

The Role of the Vane Shear Test in Mine Tailings

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ABSTRACT: The vane shear test is a widely used testing technique for determination of the undrained shear strength of soft clays. Its application in mine tailings presents several advantages but also important limitations. As a result, its use in mine tailings requires a good understanding of the principles of the test so that meaningful results can be obtained. The paper presents both the field and laboratory version of the vane shear test along with its advantages and limitations in mine tailings. The necessary modifications of the ASTM standard equipment and procedure are presented, as well as a comparison of the measured undrained shear strength from vane shear testing versus data and correlations from case histories of actual flow liquefaction failures. Finally, the applicability of the field and laboratory vane shear test are outlined with respect to various characterization metrics based on authors' experience.

1 INTRODUCTION

The field vane shear test (FVT) is the most widely used in-situ testing technique for determination of the undrained shear strength of soft clays. Originally introduced in Sweden in 1919, its use has expanded extensively worldwide after the 1940s when the primary work by Carlson (1948), Skempton (1948), and Cading et al. (1948) popularized it in Europe. The FVT is the only in-situ testing technique that allows direct measurement of the undrained shear strength, and it is commonly used as a reference shear strength in combination with the cone penetration test (CPT) to obtain more continuous shear strength profiles in soft clay deposits. Even though it was introduced as a field test, subsequent developments were made with the laboratory vane shear test (LVT), which can be used to test "undisturbed" samples and reconstituted specimens. Over the years, the FVT and LVT equipment and procedures have been standardized (e.g., ASTM D2573 and ASTM D4648, respectively).

FVT and LVT are both particularly useful in mine tailings because when the appropriate procedures are implemented, they allow for determination of the yield and liquefied undrained shear strengths used in slope stability analyses and liquefaction assessments. However, both the FVT and LVT require modifications from the ASTM standard for use in mine tailings. Among the modifications are adjustments to the wait time after vane insertion and the vane rotation rate. Several researchers (Blight (1969); Morris et al. (2000); Castro (2003)) found that the ASTM standard vane rotation rate may not be fast enough to achieve undrained conditions in mine tailings. This is due to the fact that mine tailings generally involve size reduction (e.g., crushing and grinding) and separation of the ore, which often results in drainage and compressibility attributes that differ from those of natural clays that the FVT and LVT were developed.

The paper briefly discusses the ASTM standards for FVT and LVT along with their advantages and limitations for use in mine tailings. Similarly, the applicability of the FVT and LVT in mine tailings and the necessary modifications from the ASTM standards based on the authors' experience testing a particular mine tailings are presented. Finally, the yield and liquefied

undrained shear strength ratios measured from FVT and LVT using modified equipment and procedures are compared with literature data, existing correlations, and case histories of actual flow liquefaction failures.

2 STANDARD FVT EQUIPMENT AND PROCEDURE

The FVT standard is described in detail in ASTM D2573. A variety of vane sizes and geometries are available for testing materials of different strengths. The most common vane shape is rectangular; however, the top and bottom ends of the vane can also be tapered. The vane blade thickness is typically about 2 mm, and the area ratio (i.e., the ratio of the volume of soil displaced by the vane blades upon insertion to the cylindrical volume of soil swept by the rotated vane) is less than 10 to 12 percent.

Rod friction against the surround material and/or the use of slip couplings are important factors that must be accounted for or corrected as part of the FVT, especially in very soft soils. To determine the rod friction, a test without the vane attached is performed, and the resistance generated by rod friction is recorded. The rod friction is then subtracted from the actual vane test results with the vane attached.

Per the ASTM standard, the wait time after vane insertion into the undisturbed soil generally should not exceed 5 minutes. The vane is then rotated at a constant rate by applying a measured torque to create a cylindrical failure surface within the in-situ material. The ASTM standard allows for a rotation rate of 0.1 degrees per second (6 degrees per minute) with variations between 0.05 and 0.12 degrees per second (3 and 7 degrees per minute). At this rate, failure (i.e., yield undrained shear strength) is usually reached within 1 to 5 minutes, depending on soil plasticity and coefficient of consolidation.

During the FVT, the torque required to rotate the vane (either manually or motorized) and the cumulative angle of vane rotation are measured to develop a near-continuous shear stress vs. vane rotation relationship. The most common equipment applies and measures the torque at the top of the rods. The yield undrained shear strength (S_u) is then calculated from the maximum measured torque (T_{max}) and the vane diameter (D). For rectangular vanes having a height-to-diameter ratio of 2, Equation (1), is used to calculate the yield undrained shear strength (S_u) from the FVT.

$$(S_u)_{FVT} = \frac{6 T_{max}}{7\pi D^3} \quad (1)$$

After reaching the yield (i.e., peak) undrained shear strength, the ASTM standard calls for the vane to be rapidly rotated through a minimum of 5 to 10 revolutions. Then, the remolded (i.e., post-peak) undrained shear strength is measured while rotating the vane at the standard rate of 0.1 degrees per second (6 degrees per minute), but not more than 1 minute after the remolding process. The remolded undrained shear strength is also determined using Equation (1) with the remolded measured torque ($T_{remolded}$) replacing the maximum measured torque (T_{max}). The peak and remolded FVT can be performed at regular intervals between 0.5 to 0.75 m throughout the soil deposit.

2.1 *Advantages and Disadvantages of the FVT in Mine Tailings*

Mine tailings are the waste material from mining operations, meaning that they are recent deposits of a very young geologic age, and therefore have not experienced significant aging or weathering to develop a robust soil structure. Often, mine tailings are hydraulically deposited, where the material comes into equilibrium in a very loose condition with a high in-situ void ratio. Furthermore, mine tailings generally do not experience loading other than continued mine tailings deposition and/or dam construction, resulting in the deposits being nearly normally-consolidated. Finally, mine tailings are commonly composed of non-plastic or low plasticity solids. All of these facts combined create very challenging conditions for the collection of truly “undisturbed” samples for laboratory shear strength testing. This is particularly significant because the yield undrained shear strength is largely controlled by the incipient soil fabric and in-situ void ratio,

which can be easily disturbed by conventional methods of sampling, transportation, handling, and preparation (Viana Da Fonseca et al. (2015)).

One of the primary advantages of using FVT combined with the CPT for shear strength determination is that the procedure does not require collection of undisturbed samples for laboratory testing, such that issues related to sample disturbance are eliminated. Additionally, the deposit is more comprehensively and efficiently characterized compared to laboratory testing of discrete samples because CPT produces near-continuous profiles of measurements and multiple FVT can be performed successively with depth. Thus, CPT and FVT provide a better representation of the material variability and may detect particularly strong or weak layers that may go undetected using traditional sampling methods. Finally, CPT and FVT are generally more repeatable and reliable due to the standardization of equipment and procedures.

However, in-situ testing with the FVT also presents some disadvantages or limitations with respect to the control of testing conditions, which are typically afforded a high-level of control within the laboratory environment. For example, the stress state and drainage conditions cannot be controlled or modified as part of in-situ testing, and in many cases, may not even be well known. This is particularly critical because the strain rate (i.e., cone penetration and vane rotation rates) directly affects whether that material behaves in a drained, partially drained, or undrained manner during the in-situ test, as demonstrated by Contreras and Grosser (2019, 2009).

2.2 Modifications for Using FVT in Mine Tailings

Mine tailings are comprised of the uneconomical residue left from mineral processing of the ore body, which generally involves size reduction (e.g., crushing and grinding) and separation to achieve liberation and concentration of the desired mineral. The residue then consists of material with particle sizes ranging from coarse (i.e., sand-size) to fine (i.e., silt-size and clay-size). In many instances, the mineral processing can result in a sizable portion of the mine tailings consisting of very fine clay-size materials, which may or not necessarily contain clay minerals. In this way, mine tailings fundamentally differ from natural clays, for which the FVT was originally developed, in terms of compressibility and permeability. Therefore, it can be difficult to achieve and maintain undrained conditions throughout the test if using the standard equipment and procedures in mine tailings. As a result, the authors have found that modifications from the standard, including the vane equipment, the wait time after vane insertion, and the vane rotation rate, are needed to improve data quality when performing FVT in mine tailings.

The ASTM D2573 standard does not provide strict guidelines for the equipment or procedure, but rather broad ranges of acceptable protocol. As a result, it is essential to use the best-available equipment and to develop and maintain material-specific protocol when using the FVT in mine tailings. The authors have developed a practice that uses the best-available equipment and procedures to improve data quality when assessing the undrained shear strength of mine tailings as described subsequently.

2.2.1 Wait Time After Vane Insertion

As previously indicated, the ASTM standard allows for up to 5 minutes of wait time after vane insertion until starting the test. While this is acceptable in natural clays, it is preferable in mine tailings with relatively higher permeabilities to reduce the wait time after vane insertion so that shear-induced pore water pressures resulting from vane insertion exhibit little or no dissipation and resulting shear strength gain above what exists in its in-situ condition. The authors have found that better results are obtained when vane rotation starts within one minute of vane insertion (for low plasticity, silt-sized mine tailings). Similar recommendations have been provided by Morris et al. (2000).

2.2.2 Equipment

A key component of the FVT equipment is the system applying and measuring the vane torque. Traditional systems require that the torque rods connected to the vane be manually rotated by an operator using a geared drive or directly using a torque wrench with limited control of the vane rotation rate. Torque readings are then manually collected from a calibrated spring torque measurement device, which has limited precision and resolution. Traditional systems also require

that rod friction from the surrounding materials be independently measured and subtracted from the measured vane torque.

Alternatively, for measurement of the undrained shear strength of mine tailings, the authors typically use an electronic downhole torque measurement device, whereby the drive motor and torque sensor are positioned inside a downhole equipment housing directly above the vane. The system also provides fully-digital control of the vane rotation rate and near-continuous data acquisition. This has the benefit of eliminating the need for rod friction correction, which can be of the same order of magnitude as the shear strength of mine tailings, and also providing a full shear stress vs. vane rotation relationship.

2.2.3 Procedure and Vane Rotation Rate

During FVT soundings in mine tailings, the downhole equipment housing the vane, drive motor, and torque sensor is advanced by hydraulic rams to a depth just shallower than the desired test depth. Test depths are targeted based upon data from adjacent CPT soundings specifically to be within uniform layers of the mine tailings deposit that exhibit undrained behavior during CPT advancement. The vane is then deployed from the housing to the desired test depth, and vane rotation starts within the wait time.

Following a series of field trials, the authors found that the FVT should be run with two stages at different vane rotation rates for determination of yield (i.e., peak) and remolded (i.e., post-peak) undrained shear strengths, as explained subsequently. In the first stage, the vane rotates at a specified constant rate while continuously recording torque measurements and degrees of rotation to determine the maximum torque (i.e., yield undrained shear strength). After determining the maximum torque or approximately 60 degrees of vane rotation, the vane is rapidly rotated at a faster specified constant rate through a total of 3960 degrees of vane rotation to determine the remolded torque (i.e., remolded undrained shear strength). Use of two different rates ensures that undrained conditions are achieved at the maximum shear stress and are maintained throughout the measurement of the remolded shear stresses without drainage and the associated shear strength gain. Upon completion of the test, the vane is retracted into the housing before advancing the downhole equipment housing to the next test depth.

Vane rotation rates for the first stage are determined based on the method developed by Blight (1968), which uses empirical and theoretical approaches to evaluate drainage during the test to ensure that undrained shear is occurring at failure using Equation (2).

$$T = \frac{c_v - t_f}{D^2} \quad (2)$$

In Equation (2), the time factor (T) is a function of the coefficient of consolidation (c_v), the time to failure by vane shear (t_f), and the vane diameter (D). The coefficient of consolidation (c_v) values are estimated from pore-water pressure dissipation tests performed concurrent with CPT soundings. Blight (1968) concluded that for time factors less than 0.02, the FVT could be considered fully undrained. However, the authors' field and laboratory trials have found that this time factor criteria may not be universally applicable as it is likely strongly influenced by drainage conditions, and similar observations were noted by Morris et al. (2000). The authors recommend performing multiple FVT at different vane rotation rates to determine the material-specific optimal rate for achieving undrained conditions.

Using these approaches, the authors have found that the vane rate of rotations required to ensure undrained conditions at yield are typically more than an order of magnitude faster than the ASTM standard (for low plasticity, silt-sized tailings). For example, the vane rotation rate for measurement of the yield undrained shear strength was approximately 3.0 degrees per second for a 55 mm diameter vane. Even faster rates of rotation of about 7.0 degrees per second (maximum rate of equipment used) were required for determination of the remolded undrained shear strength.

2.3 Typical FVT Result in Mine Tailings

Figure 1 shows a typical FVT result performed in mine tailings (low plasticity, silt-sized tailings) using the equipment and procedures described above in terms of the shear stress vs. vane rotation (blue line). Also included on Figure 1 is the vane rotation rate throughout the duration of the test

(red line). As can be seen, the maximum shear stress of 17.6 kPa (i.e., yield undrained shear strength) is reached at 10 degrees of vane rotation, and then the shear stress decreases rapidly. Vane rotation then momentarily pauses for less than one second at between 60 and 90 degrees of vane rotation to allow for the drive motor to adjust the vane rotation rate before continuing the test through a total of 3960 degrees. Note in Figure 1 that the momentary pause and abrupt increase in vane rotation rate causes some increase to the measured shear stresses before they continue to decrease. The rapid loss of shear stress moderates after about 360 degrees of vane rotation, although some continued shear stress loss is observed through 3960 degrees of vane rotation.

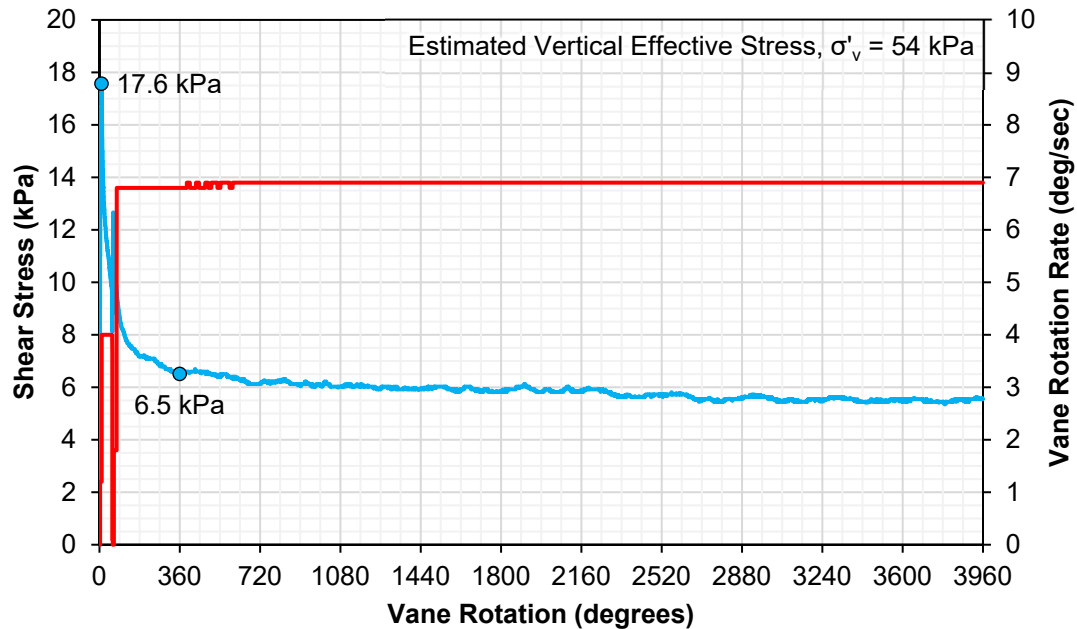


Figure 1. Typical Field Vane Shear Test in Mine Tailings

The selection of the vane rotation to be used for determination of the liquefied undrained shear strength can be contentious and is not trivial because this is the critical parameter for many designs. By thorough evaluation of available site-specific data and comparisons with case histories of actual flow liquefaction failures, as will be illustrated subsequently, the authors are confident that the liquefied undrained shear strength can be defined at 360 degrees of vane rotation for the purpose of slope stability analyses and liquefaction assessments. However, the cause of the continued slow loss of shear stress after 360 degrees is not apparent, and a cursory literature review reveals that there is limited information documenting this phenomenon (Wilson et al. (2016); McConnell (2014)).

One possible explanation is related to the nature of shearing. When the FVT was originally developed for natural clays, it was assumed that a cylindrical soil element between the vane blades rotates as a solid mass and is sheared along the static soil mass outside of the rotating cylinder such that shearing occurs along a well-defined shear band. This expected behavior is reasonable in natural clays with plasticity and developed structure. However, in the case of mine tailings with relatively low plasticity and minimal structure, the shear behavior may be different. It is speculated that as the vane is rotated through very large strains in mine tailings, a wider shear band develops and “turbulent” mixing occurs between the material within the cylindrical soil element and the surrounding soil mass. Olson and Stark (2002) integrated a similar phenomenon of continued slow loss of shear stress after reaching the liquefied undrained shear strength in their back-analysis of flow liquefaction case histories, which they attributed to hydroplaning and mixing that occurs at very large strains.

Alternatively, it has been hypothesized by the authors that through 360 degrees of vane rotation, the shear behavior and liquefied undrained shear strength may be considered from to a geotechnical perspective and applicable to slope stability analyses. However, at very large strain through as much as 3960 degrees of vane rotation, the shear behavior may be more representative

of viscous mixing that would be better considered from a rheological perspective and may, for example, be more applicable to the analysis of mine tailings runout in a dam breach scenario.

2.4 Comparison with Correlations from Actual Flow Liquefaction Failure Case Histories

Several correlations exist in the literature for estimation of the yield and liquefied undrained shear strength ratios using the CPT, which have been developed based on the back-calculation of actual flow liquefaction failure case histories. The following presents the author's database of yield and liquefied undrained shear strength ratios measured by FVT using the stated equipment and procedures in mine tailings for comparison with common correlations used in geotechnical practice (Olson and Stark 2003; Olson and Stark 2002; and Robertson 2010). The purpose of this comparison is to validate FVT equipment and procedures described herein, as well as the applicability of these correlations to mine tailings.

2.4.1 Olson and Stark (2002, 2003)

Figures 2 and 3 illustrate the authors' data representing the yield ($USSR_{YIELD}$) and liquefied ($USSR_{LIQ}$) undrained shear strength ratios, respectively, of the mine tailings computed from direct measurement of the FVT with respect to the normalized corrected tip resistance (q_{t1}) from CPT soundings performed adjacent to the FVT. Data are also compared to the case histories of actual flow liquefaction failures and the correlations proposed by Olson and Stark (2002, 2003) for estimation of yield and liquefied undrained shear strength ratios. Figure 2 shows that the yield undrained shear strength ratio measured by FVT generally ranges between 0.15 and 0.30, and the yield undrained shear strength ratio from back-calculation of actual flow liquefaction case histories generally ranges between 0.16 and 0.32. Figure 3 shows that the liquefied undrained shear strength ratio measured by FVT generally ranges between 0.04 and 0.12, and the liquefied undrained shear strength ratio from back-calculation of actual flow liquefaction case histories generally ranges between 0.03 and 0.12. Therefore, the yield and liquefied undrained shear strength ratios measured by FVT compare well with the range of values from actual flow liquefaction case histories, which provides validity to the procedure and general approach. Furthermore, the yield and liquefied undrained shear strength ratios measured by FVT is generally above the best-estimates from the Olson and Stark (2002, 2003) correlations, suggesting the correlation may be conservative in cases when material-specific data is available.

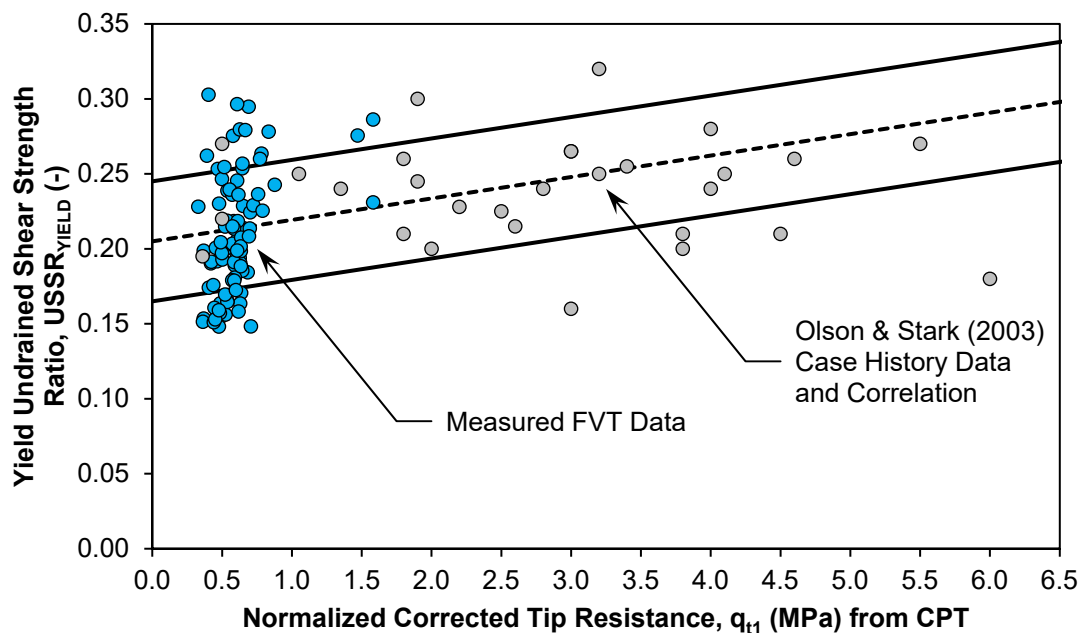


Figure 2. Comparison of Field Vane Shear Test Results to Olson and Stark (2003) Correlation

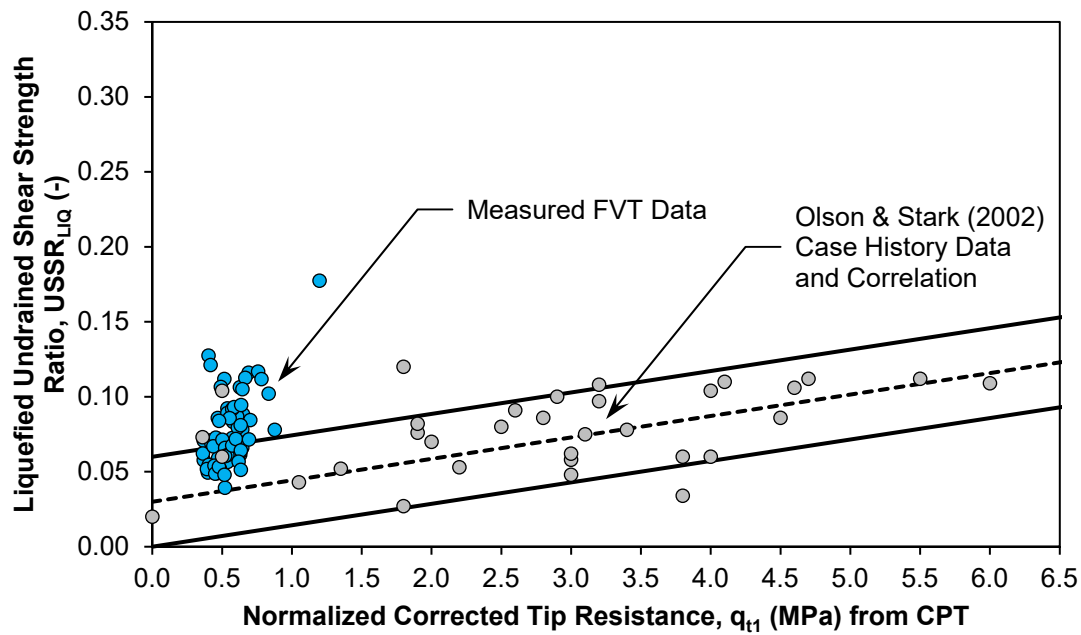


Figure 3. Comparison of Field Vane Shear Test Results to Olson and Stark (2002) Correlation

2.4.2 Robertson (2010)

Figure 4 illustrates the author's data representing the liquefied undrained shear strength ratios of the mine tailings computed from direct measurement of the FVT with respect to the equivalent clean sand dimensionless normalized corrected tip resistance ($Q_{tn,cs}$) from CPT soundings performed adjacent to the FVT. Data are also compared to the case histories of actual flow liquefaction failures and the correlation proposed by Robertson (2010) for estimation of liquefied undrained shear strength ratios. Figure 4 shows that the liquefied undrained shear strength ratios measured by FVT generally ranges between 0.04 and 0.12, and the liquefied undrained shear strength ratios from back-calculation of actual flow liquefaction case histories generally ranges between 0.05 and 0.15.

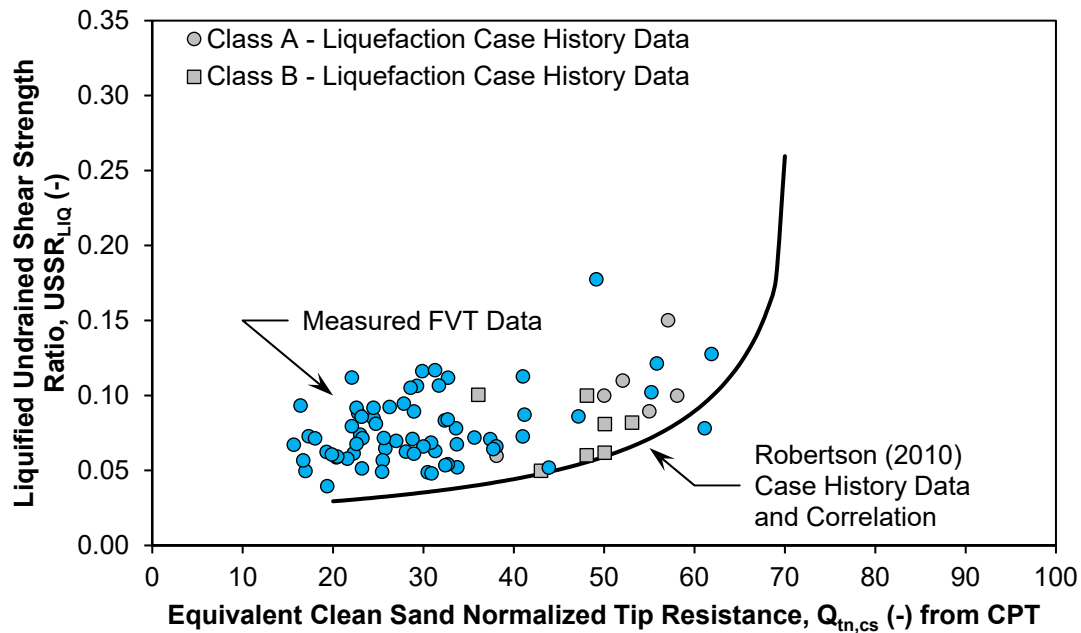


Figure 4. Comparison of Field Vane Shear Test Results to Robertson (2010) Correlation

Therefore, the liquefied undrained shear strength ratios measured by FVT compares well with the range of values from actual flow liquefaction case histories, which again provides validity to the procedure and general approach. Furthermore, the liquefied undrained shear strength ratios measured by FVT is generally above the Robertson (2010) correlation. In general, it can be concluded that the liquefied undrained shear strength ratios estimated by the Robertson (2010) correlation may underestimate the actual values, particularly when applied to fine-grained materials that behave in an undrained manner during CPT penetration. Even in comparison to the back-calculated values from actual flow liquefaction case histories, the Robertson (2010) correlation is objectively a lower-bound estimate.

2.5 Applicability of FVT in Mine Tailings

Application of the described FVT equipment and procedures in mine tailings has some limitation since the in-situ drainage conditions cannot be controlled. This is particularly problematic in material zones that exhibit interlayering of materials with high gradation variability, which is common in mine tailings deposits. In that regard, the authors have developed some guidelines to determine whether the FVT is the appropriate tool given the characteristics of the mine tailings to be investigated.

From a broad perspective, the authors found the framework proposed by Idriss and Boulanger (2008) for characterization of the liquefaction behavior of fine-grained soils based on their plasticity to be particularly pertinent – especially given the interest in obtaining the liquefied undrained shear strength from the FVT. Idriss and Boulanger (2008) defined three categories, as follows:

- “Clay-like” material refers to fine-grained materials with plasticity index greater than 7 percent that is expected to exhibit a more ductile shear response.
- “Sand-like” material refers to fine-grained material with plasticity index less than 7 percent that is expected to exhibit a more brittle shear response.
- “Transitional” material refers to fine-grained material with plasticity index between 4 and 7 percent to acknowledge that the boundary at 7 percent is neither precise nor abrupt.

Similarly, Castro (2015) also proposed that plasticity index of 7 percent separates more ductile from more brittle shear responses. The authors have found that the described FVT equipment and procedures can reliably be implemented in the field in mine tailings with “clay-like” material characteristics.

To further refine this characterization, the authors have aggregated data and integrated an understanding of cases in which the FVT was and was not used successfully in order to establish the following guidelines of when the FVT may be applicable in mine tailings.

- Plasticity index is greater than approximately 7 percent.
- Clay-size fraction ($2\ \mu\text{m}$) greater than approximately 20 percent.
- Pore-water pressure dissipation (t_{50}) from CPT is longer than approximately 60 seconds.
- Soil behavior type (I_B) per Robertson (2016) from CPT is less than approximately 18.

Figure 5 illustrates some of these guidelines with respect to the normalized corrected tip resistance (Q_m) and normalized friction ratio (Fr) classification chart by Robertson (2016). Readers should be aware that these guidelines are based on the results from a particular mine tailings deposit and may not be applicable to all sites or materials, although similar approaches may be used to develop other site-specific or material-specific guidelines.

For mine tailings that do not meet these guidelines, obtaining reliable measurements of undrained shear strength using the FVT can be very challenging, require very specialized equipment, and/or is simply not practical. However, the authors have found that mine tailings within the so called “transitional” material zone may possibly be measured with some reliability using the LVT.

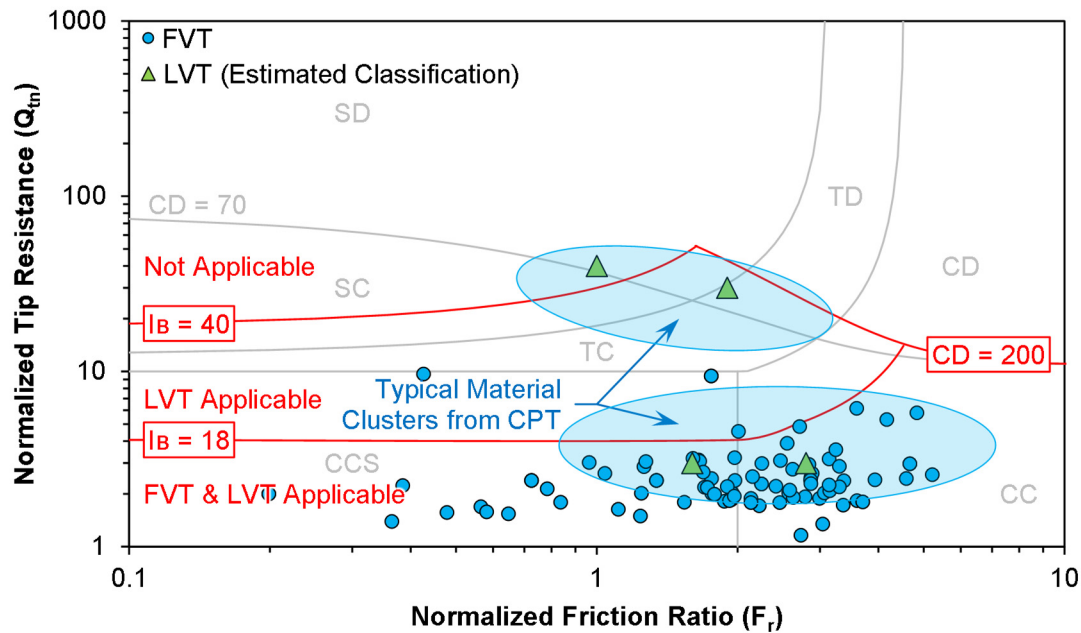


Figure 5. Applicability of Field and Laboratory Vane Shear Test based on CPT Data (Robertson, 2016)

3 STANDARD LVT EQUIPMENT AND PROCEDURE

The LVT standard is described in detail in ASTM D4648. In many ways, the laboratory version of the test is similar to the field version with the key difference being that the LVT is performed on intact samples or reconstituted specimens with more control over the testing environment and variables. A major advantage of the LVT is the testing can be performed on reconstituted specimens, which can be prepared in the laboratory with some consistency to allow for evaluation of other variables. One such variable is the vane rotation rate, which can typically be much faster and adjusted over a wider range with the equipment available in the laboratory. An important disadvantage is that the LVT is often conducted without vertical confinement. To address this issue, the authors developed an apparatus that allows for consolidation and confinement of the specimen throughout the test (a detailed description of the apparatus will be provided in subsequent publications).

3.1 LVT Program with Mine Tailings

In principle, the LVT has many of the same issues as the FVT in mine tailings, particularly related to vane rotation rate and maintaining undrained conditions. However, because the laboratory environment is more controlled, some of the variables can be better assessed – particularly by incorporating the modified apparatus allowing for vertical consolidation and confinement of the reconstituted specimen. As such, the LVT can successfully be used for mine tailings classified as either “clay-like” or “transitional” materials, which can be a substantial portion of many mine tailings deposits.

In order to verify that the modifications to the ASTM standard procedures for FVT were appropriate and to further investigate certain aspect of the shear response observed from FVT, the authors developed a testing program using LVT and other laboratory testing data. As part of the laboratory testing program, a series of LVT were performed on multiple reconstituted specimens that were representative of the mine tailings deposit, including both “clay-like” and “transitional” materials. In brief, the representative samples of mine tailings were prepared into a slurry at very high initial void ratios associated with hydraulic deposition in the field, and then poured into the cylindrical container of the LVT apparatus. Although laboratory preparation cannot replicate of the in-situ fabric/structure, the slurry preparation was thought to be suitable for the purposes of

this study. After self-weight consolidation, a top platen was placed over the specimen and incremental consolidation loads were applied until reaching the desired consolidation stress for testing. Detailed measurements during the consolidation stage were used to track the specimen void ratio and to determine the coefficient of consolidation (c_v), which was used to determine the vane rotation rate necessary to maintain undrained conditions.

Upon reaching the consolidation stress of interest, the LVT drive motor and torque measurement device were setup, and one of seven small bulkheads was removed from the top platen to allow for vane insertion while maintaining the applied load. Then, the 25 mm diameter by 50 mm high vane was inserted into the specimen. Subsequently, the procedures generally followed those used for FVT in that vane rotation began within 1 minute of vane insertion and two stages at different vane rotation rates were used to measure the yield (i.e., peak) and remolded (i.e., post-peak) undrained shear strengths. Again, one vane rotation rate was used up to 60 degrees of rotation for determining the maximum torque, and a second faster vane rotation rate was used through 3960 degrees of rotation to determine the remolded torque. Unlike the FVT, the LVT drive motor allowed for a wider range of vane rotation rates, which was utilized to rotate the vane much faster for determination of the remolded torque. In doing so, it was observed that for some mine tailings, particularly those classified as “transitional” materials, undrained conditions could be maintained throughout the remolded portion of the LVT. This is in contrast to FVT results suggesting that some drainage and shear stress increase would be observed at larger strains, which was attributed to the limited vane rotation rate in the field.

Upon completion of each LVT, the vane was retracted and the bulkhead was replaced in the top platen. The procedure was then repeated to complete another LVT in a different bulkhead either under the same consolidation stress or after consolidation to a higher load increment. Again, the vertical deformation of the specimen was tracked to estimate the void ratio at the time of the test. A series of reconstituted specimens representative of the mine tailings deposit were tested using this procedure.

3.2 Results of LVT Program

In addition to confirming that modifications to the ASTM standard procedures for FVT were appropriate, one of the objectives of the LVT program was to develop a material-specific correlation to estimate the yield and liquefied undrained shear strength ratios with respect to the state parameter. With the void ratio known from each LVT, these values could be compared to the critical state lines measured for the same representative samples of mine tailings to estimate the state parameter of each LVT.

Figure 6 shows the yield and liquefied undrained shear strength ratios measured from each LVT with respect to the associated state parameter (ψ). Note that the liquefied undrained shear strength ratio was determined from the remolded shear stress after 360 degrees of vane rotation. Trendlines drawn through these data points for both the yield and liquefied undrained shear strength ratios can be seen to decrease as the state parameter increases. The result of a consolidated-undrained triaxial compression test performed on the mine tailings that exhibited contractive behavior is also shown on Figure 6 to confirm the liquefied undrained shear strength ratios from the LVT.

For comparison purposes, a large body of triaxial compression test data performed on various natural sands and mine tailings compiled by Jefferies and Been (2016) are plotted on Figure 6 in terms of the yield undrained shear strength ratio and the state parameter. Additionally, the liquefied undrained shear strength ratios from back-calculation of actual flow liquefaction case histories, also compiled by Jefferies and Been (2016), are plotted on Figure 6. Overall, the author’s data set from LVT is in good agreement with the literature data validating the results and the LVT as an acceptable tool.

Assuming that the reconstituted specimen preparation used for LVT was sufficiently representative of the in-situ fabric/structure of the mine tailings deposit, the trendlines shown on Figure 6 could be used to estimate the liquefied undrained shear strength ratio by knowing either the in-situ state parameter using the FVRP (Contreras et al. 2020) or the yield undrained shear strength ratio, which may be measured in-situ with the FVT.

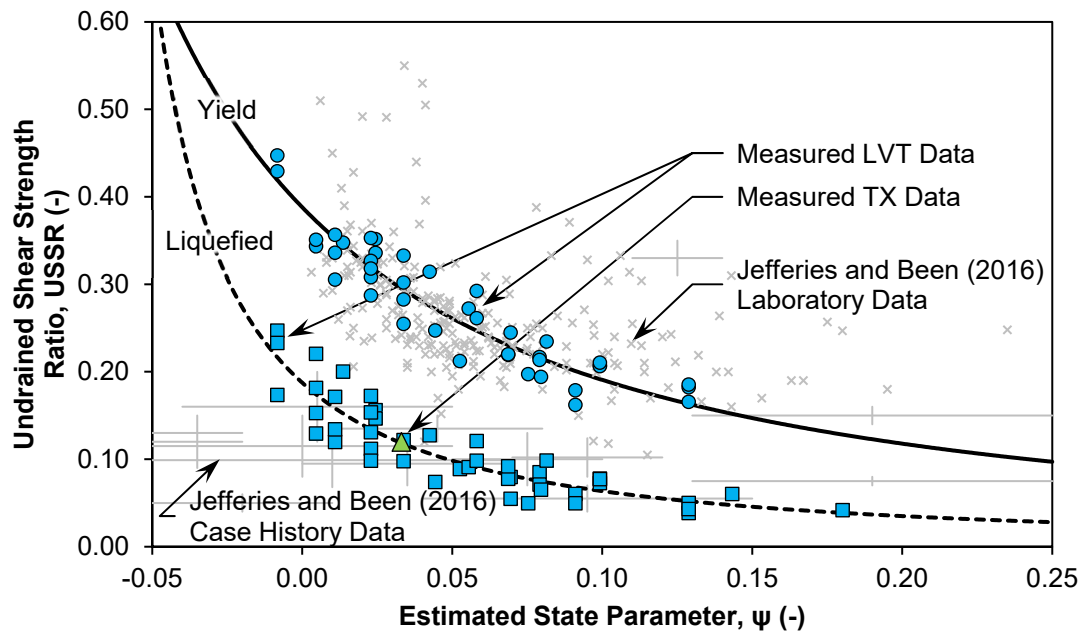


Figure 6. Comparison of Laboratory Vane Shear Test Results with Jefferies and Been (2016) Data

3.2.1 Applicability of LVT in Mine Tailings

The laboratory testing program described above has demonstrated that with some modifications the LVT can reliably test both “clay-like” and “transitional” materials. The following guidelines were established to advise when the LVT may be applicable in mine tailings, and these can be directly compared to those for the FVT as outlined previously.

- Plasticity index is greater than 2 percent.
- Clay-size fraction ($2 \mu\text{m}$) greater than approximately 10 percent.
- Soil behavior type (I_B) per Robertson (2016) from CPT is less than approximately 40.

Some of these guidelines are illustrated on Figure 5 with respect to the normalized corrected tip resistance (Q_{tn}) and normalized friction ratio (Fr) classification chart by Robertson (2016). Also shown on Figure 5 are the approximate classification ranges of similar materials to the representative samples of mine tailings that were used successfully in the LVT program, from which the soil behavior type (I_B) boundary was derived. Again, readers should be aware that these guidelines are based on the results from a particular mine tailings deposit and may not be applicable to all sites or materials, although similar approaches may be used to develop other site-specific or material-specific guidelines.

4 CONCLUSIONS

The vane shear test is a very useful tool to assess the undrained shear strength of mine tailings. However, its use requires a good understanding of the working principles of the test and modifications in the test procedure and equipment to achieve meaningful results. The following summarizes the main findings of the work presented herein.

The authors found that modifications from the standard, including the vane equipment, the wait time after vane insertion, and the vane rotation rate, are needed to improve data quality when performing FVT in mine tailings. Better and more consistent results are found when the wait time after insertion is less than one minute, the equipment measures the torque downhole above the vane, and the rotation rate is adjusted to yield undrained conditions as described. Additionally, the proposed vane shear test procedure is run in two stages and uses different vane rotation rates in each stage to measure the yield and remolded undrained shear strengths.

Data from authors' FVT database were compared with correlations for the yield and liquefied undrained shear strength ratios and generally a good comparison was found between both data sets which provides validity to the proposed approach. Results of a laboratory testing program

using the LVT are also presented and discussed. A correlation between undrained shear strength ratio and state parameter using the LVT is presented and compared with data and case histories from Jefferies and Been (2016).

General guidelines are also provided regarding the materials and limitations where the proposed FVT and LVT procedures provide satisfactory results.

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