simple shear test is practically free from compliance effects inherent in most undrained tests, and thus yields most accurate results when no drainage is supposed to simulate constant volume conditions. Considerable inovations in sample preparation techniques in both simple shear and triaxial testing have been made in order to yield sand samples of uniform density. This is particularly necessary when preparing samples of high relative density in order to measure their true resistance to liquefaction, which could be grossly underestimated by possible loose surface layer during sample preparation (5).

Samples were K_o consolidated (an inherent condition in the simple shear test) under the desired vertical confining pressure. Cyclic loading was applied by means of a electropneumatic loading system. The wave form used was sinusoidal and cyclic load was applied at a frequency of 0.1 Hz. Low frequency loading was used in order to examine, if necessary, the details of cyclic porewater pressure and strain development, not only at the completion of stress cycles but also within each loading cycle. During cyclic loading, cyclic stress, porewater pressure and shear strain were continuously monitored and records obtained on strip chart recorder.

TEST RESULTS

In tests on granular materials it is difficult to form, in the laboratory, reproducible samples of identical relative density under a given confining pressure. Therefore cyclic loading tests at each confining pressure were performed by subjecting samples reconstituted at different relative densities to a fixed amplitude of cyclic stress ratio τ_{cy}/σ'_{vo} and recording the number of stress cycles to liquefaction (defined herein as the development of shear strain $\gamma = \pm 5\%$). Several such relationships between relative density and number of cycles to liquefaction were obtained for other values of τ_{cy}/σ'_{vo}. From these results, the desired relationship between relative density and cyclic stress ratio to cause liquefaction in 10 stress cycles was determined by cross plotting the data. Results were obtained in a similar manner for other effective confining pressures and for both Ottawa and tailings sands. Cyclic loading resistance curves for both sands were developed for vertical confining pressures of 200, 400, 800, 1600 and 2500 kPa. The test data obtained showed extremely high degree of reproducibility and little scatter.

Liquefaction Resistance of Tailings Sand

Figure 2 shows the cyclic loading resistance of tailings sand as relationships between τ_{cy}/σ'_{vo} vs. D_r at several values of confining pressures σ'_{vo}. It may be readily seen that, as expected, the resistance to liquefaction under each confining pressure increases with relative density. The rate of this increase in resistance is, however, very much dependent on the range of relative density considered under each confining pressure. At lower confining pressure of 200 kPa, liquefaction resistance builds up very rapidly over a relatively narrow range of relative densities and the resistance curve is highly nonlinear in contrast to the generally assumed linear increase in resistance with relative density for sands (1). As the confining pressure increases, the resistance curves become progressively flatter over the range of relative density obtained in the tests. This implies that the build up in resistance to liquefaction with increasing relative density slows down considerably as the level of confining pressure increases. Since certain range of relative densities may not be accessible to tailings sands, particularly under high confining pressures, direct comparison of liquefaction resistance at a given relative density with variation in confining pressure may not be possible at all relative densities. This aspect will be discussed further in a later section.

It is apparent from the test result in Figure 2 that the resistance to liquefaction of tailings sand decreases considerably with increasing levels of confining pressure, except at relative densities less than about 50%. This decrease in resistance to liquefaction with increasing confining pressure becomes progressively larger as the relative density increases. For example, an increase in confining pressure from 800 kPa to 2500 kPa at a relative density of 70% causes a reduction of 15% in τ_{cy}/σ'_{vo} ratio as compared to a 23% reduction at a relative density of 80%. Most dramatic decrease in resistance appears to be associated in the confining pressure increases from 200 to 400 kPa over relative density range in excess of about 60%. At a relative density of about 50%, the liquefaction resistance curves under all confining pressures tend to converge. From the converging resistance curves for $\sigma'_{vo} = 200$ and 400 kPa, it appears that for relative densities less than about 50%, and σ'_{vo} less than 400 kPa, the resistance to liquefaction is not dependent on the level of confining pressure. For higher confining pressures ($\sigma'_{vo} > 800$ kPa), relative density states less than about 50% were not accessile to the sand. It was because the air pluviated sand samples could not be formed at initiail relative densities, D_{ri}, than about 37%. Consolidation under confining pressure of 800 kPa or greater increased their relative denstiy to levels greater than 50%. If it would have been possible to prepare sand samples looser than D_{ri} of about 37%, they could have, on consolidation under confining pressures of 800 and 1600 kPa, acquired relative densities less than 50%. From the trend of liquefaction resistance curves under these confining pressures (Figure 2), it would appear then that for relative densities less than about 50%, the liquefaction resistance under these higher confining pressures could be larger than that under the lower confining pressure. Similar observations could not be made for σ'_{vo} = 2500 kPa. Under this high confining pressure, consolidation of sand was very large and relative densities less than about 50% were unlikely at the end of consolidation, even for samples constituted at a very low relative density.

Results of one dimensional compression of the tailings sand at three initial relative densities are shown in Figure 3 in the form of void ratio, e, versus log σ'_{vo} relationships. It may be noted that considerable volume compression occurs on application of particularly large confining pressures during consolidation of angular tailings sand. Consequently certain smaller relative densities are not accessible to larger confining pressures. The effect of confining pressure on relative density increase, however, decreases with increase in initial relative density, as may be seen from the converging trends of the compression curves with increasing confining pressure. When substantial increase in relative density is associated with the application of confining pressure, it is apparent that certain smaller relative densities are not accessible to larger confining pressures. The upper limit of this accessible relative density will increase as the confining pressure increases. For the tailings sand tested, the results in Figure 2 show that relative densities of less than about 67% are not accessible to this sand when consolidated under a confining pressure of 2500 kPa even when starting from an initially loose relative density of 37%. Consequently, at relative densities less than about 67%, the concern regarding the effect of confining pressure on the resistance to liquefaction will be limited only to confining pressure levels of less than 2500 kPa. In general such limiting relative density and the corresponding confining pressure will depend on the type of sand. In fact, the sand under high confining pressure should be considered synonymous with a relatively dense sand.

The variation of resistance to liquefaction with confining pressure at fixed values of initial relative densities, D_{ri}, is shown in Figure 4. Each contour represents the resistance to liquefaction of samples lying along a typical consolidation curve in Figure 3. Since the resistance to liquefaction increases with increase in relative density and decreases with increase in confining pressure, the resistance curves in Figure 4 show the net influence of these two factors. It may be noted that at loose D_{ri} the effect of densification far outweighs that of increasing confining pressure until σ'_{vo} ~ 1600 kPa. For larger σ'_{vo}, the effect of confining pressure tends to be more predominant. At higher initial relative densities, however, a general continuous decreasing resistance with confining pressure reflects that the densification is too small (see Figure 3) to offset the reduction due to the increase in confining pressure.

In Figure 4 substantial increase in resistance to liquefaction may be seen at lower confining pressure as the initial relative density is increased. For example, at confining pressure of 200 kPa, the resistance can be increased by as much as 50% if the sand is placed at a relative density of 62% instead of 42%. But, only a mere 10% increase in resistance is achieved at a confining pressure of 2500 kPa for similar densification. That a diminishing benefit of initial densification is obtained for tailings sand under higher confining pressure is apparent in Figure 4 since the resistance curves at all initial relative densities tend to converge together as the confining pressure increases. This has considerable practical significance in deciding placement densities of tailings at various locations in the tailings dams.

Liquefaction Resistance of Ottawa Sand

Test results showing resistance to liquefaction of Ottawa sand are presented in Figure 5. The resistance curve at σ'_{vo} = 200 kPa has also been presented in earlier studies (see (5)). At each confining pressure, an extremely rapid build up of resistance with relative density may be noted from the steepness of resistance curves. The resistance curves do not seem to suffer much flattening with increasing confining pressure.

Figure 5 also shows strong dependence of resistance to liquefaction on confining pressure at relative densities greater than about 50 to 55%. Similar to the behaviour of tailings sands, there appears to be tendency for the resistance curves at all confining pressures to merge together at a relative density of about 50 to 55%. Test series at confining pressure of 400 kPa was not carried out on Ottawa sand. Earlier studies on this sand (3), however, have shown that its cyclic stress ratio τ_{cy}/σ'_{vo} is independent of the confining pressure between σ'_{vo} = 200 to 400 kPa for relative densities up to about 60%. The shape of the resistance curve at σ'_{vo} = 1600 kPa seams to suggest a crossover with the resistance curve for σ'_{vo} = 200 kPa, implying larger resistance at relative densities less than about 55%. This would of course be possible provided such relative density range could be accessible to this confining pressure at very loose placement relative densities.

Increase in relative density on the application of large confining pressures to Ottawa sand are not as dramatic as for tailings (Figure 6). Confining pressure of 2500 kPa causes the relative density of the loose sample to increase by only 15% and a mere 6% for the initially dense sample. Nevertheless, even these smaller increases in relative density are much more effective, in comparison to that for tailings, in increasing its resistance to liquefaction because of the steepness of relationships in Figure 5.

The relationships between confining pressure and cyclic stress ratio causing liquefaction at various initial densities are shown in Figure 7. For confining pressures of up to about 1200 kPa and initial relative densities up to about 61%, the cyclic loading resistance increases with confining pressure as the positive influence of densification exceeds the negative effects of increase in confining pressure. At initial relative densities higher than about 61%, the cyclic loading resistance generally decreases with increasing confining pressure because of smaller increase due to densification but much larger drop due to increasing confining pressure. Furthermore, initial densification is beneficial in increasing resistance to liquefaction over a much broader range of confining pressure because of the much larger spread of the resistance curves in Figure 7. Relatively larger benefits in resistance due to initial densification are still associated with low range of confining pressures.

Effect of Particle Angularity and Confining Pressure on Liquefaction Resistance

The two sands used in the study had identical mineral composition and gradation. Therefore, the difference in their response to cyclic loading leading to liquefaction can be attributed solely to the differences in angularity of their particles. As described previously, tailings sand used represented one end of spectrum of a very angular sand whereas Ottawa sand represented the other end of spectrum, a well rounded sand.

It has been discussed previously using results in Figure 2 and 5 that increasing confining pressure results in decreasing resistance to liquefaction regardless of the particle angularity of the sand. There seems to be a certain upper limit of relative density for both angular and tailings sand below which the resistance to liquefation seems to be unaffected by the magnitude of confining pressure, provided such relative densities are accessible to the sand under the confining pressure under consideration. For relative densities higher than this value, the decrease in resistance to liquefaction with confining pressure is dependent on both particle angularity and the level of relative density at which the effect of confining pressure is considered. Effects of particle angularity and confining pressure can not, therefore, be isolated in assessing resistance to liquefaction.

Figure 8 shows a direct comparison of resistance to liquefaction of angular and rounded sand at low (200 kPa) and high (2500 kPa) confining pressures. It may be noted that at low confining pressure, the angular sand is more resistant to liquefation over the entire range of relative densities considered. Percentage increase in resistance due to particle angularity is much larger at low relative densities in comparison to that at higher relative densities. Under high confining pressure, the two resistance curves cross each other. Under high confining pressures, relative densities less than about 60% were not accessible to both angular and rounded sand. Hence, comparison of liquefation resistance can only span relative densities larger than 60%. It may be noted that for relative densities under about 70% angular sand is more resistant to liquefaction that the rounded sand. However, for relative densities greater than 70%, rounded sand is more resistant. Thus, the resistance of angular sand can either be larger or smaller than that of the rounded counterpart depending upon the level of confining pressure and the magnitude relative density at which comparison is made. It appears from the resistance curves that tailings would be susceptible to liquefaction even at relative densities approaching 100% under moderate earthquakes. Ottawa sand on the other hand is unlikely to liquefy under even the strongest shaking for relative densities in excess of about 80-85%.

Parallel cyclic loading studies on the two sands in the triaxial test show that major particle breakage is insignificant even under a confining pressure of 2500 kPa. The particle gradation curves for both Ottawa and tailings sands after testing were virtually identical to that for the untested sands, except for a small increase in fines in tailings sands only. This increase in fines, which constitutes the fraction passing #100 sieve, was of the order or 0.5% during consolidatrion and an additional increase of about 1.5% during monotonic undrained shear of samples consolidated to confining pressures of 2500 kPa. This implies, that both consolidation and shearing of angular tailings results in breakage of sharp edges of particles with no gross particle crushing under the confining pressure used. This would be expected because of the high strength of quartz mineral constituting both sands. No detectible increase in fines content was noted for tests with confining pressures less than 400 kPa. Clearly in simple shear tests also, tailings will suffer breakage of sharp edges of particles both under consolidation and cyclic shear strains.

The consequence of particle breakage during cyclic loading is analogous to increased potential compressibility, which would result in accelerated pore water pressure rise in undrained liquefaction test. The resistance to liquefaction of such a sand will then be smaller than the case if no particle breakage would occur. This phenomena may partly explain the reduced resistance of angular sand under high confining pressure (Figure 8) where breakage of sharp edges of particles is more likely.

CONCLUSIONS

Substantial decrease in resistance to liquefaction has been shown to occur with increase in confining pressure for two quartz sands of identical mineral composition and gradation but differing in particle angularity. The decrease in resistance with confining pressure increases with increase in relative density and is larger for angular than for rounded sand. Angular sand could be susceptible to liquefaction even at relative densities approaching 100% under moderate earthquakes, if the confining pressure is high. At low confining pressures angular sand is considerably more resistant to liquefaction than rounded sand over the entire range of relative densities.

A certain critical relative density level appeared to exist for both angular and rounded sands below which the resistance to liquefaction was unaffected by confining stress level, provided such relative density states were accessible to sand under the confining pressures considered.

ACKNOWLEDGEMENTS

The financial assistance of the Natural Science and Engineering Research Council of Canada is gratefully acknowledged. The assistance of Mr. R. Brun in the reproduction of figures and Mrs. K. Lamb for preparation of the manuscript is also gratefully acknowledged.

REFERENCES

1. Alba, P.D., Chan, C.K. and Seed, H.B., "Determination of Soil Liquefaction Characteristics by Large-Scale Laboratory Tests," Report EERC 75-14, Univ. of California, Berkeley, 1975.

2. Castro, G., and Poulos, S., "Factors Affecting Liquefaction and Cyclic Mobility," Journal of the Geotechnical Engineering Division, ASCE, Vol. 103, GT6, June, 1977, pp. 501-516.

3. Finn, W.D.L., and Vaid, Y.P., "Liquefaction Potential from Drained Constant Volume Cyclic Simple Shear Tests," Proceedings, 6th World Conference on Earthquake Engineering, 1977, Session 6, pp. 7-12.

4. Seed, H.B., "Earthquake-Resistant Design of Earth Dams," International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, 1981, St. Louis, Vol. III, pp. 1157-1173.

5. Vaid, Y.P., "Invited Discussion on Liquefaction of Cohesionless Soils," International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics, 1981, St. Louis, Vol. III, pp. 973-975.

6. Volpe, R.L., "Physical and Engienering Properties of Copper Tailings," Current Geotechnical Practice in Mine Waste Disposal, ASCE, 1979, pp. 242-260.

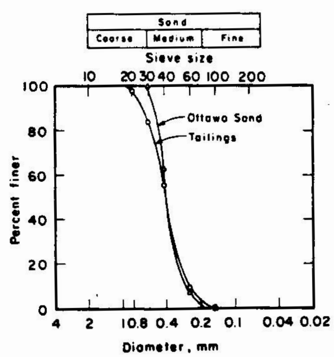

Figure 1. Grain size distribution of Ottawa and tailings sand.

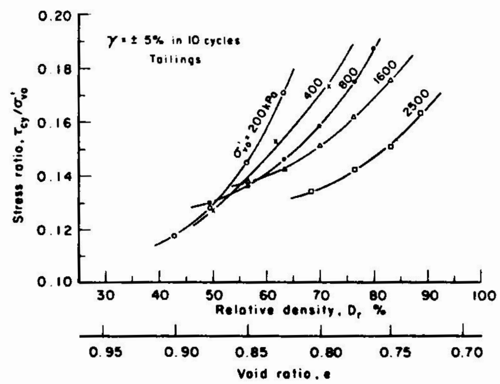

Figure 2. Resistance to liquefaction of tailings sand at various confining pressures.

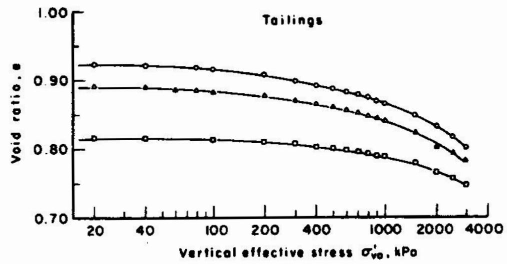

Figure 3. One-dimensional compressibility of tailings sand.

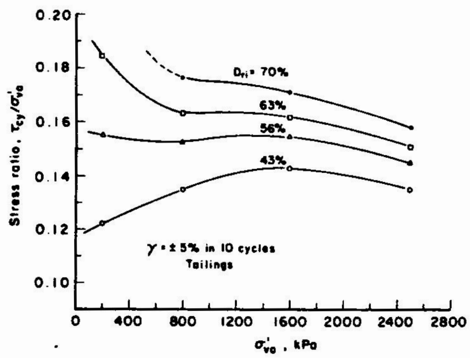

Figure 4. Effect of confining pressure on the resistance to liquefaction of tailings sand prepared at various initial relative densities.

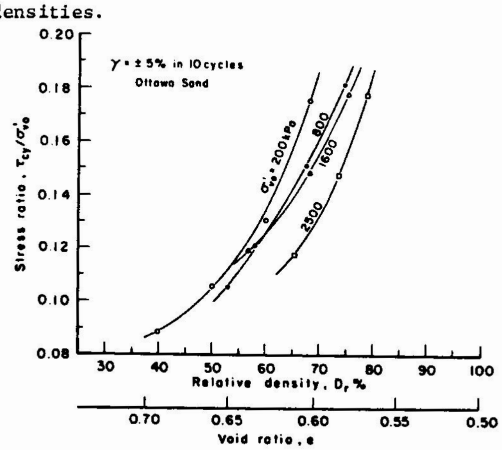

Figure 5. Resistance to liquefaction of Ottawa sand at various confining pressures.

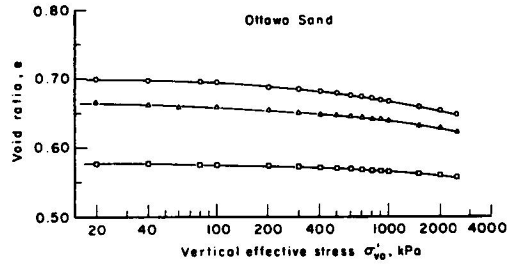

Figure 6. One-dimensional compressibility of Ottawa sand.

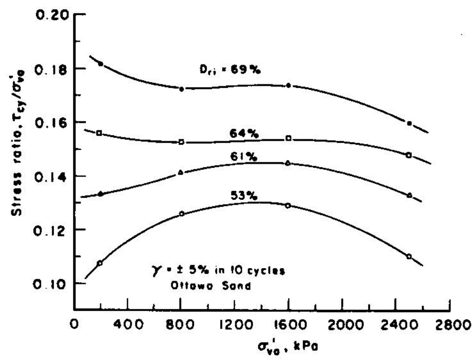

Figure 7. Effect of confining pressure on the resistance to liquefaction of Ottawa sand prepared at various initial relative densities.

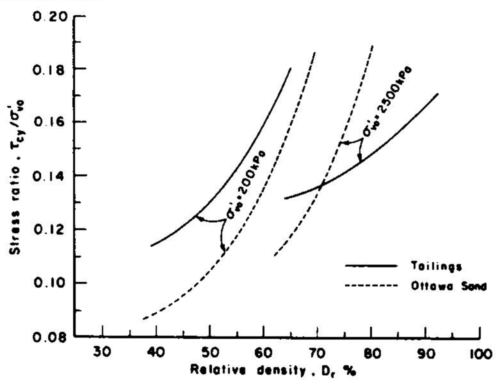

Figure 8. Comparison of resistance to liquefaction of angular and rounded sands at high and low confining pressures.