

Modified Field Vane Technology for Improved Reliability of Undrained Shear Strength Measurements in Mine Tailings

Arielle A. Hogan & Shane A. Kelly

Gregg Drilling and Testing Canada, Prince George, British Columbia, Canada

Onne Storteboom

A.P. van den Berg, Heerenveen, Friesland, The Netherlands

Peter K. Robertson

Gregg Drilling LLC., Signal Hill, California, USA

ABSTRACT: During mine tailings site investigations, the Field Vane Test (FVT) is commonly used as an accessory to Piezocone Penetration Testing (CPTu) for in-situ determination of undrained shear strength in fine-grained soil. Recent studies have identified concerns with the accuracy of the traditional ASTM standardized FVT in mine tailings. The occurrence of dam failures has demonstrated an industry-wide need to improve the reliability of in-situ undrained shear strength evaluation. Gregg Canada, in collaboration with A.P. van den Berg, present a novel innovation: a field vane with high-speed capability. In a case study from two tailings sites, the time factors (T) from FVTs completed using the traditional method and the high-speed method are compared. The results from this study indicate that the high-speed field vane is effective in providing rotation rates sufficient to maintain undrained conditions during a FVT in silty tailings, thus improving the reliability of measurements for undrained shear strength.

1 INTRODUCTION

1.1 *The Field Vane Test*

The Field Vane Test (FVT) was first introduced by Lyman Carlson in 1948 to measure the in-situ undrained shear strength of cohesive soils. To perform the test, a 4-bladed vane is inserted into the soil and rotated until shearing occurs. During the test, the torque required to rotate the vane (i.e., the resistivity of the soil) increases until the point of failure. The maximum torque required to cause failure is a direct measurement of the undrained shear strength (S_u) of the soil, provided the test is performed under undrained conditions. The insertion of a thin vane blade causes minimal soil disturbance (Carlson, 1948) and results in less changes to local stress than laboratory soil testing methods (Matsui & Abe, 1981), making it a reliable means of estimating in-situ soil undrained strength.

Since its inception, the FVT has prevailed to be the most popular means of in-situ undrained shear strength evaluation (Contreras & Harvey, 2021). While the FVT was originally designed for soft plastic clays, the application of the test has since broadened to measure S_u in peats, silts, and silty mine tailings. Recent studies have led to questions surrounding the validity of the test in non-plastic soils—particularly in mine tailings (e.g., Reid, 2016; Mundle et al., 2019; Okkels & Anderson, 2019; Contreras & Harvey, 2021). These questions stem from uncertainty regarding the drainage conditions when testing non-plastic or low plastic mine tailings.

1.2 ASTM Standard for the Field Vane Test

The current ASTM Standard (Designation: D2573), describes a test using a 4-bladed vane with a diameter ranging from 35 mm to 100 mm, depending on soil strength. Regardless of diameter, the vane must have an average blade thickness of 2 mm and a vane height-to-diameter ratio greater than 1 and less than 2.5.

For FVT using a vane blade with a height-to-diameter (H/D) ratio of 2 (such as the vanes described in coming sections), the relationship between the undrained shear strength, torque and vane diameter is given in the following equation:

$$S_u = \frac{6T}{7\pi D^3} \quad (1)$$

Where S_u is the peak undrained shear strength, T is the maximum value of measured torque which has been corrected for apparatus and rod friction, and D is the vane diameter.

ASTM Standard D2573 outlines the following parameters for determining peak undrained shear strength (S_u) and remolded undrained shear strength ($S_{u(Rem)}$):

1. Time from end of blade insertion into soil to beginning of rotation should be a maximum of 5 minutes.
2. Initial rotation of the vane should occur at 6 deg/min (0.1 deg/sec). Rotation should occur at this rate until failure, at which point the peak S_u is determined. This generally requires a time to failure of 2 to 5 min, except in very soft clays where the time to failure may be as much as 10 to 20 min.
3. Vane is then rotated rapidly for a minimum of 5 to 10 rotations.
4. Immediately following the rapid rotations (within 1 minute), the remolded $S_{u(Rem)}$ is measured by rotating the vane at 6 deg/min (0.1 deg/sec), same as it was to determine the peak S_u .

1.3 Obtaining Undrained Conditions During a Field Vane Test

Obtaining undrained conditions during a FVT is paramount for accurate evaluation of undrained shear strength. In the following equation, described by Blight (1968), the time factor (T) can be used to determine if drained or undrained conditions were maintained during a FVT:

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

Where T is the dimensionless time factor, c_v is the coefficient of vertical consolidation, t_f is the time to soil failure/shear and D is the vane diameter. It's unclear why Blight used c_v instead of c_h , since most of the drainage around a field vane with a height to diameter ratio of 2 ($H/D = 2$) is in the horizontal direction.

Blight (1968) stated that a FVT may only be considered fully undrained if the resulting T is less than 0.02. Otherwise, at least partial drainage has occurred during the test. Chandler (1988) later argues that a time factor (T) less than 0.05 is sufficient to achieve undrained conditions.

1.4 Field Vane Tests in Mine Tailings and The Drainage Effect

In the case of most soft clays, the value of c_v is such that the standard field vane test will achieve undrained conditions (Chandler, 1988). In other soil types however, the value for c_v may be outside of the range for maintaining undrained conditions during a standard FVT. The original FVT, and subsequently, the associated ASTM standard was designed exclusively for testing in low permeability clays and specifically states that the test cannot be applied to non-plastic silts, sands or other soil types with high permeability. ASTM D2573 (Section 5.4) explains that if lenses of these materials are present, partial to complete drainage of the soil will occur at the ro-

tation rate outlined in that standard. Thus, the development of a standardized fast FVT for applications in non-cohesive soils is highly recommended (Okkels & Andersen, 2019).

The degree of drainage that occurs during a FVT is a function of both permeability/coefficient of consolidation and rate of vane rotation (Sharifounnasab & Ullrich, 1985). The high permeability of silty soils (relative to clay) allows for partial drainage of porewater surrounding the vane during a standard (0.1 deg/sec) FVT (Blight, 1968). This is known as the drainage effect. If partial drainage occurs during the test, then the true undrained shear strength cannot be measured and instead, the results of the test may represent drained strength. In contractive soils, the drained shear strength is higher than the undrained shear strength. Therefore, if partial drainage occurs during a FVT in contractive soils, then the resulting measurement for S_u will be too high. Most hydraulically deposited mine tailings are loose and contractive at large strains. Silty tailings often have low plasticity and high permeability, all of which leaves them vulnerable to drainage effects during a standard FVT.

Confidence in input parameters used for tailings management facility design is crucial for assessing performance across a range of loading conditions. Developing a FVT tailored to mine tailings applications that overcomes possible drainage effects is imperative for achieving more accurate and reliable results for undrained shear strength used in the assessment of stability under undrained conditions.

The purpose of this paper is to introduce results obtained using a new high-speed digital down-hole vane through a preliminary case study. The objective of the case study was to determine if this new high-speed vane is effective in overcoming drainage during field vane testing in silty mine tailings and if it can provide more reliable S_u measurements to support safe tailings management.

2 THE A.P. VAN DEN BERG FIELD VANE

2.1 *Development of the A.P. van den Berg Icone Vane*

A.P. van den Berg (APB) is a family-owned company from Heerenveen (The Netherlands) that design and manufacture CPT equipment for both onshore and offshore applications. APB developed their first electric field vane testing tool in 1990. The first model was a stand-alone analogue system, similar to other systems at the time, with the motor and torque load cell located at the ground surface.

In 2012, APB redesigned their vane testing tool to increase the equipment's accuracy and ease of use. The result was the Icone Vane; a fully digital FVT tool with a downhole torque load cell and motor (Figure 1). Having the motor integrated into the down-hole compact housing enables easier, faster, and more accurate operation. The length of the shaft between the vane and the downhole motor and torque load cell is only from 300 mm to 500 mm, which improves measurement accuracy and avoids excessive shaft friction. Heavy-wall CPT push-rods anchor the downhole motor against rotation to essentially eliminate system compliance, such as rod flex. The Icone Vane records torque at 0.1 degree intervals and is housed in a protection tube, allowing it to be directly pushed into soft soil. This advantage means that multiple vane tests can be conducted at different depths (tracked by the device), without the need of retrieving the tool to surface level. This allows rapid vertical profiling of S_u that can be used to compare against CPT data in an adjacent sounding.

During a FVT with the Icone Vane, a digital data logger combines the depth information with the measured FVT torque and rotation. The rotation speed of the Icone Vane in its original form is adjustable from 0.1 %/s to 6.0 %/s. The Icone Vane can be equipped with a range of blade diameters, chosen based on soil type and strength, all of which meet the dimensional requirements of ASTM standard D2573/ D2573M.



Figure 1. The A.P. van den Berg Icone Vane (without protection tube).

2.2 The High-Speed Icone Vane

In response to requests by the mine tailings industry, Gregg Drilling and Testing Canada (Gregg) worked together with APB to develop a field vane tool that maintained the functionality of the original Icone vane, with the ability to provide faster rotational speeds sufficient to overcome partial drainage in silty tailings. The resulting tool was referred to as the “High-Speed Icone Vane”. The High-Speed Icone Vane is the first of its kind and is built upon the success of the “standard” Icone Vane system, with the direct push capability and down hole capacity of applying and measuring torque on an extremely stiff rod system. This modified system retained the precision and versatility of the original system, with the addition of a high-speed drive and a power amplifier. The high-speed vane maintained all dimensional requirements to meet ASTM D2573 guidelines, as well as the torque recording frequency of 0.1 degrees, however, it now offers an improved range of rotational speed up to 60.0 deg/sec. The new High-Speed Icone Vane was introduced in 2021, after a year-long development.

3 METHODOLOGY

3.1 Study Sites

At the time of writing, Gregg had completed deployment of the High-Speed Icone Vane on two geotechnical site investigations, both of which were mine tailings storage facilities. Both sites were base metal mines and had similar tailings compositions. The sites are referred to as “Site A” and “Site B”. The geotechnical site investigations conducted at these sites by Gregg consisted of Piezocone Penetration Testing (CPTu), Pore Pressure Dissipation Testing (PPDT) and Field Vane Testing (FVT). FVTs were done in undisturbed tailings adjacent to CPTu locations. Site A had 2 CPTu locations (CPTA-01 and CPTA-02) with corresponding FVTs, while Site B had 5 CPTu locations (CPTB-01, CPTB-02, CPTB-03, CPTB-04 and CPTB-05) with corresponding FVTs. The FVT tests were carried out within 5m of the adjacent CPTu locations.

3.2 Piezocone Penetration Tests

All CPTu’s in this case study were carried out using standard 15cm² APB piezocones, which had pore pressure sensors located in the u_2 position. CPTu’s were done in accordance with ASTM D5778. During advancement of the piezocone, cone resistance (q_t), sleeve resistance (f_s) and pore pressure (u_2) were measured.

3.3 Pore Pressure Dissipation Tests

During the CPTu soundings, PPDTs were done to measure the time at which 50% of the excess pore water has dissipated from around the cone (t_{50}). The t_{50} values (in units of seconds) obtained from the dissipation tests were used in following equation, described by Robertson (2010), to determine the coefficient of horizontal consolidation (c_h , in units of m^2/s) at that layer/depth:

$$c_h = (1.67 \times 10^{-6}) 10^{(1 - \log t_{50})} \quad (3)$$

For a $15cm^2$ cone, the values of c_h are increased by a factor of 1.5 (Robertson, 1992).

The coefficient of horizontal consolidation was then used to find the coefficient of vertical consolidation using the following equation described by Levadoux and Baligh (1986):

$$c_v = \left(\frac{k_v}{k_h} \right) c_h \quad (4)$$

Where c_v is the coefficient of vertical consolidation, k_v is the vertical coefficient of hydraulic conductivity, k_h is the horizontal coefficient of hydraulic conductivity and c_h is the coefficient of horizontal consolidation. For non-layered soils, a k_h/k_v ratio between 1.0 and 1.5 can be estimated (Jamiolkowski et al., 1985). Phogat et al. (2001) confirmed this in a study that found an average k_h/k_v ratio in loam-free, unlayered sands to be 1.2. Mayne (2011) states that for natural soils similar to tailings, a k_h/k_v ratio of 1.5 is an appropriate estimation, which may be applied to tailings. As the tailings in this study vary in soil behaviour type (SBT), k_h/k_v ratios (and thus, c_h/c_v ratios) of 1.0 and 1.5 are both used to calculate c_v .

3.4 Field Vane Tests

At the test sites, a total of 16 FVTs were completed; 6 at Site A, and 10 at Site B. Of the 16 tests, 7 were done at the ASTM standard rate (0.1 deg/sec), and 9 were done at higher (non-ASTM) rates, varying from 1.0 deg/sec to 13.5 deg/sec. Vane diameters used varied between 40mm, 50mm and 75mm, depending on the predicted strength and soil type. From each FVT, the time to failure, t_f , and peak undrained shear strength, S_u , were recorded. The values for t_f , in combination with the values for c_v (described in Section 3.3), were then used in Equation 2 to determine the time factor, T , for each test. Table 1 shows the depth, diameter of the vane blade used and rotation rate for each FVT done at Site A, as well as the depth of the PPDT assigned using the adjacent CPTu sounding. Table 2 shows the same information for Site B. Only FVTs with a matching dissipation test in the same SBT unit were selected for this case study.

Table 1. Field Vane Tests from Site A.

CPT ID	FVT ID	FVT Depth (m) ^(a)	Vane Diameter (m)	Rotation Rate (deg/sec)	PPDT Depth (m) ^(a)
CPTA-01	FVTA-01-1	16.20	0.040	0.10	15.80
CPTA-02	FVTA-02-1	18.20	0.050	0.10	18.85
	FVTA-02-2	19.50	0.050	4.40	18.85
	FVTA-02-3	20.50	0.050	1.00	21.85
	FVTA-02-4	21.00	0.050	4.00	21.85
	FVTA-02-5	25.40	0.040	0.10	23.61

^(a) Depth as measured from the existing ground surface.

Table 2. Field Vane Tests from Site B.

CPT ID	FVT ID	FVT Depth (m) ^(a)	Vane Diameter (m)	Rotation Rate (deg/sec)	PPDT Depth (m) ^(a)
CPTB-01	FVTB-01-1	5.50	0.040	7.60	5.00
	FVTB-01-2	9.40	0.040	7.90	9.18
CPTB-02	FVTB-02-1	5.00	0.050	13.40	5.00
	FVTB-02-2	5.35	0.075	7.20	5.00
CPTB-03	FVTB-03-1	7.40	0.040	0.10	7.00
	FVTB-03-2	14.70	0.040	0.10	12.00
CPTB-04	FVTB-04-1	9.82	0.050	7.78	9.24
	FVTB-04-2	31.10	0.050	0.10	30.92
CPTB-05	FVTB-05-1	11.70	0.050	9.84	10.54
	FVTB-05-2	29.57	0.050	0.10	28.75

^(a) Depth as measured from the existing ground surface.

4 RESULTS

4.1 t_{50} and Coefficients of Consolidation from PPDT

From the pore pressure dissipation tests at Sites A and B, t_{50} times were determined. The t_{50} times were then used in Equation 3 to calculate the coefficient of horizontal consolidation, c_h . A range in estimated c_v is presented based on c_v/c_h ratios of 1.0 and 1.5. The t_{50} times and calculated c_h and c_v values for Sites A and B are shown below in Tables 3 and 4, respectively.

Table 3. Pore Pressure Dissipation Test Results from Site A.

CPT ID	PPDT Depth (m) ^(a)	t_{50} (s)	c_h (m ² /s)	c_v (m ² /s) ($c_v/c_h = 1.0$)	c_v (m ² /s) ($c_v/c_h = 1.5$)
CPTA-01	15.80	23.00	7.26×10^{-7}	7.26×10^{-7}	7.26×10^{-7}
CPTA-02	18.85	9.00	1.86×10^{-6}	1.86×10^{-6}	1.86×10^{-6}
	21.85	178.00	9.38×10^{-8}	9.38×10^{-8}	9.38×10^{-8}
	23.61	58.00	2.88×10^{-7}	2.88×10^{-7}	2.88×10^{-7}

^(a) Depth as measured from the existing ground surface.

Table 4. Pore Pressure Dissipation Test Results from Site B.

CPT ID	PPDT Depth (m) ^(a)	t_{50} (s)	c_h (m ² /s)	c_v (m ² /s) ($c_v/c_h = 1.0$)	c_v (m ² /s) ($c_v/c_h = 1.5$)
CPTB-01	5.00	34.00	7.37×10^{-7}	7.37×10^{-7}	4.91×10^{-7}
	9.18	2.00	1.25×10^{-5}	1.25×10^{-5}	8.35×10^{-6}
CPTB-02	5.00	36.00	5.57×10^{-7}	5.57×10^{-7}	4.64×10^{-7}
CPTB-03	7.00	9.00	2.79×10^{-6}	2.79×10^{-6}	1.86×10^{-6}
	12.00	2.00	1.25×10^{-5}	1.25×10^{-5}	8.35×10^{-6}
CPTB-04	9.24	28.00	8.94×10^{-7}	8.94×10^{-7}	5.96×10^{-7}
	30.92	1026.00	2.45×10^{-8}	2.45×10^{-8}	1.63×10^{-8}
CPTB-5	10.54	22.00	1.14×10^{-6}	1.14×10^{-6}	7.59×10^{-7}
	28.75	864.00	3.30×10^{-8}	3.30×10^{-8}	2.20×10^{-8}

^(a) Depth as measured from the existing ground surface.

4.2 Peak Undrained Shear Strength and Times to Failure from FVT

The peak S_u measured and the resulting time to failure for each of the 16 FVTs are listed in in Table 5. Peak S_u values ranged from 6.88 kPa to 270.60 kPa, and times to failure varied from 1.35 seconds to 255.00 seconds.

Table 5. Field Vane Test Results and Times to Failure.

FVT ID	Peak S_u (kPa)	t_f (s)
FVTA-01-1	270.60	220.00
FVTA-02-1	38.30	120.00
FVTA-02-2	78.90	4.21
FVTA-02-3	42.90	12.50
FVTA-02-4	58.00	178.00
FVTA-02-5	59.20	255.00
FVTB-01-1	60.07	2.21
FVTB-01-2	58.50	1.87
FVTB-02-1	6.88	2.15
FVTB-02-2	24.97	2.11
FVTB-03-1	29.95	110.00
FVTB-03-2	84.08	114.00
FVTB-04-1	56.83	1.62
FVTB-04-2	42.33	70.00
FVTB-05-1	77.23	1.35
FVTB-05-2	54.77	93.00

During the FVTs, shear generally occurred within the first 20 degrees of the test. Two examples shown below in Figure 2 represent typical S_u profiles produced from field vane tests using the standard Icone Vane and the High-Speed Icone Vane.

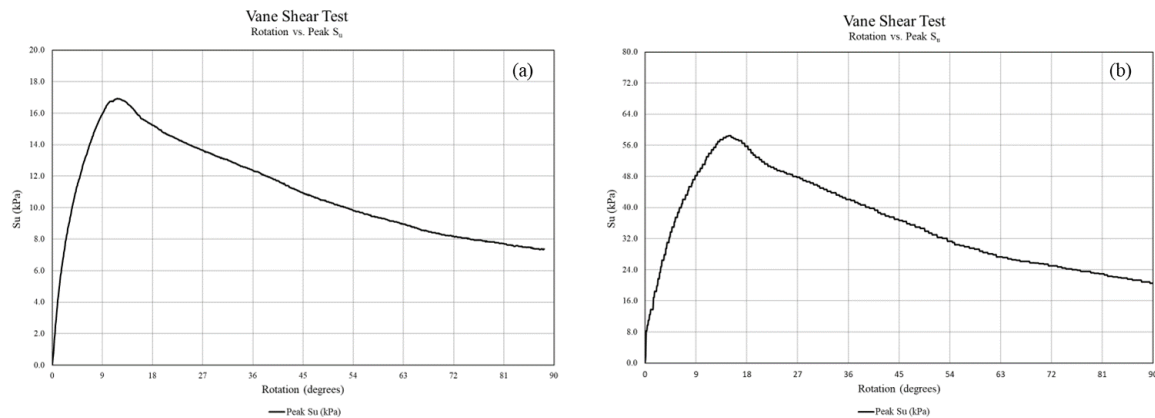


Figure 2. Example S_u profiles resulting from FVTs done with the Icone Vane. The profile on the left (a) used the standard Icone vane and rotated at the ASTM standard rate of 0.1 deg/sec. The profile on the right (b) used the High-Speed Icone vane and rotated at a rate of 7.9 deg/sec.

4.3 Time Factors

Using the times to failure listed in Section 4.2, the coefficients of vertical consolidation from Section 4.1 and the diameters of the vane blades, time factors (T) were calculated for each FVT. When a c_h/c_v ratio of 1.0 was used, the average time factor for ASTM tests was 0.20541, while the average time factor for high-speed tests was 0.00259. When a c_h/c_v ratio of 1.5 was used, the average time factor for ASTM tests was 0.13694 and the average time factor for high-speed tests

was 0.00173. Time factors calculated for FVTs when a c_h/c_v ratio of 1.0 was used, compared to time factors calculated for FVTs when a c_h/c_v ratio of 1.5 was used, are shown in Figure 3.

Of the 7 ASTM standard FVTs, only 2 plotted within Blight's (1968) threshold for undrained conditions of $T < 0.02$. This is true for T values calculated using both a c_h/c_v ratio of 1.0 and a c_h/c_v ratio of 1.5. When considering Chandler's (1988) threshold for undrained conditions of $T < 0.05$, 2 of the ASTM standard tests plotted as undrained when a c_h/c_v ratio of 1.0 was used, and 3 of the ASTM standard tests plotted as undrained when a c_h/c_v ratio of 1.5 was used. That equates to a 29% success rate for achieving undrained conditions when using a threshold of $T < 0.02$, and a 29% - 43% success rate when using a threshold of $T < 0.05$, depending on the c_h/c_v ratio.

Of the high-speed FVTs, all 9 plotted within the $T < 0.02$ threshold for undrained conditions. Thus, there was a 100% success rate in maintaining undrained conditions when using the high-speed method, regardless of the threshold used.

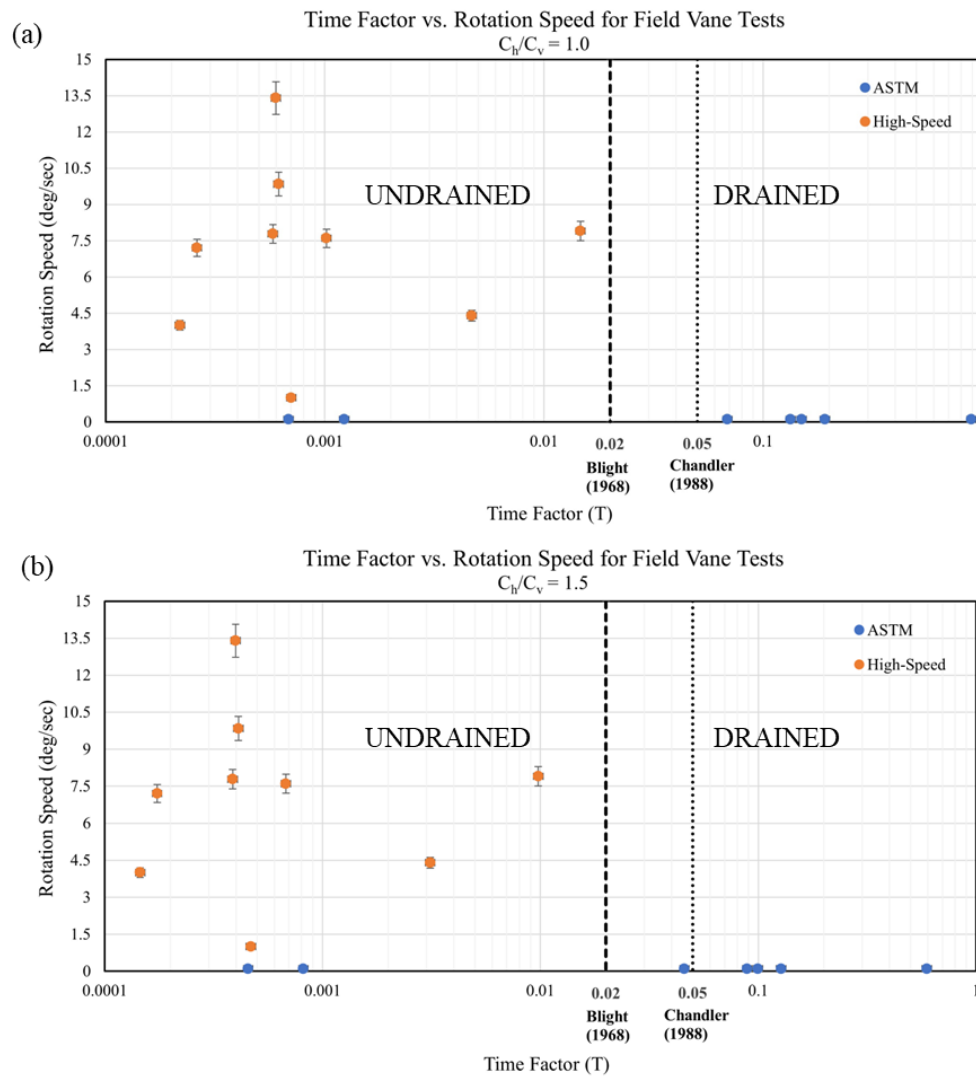


Figure 3. Time factors vs. rotation speed during FVTs. The plot on the top (a) shows resulting T s when a c_h/c_v ratio of 1.0 was used, while the bottom plot (b) shows resulting T s when a c_h/c_v ratio of 1.5 was used. Blue circles represent FVTs done at ASTM standard rate of 0.1 deg/sec and orange circles represent FVTs done at high-speeds (>0.1 deg/sec). Blight's (1968) threshold for undrained conditions is represented by the thick dotted lines, while Chandler's (1988) threshold for undrained conditions is represented by the thinner dotted lines. Results are displayed with 5% error.

5 APPLICATION

In 1992, Robertson et al. evaluated drainage effects during CPTu penetration. The study concluded that partial drainage occurs during a CPTu when t_{50} dissipation times are less than 0.5 minutes (30 seconds). Using the theoretical solution by Teh & Houlsby (1991), Robertson et al. (1992) generated a chart for evaluating c_h using t_{50} determined from pore pressure dissipation tests, for both 10cm² and 15cm² cones. Below, that chart has been modified to include time to failure. Time to failure is determined by re-arranging Equation 2:

$$t_f = \frac{T(D^2)}{c_v} \quad (5)$$

Where T is the dimensionless time factor, c_v is the coefficient of vertical consolidation, t_f is the time to soil failure/shear and D is the vane diameter. To generate the theoretical plots in Figures 4 and 5, T is assumed to be equal to Chandler's (1988) threshold for undrained conditions, 0.05. As the difference in the consolidation ratio has been shown to have minimal effect, c_v is set to be equal to c_h .

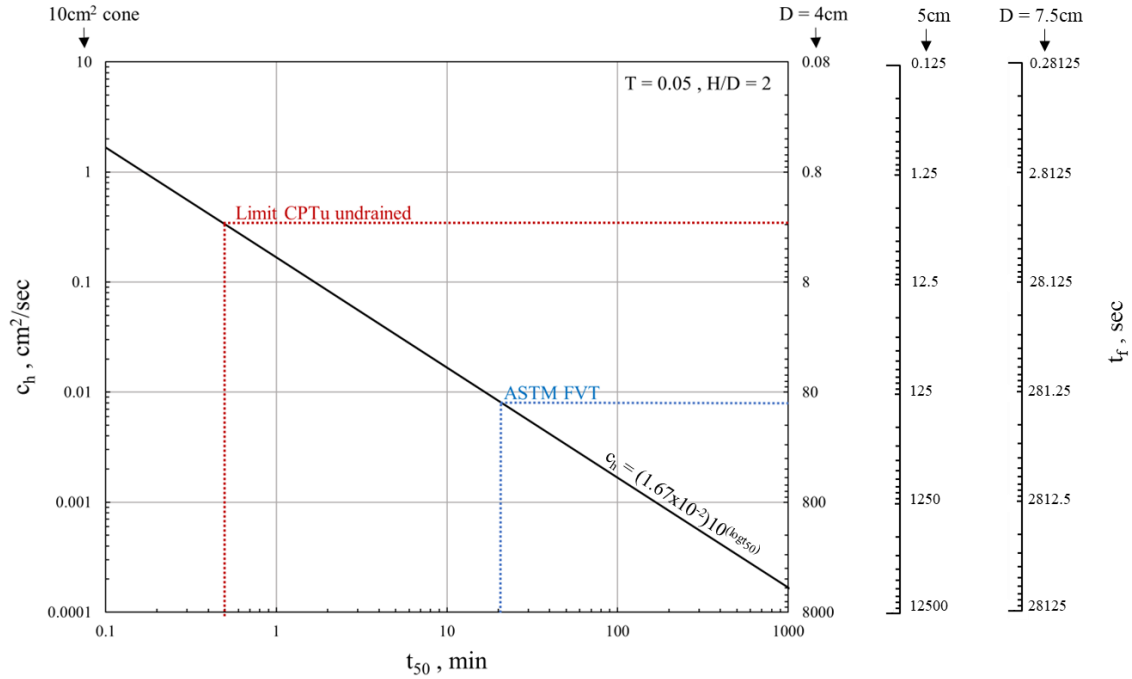


Figure 4. Modified chart from Robertson et al. (1992) showing the relationship between t_{50} , c_h and t_f when conducting dissipation tests with a 10cm² cone. Scales for t_f are displayed for vanes with 4cm, 5cm and 7.5cm diameters. The red dashed line shows the limit of undrained CPTu (Robertson, 1992), and the blue dashed line shows the limit for undrained conditions during an ASTM FVT. The solid line on the graph represents the equation for c_h , in cm²/sec.

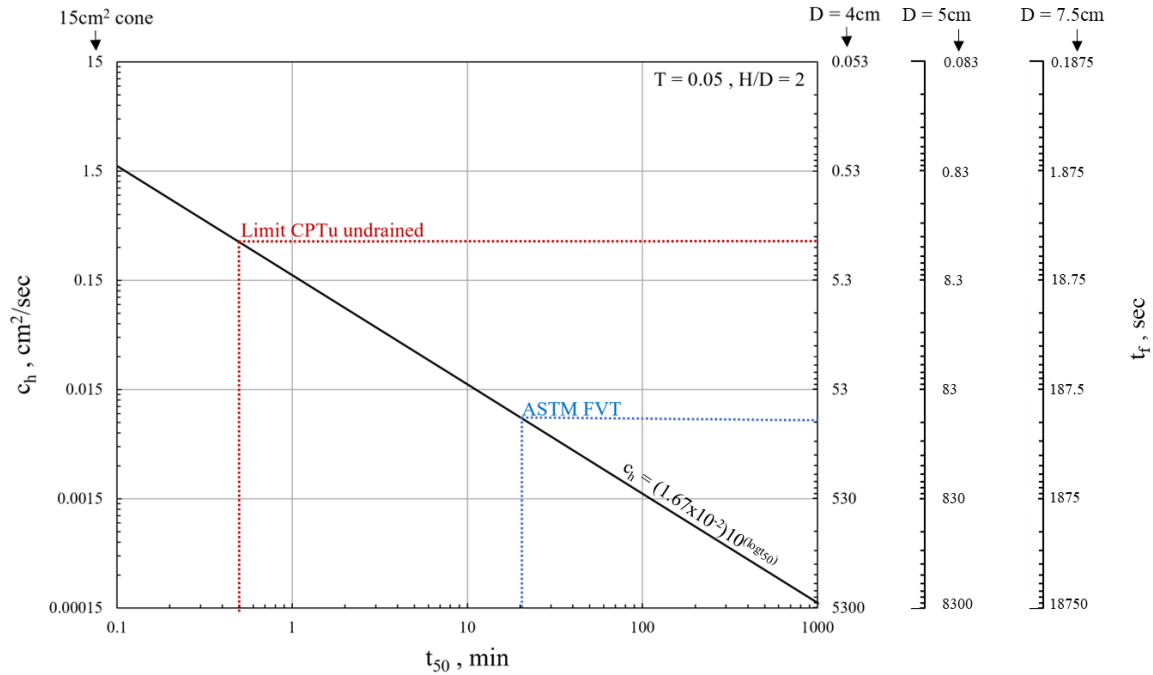


Figure 5. Modified chart from Robertson et al. (1992) showing the relationship between t_{50} , c_h and t_f when conducting dissipation tests with a 15cm^2 cone. Scales for t_f are displayed for vanes with 4cm, 5cm and 7.5cm diameters. The red dashed line shows the limit of undrained CPTu (Robertson, 1992), and the blue dashed line shows the limit for undrained conditions during an ASTM FVT. The solid line on the graph represents the equation for c_h , in cm^2/sec .

Figures 4 and 5 show the limit of the ASTM FVT in obtaining undrained conditions, compared to that of the CPTu. Using the above plots, t_{50} values measured from a dissipation test in the target material can be used to determine if the ASTM rate will suffice for maintaining undrained conditions during a FVT. Furthermore, the equation shown in Figures 4 and 5 relates t_{50} dissipation time to t_f . If failure/shear during a FVT is assumed to occur at 10 degrees, the minimum rotation rate required to obtain undrained conditions in that material can be estimated:

$$\text{Minimum rotation rate} = \frac{d_f}{t_f} \quad (6)$$

Where d_f is the degrees of rotation at which failure occurs, assumed for this purpose to be 10, and t_f is the time to failure.

6 DISCUSSION

The results above show that FVTs done at high-speed using the High-Speed Iconic Vane were 100% effective in maintaining undrained conditions, while the majority of tests done at the ASTM standard rate showed evidence of partial drainage. Although a range in coefficient of consolidation ratios (1.0 - 1.5) were used to maximize confidence in the results for T , assuming consolidation ratios inevitably introduced some uncertainty. However, the resulting difference in T values, as displayed in Figure 3, is minimal and does not significantly change the drained vs. undrained designation for the FVTs in this study. These results suggest that the c_h/c_v ratio may not be as important as suggested by others. In circumstances where the c_h is larger than the c_v , consolidation is controlled by c_h (Teh & Houlsby, 1991). The vertically dominant dimensions of the field vane ($H/D = 2$) mean drainage is likely more controlled by c_h , making small differences

in c_v values negligible to drainage conditions. Therefore, estimating a reasonable value for the consolidation ratio should suffice.

The results from this study support recent studies (Reid, 2016; Mundle et al., 2019; Okkels & Anderson, 2019; Contreras & Harvey, 2021) in the claim that the ASTM standard rotation rate is not sufficient to ensure undrained conditions are met during FVTs in silty mine tailings, and thus, cannot be relied upon to yield true measurements of S_u . If rotation rates are increased to avoid partial drainage as shown, the results can significantly improve the reliability of S_u measurements in mine tailings.

This was a preliminary study, meant to field test the ability of the high-speed vane and is therefore a very limited dataset. This was not intended to be a systematic study comparing S_u measurements resulting from different rotation rates. Subsequent studies are still required to determine the most appropriate rotation rate for field vane testing in mine tailings. Figures 4 and 5 suggest a theoretic approach to determining the rotation rate required for a FVT, however this approach will need to be validated with further field testing and studies. The High-Speed Icone Vane offers a versatile range in rotation rates up to 60 deg/sec. This versatility provides the opportunity to build upon previous studies which were limited by rotation rate (e.g. Contreras & Harvey, 2021) and to perform comprehensive studies to aid in the development of a standardized method for FVTs in mine tailings.

7 CONCLUSIONS

The novel down-hole digital High-Speed Icone Vane described in this paper was a result of requests from the tailings industry to provide a system purpose-built for the challenges of characterizing the undrained behaviour of silty tailings. In this comparative study, FVT data collected using a range of rotation rates from 0.1 deg/sec to 13.5 deg/sec from two mine sites was used. Only FVTs done at high speeds (>0.1 deg/sec) consistently yielded time factors within the threshold for maintaining undrained conditions throughout the test. The High Speed Icone vane provides rotation rates sufficient to overcome partial drainage and produce more accurate S_u measurements in silty material, making it an effective method for assessing the undrained strength of mine tailings. The high-speed vane expands the applicability of the FVT, and with it, soils up to the same undrained limit of the CPT can be tested.

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