The Vane Shear Test in Mine Tailings

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ABSTRACT

The vane shear test is a technique for determination of the undrained shear strength of soft clays. Its application in tailings presents several advantages but also important limitations. As a result, its use in tailings requires a good understanding of the principles of the test so that meaningful results can be obtained. The paper presents the field vane shear test along with its advantages and limitations in tailings. Required modifications from ASTM standard equipment and procedure are presented, as well as a comparison of the measured undrained shear strength from vane shear testing using modified procedure versus data and correlations from case histories of flow liquefaction failures.

INTRODUCTION

The field vane shear test (FVT) is a widely used in situ testing technique for determination of the undrained shear strength of soft clays. 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 continuous shear strength profiles in soft clays. The FVT equipment and procedure have been standardized (e.g., ASTM D2573).

FVT is particularly useful in tailings because when the appropriate procedures are implemented, they allow for determination of the yield and remolded (liquefied) undrained shear strengths used in slope stability analyses and liquefaction assessments. However, the FVT requires modifications from the ASTM standard for use in tailings. Among the modifications are adjustments to the wait time after vane insertion and the vane rotation rate. Blight (1968), Morris et al. (2000), and Castro (2003) among others found that the ASTM rate may not be fast enough to achieve undrained conditions in tailings.

The paper briefly discusses the ASTM standard for FVT along with their advantages and limitations in tailings. Similarly, the applicability of the FVT in tailings and the necessary modifications from the ASTM standard are presented. Finally, the yield and liquefied undrained shear strengths measured with FVT modified equipment and procedures are compared with existing correlations, and case histories data of actual flow liquefaction failures.

STANDARD FVT EQUIPMENT AND PROCEDURE

The most common vane shape is rectangular with height-to-diameter ratio of 2. The vane blade thickness is typically about 2 mm, and the area ratio is less than 10 to 12 percent. Rod friction against the surrounding material must be accounted for as part of the FVT by running a test without the vane attached and then subtracting the friction from the actual FVT with the vane attached.

Wait time after vane insertion into the soil should not exceed 5 minutes. The vane is then rotated at a constant rate of 0.1 degrees per second (with allowable variations of 0.05 to 0.12 degree per second) by applying a torque to create a cylindrical failure surface within the in situ material. At this rate, failure 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 and the cumulative angle of vane rotation is measured to develop a near continuous shear stress vs. vane rotation relationship. 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, Equation (1), is used.

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

After reaching the yield (i.e., peak) undrained shear strength, the vane is rapidly rotated through a minimum of 5-10 revolutions. Then, the remolded (i.e., post-peak) undrained shear strength is measured at a rotation rate of 0.1 degrees per second. The remolded (liquefied) undrained shear strength is computed using Equation (1) and the remolded measured torque ($T_{remolded}$).

Advantages and Disadvantages of the FVT in Mines Tailings

Tailings are recent hydraulic deposits of a very young geologic age, without significant aging to develop a robust soil structure which came into equilibrium in a very loose condition. They generally do not experience loading other than deposition, resulting in nearly normally-consolidated deposits. Finally, tailings are commonly composed of non-plastic or low plasticity solids. These facts combined make very challenging the collection of "undisturbed" samples for laboratory testing.

One of the primary advantages of using FVT combined with the CPT for strength determination is that the procedure does not require collection of undisturbed samples for laboratory testing, eliminating the sample disturbance issue. CPT and FVT produce a more comprehensive characterization and are more repeatable due to the standardization of equipment and procedures.

However, the FVT also presents some disadvantages with respect to the control of testing conditions. The stresses and drainage conditions cannot be controlled or modified as part of in situ testing. This is relevant because the strain rate directly affects whether that material behaves in a drained, partially drained, or undrained manner during the in situ test as shown by Contreras and Grosser (2009, 2019).

Modifications for Using FVT in Mine Tailings

Tailings consist of material with particle sizes ranging from coarse (i.e., sand-size) to fine (i.e., silt-size and clay-size). The very fine clay-size tailings may or may not necessarily contain clay minerals. Therefore, tailings fundamentally differ from natural clays, for which the FVT was developed and thus makes it difficult to achieve and maintain undrained conditions throughout the test using the standard equipment and procedures. As a result, the authors have found that modifications from the standard, including the vane equipment, the wait time after insertion, and the rotation rate, are needed to improve data quality when performing FVT in tailings as described subsequently.

Wait Time After Vane Insertion

ASTM standard allows for up to 5 minutes of wait time after vane insertion until starting the test. The authors have found that better results are obtained in tailings when vane rotation starts within one minute of vane insertion. Similar recommendations have been provided by Morris et al. (2000).

Vane Equipment

For measurement of the undrained shear strength of 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 and near-continuous data acquisition. This has the benefit of eliminating the need for rod friction correction, and also provides a full shear stress vs. vane rotation relationship.

Procedure and Vane Rotation Rate

The authors found that the FVT should be run with two stages at different vane rotation rates for determination of yield and remolded strengths. In the first stage, the vane rotates at a specified constant rate to determine the maximum torque. 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. 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. Harvey et al. (2023) provides specific approach for both rotation rates based on t_{50} pore-water pressure dissipation tests in adjacent CPT and a series of trials to identify the undrained rate.

Typical FVT Result in Mine Tailings

Figure 1 shows a typical FVT result performed in tailings using the equipment and procedures described above in terms of the shear stress vs. vane rotation (blue line). Also in Figure 1 is the vane rotation rate throughout the duration of the test (orange line). As can be seen, the maximum shear stress of 32.6 kPa is reached at 10 degrees of rotation, and then the shear stress decreases rapidly.

Vane rotation then momentarily pauses for less than one second at about 60 degrees to allow for the drive motor to adjust the vane rotation rate before continuing the test through a total of 3960 degrees.

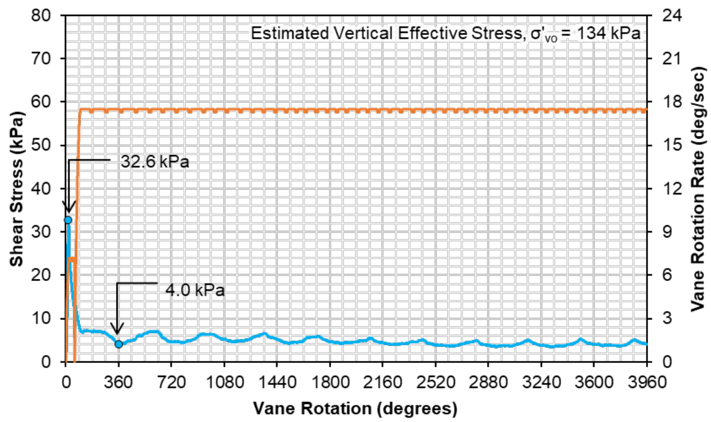

Figure 1 Typical Field Vane Shear Test in Mine Tailings

USSR is defined as the ratio of undrained shear strength and effective overburden pressure (S_u/σ'_{vo}). Using the yield undrained shear strength, $(S_u)_{YIELD}$, of 32.6 kPa and effective overburden pressure, σ'_{vo}, of 134 kPa, a yield undrained shear strength ratio ($USSR_{YIELD}$) of 0.24 is computed. Similarly, using the remolded undrained shear strength, $(S_u)_{LIQ}$, of 4.0 kPa and the same effective overburden pressure, a liquefied undrained shear strength ratio ($USSR_{LIQ}$) of 0.03 is computed. The authors believe 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.

Comparison with Correlations from Actual Flow Liquefaction Failure Case Histories

The following presents the database of yield and liquefied undrained shear strength ratios measured by FVT using the stated approach in tailings in comparison with common correlations used in geotechnical practice (Olson and Stark 2003; Olson and Stark 2002; and Robertson 2010).

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 tailings computed from direct measurement using FVT with respect to the normalized corrected tip resistance (q_{t1}) from CPT, the case histories of actual flow liquefaction failures and the correlations proposed by Olson and Stark (2002, 2003). Figure 2 shows that the $USSR_{YIELD}$ measured by FVT generally ranges between 0.15 and 0.30, and the $USSR_{YIELD}$ from back-calculation of actual flow liquefaction case histories generally ranges between 0.16 and 0.32. Figure 3 shows that the $USSR_{LIQ}$ measured by FVT generally ranges between 0.03 and 0.12, and the $USSR_{LIQ}$ from back-calculation of actual flow liquefaction case histories generally ranges between 0.03 and 0.12. Therefore, the $USSR_{YIELD}$ and $USSR_{LIQ}$ 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.

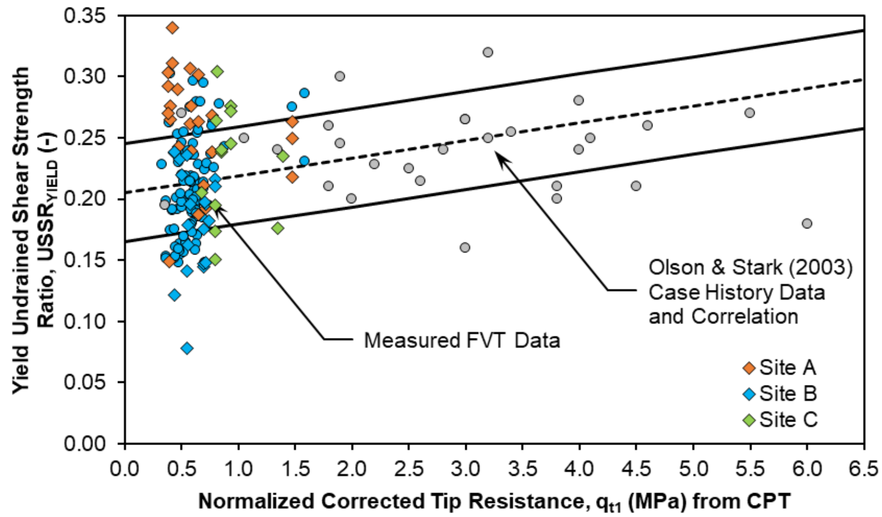

Figure 2 Comparison of Field Vane Shear Test Results to Olson and Stark (2003) Correlation

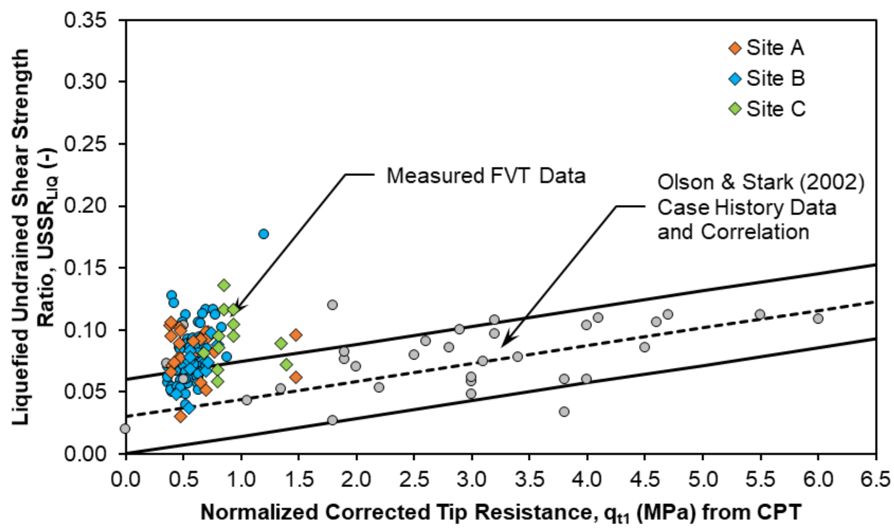

Figure 3 Comparison of Field Vane Shear Test Results to Olson and Stark (2002) Correlation

Robertson (2010)

Figure 4 illustrates the author's data representing the $USSR_{LIQ}$ 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 adjacent CPT. Data are also compared to the case histories of actual flow liquefaction failures and the correlation proposed by Robertson (2010) for estimation of the $USSR_{LIQ}$. Figure 4 shows that the $USSR_{LIQ}$ measured by FVT generally ranges between 0.03 and 0.12, and the $USSR_{LIQ}$ from back-calculation of case histories ranges between 0.05 and 0.15.

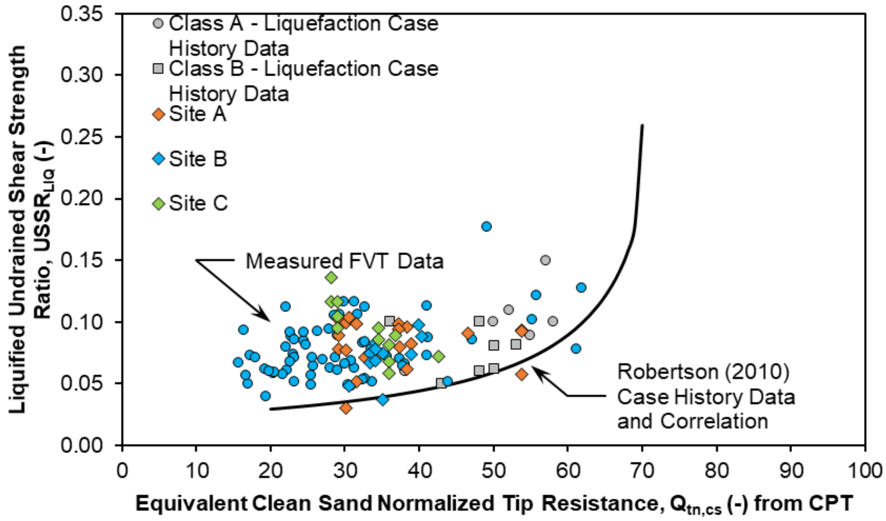

Figure 4 Comparison of Field Vane Shear Test Results to Robertson (2010) Correlation

Therefore, the $USSR_{LIQ}$ 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. The $USSR_{LIQ}$ estimated by the Robertson (2010) correlation may underestimate the actual values, particularly when applied to fine-grained (silty-sand and clayey-sand) materials of low plasticity that behave in an undrained manner during CPT penetration.

CONCLUSION

The work presented herein supports that modifications from the ASTM, including wait time after vane insertion and vane rotation rate are necessary when performing the FVT in tailings. Better and more consistent results are found when the wait time is less than one minute, the torque is measured downhole above the vane, and the rotation rate is adjusted to yield undrained conditions as described. Data from authors' FVT database were compared with correlations for yield and liquefied undrained shear strength and generally a good agreement was found between both data sets providing validity to the approach. The correlations proposed by Olson and Stark (2002, 2003) and Robertson 2010) can be considered lower bounds of the case history data.

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