Silt content and dynamic behavior of tailing sands

Contenue de silt et comportement dynamique de déchets

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SYNOPSIS Design of tailing dams in seismic countries requires considering the problems of excessive deformation and liquefaction in order to assure environmental protection. The dynamic behavior of silty sands, used in the construction of tailing dams, is analyzed to determine the influence of silt content. Triaxial tests of sands with different silt contents are reported, showing the variation of the shear modulus with strain and of the cyclic strength with the duration of the dynamic loading events.

INTRODUCTION

Dynamic behavior of tailing sands is largely controlled by the percentage of silts which form their fine content. Thus, experience has shown that a tailing dam built with sands with a low percentage of silts is more resistant to earthquake loadings than the same structure built with sands with higher silt contents. Because tailings produced by most mining processes are mainly composed by silts, resulting from fine grinding, it is necessary to mechanically separate coarse and fine fractions in order to obtain acceptable materials for tailing dams. This separation is generally expensive and it may require centrifugal cycloning to treat the complete slurry and to produce required low silt content sands as underflow product. The cost of this process rapidly increases as the acceptable percentage of fines decreases.

Therefore, the question of how high a silt content may be considered acceptable for the stability of tailing dams is of great importance in the economy of tailing disposal systems. This paper presents a contribution to this subject through the analysis of the influence of silt in the dynamic properties of tailing sands.

SEISMIC BEHAVIOR OF TAILING DAMS

Several tailing dams have failed during earthquakes, in recent years. Heavy losses in human lives and the destruction of valuable agricultural lands have resulted from catastrophic flow slides attributed to liquefaction failures of tailing materials. The consequences of these destructive failures have prompted the adoption of strong legal restrictions to construction of tailing dams resulting in substancial increases in cost and, sometimes, in the need to design more expensive conventional earth dams to contain the tailings, instead of traditional hydraulic fill structures. This problem of tailing disposal shall become more and more complex in future years as the increase in mining operations shall require more and larger tailing dams and as the growth of population shall reduce the availability of low risk dam sites.

Frequent problems associated with seismic failures of tailing dams have been related to substancial losses of shear strength induced by cyclic loadings in loose lenses of fine silty sands. The strength reduction is a consequence of pore water pressure increase during or inmediately after occurrence of an earthquake of strong magnitude and long duration. Cyclic decrease of shear strength in a lense of silty sand may induce slope stability failures or displacements in parts of a tailing dam, which even if limited to a small volume, do cause decrease of confinement and consequent increase in liquefaction potential of adjacent soils. Thus, a progressive failure is induced which worsens itself until complete failure may occur.

Progress of a liquefaction and slope stability failure process stops when pore water pressure dissipates to the extent necessary to bring shear strenth back to values larger than acting stresses. The rate of pressure dissipation depends upon the permeability of the soils and here, again, silt content is an important variable since smaller fine contents should contribute to faster decrease of water pressures.

RESEARCH PROGRAM

To analyze the influence of silt content in the dynamic behavior of tailing sands, a laboratory testing program was performed. Tested tailing soils were obtained, from a copper mine located in Central Chile, and prepared to form compacted specimens for static and cyclic triaxial tests. These soils were fine sands, SP, and silty sands, SM, with 0.42 mm maximum diameter. X-ray microscope photographs have shown solid particles to be very irregular and angular in shape (Troncoso, 1982). Fine fraction contained up to 18 percent colloidal particles.

After complete separation of fine and coarse fractions, in 74 micron-mesh, homogeneous mixtures of sands and silts were prepared to contain 0, 5, 10, 15, 22 and 30 percent fines.

Properties of the different silty sands were measured to define index and mechanical characteristics. In particular, properties of the soil structure were determined in static triaxial tests through the analyses of stress-strain curves and shear strength parameters.

Dynamic behavior of these soils was determined by cyclic triaxial testing. First, series of tests were performed to define hysteretic loops of stress-strain and dynamic shear modulus as a function of strain. Second, shear strength and liquefaction tests were performed to monitorize pore pressure build-up and strain history, and to determine stress ratios required to induce cyclic failure as a function of duration of the loading event. Equipment used for these dynamic tests was a Seiken triaxial compression press which characteristics have been described elsewhere (Verdugo, 1983).

PROPERTIES OF SOIL STRUCTURE

Static mechanical properties of the silty sands are herein discussed on the basis of series of test results obtained with different silt contents and with same initial void ratio comparable to those representative of specimens tested in dynamic tests. Static shear strength of tested silty sands, as measured in consolidated drained triaxial tests, is due to frictional resistance between highly angular particles. Therefore, effect of silt content is well represented by results of a series of triaxial tests as shown in Fig. 1. Internal friction angle, Ø, determined by the slope of the envelope of shear strength as a function of effective stress, σ_0', decreases as silt content increases. These results, which correspond to soils compacted to same void ratio equal to 0.9, show that Ø decreases from 44° to 39° as silt content increases from 0 to 30 percent. Volumetric deformation measurements of tailing silty sands, under same confining pressure, show strong dilative tendency for these soils. Measurements recorded for 147 kPa confining pressure, indicate that, at maximum deviator stress, dilatancy of silty

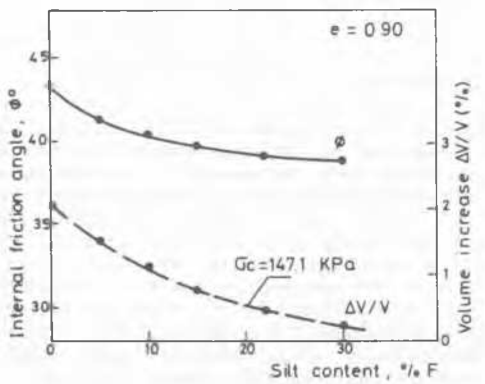

FIG. 1 SHEAR STRENGTH AND DILATANCY OF TAILING SANDS.

sands decreases, from 2.2 to 0.3 percent, as silt content increases, from 0 to 30 percent. Compressibility of silty sands, represented by initial tangent modulus, increases very significantly as fine content increases from 0 to 15 percent and further increases for 22 and 30 percent.

Critical state lines were determined in monotonic triaxial compression tests to analyze the influence of silt content on the relationships between volume change and confining pressure. Critical void ratio, as defined by Casagrande (1979), was found to range between 1.15 and 1.05, for clean tailing sand, and to decrease to a range between 1.0 and 0.8, for silty sands with 15 percent silt, for same range of confining pressures between 10 and 588 kPa. Therefore, silt content decreases the void ratio that marks the boundary between compressional and dilatational behavior. The silt content has then an unfavorable influence upon volume change characteristic under shear stresses. This fact will be reflected in the dynamic behavior of these soils as will be analyzed in next section.

CYCLIC STRENGTH AND DYNAMIC SHEAR MODULUS

The effects of dynamic loading on tailing sands have been measured in series of cyclic triaxial tests devoted to determine curves of shear modulus as function of shear strain and curves of cyclic strength as function of number of cycles. In both types of tests silt content was the main parameter. Compacted soil specimens were consolidated and tested with a combination of deviator stress, σ_d, and consolidation stress, σ_0', such that cyclic stress ratio varied between $+\sigma_d/2\sigma_0'$ and $-\sigma_d/2\sigma_0'$. Relevant test results are summarized in Figs. 2 to 4.

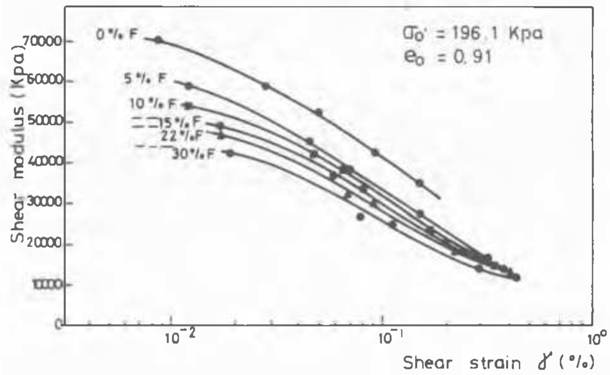

FIG. 2 SHEAR MODULUS AS A FUNCTION OF STRAIN

Curves in Fig. 2 show that shear modulus decreases in a significant amount, as shear strain increases, for all tested silty sands. In effect, under 196 kPa effective confining stress, and for 0.91 initial void ratio, modulus decrease rate is about 40 percent, as shear strain increases from 10^{-2} to 10^{-1} percent. It is also noticeable that, for any given strain value, shear modulus decreases as silt content increases. These results confirm that deformability of tailing sands increases with silt content and with magnitude of strain. Therefore, it should be expected that, when these soils become saturated, their behavior under cyclic loading should be strongly influenced by their capabilities to deform.

This assumption is indeed confirmed by results of cyclic strength and liquefaction tests. For instance, as it is observed in Fig. 3, for same pore water pressure increase, much larger axial deformations are obtained in tailing soils with greater silt content. This is so because, as shear modulus, G, is proportional to effective stress, or:

$$G = K(\sigma_0 - u_W)^{1/2} \qquad (1)$$

where: K = coefficient dependent on silt content, strain level and density
σ_0 = confining stress
u_W = pore water pressure

any increase in the pore water pressure results in a decrease in shear modulus, which in turn leads to a further increase in pore pressure. This fact, compounded with the lower permeabilities of siltier sands, results in that, if the number of repetitions of loadings is sufficiently large, liquefaction failure should occur, and it should occur in a smaller number of cycles in tailing sands with higher silt contents.

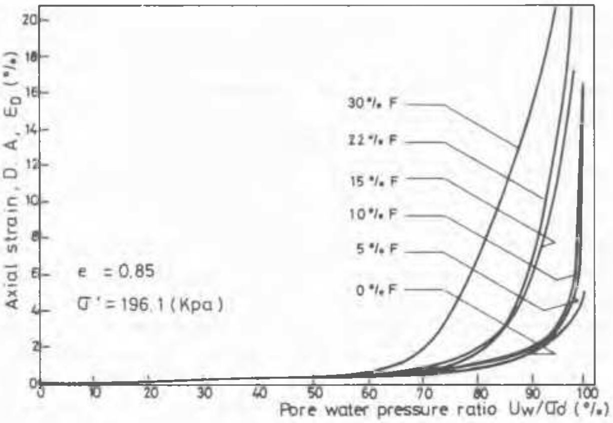

FIG. 3 STRAIN AS A FUNCTION OF PORE WATER PRESSURE INCREASE FOR TAILING SANDS WITH DIFFERENT SILT CONTENT.

In fact, noticeable differences are appreciated in the cyclic strength, or stress ratio required to reach a state of liquefaction, of tailings with different silt contents. For instance, under same initial confining stress and void ratio, curves in Fig. 4 show that cyclic strength may be larger by a factor of 2.7, if silt content is reduced from 30 to 0 percent. A moderate reduction in silt content from 30 to 15 percent may improve cyclic strength by 50 percent.

The duration of the cyclic loading event similarly affected all tested soils in the sense that significative reductions of strength occurred as number of cycles increased.

Therefore, silt content is a very important variable in cyclic strength and in cyclic deformability of tailing sands. This is so because of the mechanical characteristics of progressive decrease of strength and of liquefaction phenomena.

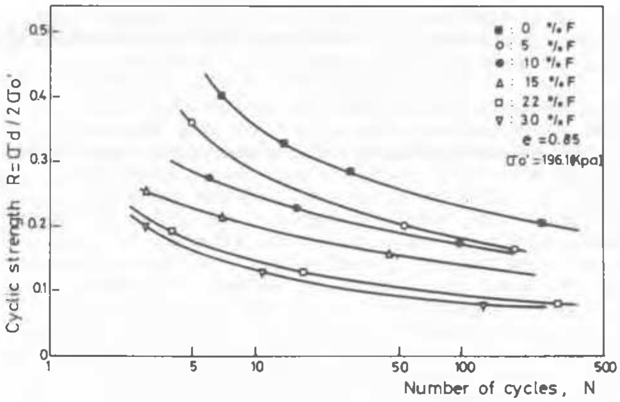

FIG. 4 CYCLIC STRENGTH OF TAILING SANDS WITH DIFFERENT SILT CONTENT.

The important influence of silt content in cyclic behavior of tailing sands may be further attributed to significative changes in the fabric and structure of these soils as particles of fine non-cohesive silts fill in the voids of otherwise stronger angular sands and, therefore, increase their tendency to fail in shear during dynamic loading events.

The effects of these changes are much more important in cyclic behavior than in static conditions, as it may be noticed from comparison of Figs. 1 and 4, because the advantages of dilatational capabilities do not have time to materialize when repeated short-period cycles of loading and low permeabilities preclude fast dissipation of the net increments in pore water pressures.

CONCLUSIONS

Tailing soils, which result from fine grinding and flotation process of rock minerals, such as copper mineral tailings, are composed of angular particles with sharp edges and irregular shapes. These particles form structures characterized by strong resistance to shear deformation because of interlocking between particles. Large energies are required to overcome this resistance and to cause relative displacements of the particles. This is demonstrated by large internal friction angles and by strong tendencies to dilate under shear.

Inclusion of silt particles, much smaller in size than sand particles, reduces the strength of resulting silty sands. This may be due to an effect of silt particles filling in irregular voids of larger sand grains and thus decreasing favorable interlocking effects. Then, angle of internal friction, tendency to dilate and moduli of compressibility are reduced as silt content is increased.

Cyclic strength of tailing sands is significantly and unfavorably affected by silt content. Thus, it has been shown that even a moderate increase in percentage of fines may cause substantial increase in the susceptability of the soils to suffer liquefaction failure. The reasons are larger compressibilities and smaller permeabilities of sands with higher silt contents.

Test results summarized in preceding sections show that larger stress ratios and greater number of repetitions of loadings are required to cause cyclic failure of clean sands as compared with silty sands. These results indicate that while a deposit of clean tailing sand should be able to stand without failure a strong earthquake, equivalent to a given acceleration level in a certain number of repetitions, a similar deposit of silty sands should fail with a much weaker event, equivalent to accelerations only one-half or one-third as large, or for a same acceleration with only a small fraction of the duration of the strong event.

The differences in the behavior of silty sands with different silt contents is important for practical purposes. Changes seem to be more noticeable in the lower range, such as between 0 and 15 percent, and 15 and 22 percent, than between 22 and 30 percent. Therefore, depending upon seismicity of an area where tailing dams are to be built, it is worthwhile to invest in necessary cycloning efforts required to lower silt content. However, since small differences may result in significantly different seismic behavior, the precise allowable percentage of silts should be determined by an adequate program of dynamic tests.

ACKNOWLEDGMENTS

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