Effects of stress state on the cyclic response of mine tailings and its impact on expanding a tailings impoundment

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ABSTRACT
In order to increase the capacity of an existing mine tailings impoundment in the Peruvian Andes, a rockfill dike which will be partially supported on different types of older tailings is being raised. Achieving adequate performance during and after possible seismic loading requires a thorough understanding of the cyclic (and post-cyclic) response of these different foundation materials over a range of consolidation stress levels and static shear conditions. In addition, one or more methods of ground improvement will be assessed to be applied to limited sections of the foundation to improve the system performance, and this is expected to play an important role in its seismic stability.

The current paper focuses on the characterization of the two primary tailings deposits. This includes the cyclic response over a range of stress conditions, the compressibility and its implications for liquefaction potential after construction of the dike, and the likely settlements to be expected after shaking. The laboratory program performed includes undrained cyclic simple shear testing under both the current and projected stress conditions after expansion, consolidation testing under conventional and post-cyclic conditions, and assessment of the steady state relationship of these materials. These results are complemented by cone penetration tests and borings from the field.

Given their current state and the seismic environment, both the coarser, tailings deposit and a finer-grained deposit are capable of large pore pressure generation and excessive shear deformations. While the response of the coarser material is much like a conventional sand, the finer-grained tailings are significantly more compressible, and this appears to alter the liquefaction potential under differing stress conditions in less predictable ways. Understanding how these tailings will respond to the elevated confining stresses and static shear stresses beneath the new dike is critical to analyzing potential designs, and insuring the safe development of this facility.

1 INTRODUCTION

In order to expand the capacity of an existing impoundment facility, the operators of a tin mine in the Andes of Perú are planning to raise the elevation of the pond by about 15m, through the raising of the secondary dike, which will need to be founded in part on the older tailings previously deposited. The engineering properties of selected portions of these older tailings will be enhanced through ground improvement methods.

Because of the relatively active seismic environment, with a design ground motion that corresponds to the maximum credible earthquake (MCE) at bedrock of approximately 0.34g, adequate response of the newly constructed system will depend on the response of these foundation soils to cyclic loading.

The stratigraphy of the foundation soils is relatively complex, including variable natural lake deposits overlying the bedrock. In addition, two distinct types of tailings have been deposited behind the original dike: one relatively coarse, and the other substantially finer-grained in composition. The laboratory testing program has provided direct information about the response of these materials under a variety of stress states, but also provides important calibration data for numerical models used to analyze a wider variety of conditions and seismic scenarios.

2 IN SITU CONDITIONS

A series of Seismic Cone Penetration Tests with pore pressure measurements (SCPTUs) were carried out in the field in order to evaluate the conditions of the foundation materials that will support the raising of the dam.

Figure 1 shows the evaluation of the tailings behavior based on the data obtained from the CPTu soundings, through the State Parameter (Ψ) which is defined as the difference between the existing soil void ratio and the critical void ratio at the current stress. Positive values of the State Parameter and even negative values higher than -0.05 indicate a contractive behavior, while negative values lower than -0.05 indicate a dilative behavior according to Jefferies & Been (2015). Contractive tailings under undrained conditions are prone to generating positive pore-water pressure during shear; however, in the case of the dilative materials, they develop negative pore pressures due to a tendency for volume to increase during shear. The state parameter was estimated using the data from the CPTu and the Robertson (2010) correlation, which was developed from the re-evaluation of case histories on a fairly wide range of soils, including tailings and other soils with significant fines contents. From Figure 1 it can be observed, that there is a predominance of contractive behavior below approximately 2 meters.

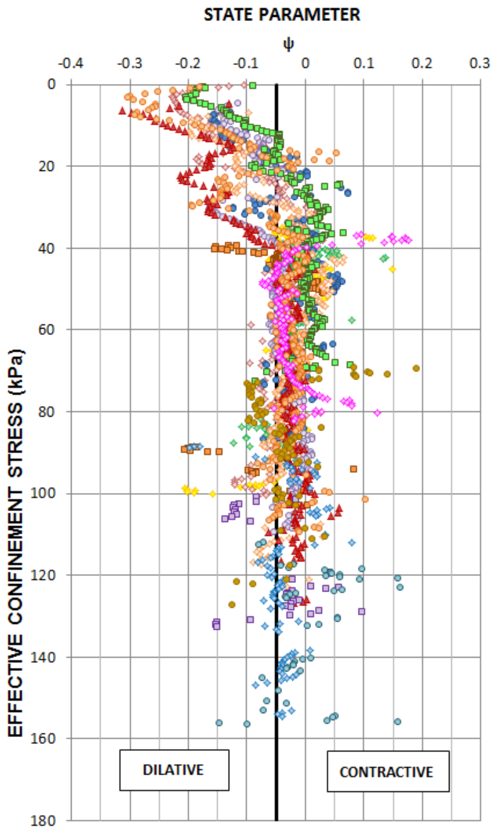

Figure 1. Estimated state parameter based on CPTu correlation

According to the data, most of the tailings (loose to medium dense) will show a contractive behavior during shear, except for some surficial points (densified due to desiccation processes) which present dilative behavior. Therefore, the results suggest that it is necessary to evaluate the potential susceptibility of the tailings to liquefaction phenomena.

3 TESTING PROGRAM

3.1 Material

The "Coarse" tailings classify as a silty sand (SM), while the "Fine" tailings classify as a low plasticity clay (CL) with plasticity index (PI) values ranging between 5 and 20, depending on location.

The fines content, defined as the amount of material that passes through the 200 sieve, of the Coarse material varies between 8% and 24%. The fines content of the Fine tailings is between 85% and 100%, as can be seen in Figure 2.

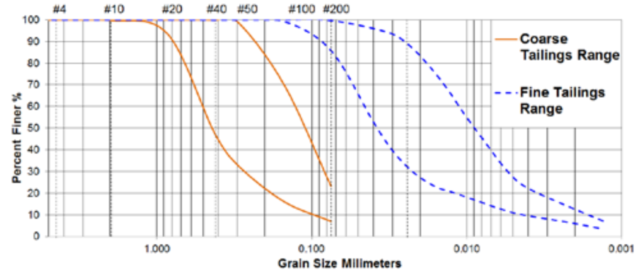

Figure 2. Grain Size ranges of Tailings

3.2 Scope

The Cyclic Simple Shear (CSS) testing program described here includes a total of 9 cyclic tests: 3 on the Coarse tailings, all of which were performed at the elevated stress levels anticipated after construction; and 6 on the Fine tailings, with some at lower stresses, some at elevated stresses, and a pair performed after applying static shear stress during consolidation, to explore the effect of an overlying structure on the cyclic and post-cyclic response. Table 1a summarizes the test numbers, the material, and the consolidation stress and density for all of the simple shear tests.

Unfortunately, undisturbed specimens of the tailings could not be successfully retrieved during the field investigation, so all of the tests were performed on specimens reconstituted from the bulk samples that were obtained. In addition to the conventional results from such cyclic tests, the vertical strains of the specimens during subsequent reconsolidation to their initial effective stress state were also recorded (and are reported in Table 1a).

Table 1a. Cyclic simple shear tests, including type, consolidation conditions, and results.

Test Name	Vertical Cons. stress kPa	Kα[1]	Cons. Dry density (g/cm3)	CSR[2]	N[3]	Vertical Recons. strain (%)
Coarse1	396	0	1.57	0.197	2.5	4.8
Coarse2	390	0	1.62	0.122	39	3.4
Coarse3	383	0	1.71	0.164	12	3.7
Fine1	391	0	1.45	0.161	11	5.3
Fine2	391	0	1.43	0.127	46	5.9
Fine3	97	0	1.35	0.149	7	5
Fine4	99	0	1.37	0.109	168	4.3
Fine5	392	0.1	1.44	0.126	28	2.5
Fine6	395	0.1	1.46	0.160	1.5	3.1

[1] Shear Stress Ratio
[2] Cyclic Shear Stress
[3] Number of Cycles to failure

In addition to these, two suites of Triaxial tests were performed on the tailings, consisting of three specimens on each of the materials, in order to evaluate the steady state behavior of these materials and help to put the specimens from the CSS testing program into context.

Testing conditions and results of triaxial testing are shown in Table 1b. Consolidation testing was also performed for this reason, since the Fine tailings in particular are more compressible than expected. All of the specimens for triaxial and consolidation testing were also reconstituted from slurry using the bulk samples retrieved from the field.

Table 1b. Triaxial tests, including type, consolidation conditions, and results.

Test Name	Tailings	Isotropic stress (kPa)	Consolidated Dry density (g/cm3)	Final Void Ratio	Final Mean Effective stress (kPa)
CUTX1	Coarse	395	1.67	0.675	230
CDTX2	Coarse	198	1.63	0.665	410
CDTX3	Coarse	49	1.56	0.765	100
CDTX4	Fine	28	1.27	1.15	55
CDTX5	Fine	198	1.36	0.93	360
CDTX6	Fine	87	1.35	1.01	150

3.3 Equipment

All of the CSS testing was performed using the UC Berkeley Bi-Directional simple shear device originally developed by Boulanger (1991). This device utilizes pneumatic pistons to control both vertical and shear loads or displacements, and includes a sealed chamber that enables application of chamber and back pressures to prepare saturated specimens and conduct truly undrained simple shear tests. The vertical loading system is very rigid to minimize any rotations which could lead to non-uniform stress states within the specimen. Three LVDTs around the perimeter of the specimen are used to monitor both changes in height, and the degree of rocking that could occur. While the device is capable of controlling shear loads and displacements in two orthogonal horizontal directions simultaneously, this feature was not utilized in the current study. Wire-reinforced membranes were utilized on all the cyclic simple shear specimens, which were nominally 10.1 cm in diameter and approximately 2.4 cm in height.

Triaxial testing was performed on specimens of 6 cm in diameter and 15 cm in height, using a conventional chamber. The tests on Coarse tailings (TX1 through TX3) were performed using the ATTS system (Chan, 1982) in the load control mode. The Fine tailings (Tests TX4 through TX6 were performed at a constant deformation rate, using a Wykeham-Farrance testing frame, with the expectation that this mode would be better considering the likelihood of strain softening at large deformations in the Fine material.

3.4 Preparation Procedures

As mentioned earlier, all of the specimens tested were reconstituted from bulk samples, by mixing the tailings with deaired water to form a slurry thin enough to preclude large voids or bubbles. The slurry was then poured into the specimen molds, already lined with the appropriate testing membrane, in a series of lifts, or layers. Simple shear specimens were prepared in 2 layers, while triaxial specimens were prepared in 5 layers.

For the Coarse tailings, this method resulted in some observable layering or segregation of the particle sizes within each layer, as would be expected in the field deposition of these materials. For the Fine tailings, such layering could not be observed visually, but presumably occurred to at least some extent. Due to the different gradations, it took much longer for each layer of the Fine tailings to stabilize prior to adding the subsequent layer. Specimens of the Fine tailings reconstituted in this way were particularly loose and compressible, and large volume changes were observed when initial effective stresses were applied prior to saturation.

The initial heights and volumes of all specimens were obtained after equilibration under a modest level of internal vacuum. The specimens were then vacuum and back-pressure saturated under a constant effective stress to achieve saturation, prior to testing.

4 TESTING AND RESULTS

4.1 Cyclic Simple Shear

Consolidation to the desired vertical effective stress was achieved by applying a combination of deviatoric load, chamber pressure and back pressure. Chamber pressure was kept sufficiently low to insure that the lateral effective stress was controlled by the K_0 response to the vertical stress within the wire-reinforced membrane. All cyclic loading was stress-controlled, consisting of essentially uniform sinusoidal cycles with amplitude characterized by the Cyclic Stress Ratio (CSR), where

$$CSR = \tau_h / \sigma'_{v,consol} \quad [1]$$

This formulation is directly comparable to that used in the field, assuming that the K0 value will be the same in level ground in the field as in the laboratory. The specimen conditions during cyclic loading were undrained (with a closed drainage valve on a saturated specimen) as well as constant height (with the vertical loading system locked to prevent displacement above the vertical load cell). In this mode of loading, loss of effective stress is reflected in both a reduction in vertical load, and the generation of positive pore pressures.

Figure 3 shows the time history of effective vertical stress, and the observed hysteretic behavior for Test KPC2. Cyclic loading was applied at a frequency of 0.1 Hz in all CSS tests, which based on the consolidation behavior was judged to result in essentially equilibrated pore pressures in the Coarse material, but was likely still too fast to allow full equilibration of pore pressures for measurement purposes in the Fine tailings.

As often occurs with CSS testing, large strains were typically observed without ever reaching a complete loss of effective stress, so failure was defined as the number of cycles (N) to reach 5% shear strain in either direction (N=39 cycles for the test in Figure 3). Tests were stopped within a few cycles of reaching failure, after which the specimen was returned to its original position under approximately the original horizontal shear stress (usually about 0), after which the drainage valve was opened and the vertical piston unlocked, thereby allowing the specimen to reconsolidate under essentially its original conditions. The vertical, one-dimensional strains measured in reconsolidation are tabulated in Table 1a.

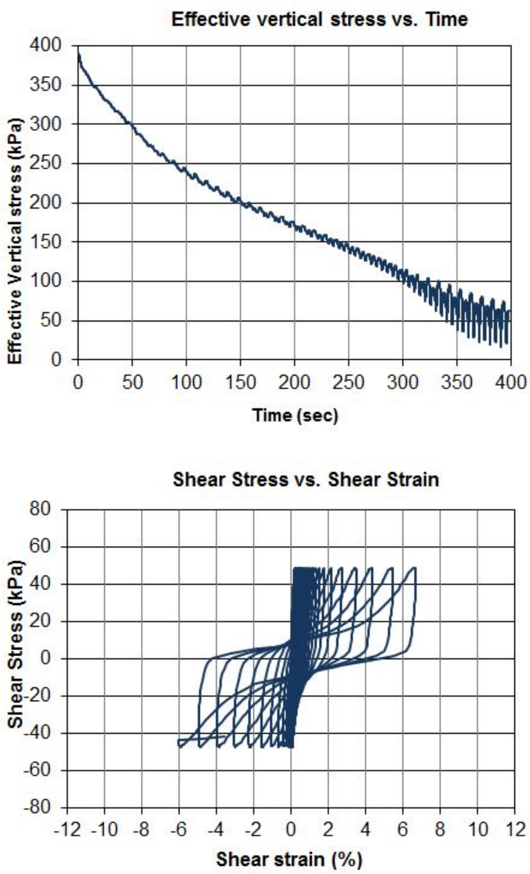

Figure 3. Time history of vertical effective stress and hysteresis for KPC2.

Figure 4 shows the liquefaction plot for all of the CSS data, being the number of cycles to failure plotted against the applied CSR. As commonly observed for tailings and other soils with considerable fines, the slopes of the curves defined by multiple tests on comparable specimens are quite flat, and the cyclic resistance for the variously prepared specimens are all modest, with none of the CSR values exceeding 0.2. It is interesting to note that while the Coarse and Fine tailings have quite different characteristics, their resistance curves on the liquefaction plot are very similar for the comparable stress condition of approximately 400 kPa.

What is quite unusual is the observation that for the Fine tailings, raising the consolidation stress level from approximately 100 kPa to approximately 400 kPa did not produce the expected reduction in normalized cyclic resistance, often characterized by a Kσ factor less than 1, but in fact appeared to slightly raise the resistance. The data in Figure 4 also illustrate that applying a static shear stress during consolidation to a Ka value of 0.1 does reduce the number of cycles to failure for the Fine tailings significantly. The significance of these trends may be clouded by the substantial scatter in the densities among specimens intended to be the same: this is due to the more variable preparation procedure, which was less reproducible than standard techniques for moist tamping or pluviating uniform sand specimens, but which was felt to more reasonably model the deposition in the field.

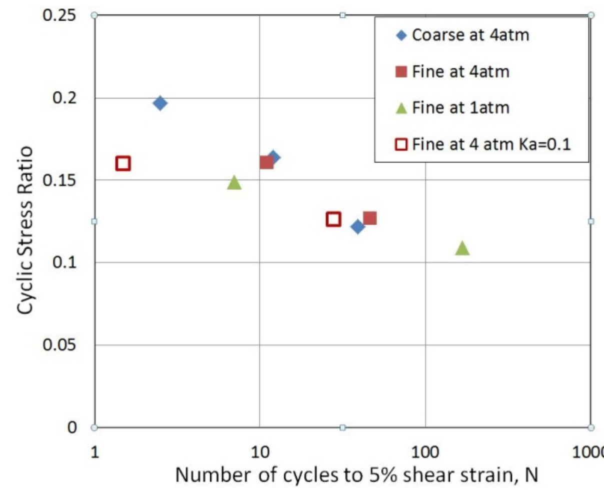

Figure 4. Summary curves of CSS testing

The most notable observation from the reconsolidation data, shown in Figure 5, is the effect of the static driving shear stress. While the specimens with $K\alpha=0.1$ were prone to developing large cyclic shear strains in a relatively small number of cycles, the presence of the shear stress during reconsolidation reduced the vertical strains to about half of the level ground values.

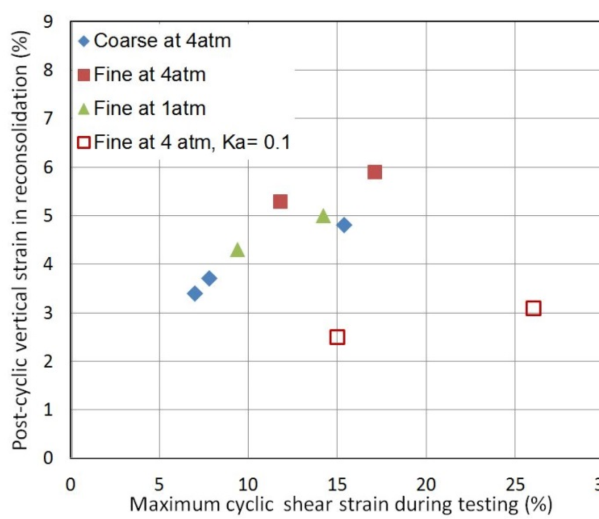

Figure 5. Reconsolidation strains after CSS testing.

4.2 Triaxial Testing

Triaxial specimens were isotropically consolidated to a range of stresses prior to shearing. A combination of undrained and drained tests were used to define the steady state line for the Coarse tailings (as suggested by Jefferies and Been, 2015) while only drained tests were performed on the Fine tailings. Loading rates were limited to values slow enough to ensure equilibrium in the shearing specimens, and volume changes or pore pressures were measured to complement the deviatoric stress and axial strains during shearing. From this data, "state paths" can be plotted showing how the specimens move during shearing in the void ratio - effective stress space, as shown in Figure 6 for the triaxial tests on the Fine tailings. Additional symbols in Figure 6 highlight the isotropically consolidated initial state of each specimen, as well as the interpreted steady state at large strains, while a consolidation curve from a companion test on another reconstituted specimen of the same Fine tailings is superimposed.

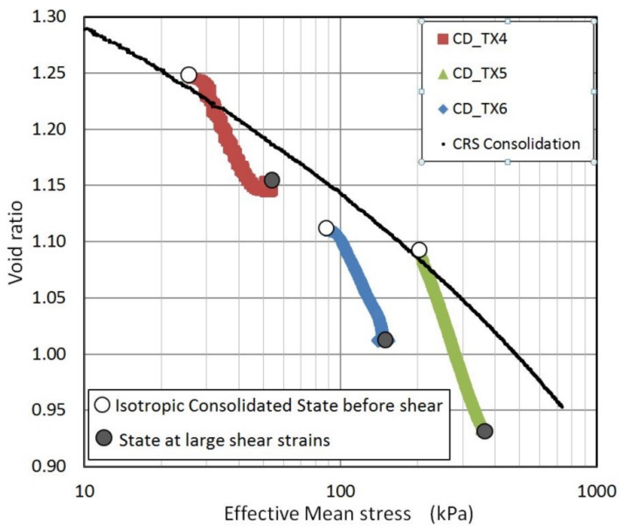

Figure 6. Compilation of the state curves for triaxial tests on Fine tailings, along with the consolidation relationship observed in CRS consolidation on the material.

Figure 6 shows that over the range of stresses examined, these tailings are quite compressible, with the consolidation curve close to steady state line at low stresses, and dropping nearly as steeply as the steady state line at higher stresses. This implies that specimens consolidated to larger stresses are only becoming modestly more contractive, particularly compared to cleaner, cohensionless materials on which the empirical models for $K\sigma$ and $K\alpha$ were developed. This highlights the value of having material specific liquefaction data at multiple stress levels.

5 USE OF THE DATA FOR CALIBRATION OF CONSTITUTIVE MODELS

Based on the results from the laboratory tests and field tests the tailings were considered materials prone to liquefaction. Their dynamic behavior is being modeled using appropriate constitutive models (including UBCSAND) with properties calibrated from the tests described in the previous sections for both materials. Dynamic analysis for different conditions will be performed in order to assess the effectiveness of different options for foundation treatment and to define and optimize the treatment area.

6 SUMMARY AND IMPLICATIONS FOR DESIGN

The testing program described has provided information on the nature of two distinct tailings materials which will form a foundation for the new dike constructed to expand the impoundment. The cyclic data suggests that at any stress level, the unimproved tailings of either kind may experience large cyclic strains at CSRs above approximately 0.12, and that portions subjected to static shear may accumulate strains "downslope" in even fewer cycles. The triaxial and consolidation testing on the Fine tailings has shown this material to be more compressible than most "liquefiable" materials, which may be a factor in the unusual observed consolidation stress effects on the liquefaction resistance.

Calibrating the numerical models with soil specific parameters has enabled sophisticated analyses to help optimize the ground improvement program for efficiently and safely expanding this facility.

7 ACKNOWLEDGMENTS

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