Laboratory Vane Shear Testing Apparatus for Evaluating Critical State Parameters and Undrained Shear Strength of Mine Tailings

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ABSTRACT: The field vane shear test has been widely used in geotechnical practice since the 1940s because it provides the only direct measurement of in-situ undrained shear strength. However, the inherent uniqueness and variability of mine tailings deposits presents the need for laboratory vane shear testing for more detailed evaluation of mine tailings behavior. In this paper, the authors describe the development of a unique laboratory vane shear testing apparatus and the implementation of a laboratory testing program to investigate the relationship between material characterization, vane rotation rates, critical state soil mechanics properties, and the undrained shear strength for several representative samples from a tailings storage facility. Results of the laboratory vane shear testing program were then compared with existing field vane shear testing data to validate behavior and modify procedures for field vane shear testing. Furthermore, the results were used to develop site-specific correlations of yield and liquefied undrained shear strengths versus critical state soil mechanics properties for selection of input parameters for static liquefaction analyses. The correlation was also compared to back-analyzed undrained shear strength and state parameters from flow liquefaction case histories.

1 BACKGROUND

Mine tailings commonly comprise non-plastic or low plasticity solids with a very young geologic age due to recent deposition; thus, they have not experienced significant aging or weathering to develop a robust structure. And because mine tailings are often deposited hydraulically, the material comes into equilibrium in a very loose condition with a high void ratio. These combined factors create very difficult conditions for collecting truly "undisturbed" samples for laboratory shear strength testing. This is particularly significant because undrained shear strength is largely controlled by the incipient soil fabric and void ratio, which can be easily disturbed by conventional sampling methods, transportation, handling, and preparation (Viana Da Fonseca, et al., 2015). As a result, engineers tend to prefer the use of in-situ testing when characterizing mine tailings because (1) there is no need for undisturbed sampling, (2) in-situ testing more comprehensively and efficiently characterizes the deposit, and (3) results are more repeatable and reliable due to the standardization of equipment and procedures.

However, in-situ testing methods also present some limitations with respect to the control of the testing conditions, which are typically afforded a high level of control within the laboratory environment. For example, the state of stress and drainage conditions cannot be controlled or modified during in-situ testing and, in many cases, may not even be well known. This is particularly critical because the strain rate used (cone penetration rate and vane rotation rate) directly affects whether the material behaves in a drained, partially drained, or undrained manner during the test. In recognition of these limitations, the authors have performed analyses and evaluations to better understand these aspects and/or modify in-situ testing procedures to account for them, specifically with regard to mine tailings (Contreras and Harvey, 2021). Moreover, the inherent uniqueness and variability of in-situ mine tailings deposits present challenges when performing detailed evaluations for which the material itself must serve as an experimental control and not subject to changes or variability in gradation and/or plasticity.

In this regard, laboratory testing serves a valuable purpose for characterization and understanding the overall behavior of mine tailings. And in the context of critical state soil mechanics, laboratory testing provides a more controlled environment where reconstituted specimens with known index properties can be prepared to void ratios similar to those in-situ. Then the void ratios can be monitored and recorded throughout the test. Laboratory testing also allows the same specimen to be tested using various methods to develop a comprehensive understanding.

2 OBJECTIVES

In this study, the authors' primary objective was to use existing laboratory testing results (in which the critical state line parameters were determined) to develop a site-specific correlation for estimation of the yield and liquefied undrained shear strength ratios as a function of the state parameter for use in slope stability analyses of the tailings storage facility. The authors also evaluated the appropriate amount of strain (or vane rotation) to define the liquefied undrained shear strength from field vane shear testing for use in subsequent slope stability analyses. To this end, the authors developed a unique laboratory vane shear testing apparatus, which allowed for monitoring the void ratio and measuring the undrained shear strength of specimens with greater repeatability for evaluation of the mine tailings in a critical state soil mechanics framework. This paper describes, in detail, the laboratory vane shear testing apparatus, as well as the implementation and findings of the laboratory testing program.

3 LABORATORY TESTING PROGRAM

The laboratory vane shear testing described herein was performed as part of a comprehensive laboratory testing program to evaluate mine tailings within the critical state soil mechanics framework. This included index property testing, consolidation testing, triaxial compression testing, and direct simple shear testing. This paper will focus on the sample preparation, equipment, procedure, and evaluation of laboratory vane shear testing results. Detailed descriptions of the other laboratory testing components are not included herein except to provide a summary of the results applicable to an integrated assessment of the laboratory vane shear testing.

3.1 *Sample Collection*

In total, five representative samples of the mine tailings were used as part of the laboratory testing program. The same material from these original representative samples was used and reused for each test to the greatest extent possible to limit the effects of material variability on the results. Index property testing was performed throughout the laboratory testing program to ensure that no substantive changes occurred because of the wetting and drying of the material.

Most of the mine tailings used in the laboratory testing program were excavated from a subaqueous tailings delta and stored in a 200-liter barrel. Upon delivery to the laboratory, the mine tailings were thoroughly mixed with site process water until reaching the consistency of a slurry. After sedimentation, the mine tailings were subdivided into three representative samples (FT/S-1, FT/S-2, and FT/S-3) graded from finer material at the top and coarser material at the bottom. A fourth representative sample (FT/S-4), typical of the coarsest portion of the mine tailings deposit, was prepared by combining material from geotechnical boring samples. Due to losses of material with each test, the volume of one representative sample (FT/S-3) was reduced to the extent that a new representative sample was needed to complete the testing. This new representative sample (FT/S-3') was also prepared by combining material from geotechnical boring samples. Despite having very similar gradations, the representative samples (FT/S-3 and FT/S-3') exhibited differences in critical state line parameters due to minor material variability.

3.2 *Material Characterization*

Table 1 summarizes the index properties of each representative sample in terms of plasticity, clay-size fraction (less than 2 μm), specific gravity, and USGS soil classification. Table 1 also includes the critical state line parameters, λ_{10} and Γ, determined from triaxial compression tests.

Table 1. Index Properties and Critical State Line of Mine Tailings Used in Laboratory Testing Program

Sample	Liquid Limit (%)	Plastic Limit(%)	Plasticity Index (%)	Clay-Size Fraction (%)	Specific Gravity	USGS Soil Type	CSL λ_{10}	CSL Γ
FT/S-1	31	23	8	21.6	2.94	CL	0.117	1.07
FT/S-2	40	25	15	30.6	2.98	CL	0.186	1.34
FT/S-3	21	19	2	12.9	2.93	ML	0.107	1.05
FT/S-3'	22	NP	NP	14.6	2.94	ML	0.103	0.87
FT/S-4	NP	NP	NP	1.7	2.92	SM	0.064*	1.09*

* Nonlinear critical state line assumed to be linear over the stress range of interest.

Figure 1 illustrates the plasticity of the representative samples used in the laboratory testing program compared to samples of the in-situ mine tailings. Contours have been added to illustrate areas within the chart where more of the in-situ material is clustering. As shown in Figure 1, the representative samples used in the laboratory testing program cover nearly the full range of the in-situ mine tailings deposit. FT/S-1 and FT/S-2 exemplify the predominant "clay-like" portion of the mine tailings deposit. FT/S-3 and FT/S-3' represent "transitional" materials, and FT/S-4 represents the least common "sand-like" material within the mine tailings deposit.

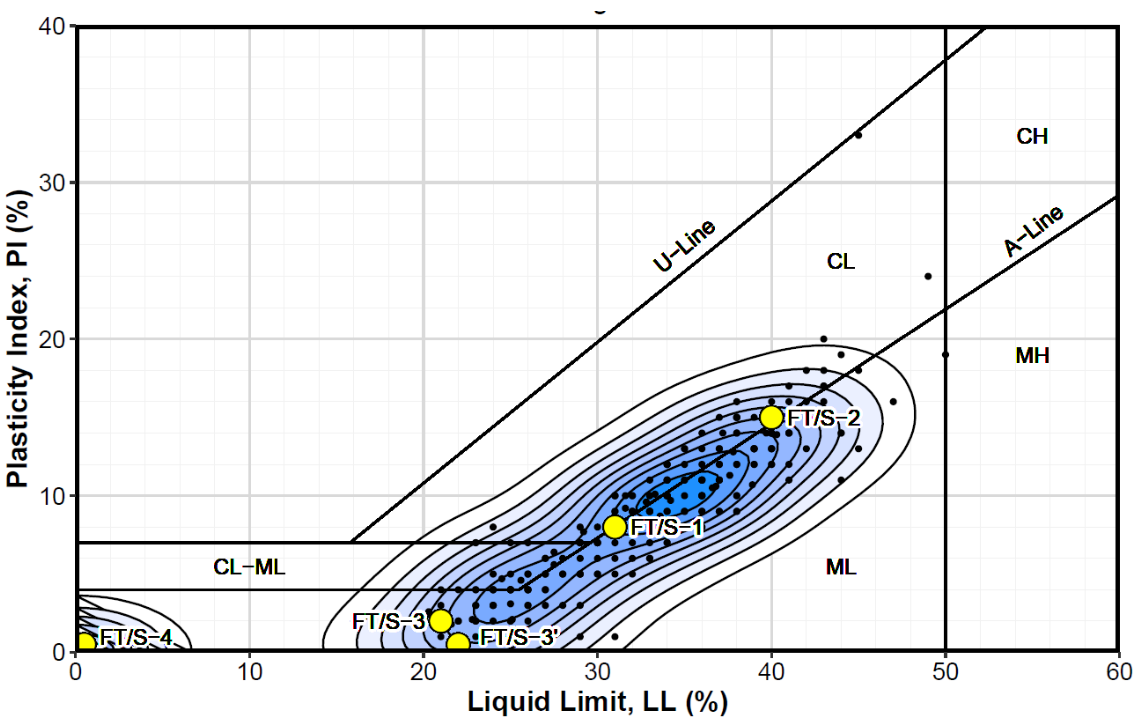

Figure 1. Comparison of Representative Samples to Mine Tailings Deposit in Terms of Plasticity

The critical state line parameters, λ_{10} and Γ, were determined from consolidated-drained and consolidated-undrained triaxial compression tests performed on reconstituted specimens prepared to a loose state using the moist-tamping method described by Ladd et al. (1977). Triaxial compression tests were conducted to large axial strains, up to 30 percent, to ensure the critical state was reached. A modular base-platen system similar to one developed by Reid and Fourie (2019) was manufactured and used for handling the specimen, such that the specimen could be frozen for accurate determination of void ratio at the end of the test. A minimum of six to eight tests were completed on each representative sample to determine their unique critical state line parameters. Data used to develop the critical state lines are shown in Contreras et al. (2022).

3.3 *Laboratory Vane Shear Testing Equipment*

Typical laboratory vane shear testing equipment allows for the preparation and shearing of only one specimen at a time without any vertical confining pressure. As such, the results from this type of equipment may be misinterpreted due to inconsistencies in the reconstituted sample preparation and/or the inability to replicate in-situ stress conditions without confinement.

For this testing program, an innovative laboratory vane shear testing apparatus was manufactured consisting of an automated load frame, rigid-wall cell with top loading platen, and digital vane shear motor and torque measurement device. The equipment was designed with multiple bulkheads to allow up to seven vane shear tests on the same reconstituted specimen at different consolidation stresses or test procedures, such as vane rotation rate. The equipment also facilitates the measurement of vertical deformation to track the void ratio. This equipment allowed for greater control of laboratory testing conditions to validate field vane shear testing procedures and measure undrained shear strengths for development of a correlation with state parameter.

Specifically, the laboratory vane shear test apparatus consisted of a stainless-steel, cylindrical container with an inside diameter of 203.2 mm, a height of 279.4 mm, and a bottom porous stone to allow drainage. An 203.2 mm diameter machined-steel rigid top platen was placed on top of the prepared reconstituted specimen within the cylindrical container. The top platen included seven removable bulkheads to allow the vane to be inserted into the specimen. Each bulkhead was 25.4 mm in diameter and arranged in a 133.35 mm diameter circular pattern with one bulkhead in the center. Bulkheads had a center-to-center spacing of 48.26 mm, minimizing the influence of adjacent vane shear tests or any wall side effects. Another rigid platen was secured to the top platen to prevent the bulkhead covers from displacing during consolidation or when not in use. Two vertical steel columns were welded to an outer ring of the top platen and connected at the top to a crossbeam. A load cell was set up between the crossbeam and load frame, Geocomp LoadTrac II, to measure the load applied to the top platen.

The digital vane shear motor and torque measurement device were specially manufactured by Geocomp Corporation for research purposes (not commercially available) and accommodate variable vane rotation rates between 0.1 and 300 deg/sec. Another steel frame was used to support the vane shear motor and torque measurement device and allow it to be repositioned over each bulkhead with minimal disturbance to the specimen. The vane used for the duration of the laboratory testing program consisted of four rectangular stainless-steel blades with a diameter of 12.7 mm, a height-to-diameter ratio of 2:1, and a blade thickness of 0.508 mm.

Photographs of the laboratory vane shear testing apparatus are shown in Figure 2.

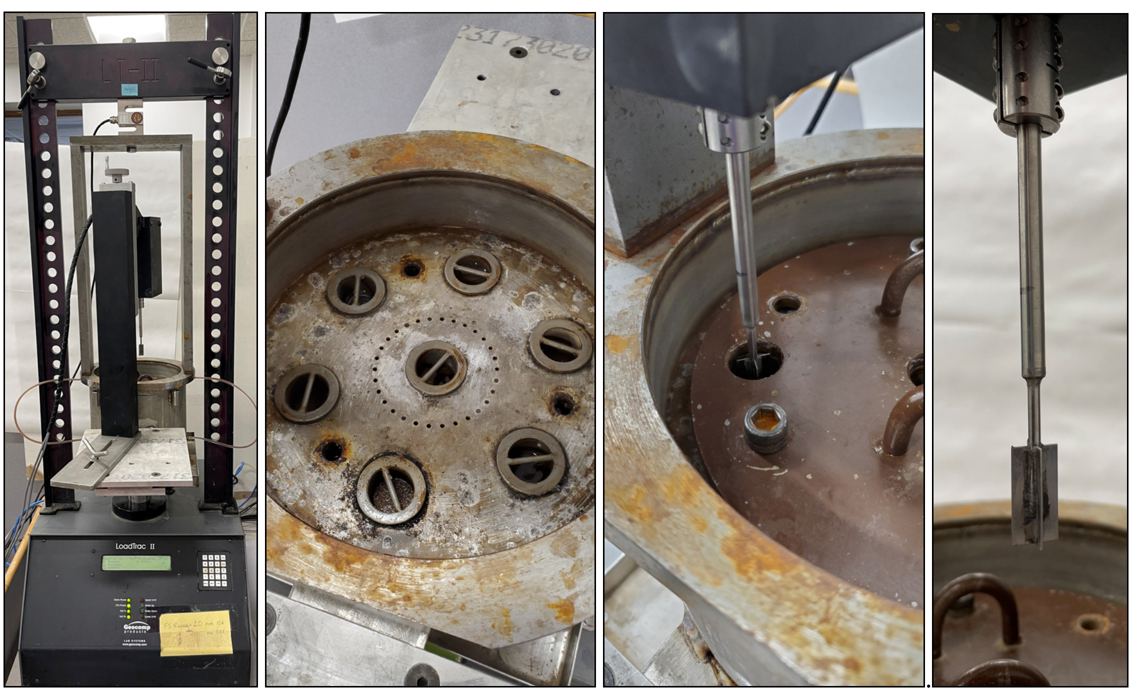

Figure 2. Photographs of Laboratory Vane Shear Testing Equipment

3.4 *Sample Preparation for Laboratory Vane Shear Testing*

Prior to laboratory vane shear testing, representative samples of mine tailings were prepared into a slurry using site process water to achieve the target initial water content and relatively high initial void ratios associated with hydraulic deposition at the tailings storage facility. Prepared slurry was then poured into the cylindrical container of the laboratory vane shear test apparatus after placing the porous stone at the bottom. After allowing for self-weight consolidation and application of very small consolidation loads using dead weights, additional mine tailings were added until the cylindrical container was full. Subsequently, the top platen was placed on the specimen, and the cylindrical container was set up into the load frame to begin consolidation.

Results from the previously noted consolidation and triaxial compression tests were used to select the initial water contents for slurry preparation such that the void ratio of each specimen was above the critical state line ($+\psi$). This allowed for a contractive response during laboratory vane shear testing. Although it was recognized that the laboratory sample preparation could not replicate the in-situ fabric/structure of the mine tailings, the slurry preparation method was judged to be a reasonable approach for this specific material and tailings storage facility.

Laboratory vane shear testing was only performed on representative samples FT/S-1, FT/S-2, and FT/S-3' as part of this laboratory testing program. As indicated previously, the available volume of FT/S-3 was too limited for the cylindrical container used for laboratory vane shear testing. FT/S-4 was not included because it was considered too granular in nature. Again, the same material was used in laboratory vane shear testing and triaxial compression testing to determine the critical state line parameters.

3.5 *Procedure for Laboratory Vane Shear Testing*

Laboratory vane shear testing begins by consolidating the specimen in load increments until the desired normal pressure is reached. After applying each load increment, the vertical deformation was monitored over time using a vertical dial gauge to identify when the specimen reached the end-of-primary consolidation and to track the void ratio, which was verified at the end of the test by measuring water content. Consolidation data was also used to determine the coefficient of consolidation, c_v, under the applied load, which was subsequently used to determine the optimal vane rotation rate necessary to maintain undrained conditions per Blight (1968).

After reaching end-of-primary consolidation at a load increment to be used for laboratory vane shear testing, the vane shear motor and torque measurement device were set up. The bulkhead was removed to allow vane insertion while maintaining the applied load on the top platen. The vane was then inserted, so the vane blades were at least 1-inch into the specimen.

Vane rotation began within 1 minute to minimize the dissipation of excess pore-water pressures and strength gain from disturbance caused by vane insertion. Initially, the vane was rotated at a specified constant rate per Blight (1968) while continuously recording the measured torque and degrees of rotation to determine the maximum torque or yield undrained shear strength. Soon after reaching the maximum torque, the vane was rotated at a much faster constant rate through a total of 3960 degrees of rotation while continuously recording the measured torque to determine the remolded torque or liquefied undrained shear strength. Throughout the test duration, the vane is maintained at a fixed elevation. A thin pool of site process water was kept on the specimen to minimize moisture loss and desiccation.

After each vane shear test was completed, the vane was retracted from the specimen, and the bulkhead was replaced. The procedure was then repeated in a different bulkhead either under the same applied load or after consolidating under a new higher applied load. Vertical deformation of the specimen was tracked throughout the duration and used to estimate the void ratio at the time of each vane shear test. Up to seven vane shear tests could be completed on each specimen.

4 LABORATORY RESULTS

The following sections discuss the laboratory vane shear testing results with an interpretation of various aspects of the data. In total, 69 laboratory vane shear tests were performed on 11 specimens. Table 2 summarizes the number of specimens prepared and the number of tests performed on each representative sample of mine tailings. Of those, 46 tests were considered to be of high enough quality to include in further data analysis and interpretation of aspects related to critical state parameters. In general, tests were excluded due to (1) suspect estimates of void ratio based on comments from laboratory technicians, (2) the vane rotation rate and time factor to failure being substantially outside the target range to maintain undrained conditions, and (3) the stress versus rotation responses appearing to be drained or otherwise abnormal.

Table 2. Summary of Laboratory Vane Shear Testing

Sample	Trial Specimens	Tests Completed	Tests Used for Data Analysis
FT/S-1	5	28	10 *
FT/S-2	2	14	14
FT/S-3	N/A	N/A	N/A
FT/S-3'	4	27	22
FT/S-4	N/A	N/A	N/A
Total	11	69	46

* Excludes tests completed as part of the initial trials to evaluate the vane rotation rate.

4.1 *Shear Stress versus Vane Rotation Relationship*

Figure 3 illustrates the results of typical laboratory vane shear tests in terms of the measured shear stress ratio versus vane rotation. Each trace on the plot represents one of the seven tests performed on that particular specimen, and each was consolidated to a different applied load increment before testing. The shear stress ratio was used to normalize the data with respect to the consolidation stress so that differences between the various tests were generally only indicative of changes in vane rotation rate and state parameter, among other minor factors.

As exemplified in Figure 3, the peak undrained shear strength ratio was generally reached between 12 and 17 degrees of rotation. Subsequently, the shear stress ratio decreased rapidly. Perturbations observed at 60 degrees of vane rotation are associated with shifting the vane rotation rate to higher speeds and not necessarily material behavior. Figure 3 shows that the most significant strength loss occurs through the first 360 degrees of vane rotation, and from 360 to 3960 degrees of vane rotation, there is continued strength loss, although minimal. It is not conclusive whether the continued strength loss was characteristic of the mine tailings or induced by some aspect of the test; however, the authors provide one hypothesis at the conclusion of this paper.

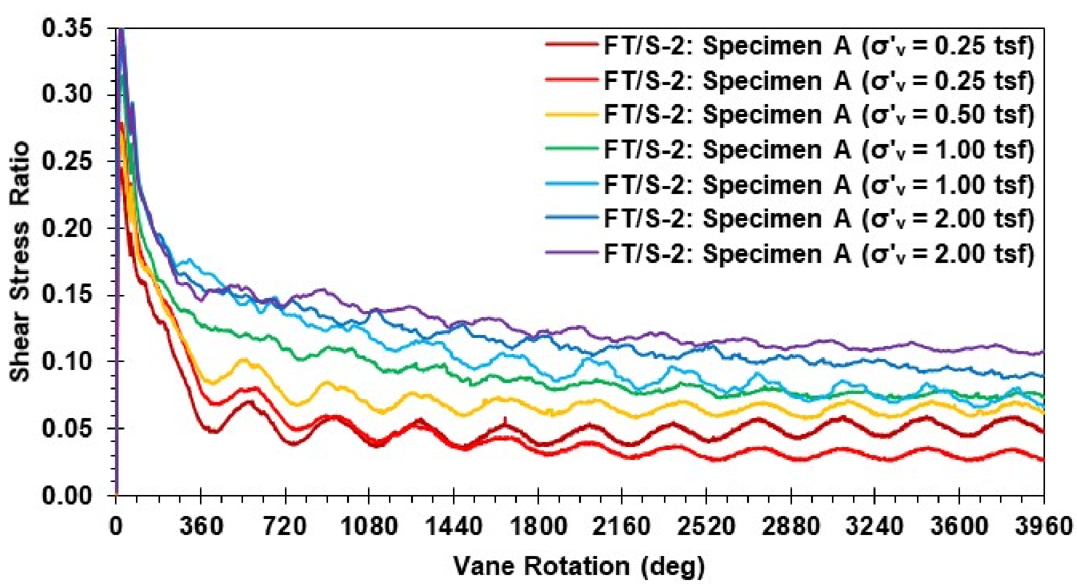

Figure 3. Typical Shear Stress Ratio Versus Vane Rotation from Laboratory Vane Shear Testing

As part of the data analysis, the shear stress ratio versus vane rotation rate relationships for each of the laboratory vane shear tests were reviewed to determine the yield (i.e., peak) undrained shear strength ratio and liquefied (i.e., remolded or residual) undrained shear strength ratios at 180, 360, and 3600 degrees of vane rotation and tabulated for subsequent evaluations.

4.2 *Vane Rotation Rate Relationship*

At the beginning of the laboratory vane shear testing program, a series of tests were performed on a specimen of FT/S-1 to understand the vane rotation rates that maintain undrained conditions at peak and through large strains at 360 and 3600 degrees of vane rotation. For these tests, the vane rotation rate varied between 0.01 and 100 deg/sec. A torsional ring shear test was also performed on FT/S-1 at a very slow rotation rate of 0.0004 deg/sec to determine the shear strength under drained conditions. These results were then supplemented with laboratory vane shear tests completed on specimens of FT/S-2 and FT/S-3' for confirmation. Only tests run with a consolidation stress of 191.5 kPa were included to minimize the effects of other variables that may be stress-dependent, such as coefficient of consolidation and state parameter.

Results of these tests are compiled in Figure 4, emphasizing the effects of vane rotation rate on measured shear stress at large strains. For reference, the shear strength ratio from the torsional ring shear test was 0.625 (ϕ' = 32 deg) at the slowest rotation rate associated with fully drained conditions. Laboratory vane shear tests show that the lowest liquefied undrained shear strength ratios were measured at vane rotation rates between 10 to 30 deg/sec, with higher values at slower rates due to partially drained conditions and at higher rates due to viscous effects.

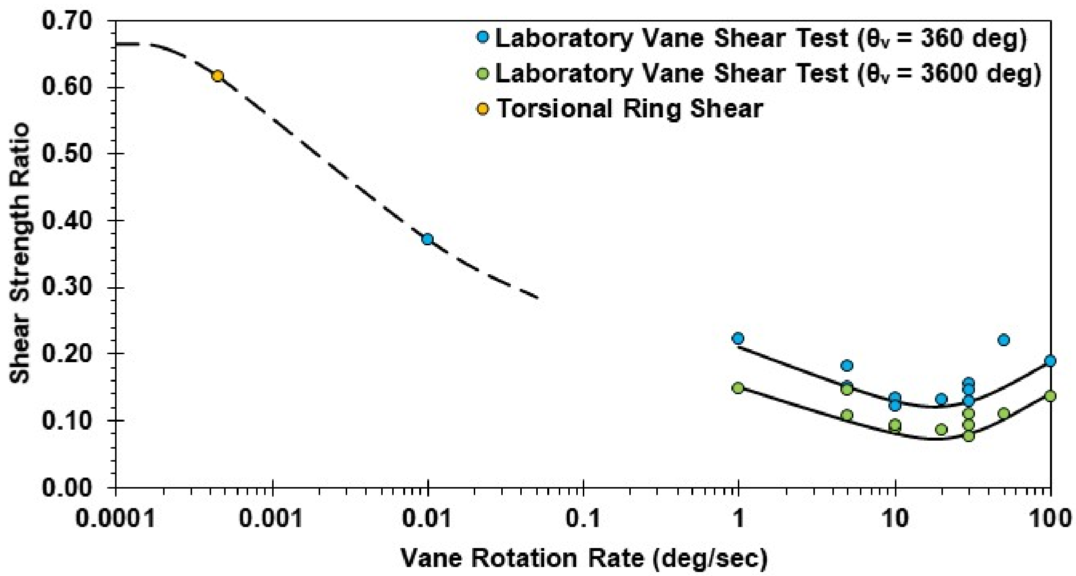

Figure 4. Shear Strength Ratio Versus Vane Rotation Rate from Laboratory Vane Shear Testing

Through assessment of data from all laboratory vane shear tests, it was determined that undrained conditions should be achieved at yielding if the vane rotation rate was such that the time factor, T, was between 0.07 and 0.1 using the Blight (1968) formulation. Furthermore, undrained conditions should be maintained at large strains (assumed to be 360 degrees) if the vane rotation rate was approximately 10 times faster than required for yield failure. These time factors and approach for selecting vane rotation rates were used throughout the laboratory testing program as targets that would most likely achieve and maintain undrained conditions; however, the time factors may have limited applicability beyond this specific study and the materials used. Furthermore, the time factors found in the laboratory setting may not necessarily apply to field vane shear testing due to differences in the drainage conditions. Thus, the time factors for yielding are higher than those reported by Blight (1968).

With that said, it should be noted that under controlled laboratory conditions, it was feasible to obtain fully undrained conditions at both yield and at large strains for each of the representative samples of mine tailings. This differs from the authors' experience with field vane shear testing, where it is difficult to achieve fully undrained conditions in non-plastic mine tailings similar to those represented by FT/S-3'. Thus, it is important that these materials be considered as potentially mobilizing an undrained shear strength even if available in-situ testing methods cannot measure that condition.

4.3 *Undrained Shear Strength Ratio versus State Parameter Relationship*

As indicated previously, the primary objective of the laboratory vane shear testing was to use critical state line parameters obtained from other laboratory testing to develop a site-specific correlation to estimate the yield and liquefied undrained shear strength ratio with respect to the state parameter. Findings of the data analysis and interpretation relative to that purpose follow.

4.3.1 *Estimation of State Parameter*

With the yield and liquefied undrained shear strength ratios tabulated directly from each laboratory vane shear test, only the state parameter remained to be determined. Because the laboratory vane shear testing equipment allowed for the measurement of vertical displacement, the void ratio of each specimen at the time of each test could be computed. These void ratios were then compared to the critical state line for the respective material to calculate the state parameter. Again, specimens were prepared with high initial water contents and void ratios to produce positive state parameters conducive to contractive behavior during laboratory vane shear testing.

Figure 5 shows a typical example of the void ratios versus vertical consolidation stress derived from measurements collected during the consolidation stage of laboratory vane shear testing on two different specimens of FT/S-2. The interpreted critical state line for FT/S-2 (converted from mean effective stress to vertical effective stress) is also shown. Consolidation curves for both specimens were not strictly parallel to the critical state line but rather quasi-parallel such that the state parameters tended to decrease as the vertical consolidation stress increased. This was also observed in specimens of FT/S-1, although consolidation data from specimens of the coarser-grained and non-plastic FT/S-3' were generally parallel to its critical state line.

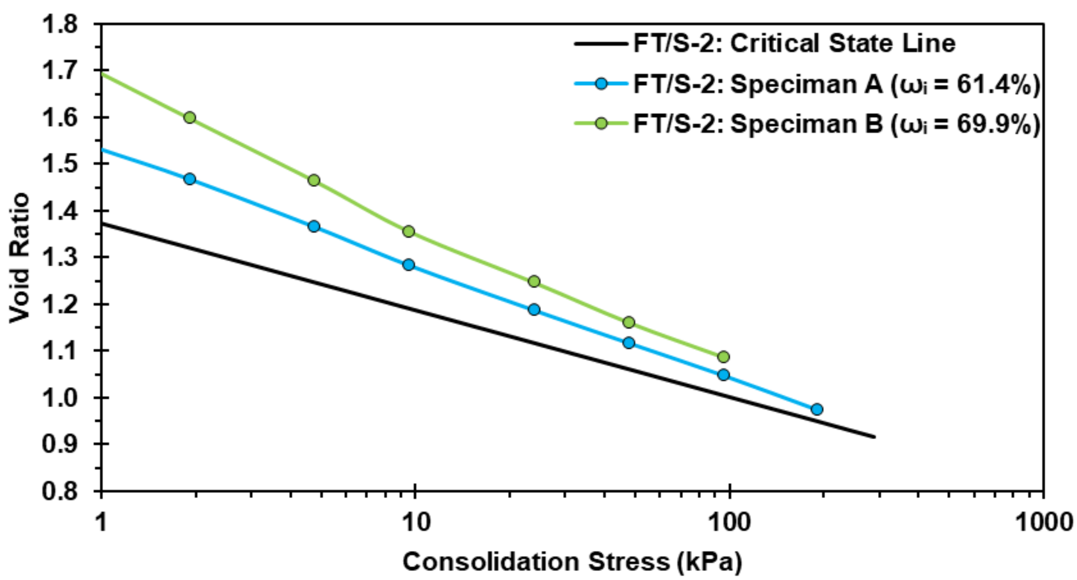

Figure 5. Typical Consolidation Data from Laboratory Vane Shear Test Compared to Critical State Line

4.3.2 *Yield Undrained Shear Strength*

Figure 6 shows that the measured yield undrained shear strength ratio from laboratory vane shear testing decreases as the estimated state parameter increases or as the initial state of the material is more contractive. Additionally, there does not appear to be any significant difference in the overall trend among FT/S-1, FT/S-2, and FT/S-3'. As such, alternate forms of the state parameter corrected by the material compressibility, ψ/λ_e, are not plotted herein for conciseness. Data excluded from analysis and interpretation of results for reasons described previously are not shown. Figure 6 also includes the best-fit line used to characterize the yield undrained shear strength relationship with state parameter based on the laboratory vane shear testing results. The best-fit line also goes through the shear strength ratio of 0.665 at a state parameter of -0.05, indicative of the drained shear strength from laboratory triaxial compression testing.

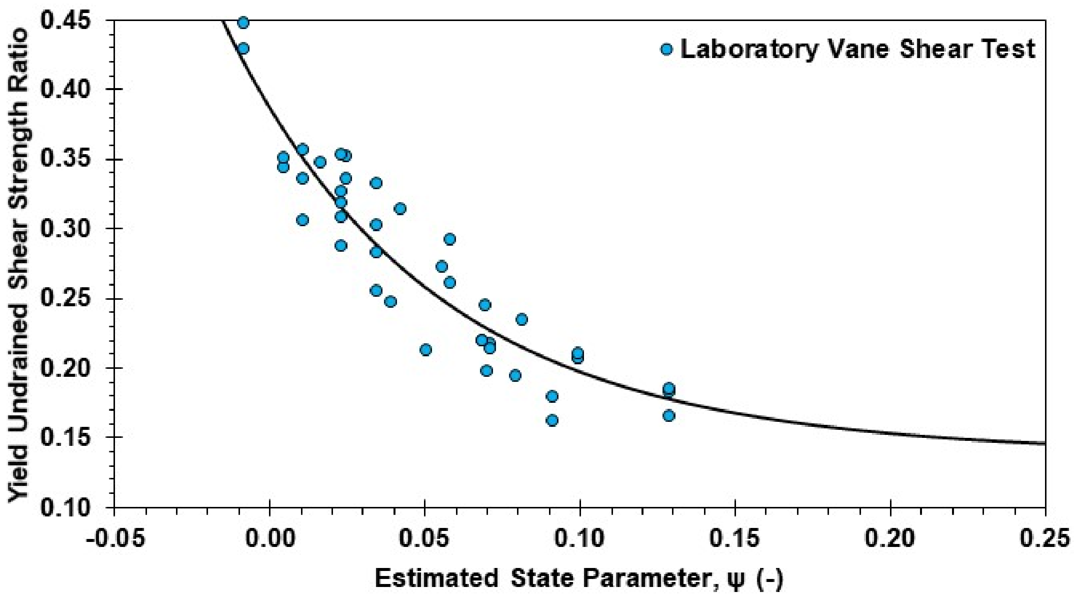

Figure 6. Yield Undrained Shear Strength Ratio Versus State Parameter

4.3.3 *Liquefied Undrained Shear Strength*

Figure 7 shows that the measured liquefied undrained shear strength ratio from laboratory vane shear testing also decreases as the estimated state parameter increases or as the initial state of the material is more contractive. Datasets defining the liquefied undrained shear strength ratio at 180, 360, and 3600 degrees of vane rotation are shown separately with different color markers and illustrate that the liquefied undrained shear strength ratio decreases with additional vane rotation. As with the yield undrained shear strength, there does not appear to be any significant difference in the overall trend among FT/S-1, FT/S-2, and FT/S-3'. Again, alternate forms of the state parameter corrected by the material compressibility, ψ/λ_e, are not plotted herein. Data excluded from analysis and interpretation of results for reasons described previously are not shown. Figure 7 includes best-fit lines to characterize the relationship between liquefied undrained shear strength at 180, 360, and 3600 degrees of vane rotation and state parameter based on the laboratory vane shear testing results. Each best-fit line goes through a shear strength ratio of 0.665 at a state parameter of -0.05, indicative of the drained shear strength.

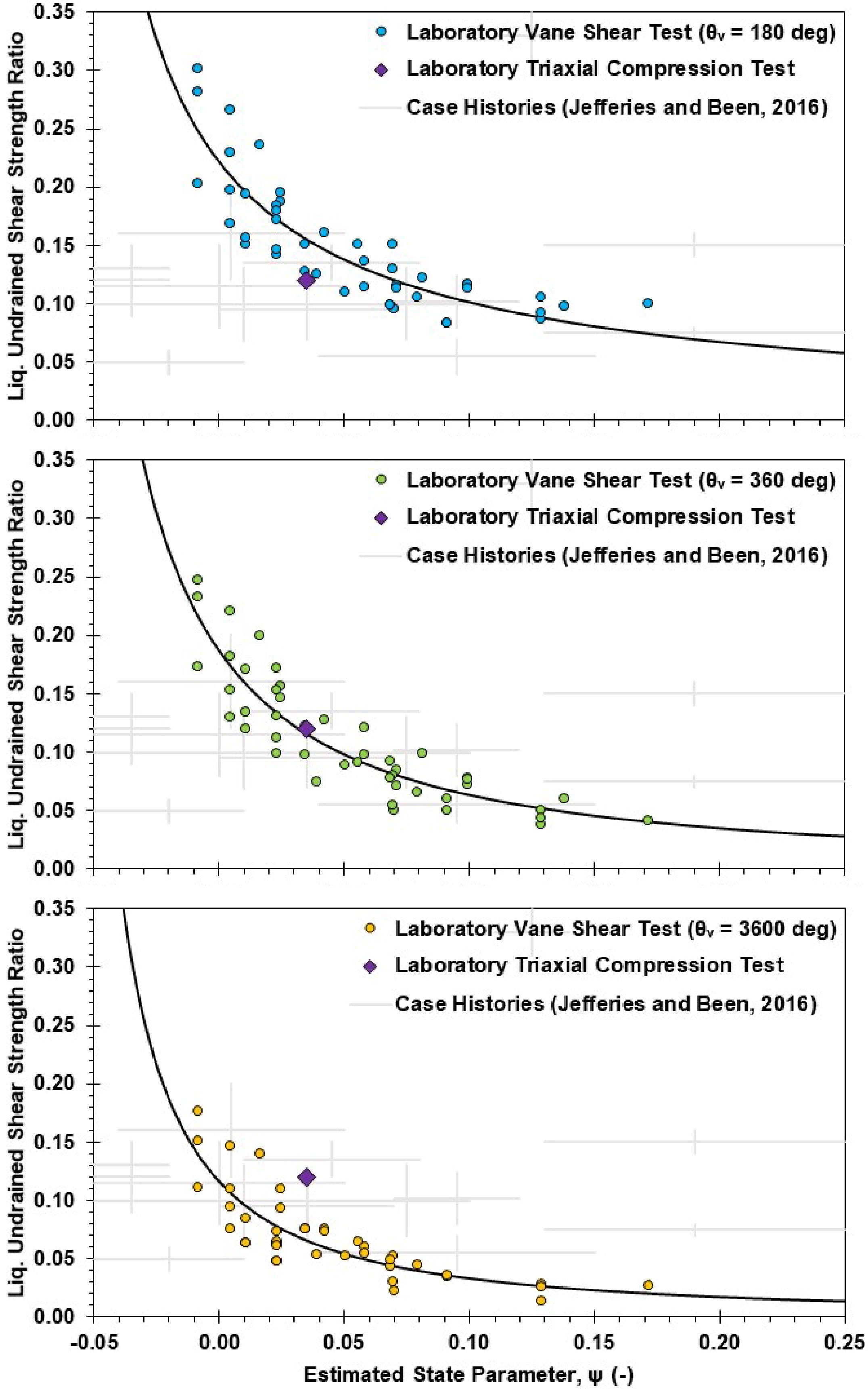

Figure 7. Liquefied Undrained Shear Strength Ratio Versus State Parameter

5 CONCLUSIONS

The results of the laboratory vane shear testing and other components of the laboratory testing program, including the site-specific correlations of yield and liquefied undrained shear strength ratios versus state parameter, can be considered comprehensive and applicable to mine tailings across the tailings storage facility because they are representative of a wide spectrum of gradations and plasticity. As such, the authors have proposed integrating these site-specific correlations as a component in the procedure for determining the liquefied undrained shear strength ratio of the mine tailings for slope stability and post-liquefaction deformation analyses. If the in-situ state parameter is known, then both the yield and liquefied undrained shear strength ratios can be estimated. Alternatively, if the yield undrained shear strength ratio is known, then the characteristic state parameter and liquefied undrained shear strength ratio can be estimated.

However, the laboratory vane shear testing results suggest significant strength loss after yielding within the initial 360 degrees of vane rotation and then continued but minimal strength loss through 3960 degrees of vane rotation. This behavior complicates the selection of the vane rotation at which to define the liquefied undrained shear strength. To assess whether vane rotation to 180, 360, or 3600 degrees should be used for defining the liquefied undrained shear strength, the authors compared the laboratory vane shear testing results with consolidated-undrained triaxial compression testing results and case histories of actual flow liquefaction failures.

5.1 *Comparison with Triaxial Compression Testing Results*

As part of the overall laboratory testing program, one specimen of FT/S-1 exhibited contractive response under consolidated-undrained triaxial compression testing to the extent that the liquefied undrained shear strength could be measured. The measured liquefied undrained shear strength ratio for this specimen was 0.12 at a state parameter of approximately 0.03 to 0.04. Figure 7 shows this triaxial compression testing result (denoted with a diamond shape marker) relative to the laboratory vane shear testing data and best-fit lines. Upon review, the triaxial compression testing result is within the range of data and nearly matched the best-fit line when the liquefied undrained shear strength is defined at 360 degrees of vane rotation.

5.2 *Comparison with Case Histories of Flow Liquefaction Failures*

Jefferies and Been (2016) used available data from case histories of actual flow liquefaction failures and the theoretical framework for critical state soil mechanics to plot each of the case histories with respect to the estimated liquefied undrained shear strength ratio and the characteristic state parameter. Of the case histories reviewed by Jefferies and Been (2016), about half had estimated compressibility, λ_{10}, values within the range measured for the representative samples of mine tailings in this study. Nevertheless, all case histories are shown on Figure 7 compared to the laboratory vane shear testing results. Again, the data suggests that when the liquefied undrained shear strength is defined at 360 degrees of vane rotation, the laboratory vane shear testing results best match the case histories of actual flow liquefaction failures.

5.3 *Findings of Analysis and Interpretation*

Based on the authors' analysis and interpretation of the laboratory vane shear testing results relative to other available data, it is anticipated that the fabric/structure of the mine tailings has been essentially destroyed after 360 degrees of vane rotation and the shear deformation at that magnitude is sufficient to bring the material to its residual state. Therefore, the authors proposed to use 360 degrees of vane rotation to define the liquefied undrained shear strength for the mine tailings when using field or laboratory vane shear testing methods.

5.4 *Future Research*

While the authors are confident that the liquefied undrained shear strength can be defined at 360 degrees of vane rotation for slope stability analyses, the cause of the continued minimal strength loss past 360 degrees of vane rotation is not apparent and suggests a transformation in the nature of shearing. A cursory literature review found limited documentation of this phenomenon (Wilson et al., 2016; McConnell, 2014). However, one possible explanation is that the vane shear test was originally developed for natural clays with plasticity and a developed structure, such that shearing occurs along a thin band between the rotating cylindrical soil mass and stationary outside soil mass. In contrast, mine tailings with relatively low plasticity and less structure may form a much thicker zone of shearing and turbulent mixing. This may be similar to the hydroplaning and mixing incorporated into the back-calculation of flow liquefaction case histories (Castro et al., 1992; Olson and Stark, 2002). Studies of torsional ring shear testing by Lupini (1981) and Skempton (1985) found that soils with clay-size fractions less than 25 percent did not form well-defined shear bands and particles effectively rolled over one another (rolling shear). Whereas soils with clay-size fractions greater than 50 percent formed thin shear bands and particles tended to reorientate and slide past one another (sliding shear). Mine tailings may exhibit rolling shear given their low clay-size fraction and plasticity.

Alternatively, one could speculate that through 360 degrees of vane rotation, shearing may be controlled by geotechnical mechanisms and applicable to slope stability analyses. Whereas, at very large strains, behavior may be more associated with rheological mechanisms and applicable to post-liquefaction deformation analyses and estimates of runout distances as part of dam breach analyses. These discussion topics are only hypotheses, but these observations raise an opportunity for future research and consideration beyond the work presented herein.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the efforts of our colleagues at Soil Engineering Testing of Bloomington, Minnesota, who performed the laboratory testing program described herein. This work would not have been possible without their interest in advancing the state-of-practice and their technical support in designing and manufacturing this unique laboratory equipment.

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