

Establishing A Site-Specific Standard of Practice for Field Vane Shear Testing in Mine Tailings

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Abstract

The field vane shear test (FVT) provides the only direct measurement of in-situ yield and residual undrained shear strength and is widely used in geotechnical practice. However, use of this test in mine tailings requires modifications from the ASTM standard to achieve and maintain undrained conditions. This paper advances research presented in recent publications that identified concerns with the accuracy of data obtained in mine tailings using the ASTM standard, as well as those introducing high-speed FVT equipment and modified procedures for mine tailings applications. Herein, the authors present the results and interpretation of a field investigation program commissioned by a confidential mining client across multiple tailings storage facilities (TSFs). The investigation used these modified procedures and high-speed FVT equipment with the objective of mitigating risk associated with the uncertainty of whether FVT results used for selection of design parameters were in an undrained condition. To this end, a series of FVTs were performed at the same depths in adjacent soundings using a range of vane rotation rates for evaluation of both drainage and viscous effects on the measured yield and residual undrained shear strength. Companion cone penetration test (CPT) soundings with pore water pressure dissipation (PPD) tests were also conducted to support the characterization and interpretation. Results from this program demonstrate how the client, in a practical manner, was able to validate their standard of practice for high-speed FVT and determine optimal vane rotation rates that achieve undrained conditions while avoiding viscous effects for the various mine tailings across their portfolio of TSFs. For the mining industry, this provides a model for implementation of similar investigation programs at other TSFs to gain site-specific knowledge of vane rotation rate effects on the measured undrained shear strength for respective mine tailings, as well as a basis and directive for development of modified standards for mine tailings applications superseding the existing ASTM standard.

Introduction

The field vane shear test (FVT) is one of the most widely used in-situ geotechnical testing methods for determination of the undrained shear strength of cohesive soils. Originally introduced in 1919, use of the FVT was further developed in the 1940s (Carlson, 1948; Skempton 1948; Cadling and Odenstad, 1950). In current practice, it remains the only direct measurement of the in-situ yield undrained shear strength (s_u) and residual undrained shear strength (s_{ur}). This is particularly relevant for characterization of mine tailings because the undrained shear strength is largely controlled by the in-situ soil structure and void ratio, which can be easily disturbed by conventional sampling methods. As the only direct measurement of the in-situ undrained shear strength, the FVT is commonly used as a reference undrained shear strength for calibrating cone penetration testing (CPT) data into near-continuous profiles of yield undrained shear strength (s_u) and for evaluation residual undrained shear strengths (s_{ur}) and sensitivity, or brittleness, that can be anticipated under post-liquefaction conditions. Thus, the FVT serves a critical role for characterization and determination of input parameters for slope stability and deformation analyses of TSFs.

Background

As an in-situ geotechnical testing method, the data obtained from FVT is generally thought to be repeatable and reliable due to the use of standardized equipment and procedures described in ASTM D2573. In brief, the ASTM standard outlines the following procedure. After advancing the vane to the desired test depth, the wait time before starting vane rotation should not exceed five (5) minutes. To begin the test, the vane is rotated at a nominal rate of 0.1 degrees per second to determine the yield undrained shear strength (s_u). Subsequently, the vane is rapidly rotated through five (5) to ten (10) revolutions without measuring or recording the applied torque. Finally, the vane is again rotated at a nominal rate of 0.1 degrees per second to determine the residual undrained shear strength (s_{ur}).

In the absence of practical methods to obtain undisturbed samples for laboratory testing or other in-situ testing methods for measurement of undrained shear strength, ASTM standard equipment and procedures for FVT are often used for evaluation of intermediate soils – such as mine tailings – despite these materials being outside of the ASTM standard's intended applicability. Due to the relatively high permeability and differing compressibility characteristics of mine tailings compared to the natural clays for which the ASTM standard was developed, partial drainage of pore-water pressures can occur during FVT performed in accordance with the ASTM standard procedure thus precluding undrained conditions (Reid, 2016; Mundle et al., 2019; Okkels and Anderson, 2019; Contreras and Harvey, 2021; Hogan et al., 2022). In mine tailings, the ASTM standard vane rotation rate of 0.1 degrees per second is often too slow to achieve undrained conditions at failure (Blight, 1968). For contractive mine tailings exhibiting higher shear strengths in the

drained condition than undrained condition, FVT performed in accordance with the ASTM standard will result in measured shear strengths that over-estimate the actual undrained shear strength due to drainage effects (Reid, 2016). Furthermore, allowing up to five (5) minutes of wait time after vane insertion per the ASTM standard may also contribute to an exaggerated undrained shear strength due to strength gain from localized consolidation after vane insertion (Aas, 1965; Torstensson, 1977; Roy and Leblanc, 1988).

Another phenomenon that influences undrained shear strength measurements are viscous effects, or rheological effects, which are forces resulting from pore-water fluid's resistance to flow and its interactions with the soil particles. For FVTs performed at excessively fast vane rotation rates, viscous forces will mobilize higher undrained shear strengths. As noted by Chandler (1988), relatively few studies have evaluated the effects of viscous behaviour on measured undrained shear strengths, although testing on natural clays by Torstensson (1977) and Wiesel (1973) confirm the impacts are of importance. Thus, given the conflicting effects of drainage and viscous forces, an optimal range of vane rotation rates must be determined to mitigate the potential for over-estimation of the actual undrained shear strength during FVT.

Several recent studies have evaluated the effects of partial drainage on the measured yield undrained shear strength (s_u) and residual undrained shear strength (s_{ur}) from FVTs, including efforts by some to develop and utilize high-speed FVT equipment designed specifically to mitigate these effects and produce more reliable measurements for mine tailings applications (Pérez-Foguet, 1998; Schlue et al., 2010; Reid, 2016; Mundle et al., 2019; Okkels and Anderson, 2019). In particular, the authors of this paper previously identified limitations of the ASTM standard equipment and procedures, and proposed modifications to be used in mine tailings (Contreras and Harvey, 2021). In addition, the authors recently introduced improved direct-push high-speed FVT equipment and demonstrated that its use could effectively achieve undrained conditions using faster vane rotation rates in mine tailings, when ASTM standard vane rotation rates could only achieve partially-drained conditions (Hogan et al., 2022).

While drainage effects on the measured undrained shear strength (s_u) have been well documented in recent studies, less attention has been given to the viscous effects – which may be due to limitations on the upper bound of vane rotation rates achievable from available FVT equipment. Moreover, most studies have focused on vane rotation rate effects with respect to the yield undrained shear strength (s_u) rather than the residual undrained shear strength (s_{ur}), which may be of even greater importance given the consequences of post-liquefaction slope stability. The work presented herein builds upon the authors' previous publications utilizing the improved high-speed FVT equipment introduced by Hogan et al. (2022) and the modified FVT procedures proposed by Contreras and Harvey (2021) to evaluate the effects of drainage and viscous forces on both the yield undrained shear strength (s_u) and residual undrained shear strength (s_{ur}) measurements from FVTs performed in mine tailings.

Objectives

In this study, the authors' principal objective was to mitigate our confidential mining client's risk associated with the uncertainty of whether the FVT data being used for selection of design parameters for geotechnical slope stability and deformation analyses were in fact representative of undrained conditions, particularly because FVT equipment previously used at their sites had limitations on the maximum vane rotation rate.

Accordingly, a field investigation program was developed by the authors and commissioned by the mining client across multiple TSFs utilizing modified procedures and improved high-speed FVT equipment (Contreras and Harvey, 2021; Hogan et al., 2022) to define site-specific vane rotation rates for reliable and accurate determination of yield undrained shear strengths (s_u) and residual undrained shear strengths (s_{ur}) accounting for the mine tailings variability across the sites. In doing so, vane rotation rates would also be identified that exhibit evidence of drainage or viscous effects influencing the measured undrained shear strength. Ultimately, these findings would be used to develop site-specific best practices for FVT performed in mine tailings at the client's sites, as well as providing the opportunity to obtain data demonstrating the effects of vane rotation rate for the consideration of the broader mine tailings industry.

Field Investigation Program

The field investigation program described herein was performed to provide a comprehensive evaluation of two (2) locations at each of four (4) different TSFs for a total of eight (8) locations that were investigated as part of this program. At each of the investigation locations, two (2) CPT soundings and four (4) FVT soundings were performed in close proximity for the purpose of direct comparison of the measured results. Specifically, the companion fieldwork performed at each investigation location consisted of:

- One (1) CPT sounding advanced continuously for material characterization and selection of test depths for subsequent FVT and PPD in the adjacent soundings.
- One (1) CPT sounding advanced incrementally pausing to perform PPD at depths selected for FVT in the adjacent soundings. Shear wave velocity (v_s) testing was also performed concurrently.
- Four (4) FVT soundings advanced to perform multiple tests within each sounding. Tests were performed at the same nominal depths within each of the adjacent FVT soundings so that different vane rotation rates could be applied to the same layer of mine tailings for comparison of the results.

Results from only three (3) TSFs are featured herein because at the other TSF some details of the fieldwork were tailored to specific needs of geotechnical design and data was not relevant to the focus of this paper.

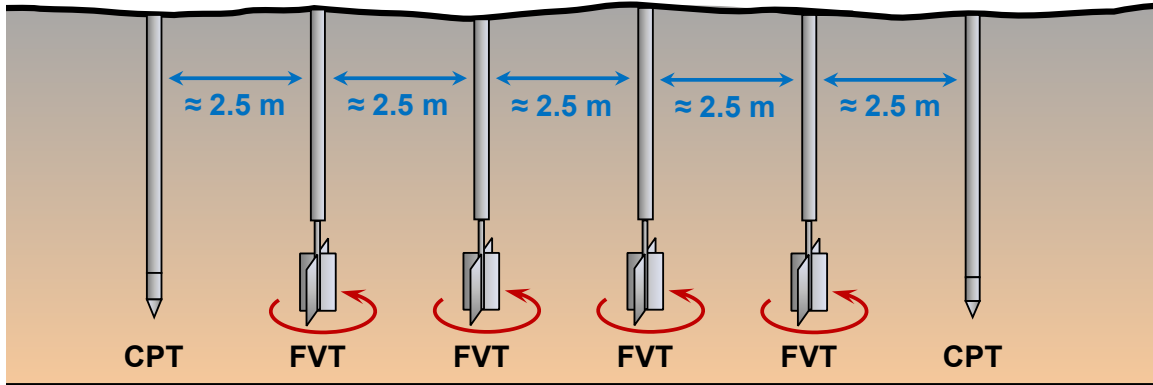


Figure 1: Generalized Layout of Field Activities at Each Investigation Location

Material Characterization

The TSFs studied for this field investigation program use conventional tailings disposal methods, whereby the mine tailings are hydraulically-deposited via gravity or pipeline into surface impoundments. As such, the materials of interest were generally contractive and consisted of the finer fraction of the mine tailings.

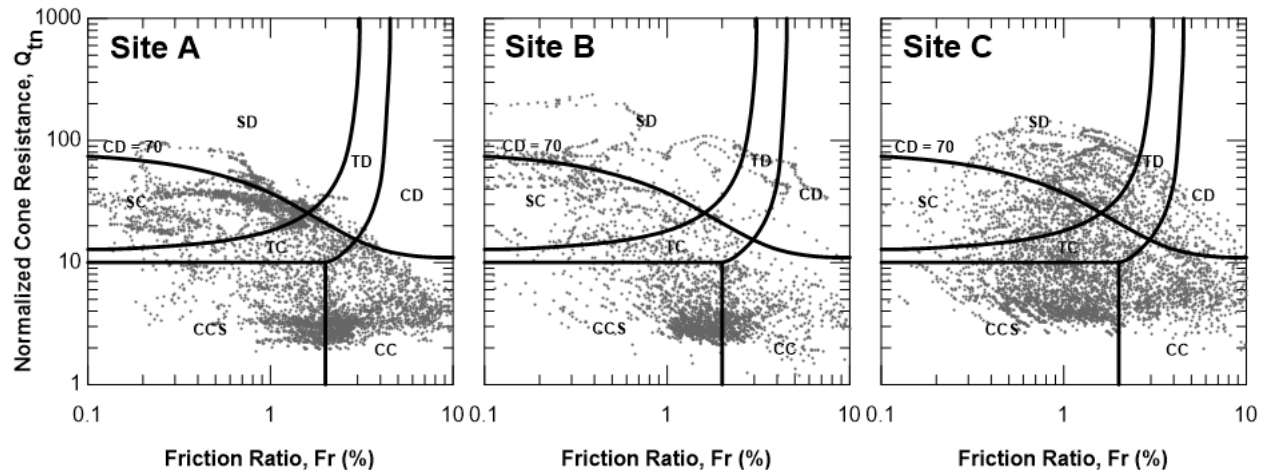


Figure 2: Soil Behaviour Types (after Robertson, 2016) of Mine Tailings

For context, Figure 2 illustrates the normalized soil behaviour types (SBT_n) after Robertson (2016) based on CPT sounding data collected from the mine tailings. As shown in Figure 2, the mine tailings at Site A consisted of contractive clay-like (CC and CCS) materials along with interbedded contractive transitional and sand-like (TC and SC) materials. Site B largely consisted of relatively uniform contractive clay-like (CC and CCS) materials. Finally, the mine tailings at Site C were interbedded throughout with materials ranging from contractive clay-like (CC and CCS) to contractive sand-like (SC) in addition to some dilatant materials (CD, TD, and SD). The mine tailings at each of these TSFs are also differentiated by the time to 50 percent dissipation (t_{50}) of dynamic pore-water pressures (u_2) from PPD testing performed concurrently with the CPT soundings, which were slowest at Site B, moderate at Site A, and quickest at

Site C (Figure 6). Relative material characterizations are also corroborated by index properties, whereby the mine tailings at Site B are the finest gradation and most plastic (typical clay-size fractions of 15 to 35 percent), those at Site C are the coarsest gradation and nearly non-plastic (typical clay-size fractions less than 15 percent), and those at Site A are intermediate (typical clay-size fractions of 5 to 25 percent).

Field Vane Shear Testing Equipment

For this field investigation program, the A.P. van den Berg High-Speed Icone Vane was utilized for its capability to accommodate variable vane rotation rates between 1.0 and 60.0 degrees per second. The High-Speed Icone Vane, as described in detail by Hogan et al. (2022), consisted of a direct-push electronic downhole torque measurement device and drive motor specially modified by the manufacturer for higher speeds while respecting the dimensional requirements of ASTM D2573. Additionally, this system utilized fully-digital controls and data acquisition allowing for the vane rotation rates to be applied with specificity and to be changed in the middle of a test while maintaining near-continuous vane rotation, as described subsequently. In general accordance with the dimensions and tolerances of ASTM D2573, the vanes used for this field investigation program were constructed of four (4) high-strength, stainless steel rectangular blades having a height-to-diameter ratio of two (2). Based on the anticipated maximum torque, 50 mm diameter vanes were used at Site A, and 40 mm diameter vanes were used at Sites B and C.

Field Vane Shear Testing Procedure

To begin the field investigation program at each location, one (1) CPT sounding was advanced to refusal only pausing momentarily to add rods. Other advancement interruptions, like PPD and v_s testing, may cause dissipation of excess pore-water pressures affecting the data and material characterization. Based on this data, specific layers of the mine tailings producing relatively low tip resistances (q_t) and positive dynamic pore-water pressures (u_2) were identified for FVT. The mine tailings identified for FVT are highlighted in Figure 3 based on their SBTn (Robertson, 2016). Subsequently, one (1) additional CPT sounding was advanced for confirmation that layers of mine tailings identified in the previous test were continuous in the area and to perform PPD and v_s testing within those layers. Before performing the FVT soundings, PPD data was evaluated to estimate the anticipated optimal vane rotation rates based on Blight (1968).

After deploying the vane to the specified test depth in the adjacent FVT soundings, vane rotation was started as soon as possible, keeping the time between the end of vane insertion and the start of vane rotation to not more than one (1) minute – a criteria selected based on previous research and laboratory testing performed on similar mine tailings. Each vane test consisted of two stages performed consecutively without pause with different vane rotation rates to determine the yield undrained shear strength (s_u) and residual undrained shear strength (s_{ur}), respectively. Upon beginning the test, the vane was rotated at an initial vane rotation rate for sixty (60) degrees to determine the maximum torque associated with the yield undrained

shear strength (s_u). After sixty (60) degrees of vane rotation, the vane rotation rate was nearly instantaneously increased and vane rotation – along with torque measurements – continued uninterrupted through 3960 degrees, or eleven (11) revolutions, to remold the mine tailings. Following completion of each test, the vane was advanced to the next specified test depth within the same FVT sounding.

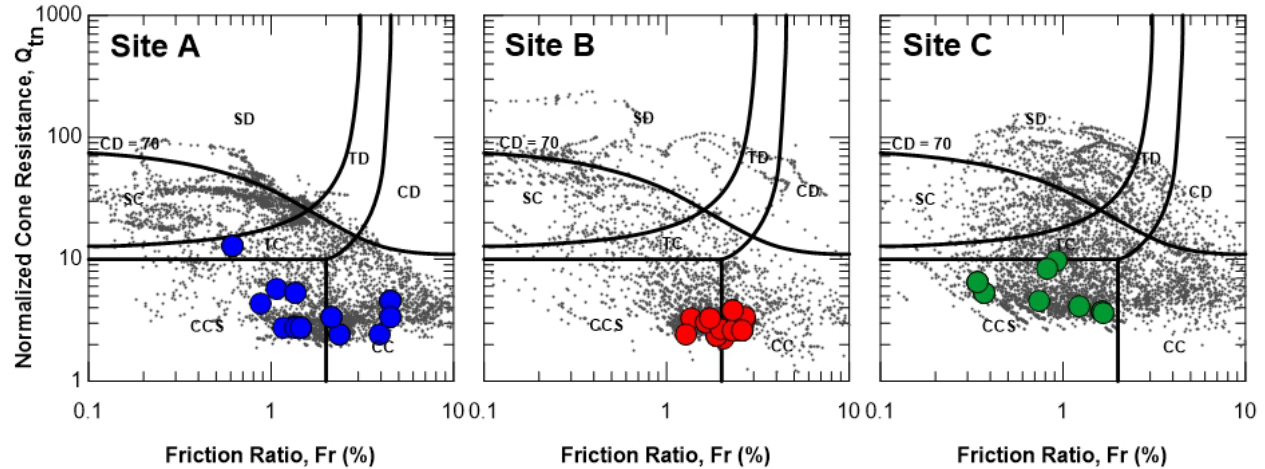


Figure 3: Material Characterization of Mine Tailings Identified for FVT Shown with Respect to Soil Behaviour Types (after Robertson, 2016)

To evaluate the effects of vane rotation rate on the measured yield undrained shear strength (s_u) and residual undrained shear strength (s_{ur}) with respect to both drainage and viscous effects, the procedure outlined above was repeated at each of the four (4) FVT soundings per location. A range of vane rotation rates between 1.0 and 60.0 degrees per second were performed at the same nominal depths for direct comparison. As indicated above, a vane rotation rate for the first stage (i.e., yield failure) was selected based on Blight (1968), and subsequent vane rotation rates were selected in the field based on the observed response. Note that because of some equipment features to protect the drive motor from rapid impulses and that yield failure occurred relatively quickly (i.e., within 10 to 30 degrees of vane rotation), vane rotation rates were effectively limited to less than 10.0 degrees per second for evaluation of yield undrained shear strength (s_u). The vane rotation rate are larger degrees of vane rotation associated with the residual undrained shear strength (s_{ur}) were not appreciably affected by this matter.

Results

The following section discusses the results of the field investigation program with interpretation of various aspects of the data. In total, 175 FVT were performed across six (6) different investigation locations at Sites A, B, and C. A portion of the tests were excluded from data analysis and interpretation due to considerations of general test validity (e.g., interruptions of vane rotation during the tests; exceeding equipment torque limitations before yield failure) and proximity of PPD to the specified depth of FVT.

As an initial step in the data analysis process, the measured shear stress versus vane rotation rate relationships for each FVT were reviewed to determine the following:

- Yield undrained shear strength (s_u),
- Residual undrained shear strength at 360 degrees of vane rotation ($s_{ur,360}$), and
- Residual undrained shear strength at 3600 degrees of vane rotation ($s_{ur,3600}$).

These measurements were then directly compared to the results from companion tests performed at different vane rotation rates at the same depths (i.e., the same layer of mine tailings) within adjacent FVT soundings, as described previously. Figure 4 shows typical results from comparison of the measured shear strengths plotted as a function of vane rotation rate using selected data from both investigation locations at Site A.

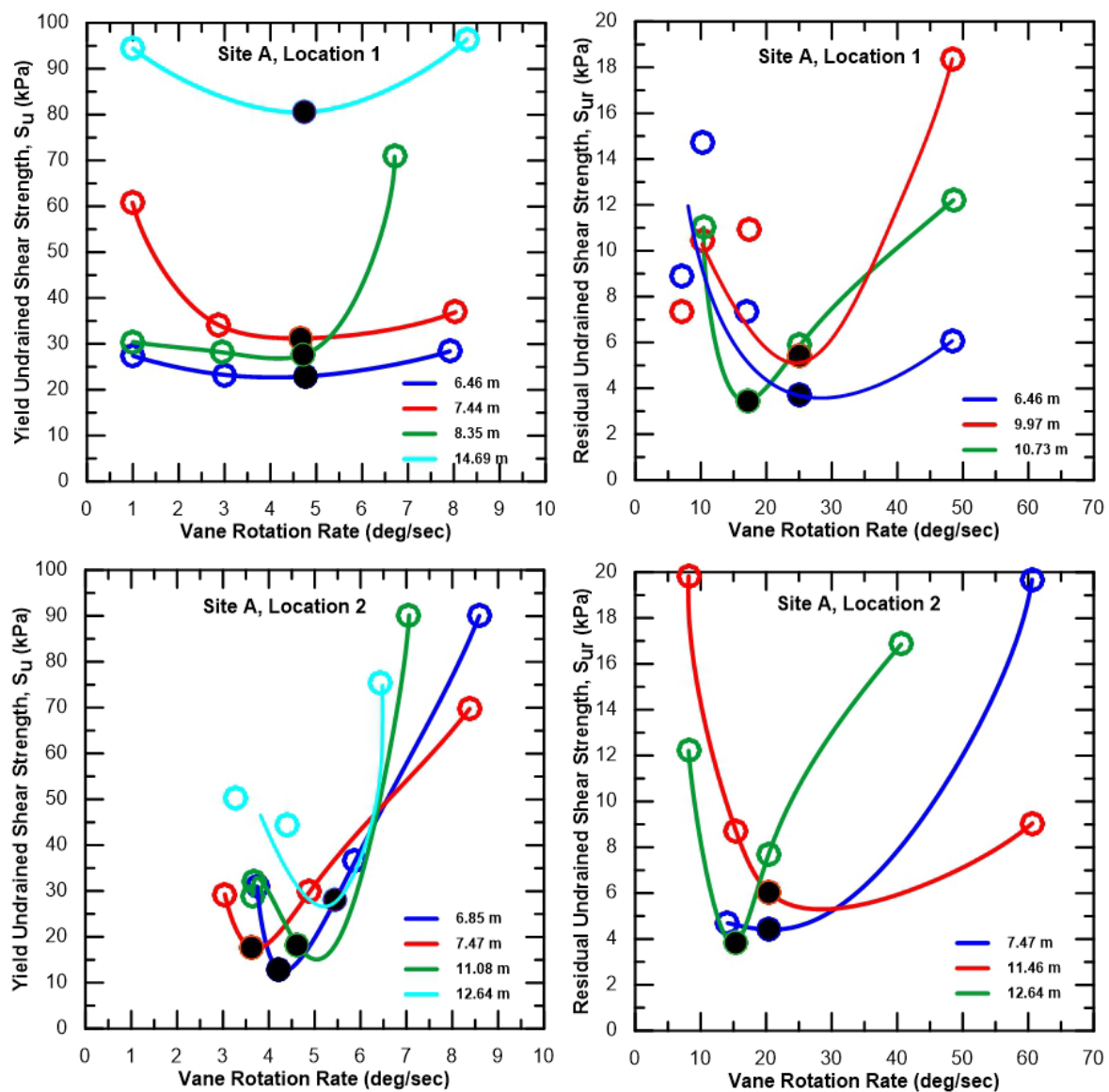


Figure 4: Effect of Vane Rotation Rate on Measured Undrained Shear Strength in Mine Tailings

As illustrated in Figure 4 for Site A and corroborated by similar results from investigation locations at each of the other TSFs, a “U” shaped trend was observed in the measured yield undrained shear strength (s_u) and residual undrained shear strength (s_{ur}) with respect to the variation in vane rotation rate. At slower vane rotation rates, relatively higher shear strengths were measured and attributed to drainage effects. As incrementally faster vane rotation rates were applied, relatively lower undrained shear strengths were measured, which were thought to be associated with the actual undrained condition and nearly unaffected by drainage or viscous effects. Finally, higher shear strengths were measured again as the vane rotation rate increased further to the extent that viscous effects were contributing to the shearing resistance. For the range of vane rotation rates applied as part of this program, the measured shear strength over-estimated the actual undrained shear strength (i.e., assumed to be the lowest measured value at each test depth) by at least ten (10) to a hundred (100) percent with several tests over-estimating by a factor of five (5) or more. These results highlight the significance of performing the FVT within an optimal range of vane rotation rates.

To that point, the bottom of the “U” shaped trend, representing the most conservative value associated with the actual undrained shear strength assumed to be nearly unaffected by drainage or viscous effects, was within a relatively consistent range across the various test depths and investigation locations performed site-wide for a particular TSF. For example, using the data shown in Figure 4 from Site A, the vane rotation rates at the bottom of the “U” shaped trend providing acceptable measurements of the yield undrained shear strength (s_u) were generally between four (4) and five (5) degrees per second at both Locations 1 and 2. For residual undrained shear strengths ($s_{ur,3600}$) the vane rotation rates were between approximately fifteen (15) and twenty-five (25) degrees per second at both Locations 1 and 2. However, Table 1 demonstrates that the optimal vane rotation rates providing acceptable measurements at the bottom of the “U” shaped trend varied from one TSF to another based on the characterization of the mine tailings at each site, as represented for context in the table by the typical range of the time to 50 percent dissipation (t_{50}) of dynamic pore-water pressures (u_2) from PPD testing performed at the specified FVT depths.

Table 1: Summary of Optimal Vane Rotation Rates for Mine Tailings at Various Sites

TSF	Typical PPD t_{50} (sec)	Vane Diameter (mm)	Average Vane Rotation Rate (deg/sec)		
			Yield Undrained Shear Strength (s_u)	Residual Undrained Shear Strength ($s_{ur,360}$)	Residual Undrained Shear Strength ($s_{ur,3600}$)
Site A	40 (10 – 80)	50	4.4	16.2	25.8
Site B	185 (140 – 250)	40	4.3	18.1	38.0
Site C	25 (10 – 40)	40	7.0	23.1	47.6

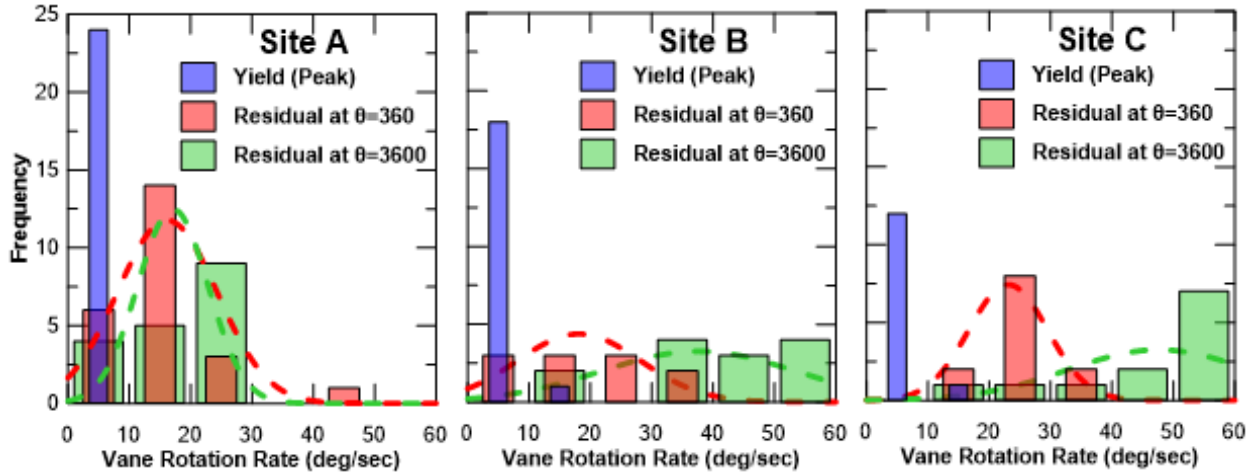


Figure 5: Distribution of Optimal Vane Rotation Rates in Mine Tailings at Various Sites

Figure 5 illustrates the distribution of vane rotation rates that provided acceptable measurements at the bottom of the “U” shaped trends for each of the TSFs studied as part of this field investigation program. First and foremost, the required vane rotation rates to achieve and maintain undrained conditions are significantly greater than the ASTM standard vane rotation rate of 0.1 of a degree per second. Beyond that, the data shown in Figure 5 demonstrates that ever increasing vane rotation rates are required to maintain undrained conditions after yield failure through large strains associated with the residual undrained shear strength (s_{ur}) due to drainage effects. Additionally, it is evident that there is an effect of the material characterization on the required vane rotation rate to maintain undrained conditions. For comparison, at Site A the required vane rotation rate is on the order of ten (10) to thirty (30) degrees per second for determination of the residual undrained shear strength at 3600 degrees ($s_{ur,3600}$), whereas at Site C vane rotation rates of about forty (40) to sixty (60) degrees per second are required.

Expanding on the effects of the material characterization, Figure 6 illustrates how the vane rotation rate required to provide acceptable measurements of the yield undrained shear strength (s_u) varied as a function of the time to 50 percent dissipation (t_{50}) of dynamic pore-water pressures (u_2) from PPD testing performed at the same depths (i.e., the same layer of mine tailings) as the FVTs. Although this effect was discussed in Blight (1968), the correlation developed from this data is beneficial for quick confirmation of appropriate vane rotation rates to be used during future investigation programs at the mining client’s TSFs. Note that the tangential velocity along the vane circumference is also presented because it is independent of the vane diameter, whereas the vane rotation rate (i.e., expressed as angular velocity) from Site A was corrected to a normalized vane diameter of 40 mm for direct comparison with data from Sites B and C.

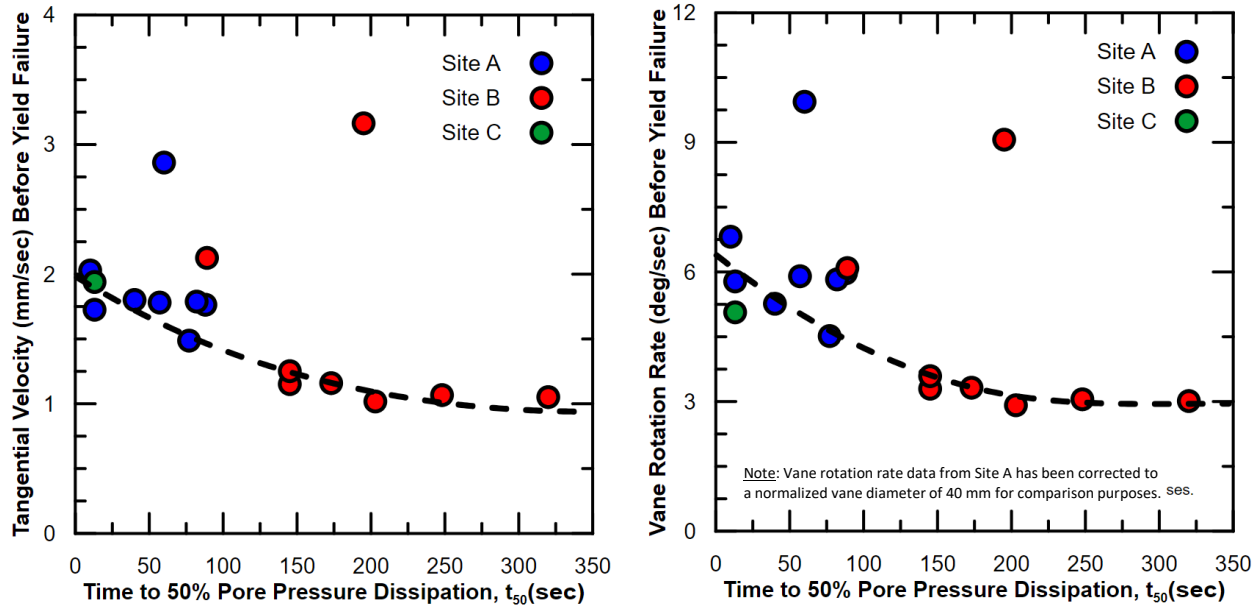


Figure 6: Correlation of Optimal Vane Rotation Rates and Pore-Pressure Dissipation Test Data in Mine Tailings at Various Sites

Conclusions

Findings from this field investigation program unambiguously demonstrate the significant impact that the applied vane rotation rates during FVT have on the measurements of yield undrained shear strength (s_u) and residual undrained shear strength (s_{ur}), whereby both vane rotation rates that are too slow allowing drainage and that are too fast imposing viscous effects cause unconservative, over-estimated measurements. Thus, selection of appropriate vane rotation rate is paramount for minimizing uncertainty and obtaining representative measurements of undrained conditions. However, as shown herein with even relatively similar mine tailings, the appropriate vane rotation rate is not universal, as suggested by the ASTM standard, but rather is highly dependent on the in-situ material. Further, the appropriate vane rotation rate must even be adjusted during the test for evaluation of yield failure differently from shear strengths at larger strains.

This field investigation program demonstrates how one mining client used modified procedures and high-speed FVT equipment in a practical manner to determine the appropriate vane rotation rates for site-specific conditions, whereby mitigating the uncertainty of whether FVT data was in fact representative of undrained conditions. However, given that the appropriate vane rotation rates are material dependent, the authors propose that this field investigation program be a model for implementation of similar investigation programs at other TSFs to gain site-specific knowledge of vane rotation rate effects on their respective mine tailings. Further aggregation of additional data sets may ultimately serve as a basis and motivation for development of modified standards of practice for the mine tailings industry superseding the existing ASTM standard.

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