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CYCLIC BEHAVIOR OF TAILINGS SANDS UNDER HIGH PRESSURES

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ABSTRACT

Currently, one of the major challenges in the copper mining industry is related to the design of tailings dams. The decrease of ores grade and ores reserves, under the current copper demand, leads to an increase in mining production. Therefore, reservoir capacity (height) has to increase in order to support required production levels.

Since 1970, tailings dams in Chile have been mainly designed according to the downstream method, using compacted cyclone tailings sands to conform a resistant buttress. The slimes (silts) generated during the tailings cycloning process are deposited into the basin. At present, the main tailings deposits under operation have been designed with maximum heights of about 150 m. In order to fulfill current production levels, tailing dams up to 250 m high or more need to be designed.

To reproduce the cyclic behavior of cycloned tailings sands according to the new pressure conditions expected in the field, the execution of laboratory tests under unusual high confining pressures has been requested. This article presents the results obtained from a series of cyclic triaxial tests carried out at high confining pressures using various copper tailings sands, with different fines contents and initial densities, which served to evaluate the liquefaction potential of these granular materials.

Keywords: Tailings sands, high pressures, cyclic triaxial tests, liquefaction

INTRODUCTION

The new dimensions projected for tailings dam walls to be constructed with cycloned sands (new tailings dams or rising of existing facilities) has made it necessary to investigate the mechanical behavior of tailings sands under high confining pressures. In Chile, the high seismicity and the increasing height of sand walls are very important issues to be considered in the design. In order to reproduce the behavior of tailings sands subjected to high confining pressures, similar to those expected in the field, a large laboratory test program has been carried out. Tests under high pressures are unusual in the traditional geotechnical practice, and in particular, in Chile. The results presented in this article correspond to those obtained from cyclic triaxial tests carried out at high confining pressures, using cycloned tailings sands obtained from different copper mines, presenting different fines contents and densities.

Several technical publications have dealt with the variation of the cyclic resistance of sands as a function of the confining pressure, the fines content, the fines plasticity, the density and initial fabric. Commonly, these studies considered natural sands, for the most part at low confining pressures and with low initial densities, due to they were principally interested to analyze the liquefaction potential of natural deposits. In particular, Seed & Lee (1965) using sands from the Sacramento River, demonstrated that for a same number of cycles, the cyclic resistance increases significantly as the material density increases (Figure 1).

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Verdugo (1983) tested cycloned tailings sands under a constant initial density and demonstrated that cyclic stress ratio (CSR), as a function of the number of cycles, decreases as the non-plastic fines content increases (Figure 2). In both studies, low confining pressures were imposed (σ'_3 <0.2MPa). Ishihara (1996), on the other hand, demonstrated that plasticity of the fines improves CSR values for PI (Plasticity Index) greater than 10 (Figure 3). Hosono & Yoshimine (2008) analyzed the effect of anisotropic or initial shear stress, pointing out that the CSR of sands decreases or increases according to the K_c ratio ($K_c = \sigma'_3/\sigma'_1$; Figure 4).

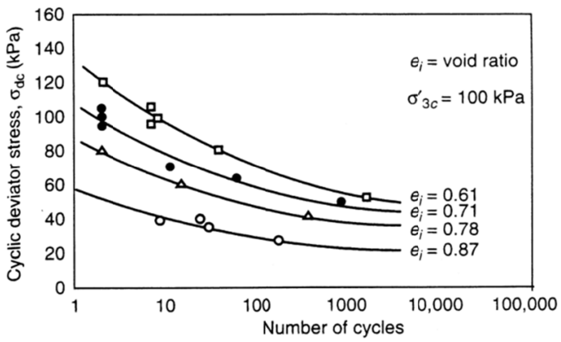

Figure 1: Variation of cyclic stress with density, for 20% of deformation. Sacramento River sands (Seed & Lee, 1965).

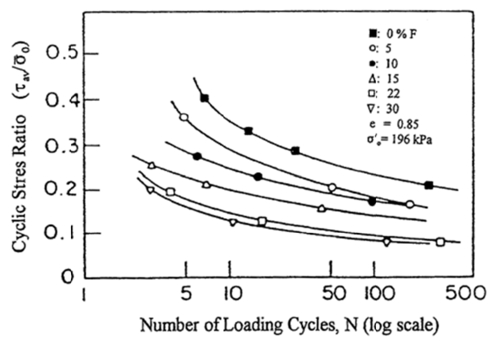

Figure 2: Variation CSR with fines content (Verdugo, 1983).

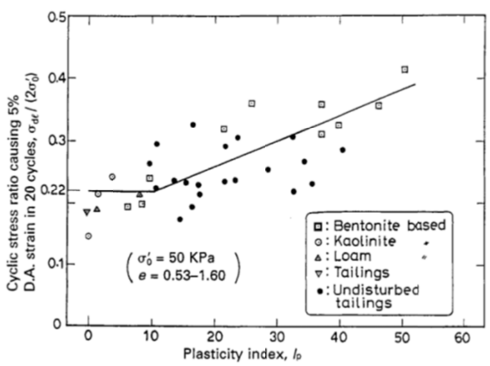

Figure 3: Variation of CSR with Plasticity Index of fines (Ishihara, 1996).

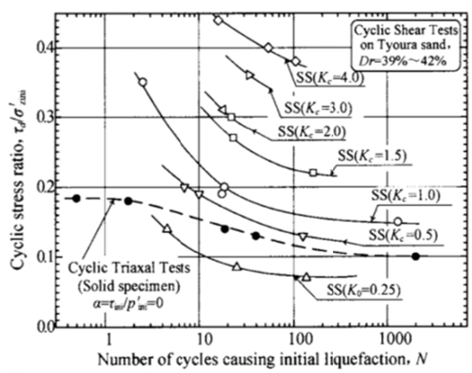

Figure 4: Variation of CSR with initial shear stress, $K_c=\sigma'_3/\sigma'_1$(Hosono&Yoshimine, 2008).

Usually, in liquefaction analysis the effect of high confining pressures is considered applying the correction factor K_σ. Diverse authors have proposed expressions and fitted curves or ranges of value for estimate this factor as shown in Figure 5. Is important to point out that mostly all the information associated to cyclic behavior of sands, corresponds to natural sands or sands which are not from tailings, tested under pressures lower than 0.8 MPa.

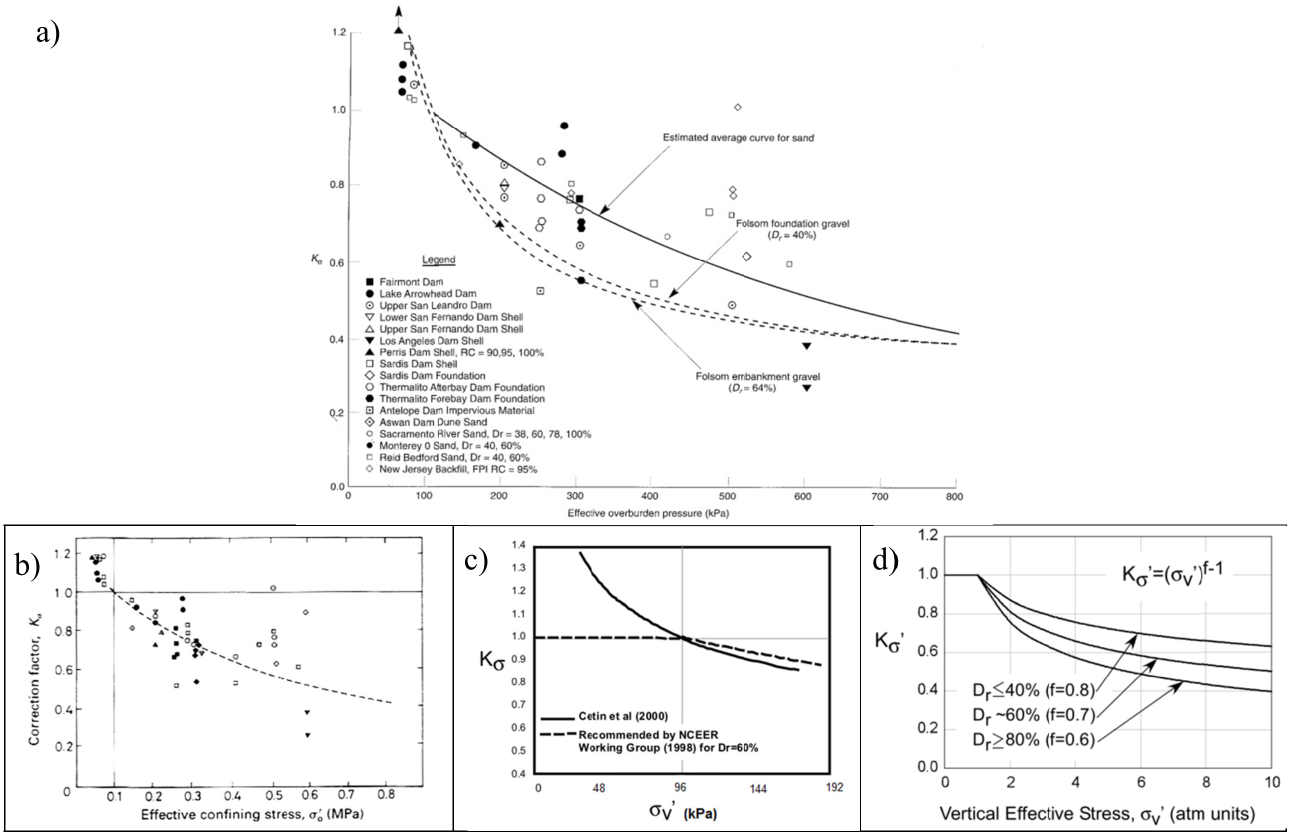

Figure 5: Recommendations to determine K_σ, according to different authors: a) Marcuson, 1990; b) Seed & Harder 1990; quoted by Kammerer et al, 2002 c) Cetin et. al., 2000; Youd, 1998; d) Seed et. al, 2003.

TESTING PROGRAM

Sands tested

Sands tested correspond to samples taken from 4 different copper mines, ranging from tailings deposits currently in operation to mining projects under study: the "Tórtolas Sands" (S1) come from the Las Tórtolas tailings deposit, which stores tailings from the Los Bronces mine, belonging to Anglo American Chile; the remaining three samples (S2 to S4), correspond to two different mines in Chile and one in Peru.

PROPERTIES OF THE TESTED SANDS

Mineralogical analysis

Mineralogical analysis were carried out in three of the four samples, two by means of a thin section description (S1 and S2) and one by X-ray diffraction (S4). The results obtained are summarized in Table 1.

Table 1. Minerals presentin samples of tailings sands

Mineral	Unit	S1	S2	S4 (*)
Quartz	%	45	45	60
Muscovite	%	-	-	15.5
Sericite	%	-	42	-
Muscovite-sericite	%	30	-	-
Albite	%	-	-	18
Iron Oxides	%	-	4	-

Mineral	Unit	S1	S2	S4 (*)
Plagioclase	%	15	-	-
Feldspar	%	-	3	-
Opaque minerals	%	5	3	-
Biotite	%	4	3	-
Kaolinite	%	-	-	2
Otherminerals	%	1	-	4.5

(*) average value from 3 samples

As shown in Table 1, the cycloned tailings sands particles contain a high percentage of quartz and a low content of clays, which implies that the major mineral constituents the particles are relatively hard. In addition, the shape of the particles is angular due to the crushing and grinding processes used to produce the tailing grain size distribution.

Index Properties

According to the U.S.C.S. all the tested sands classify as silty sands (SM) and the fines present a low Plasticity Index, lower than 7. The index properties of the samples tested are shown in Table 2.

Table 2. Index Properties of Tailings Sands Tested

USCS Clasif.	% Fines	Gs	e_{max}	e_{min}	Cc	Cu	PM		PE		Notation
							MDD (kN/m^3)	w_{opt}(%)	MDD (kN/m^3)	w_{opt}(%)	
S1 - Las Tórtolas											*Fines: particles< 0,074mm*
SM	15	2,73	1,100	0,460	1,4	3,3	16,78	14,0	15,89	18,0	*Gs: Specific weight*
SM	18	2,73	1,068	0,444	1,5	3,6	16,97	14,0	16,38	16,0	e_{max}*: Maximum void ratio*
SM	21	2,73	1,084	0,414	1,0	4,0	17,36	12,5	16,38	16,0	e_{min}*: Minimum void ratio*
S2											*Cu: Coefficient of Uniformity*
SM	15	2,75	1,310	0,647	1,2	1,7	16,68	10,0	15,30	14,0	
SM	21	2,75	1,331	0,571	1,2	1,8	16,87	11,0	15,99	18,0	*Cc: Coefficient of Curvature*
S3											*PM: Modified Proctor*
SM	12	2,70	0,942	0,525	1,2	4,2	17,46	13,5	16,48	15,5	*PE: Standard Proctor*
SM	18	2,70	0,956	0,484	3,1	12,9	18,25	11,0	16,77	14,5	w_{opt}*: Optimum moisture*
S4											*MDS: Maximum Dry Density*
SM	24	2,70	0,915	0,406	2,7	165	18,84	8,0	17,36	12,5	
SM	20	2,69	1,280	0,601	1,2	4,2	16,48	15,0	15,40	18,0	*USCS: Unified Soil Classification System*
SM	30	2,69	1,280	0,592	3,1	12,9	17,85	11,5	16,87	14,0	

According to the results of monotonic triaxial test under high confining pressures, the cohesion is lower than 10 kPa for the Tórtolas sand and null in the other three samples. The effective internal friction angle ranges between ϕ=33°-35° for Las Tórtolas sand (Campaña et. al, 2007), ϕ=33° for S2 sand, ϕ=35 to 36° for S3 sand and ϕ=33° for S4 sand (Campaña, 2010). For all samples, high confining pressures up to 3 MPa do not induce an important change in the effective internal friction angle neither in the initial grain size distribution of the different sands (Campaña, 2010).

Preparation of samples

The different sand samples were prepared considering the following steps: 1) drying of the entire sample; 2) full screening of the dried sample; 3) separation of the sample in two fractions: a fine fraction (< 0.074 mm) and coarse fraction (> 0.074 mm); 4) preparation of the sample with the desired fines content by adding the required proportion of fine material into the coarse fraction.The specimens were then compacted by layers to the desired initial density using the moist tamping method, with moisture content close to optimum (+- 2%), determined using the Standard Proctor test.

Cyclic triaxial tests

The cyclic triaxial tests were carried out on reconstituted samples with a nominal diameter of 5 cm (S1, S2 and S4) and 7 cm (S3) and nominal heights of 10 cm and 15 cm, respectively. In all cases, parameter B at the end of the saturation stage was greater than 0.95. Backpressure was applied according to the magnitude of isotropic confining pressure: 0.3 MPa for sands S1, S2 and S4 and up to 0.9 MPa for sand S3. A uniform sinusoidal cyclic load was applied with a frequency of 0.1 Hz for sand S4 and of 0.05 Hz for sands S1, S2 and S3.

Cyclic Test Results – CSR vs Number of cycles

Test results are synthesized in several graphs, differentiated by the fines content, confining pressure (σ'_3) and density achieved at the end of the consolidation stage. Figures 6 to 11 present the cyclic stress ratio (CSR) variation with regard to the number of cycles (N) required to reach liquefaction, defined as $\Delta u/\sigma'_3 \approx 1$.

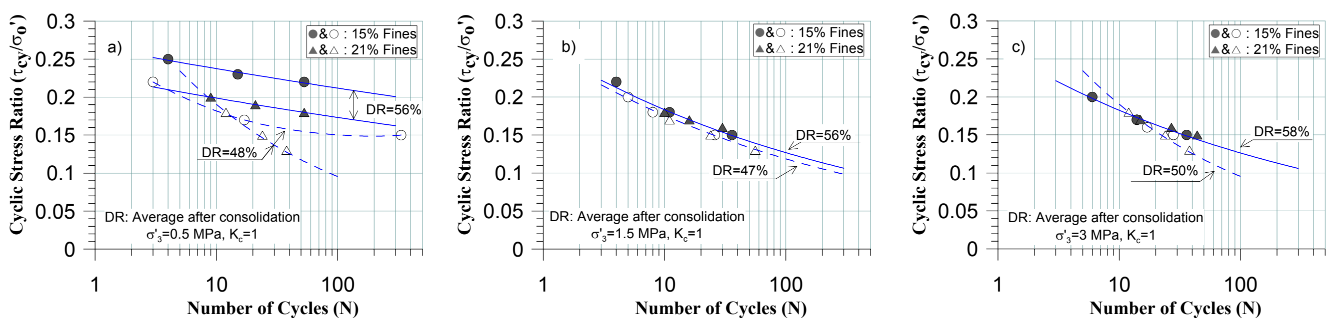

Figure 6. Sands S1, CSR as a function of the number of cycles, K_c=1

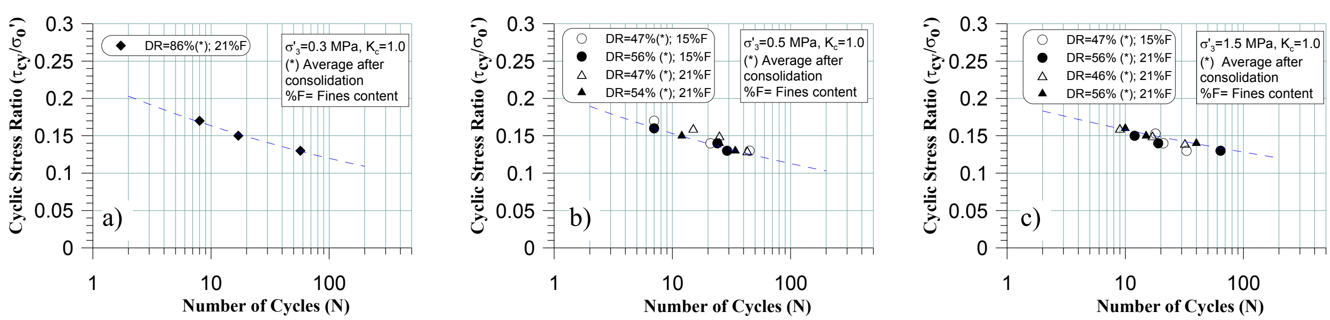

Figure 7. Sands S2, CSR as a function of the number of cycles, K_c=1

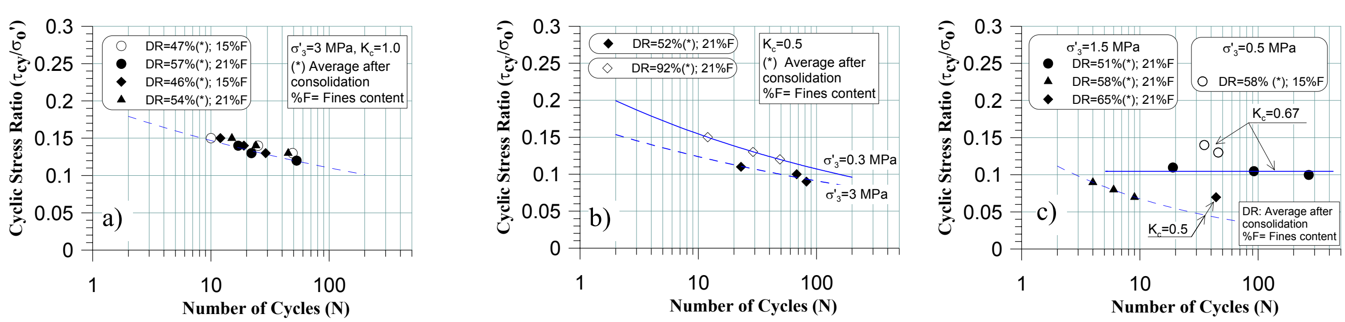

Figure 8. Sands S2, CSR as a function of the number of cycles, K_c=1, 0.5 and 0.67

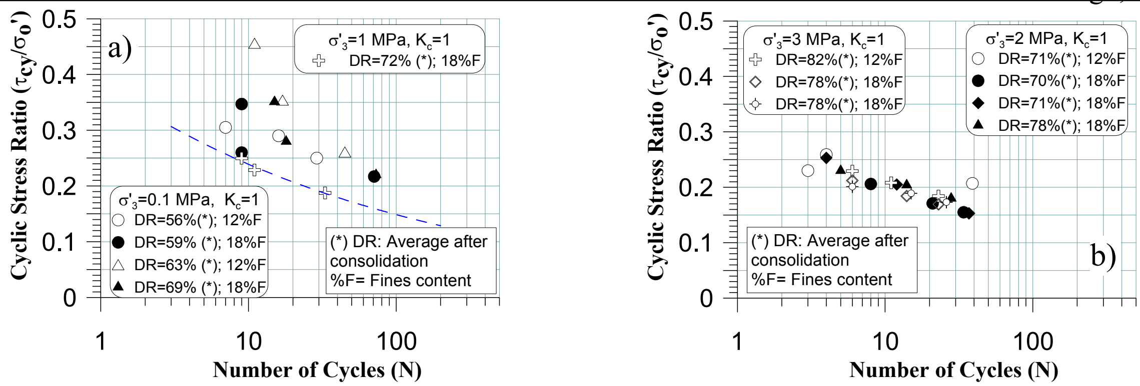

Figure 9. Sands S3, CSR as a function of the number of cycles, K_c=1

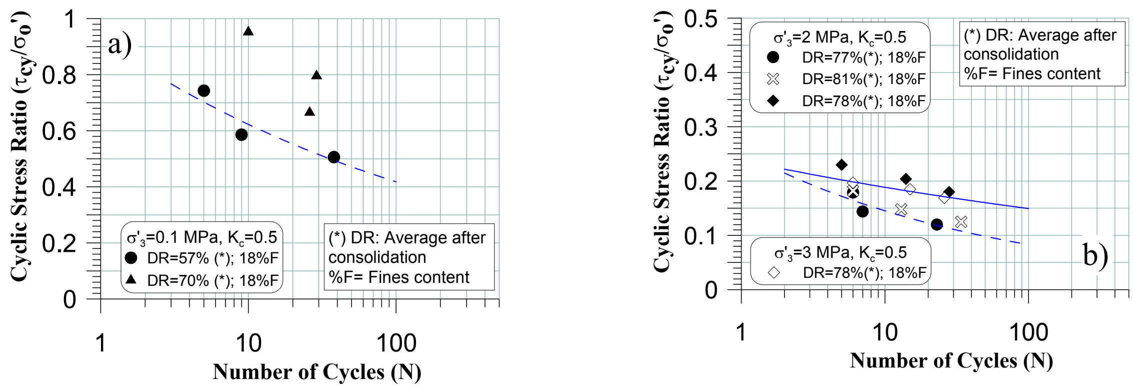

Figure 10. Sands S3, CSR as a function of the number of cycles, K_c=0.5.

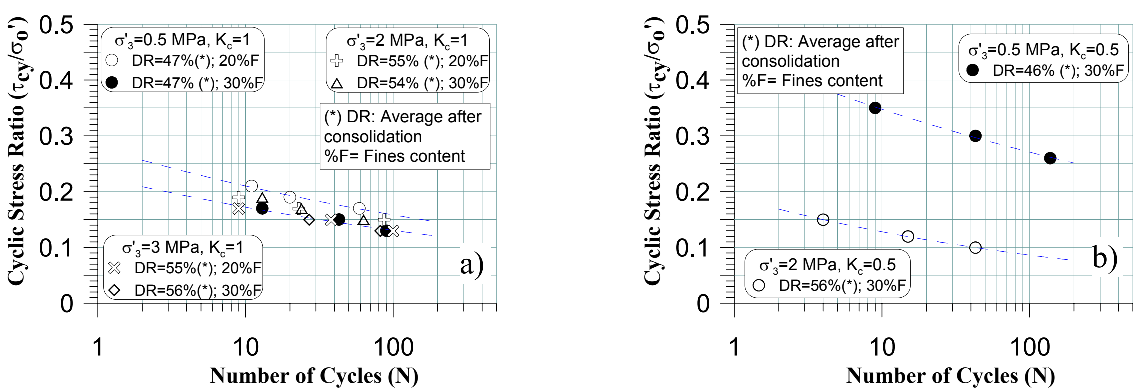

Figure 11. Sands S4, CSR as a function of the number of cycles, K_c=1 and 0.5

Cyclic Test Results – CSR vs σ´₃

Using empirical data, Seed et al (1975) proposed by means of curves equivalence between a number of uniform stress cycles and the irregular time history of an earthquake magnitude (Figure 16). Extrapolating these curves, a number of cycles (N) between N=20 and N=40 could be equivalent to the shear stress history induced by earthquakes with magnitudes M=8 and M=8½, respectively (is important to point out that Figure 16 do not show information of earthquakes magnitude greater than M=8). The design of large tailings dams in Chile usually considers earthquakes magnitudes M=8 to M=8½. Therefore, in the tests performed the CSR variation with the confining pressure (σ'_3) was determined for N=20 and N=30 cycles.

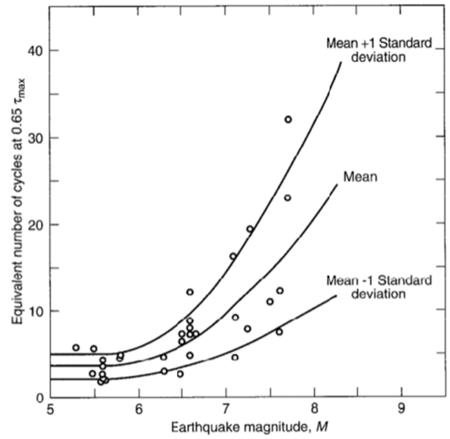

Figure 12. Equivalent numbers of cycles associate to earthquake magnitude
(Seed et al. 1975, quoted by Kramer, 1996).

Figures 13 to 16 present the cyclic stress ratio (CSR) required to induce the liquefaction of the sample for 20 cycles or 30 cycles, respectively, as a function of the initial confining pressure (σ'_3), obtained from the data reported in Figures 6 to 11.

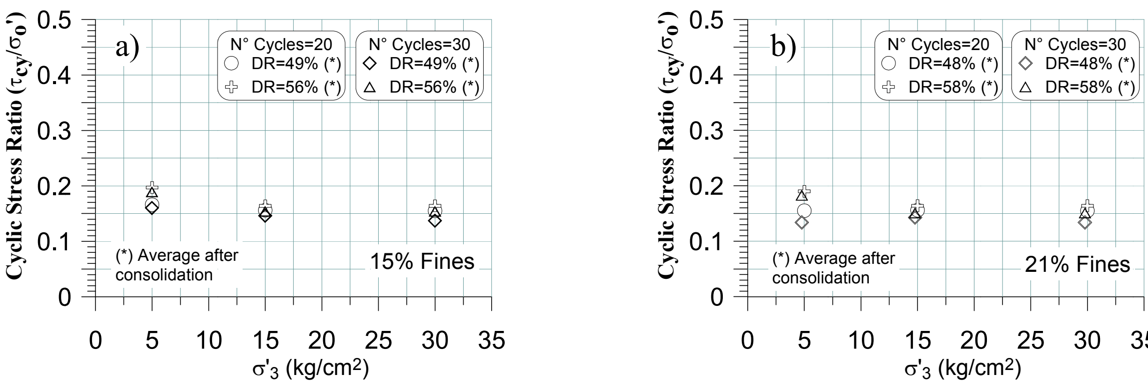

Figure 13. Sands S1, variation CSR with σ'_3, Kc=1.0

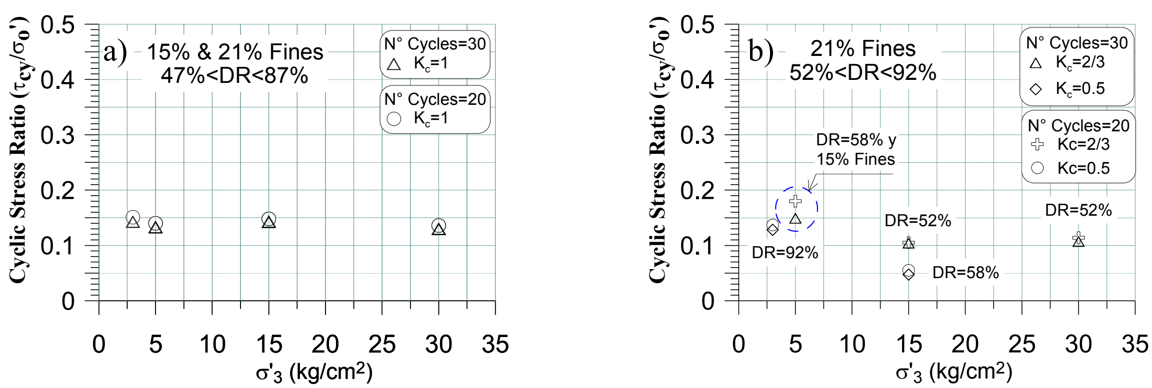

Figure 14. Sands S2, variation CSR with σ'_3, Kc=1, 0.5 and 2/3.

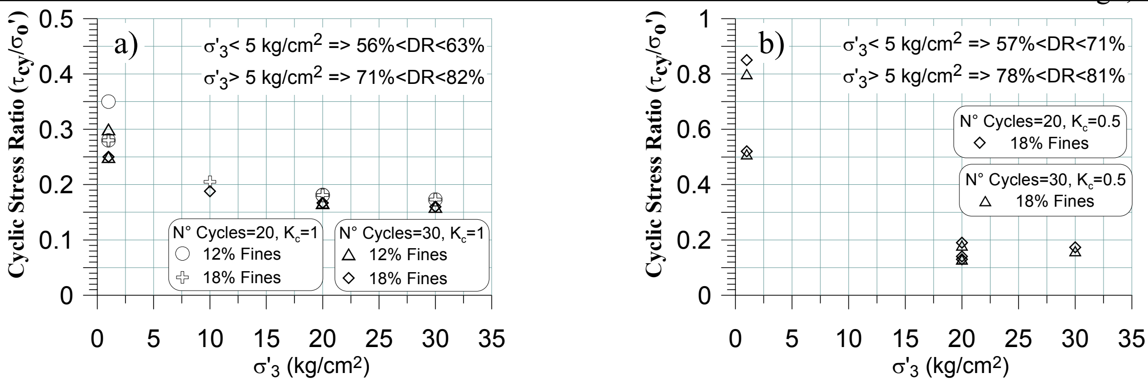

Figure 15. Sands S3, variation CSR with σ’$_3$, Kc=0.5 and 1.

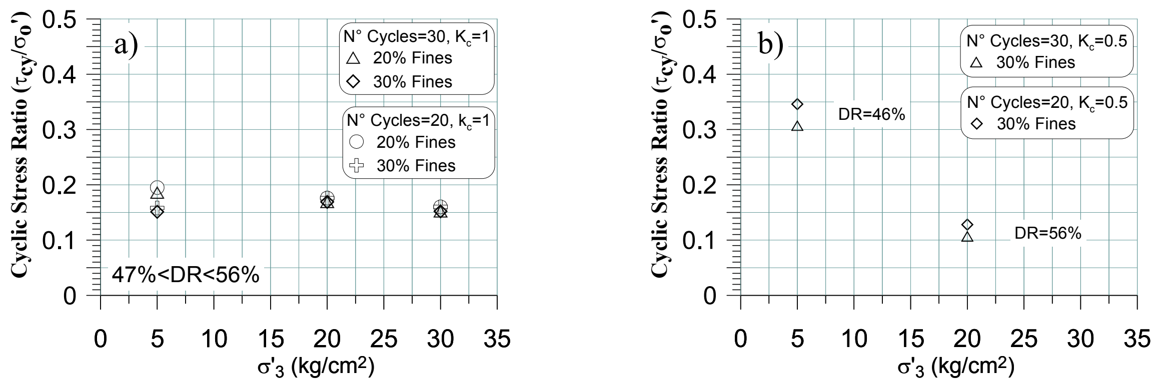

Figure 16. Sands S4, variation CSR with σ’$_3$, Kc=0.5 and 1.0

RESULTS ANALYSIS

The results from tests performed verify for lower confining pressures (σ’$_3$≤ 0.5 MPa) the tendency reported by Verdugo (1983), related to the decreasing of the required CSR to produce liquefaction when the non-plastic fines content increases. This trend is observed in Figures 6a, 9a and 11a. However, this tendency disappears for confining pressures greater than 0.5 MPa and practically a constant CSR is obtained for greater confining pressures. To reinforce this important finding, all the results obtained have been plotted separately in Figure 17a for low confining pressures (under σ’$_3$ ≤ 0.5 MPa), and in Figure 17b, for σ’$_3$ ≥ 1 MPa. In Figure 17a, a great scattering in the CSR values can be observed for the four sands tested, while a general decreasing trend of CSR values with the increasing number of cycles can be perceived. It also can be observed that results corresponding to sand S3 contribute significantly to the wide of the resulting band. Contrary, in Figure 17b where tests results carried out with confining pressures σ’$_3$≥1 MPa have been reported, no significant variations in the CSR value for the different fines contents considered were appreciated, even when the differences in these fines content were greater than 10%. In fact, the CSR values obtained range in a very narrow band, without important differences due to initial density or fines content or the cycloned tailings sands. Complementing this conclusion, Figure 18 presents the variation of the CSR values with the confining pressure for N=30 cycles, for all the tests performed on the four sands.

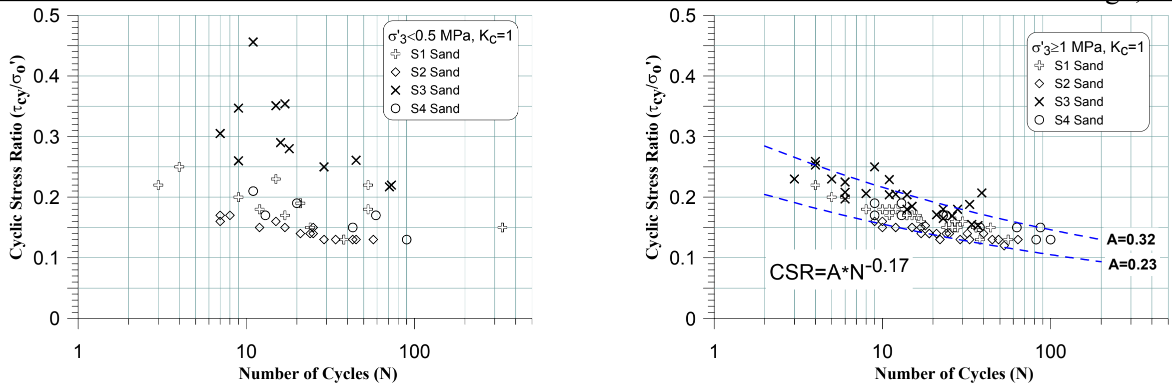

Figure 17. Summary all test results: a) for $\sigma'_3 \leq 0.5$ MPa, b) for $\sigma'_3 \geq 1$MPa, $K_c = 1.0$

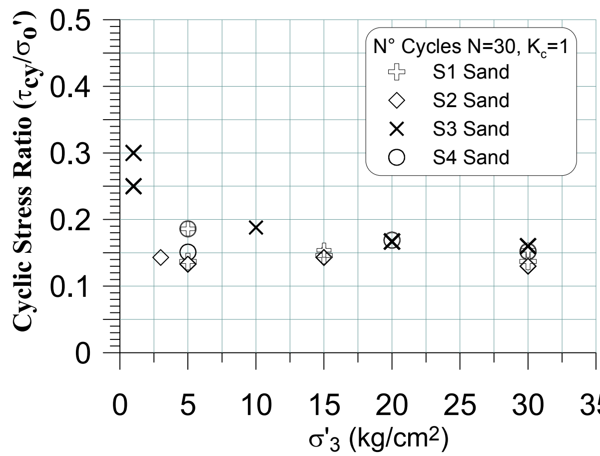

Figure 18. Summary all test results: variation of CSR vs σ'_3, for N=30

The results of tests performed with anisotropic consolidation follow, in general, the trend reported by Hosono & Yoshimine (2008), related to the decrease in the CSR when consolidation rate K_c (σ'_3/σ'_1) decreases (Figure 8c and 10b). There are, however, a few cases where the CSR increases as this rate goes up (Figure 11b). Another aspect that is important to point out is that it was not possible to observe a clear dependency between CSR, K_c and the fines content in the four sands tested. However, it was also possible to observe that for confining pressures higher than 1.5 MPa, the effect of K_c is very slightly sensible on the CSR value. In fact, for σ'_3=3 MPa, a decrease in the value of K_c does not produce a significant decrease in the CSR value, as it is possible to be observed in Figure 19a. On the other hand, it was found that the influence of the initial shear strain ratio as a function of the initial relative density (D_R) tends to disappear for D_R>70%, as shown in Figure 19b.

Another relevant aspect to point out from the results of the tests carried outin sands S2 and S4 for confining pressures greater than 0.5 MPa, are the relatively constant CSR values obtained despite the confining pressure applied (K_σ=1), the fines content, the relative density and even the initial shear stress (Figure 14a and 16a). In sands S1, the reduction in CSR did not exceed 25% as the confining pressure increased (Figure 13a) and only in sands S3 (Figure 15a) a similar reduction as the reported by other authors has been observed but in a lesser proportion (Marcuson, 1990; Seed & Hard, 1990; Cetin et al., 2000; Seed et al., 2003). Finally, a comparison of the variations recorded for K_σ in this study with recent evolution curves for this parameter (Seed et al; 2003) is presented in Figure 20.

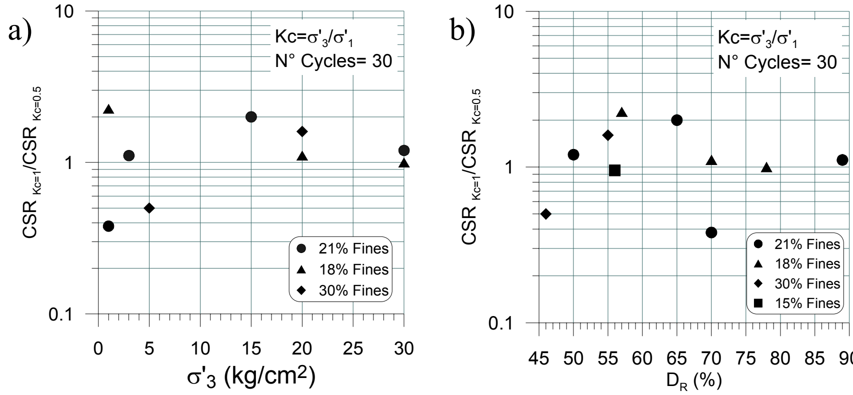

Figure 19. Variation of CSR with regard to Kc, σ'$_3$ and RD.

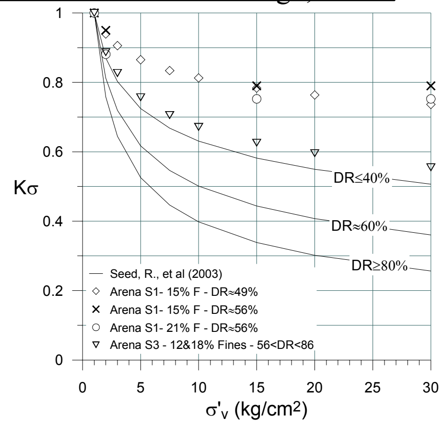

Figure 20: Variation of factor K_σ with regard to σ'$_v$.

CONCLUSIONS

The results of cyclic triaxial tests carried out on four cycloned sands samples taken from four different copper tailings, one in Peru and three in Chile have been discussed. Tests were performed on samples with low fines plasticity and fines content ranging between 12% and 30% with different degrees of densification and applying confining pressures from σ'$_3$=0.1 MPa to 3 MPa. The main conclusions obtained are summarized as following:

- For the fines content tested and confining pressures greater than 0.1 MPa, the cyclic stress ratio (CSR) to produce liquefaction are practically insensible to the fines content. This results differs from what was observed in tests performed on tailings sands at low pressures, in which this content importantly affects the required CSR value (Verdugo, 1983),
- As reported by Hosono & Yoshimine (2008), the CSR value seems to be affected by the magnitude of the initial shear stress for confining pressures lower than 1.5 MPa. Notwithstanding, for σ'$_3 \geq$ 1.5 MPa the initial shear stress does not have a sensible effect upon the CSR value,
- It was also possible to observe that, for relative densities greater than 70%, the CSR value is not affected by the magnitude of the initial shear stress,
- The effect of the high pressures upon the CSR value was practically nil in three of the four cycloned sands tested (S1, S2 and S4), and a relative common value was obtained for all the range of confining pressures applied. In the S3 cycloned sand sample, the CSR value to induce liquefaction decrease as the confining pressure increase till 1.5 MPa. For greater confining pressures, the same CSR obtained with the other three samples is reached,
- Due to these results, for cycloned tailings sands the consideration of typical factors K_σ reported in technical literature may conduce to an underestimation of CSR value.

Finally, the difference observed in the behavior of cycloned tailings sands with respect to natural sand could be explained due to the following aspects: the fines of tailing sand have a low plasticity index and correspond mainly to a "rock flour" composed by angular and hard particles (the mineralogical analysis indicated that more than 40% of sand tailings tested is quartz). According to this, it is possible to anticipate that tailing sands could have CSR values greater than expected as a lesser detriment of their properties by the effect of both high confining pressures and fines content.

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