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Effects of vane size and aspect ratio on the measurement of undrained shear strength of a fine-grained soil

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ABSTRACT

The field Vane Shear Test (VST) is a widely used in-situ test method to measure undrained shear strength and sensitivity of saturated, fine-grained soils. The United States Bureau of Reclamation (Reclamation) commonly performs this test method to help inform numerical modeling of earth embankment dams when undergoing a risk analysis or design. Although the test method itself has been a geotechnical tool for quite some time, its primary use has traditionally been limited to sites with soft and/or relatively shallow clay soil. Typically, embankment and foundation materials of interest at Reclamation facilities are at greater depths, under higher effective stresses, and can be relatively stiff. Testing of stronger soils poses issues when performing the VST; typical commercially available equipment has a limited torque capacity to cause yielding of the soil. As a solution, modifying the dimensions and aspect ratio of the vane is an economic means of increasing the measurable range of undrained strength. Yet, the effects of these modifications are not well understood. Soil strength anisotropy is one of the primary components of this uncertainty. Testing on a sandy lean clay has been conducted to enable side by side comparisons of traditional aspect ratio vanes versus the proposed modified vanes to quantify the potential differences in measured undrained strength. In addition, measured undrained strengths from the various vanes are compared to results of laboratory testing on the same sandy lean clay (i.e., direct simple shear and triaxial compression) to provide a better understanding of the differences between the in-situ and laboratory test methods. This paper presents the apparatus developed to allow full scale vane shear tests to be conducted in the laboratory and summarizes the results of tests on a normally consolidated sandy lean clay.

Keywords: vane shear test; undrained shear strength; soil anisotropy; fine-grained soil; vane dimensions.

1. Background

The field VST was developed in Sweden during the early 1900s (Wroth, 1984) and has since been standardized through various organizations. Although Reclamation adopted and revised an internal standard test method for field VST, its latest revision was published in the early 1990s (Earth Manual, 1990). This publication is device specific and did not include electro-mechanical systems that are often used today. Currently, Reclamation follows the ASTM International standard D2573/D2573M-18 – Standard Test Method for Field Vane Shear Test in Saturated Fine-Grained Soils (D2573), (ASTM, 2024) when performing field VST due to its on-going, active revision process through consensus balloting and incorporation of modern techniques.

1.1. Vane Dimensions

Although D2573 allows the use of vane aspect ratios ranging from 1:1 to 2.5:1 (height:diameter), much of the literature and development of the vane test was based on tests performed with the 2:1 vane. Chandler (1988) recommended that the 2:1 vane be considered as the only acceptable standard. Similarly, Reclamation methods (Earth Manual, 1990) only allow the use of 2:1 vanes, so historical testing performed by the agency is limited to their use. Further, vane diameters within a given aspect ratio may range from 1.5 to 4.0 inches (about 35 to 100 mm) per D2573, but it is generally assumed that size is selected based on soil strength (and subsequently the VST torque system capacity) and should not influence the results of the test. Reclamation is seeking to understand the effects of vane size and aspect ratio on the measurement of undrained shear strength (or simply referred to as undrained strength), specifically to reduce uncertainty in the use of smaller vanes to test stiffer soils.

1.2. Field Applications

The VST has been primarily used to evaluate the undrained strength of relatively low to medium strength, saturated, fine-grained soils (Wroth, 1984). This is partly because the 2:1 aspect ratio and practical vane diameters typically used require a significant amount of torque to fail relatively strong soils. D2573 states that the test method is only applicable to materials with undrained strengths less than 4,000 lbf/ft^2 or about 200 kilopascals (kPa). Reclamation is often interested in testing compacted embankment fill and foundation units having undrained strengths in excess of this value. Although other methods of measuring undrained strength are often utilized (e.g., CPT, Direct Simple Shear, Triaxial Compression), VST can offer another valid dataset and is economical to perform while advancing drill holes for soil sampling. With the limited torque capacity of commercially available devices that offer high resolution data acquisition, the use of smaller vanes and aspect ratios offer an attractive solution to obtaining valid measurements in stronger soils.

1.3. Previous Studies and Literature

Several studies have been conducted to investigate the effect of vane size and aspect ratio on the measurement of undrained strength from the field VST. However, these studies were inherently investigating soil anisotropy of in-situ materials. While in-situ testing is significant for site specific investigations, it does not necessarily provide ideal conditions for evaluating the effects of vane size and aspect ratio. Natural variations in deposition (potential drainage paths), fissuring, and structuring in soils are variables that can affect the field VST results, making it difficult to discern trends solely due to differences in the vane. It is the purpose of this study to identify the effect of vane size and aspect ratio solely on the measured undrained strength through control of other influencing variables. To further identify confidence in the findings of this paper, or lack thereof, the following literature has been considered:

Aas (1965) investigated the possibility of measuring anisotropy of the undrained strength of a highly sensitive normally consolidated clays using vanes of different shapes. Soil strength anisotropy was believed to be the reason why laboratory tests performed on the sensitive clay deposit consistently resulted in higher undrained strengths than the field VST. This was not typical in other studies as later explained by Law (1979) and experiences within Reclamation, which have generally observed higher values obtained from field VST when compared to lab testing. Aas's analysis utilized the assumption of a perfectly cylindrical failure surface to derive the ratio of the shear strength on the horizontal plane vs. the vertical plane (i.e., anisotropy). The results from utilizing vanes with variable vertical and horizontal shear areas showed anisotropy ratios ranged from 1.5 to 2.0 for the normally consolidated material.

Donald et al. (1977) investigated the effects of vane size and aspect ratio as part of an anisotropic strength analysis on two highly plastic clays. Further, a finite element analysis was conducted to better understand the actual stress distribution imposed on the soil through differences in vane geometry. It was concluded that the use of vanes with larger aspect ratios resulted in higher peak strengths than smaller aspect ratios having the same diameter. Furthermore, finite element analyses showed a roughly parabolic stress distribution across the top and bottom of the vane and that the side of the vane had significantly higher shear stresses at the ends than in the center.

Law (1979) developed a laboratory based VST using a triaxial chamber and miniature vane device. The study did not focus on using vanes of different sizes/aspect ratios, rather on the effects of consolidation stresses on relatively small triaxial specimens. Therefore, only very small 2:1 vanes were utilized. An important finding with the limited data was that the measured undrained strength was fairly independent of vertical consolidation stresses, but relatively dependent on horizontal consolidation stresses. Wroth (1984) expands on this idea and states that when assuming a cylindrical failure surface on a 2:1 vane, 86% of the shearing resistance is in the vertical plane (horizontal consolidation stresses being the principal normal stress on this plane). This value increases to 94% when non-uniform stress distributions are considered. He suggests studying soil anisotropy with the vane has limited applications due to this fact, whom Donald et al. (1977) agree. Chandler (1988) goes on to summarize Wroth's findings and much of the vane research performed to date, making it a convenient reference used in D2573.

More recent considerations include Stark & Contreras (1998) who investigated the 4th Ave landslide from the 1964 Alaskan earthquake where slip surfaces occurred in the Bootlegger Cove Clay. They recommend that vanes should have a 2:1 aspect ratio. They also found that the VST affords an accurate means to assess residual strength provided that at least 10 revolutions be used ensure that the residual state has been reached.

2. Methods

To investigate the effects of vane size and aspect ratio on VST measurements of undrained strength, a custom apparatus was designed and commissioned to test consolidated soil specimens in the laboratory at a larger scale than performed by Law (1979). Although lab based VST is common and has a separate ASTM International standard test method from field VST (ASTM D4648/D4648M-16), the test is performed on unconsolidated soil specimens (i.e., no principal stresses are applied prior to shearing), unlike field VST which is performed on materials in-place, typically consolidated under the in-situ effective stresses. Further, D4648 testing is performed on relatively small soil specimens requiring the use of much smaller vanes than those used in D2573. Therefore, use of the typical lab-based approach as a method for this research was not desirable. Rather, an apparatus was developed by Reclamation using a commercially available loading frame, commercially available VST torque device and in-house fabrication of a soil mold and components.

2.1. Laboratory Based Apparatus

As shown in Fig. 1, the apparatus was designed such that an approximately one cubic foot (0.03 m^3) soil specimen could be consolidated, and principal stresses maintained during to the insertion and rotation of a vane.

The control of the testing apparatus, soil preparation, consolidation process and testing procedures allowed for repeatability of the lab based VST while mimicking field conditions and evaluating the effects of realistic vane sizes used in the field. The apparatus consists of a 10,000-lbf (45-kN) load frame, axial load cell, axial LVDT, soil specimen box, sintered metal porous media filters, top platen, moment break, drainage pipette, VST torque device, vanes, and large C-clamps.

Note that the top porous media filter and top platen were machined to accept the vane during insertion while still maintaining axial load on the soil specimen. The vane-shaped void in the platen was plugged using a 3D-printed insert during the consolidation phase.

Figure 1. Lab based VST apparatus during consolidation

2.2. Vanes

The vanes used for testing had squared ends (i.e., no significant taper) with diameters ranging from 1.0 to 3.0 inches (25 to 75 mm), in 0.5-inch (13 mm) increments. Three aspect ratios were utilized: 2:1, 1:1, 0.5:1. Each vane was measured to provide accurate inputs for the average height and diameter used in the shear strength calculations. The nominal geometry of the vanes used for testing is presented in Table 1. Fig. 2 showcases the range of 1:1 vanes used for testing as a visual reference.

Table 1. Vane Geometry

Nominal Vane Size D x H (in)	Aspect Ratio (H:D)	Nominal Vertical Area (in^2)	Nominal Horizontal Area (in^2)	V:H Area (-)
3 x 6	2	56.55	13.84	4.09
3 x 3	1	28.27	13.84	2.04
3 x 1.5	0.5	14.14	13.84	1.02
2.5 x 5	2	39.27	9.52	4.13
2.5 x 2.5	1	19.63	9.52	2.06
2.5 x 1.25	0.5	9.82	9.52	1.03
2 x 4	2	25.13	5.98	4.20
2 x 2	1	12.57	5.98	2.10
2 x 1	0.5	6.28	5.98	1.05
1.5 x 3	2	14.14	3.23	4.38
1.5 x 1.5	1	7.07	3.23	2.19
1.5 x 0.75	0.5	3.53	3.23	1.09
1 x 2	2	6.28	1.27	4.94
1 x 1	1	3.14	1.27	2.47
1 x 0.5	0.5	1.57	1.27	1.24

Figure 2. 1:1 aspect ratio vanes

2.3. Subject Material

Initial testing has been performed on a residual soil from northern California, U.S.A., obtained in bulk during a borrow source investigation. The soil was first screened over a No. 4 (4.75 mm) U.S. Sieve and blended to create a homogenous composite sample. Specimens were tested for particle size distribution, plasticity, and specific gravity. The material classifies as a CL – sandy lean clay according to the Unified Soil Classification System (USCS) with a fines content (passing the No. 200 U.S. Sieve, 0.075 mm) of 55%, a Liquid Limit (LL) of 41, and Plasticity Index (PI) of 18. Specific gravity of the material is 2.75. The coefficient of vertical consolidation (c_v) is 0.53 ft^2/day (18 m^2/year), and the coefficient of vertical hydraulic conductivity (k_v) is 2.53E-08 ft/s (7.72E-07 cm/s).

2.4. Testing Procedure

2.4.1. Specimen preparation

The goal of the specimen preparation and placement procedure was to create uniform, repeatable, normally consolidated and saturated specimens. The subject material was blended with a small rototiller device and moisture conditioned to an average initial water content of about 27%. The water content was chosen through trial and error to optimize workability without excessive pumping and promote higher initial specimen saturation. The material was then manually compacted (i.e., tamped) in lifts within the soil specimen box containing the bottom porous media filter to an average initial dry unit weight of about 97 lbf/ft^3 (15.4 kN/m^3). This resulted in an average initial degree of saturation of about 98%. The top porous media filter, top platen, and moment break were then placed on the soil specimen and the soil specimen box was hoisted into the load frame to commence consolidation.

2.4.2. Consolidation

Upon seating of the load cell and configuration of the LVDT, a target vertical consolidation stress of 1 atmosphere (about 2,120 lbf/ft^2 or 100 kPa) was applied to the soil specimen in three increments using the load frame. Applied loads were doubled between increments. This loading sequence and consolidation stress resulted in normally consolidated soil specimens given the initial water content and relatively low compactive effort used during specimen preparation. Axial deformations of the soil specimens were monitored using the LVDT to ensure primary consolidation was complete and that a well-defined state of secondary consolidation was established for each load increment before increasing to the next load. During consolidation, drainage ports were left open and porous media filters (top and bottom) had free access to water at atmospheric pressure, essentially submerging the specimen. This allowed for pore volume change and encouraged saturation of the soil specimens. Axial deformations were used to determine post-consolidation dry unit weight and degree of saturation of the specimens. Post-consolidation, the average water content was about 24% with an average dry unit weight of about 106 lbf/ft^3 (16.7 kN/m^3). This resulted in an average calculated degree of saturation of about 105%. These values are approximate due to small errors in specimen measurements and assumptions as well as small losses of soil due to extrusion between and around the platens and porous media filters.

2.4.3. Vane Insertion

Post-consolidation, prior to removing the axial load applied by the load frame, four large C-clamps were secured to the corners of the top platen and bottom of the soil specimen box to maintain a constant volume of the specimen and to maintain the applied consolidation stress (Fig. 3). The 3D printed top platen insert was removed to expose a small portion of the soil specimen and allow for insertion of the vane (Fig. 4). The lower drainage port was the closed. The vane was attached to a small rod and driven into the specimen using the cross member of the load frame (Fig. 5). The vane advancement was measured such that the vane was approximately vertically centered in the soil specimen (i.e., distances to the porous media filters above and below the vane were equal).

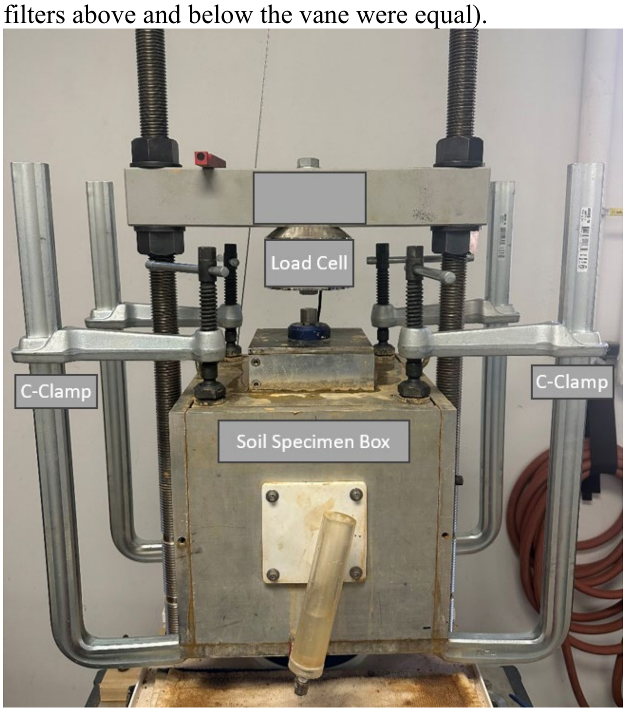

Figure 3. Lab based VST apparatus post-consolidation after attaching C-clamps

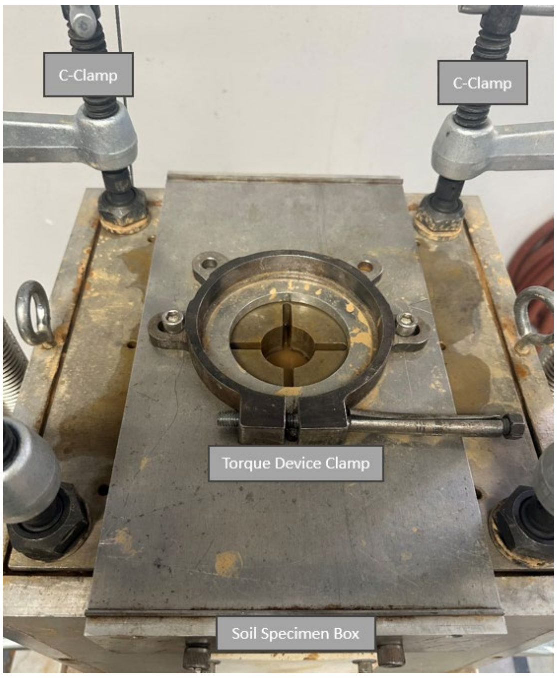

Figure 4. Lab based VST apparatus prior to vane insertion

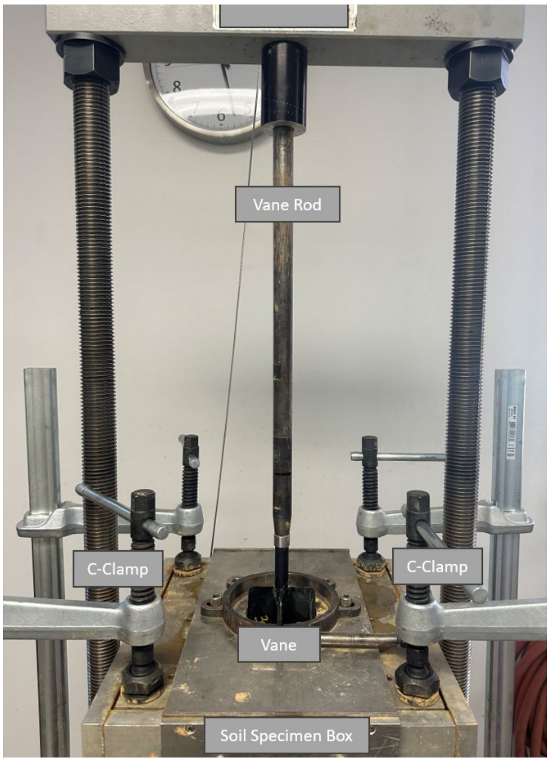

Figure 5. Lab based VST apparatus during vane insertion

2.4.4. Shearing

Once the vane was inserted, the VST torque device was quickly secured in place over the vane rod and rotation of the vane rod commenced within 5 minutes, per D2573. The rotation rate was fixed within a range of 6 to 7 degrees/minute, which is the upper limit of the recommended rate in D2573.

The VST torque device was electronically connected to a computer containing data acquisition software to monitor the test. Shearing of the soil continued until a clear peak in measured torque was observed, indicating that the peak undrained strength of the specimen was mobilized. The test was then repeated twice to obtain post-peak undrained strengths per the following sequence. The vane rod was manually rotated one additional revolution (360 degrees) to obtain an undrained strength dubbed "remolded." Once complete, the vane rod was manually rotated ten additional revolutions (3,600 degrees) to obtain an undrained strength dubbed "residual." After the more than eleven total vane revolutions, the soil was assumed to be in a fully residual state as suggested by Stark & Contreras (1998).

Note that in a traditional field VST, where more significant lengths of the vane rod are in contact with the soils, the use of a slip coupling device is employed to measure rod friction prior to the rotation of the vane. D2573 does not require a slip coupling device when using retractable vanes in the field which typically only expose about 14 to 20 inches (350 to 500 mm) of vane rod, stating that the friction is negligible. The exposure of the vane rod in the lab based VST apparatus was significantly less than 14 inches. Therefore, rod friction was deemed negligible, and a slip coupling was not used.

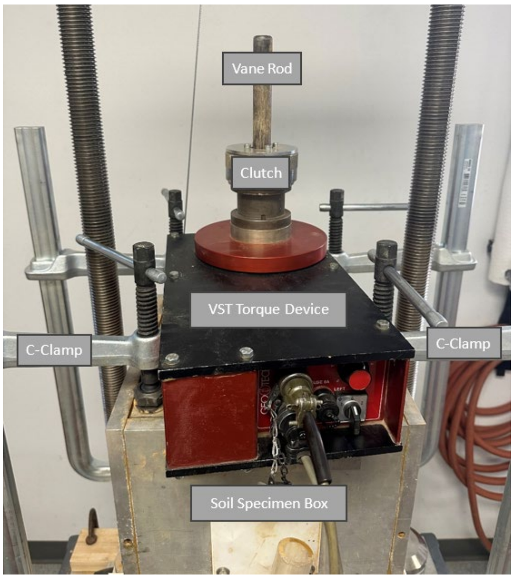

Figure 6. Lab based VST apparatus during shear phase

3. Results

At the time of this paper, 62 tests were completed using 15 different vane configurations (five different vane diameters for aspect ratios of 2:1, 1:1, and 0.5:1). The 0.5:1 vane testing is still in progress, and therefore the dataset presented is limited. All calculations of undrained strength were performed under the assumption of a uniform cylindrical failure surface using equations presented in D2573. Corrections for plasticity, overconsolidation ratio, and time to failure have not been performed – presented undrained strengths are based on raw measurements.

For the purposes of this paper, peak and residual undrained strength, vane size, and vane aspect ratio were considered. In addition, the subject material was tested for peak undrained strength using traditional laboratory methods for comparison (i.e., DSS and Triax).

Despite careful efforts to create identical specimens, variations in specimen properties were observed. Some tests have been eliminated from the following analysis due to such properties as dry unit weight, water content, and axial strain during consolidation being greater than one standard deviation away from the mean. Further, some tests were deemed outliers based on measured strengths or time to failure being outside of reasonably expected variations. Based on analysis of time factors (*T*) determined from c_v, time to failure, and relationships presented by Chandler (1988), there may be slight effects of partial drainage in the 1.0 and 1.5-inch diameter vanes, where *T* averaged 0.19 and 0.10 respectively. The average of *T* was 0.06 for all other vane sizes, suggesting undrained loading. Further, soil boundary effects on tests performed with the larger vanes were considered, but no conclusive evidence of significant influences were observed.

Of the 62 tests performed, 42 have been included in the analysis. Figure 7 shows all test data for peak and residual undrained strength, with data points removed from the analysis shown as open symbols.

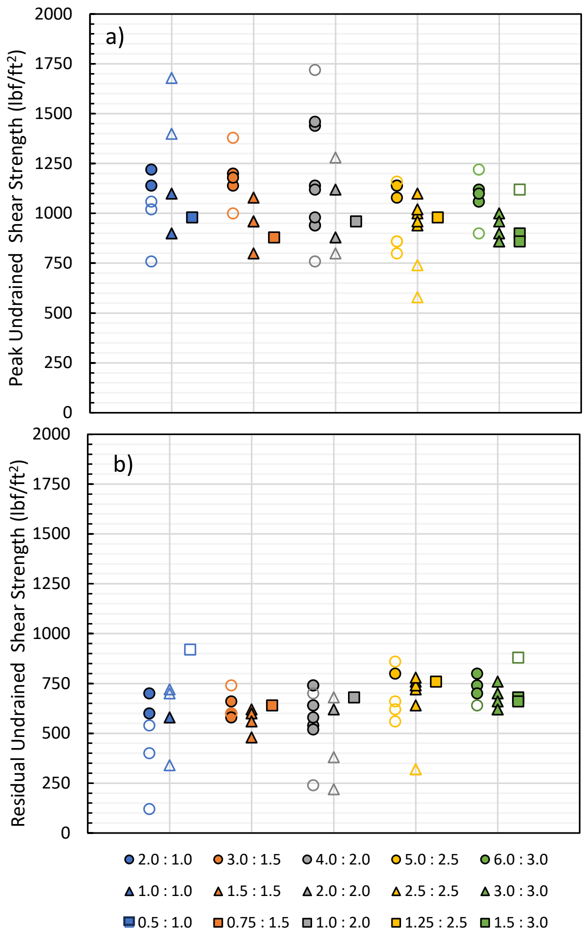

Figure 7. Peak, a) and residual, b) undrained strength vs. vane dimension

3.1. Variable Vane Diameter

The results of the testing were evaluated by varying the vane diameter and keeping the aspect ratio constant. Measured peak and residual undrained strengths were averaged for each vane diameter, respectively. As observed in Fig. 8, there is a clear trend of decreasing peak undrained strength with increasing vane diameter for all aspect ratio vanes. The opposite trend is observed for residual strength and is remarkedly similar among all aspect ratios.

The trend in peak undrained strength is most prominent with the 2:1 vanes. The data shows the reduction in measured peak strength is about 7%, and the increase in measured residual strength is about 13% from the 1-inch to the 3-inch diameter vane. Further, although the dataset for the 0.5:1 is limited, the similarity in trend in peak strength is remarkedly similar to that of the 1:1 vanes as later shown in Fig. 12.

The opposite trends between peak and residual strength have compounding effects on the calculation of sensitivity. Although the material tested is not considered very sensitive (values between 1.2 and 1.8), the inferred reduction in sensitivity was as high as 39% in some cases. Speculation into reasons for the trend of increasing residual strength with increasing vane diameter appears to be convoluted and warrants further investigation.

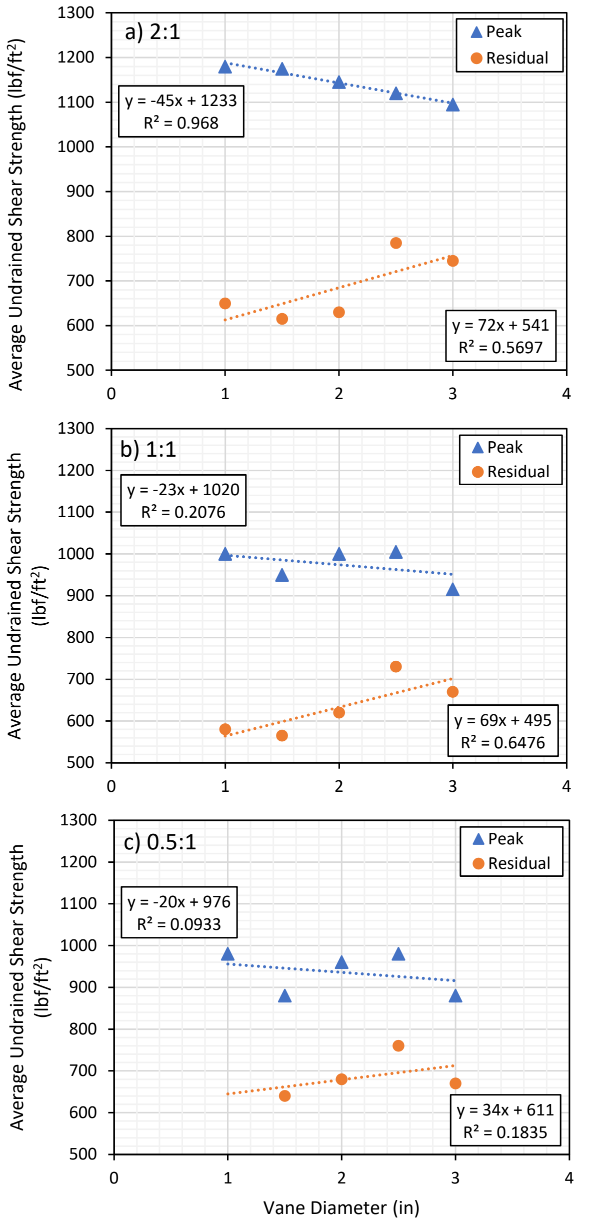

Figure 8. Average undrained strength vs. Vane diameter: a) 2:1 aspect ratio, b) 1:1 aspect ratio, c) 0.5:1 aspect ratio

When considering the trend in peak strength, it can be purported that when vane aspect ratio remains constant and the vane diameter is increased, both the vertical and horizontal areas increase. Their ratio (V:H), shown in Table 1, decreases by about 17% over the span of the 1-inch to 3-inch diameter vane for all aspect ratios. In turn, more of the shear stress is distributed on the horizontal plane. Further considering the theory of non-linear stress distribution, it is expected that the magnitude of the horizontal shear stress increases more significantly with changes in the diameter of the vane (polynomial function depending on D/2), than does the vertical shear stress with changes in height (Wroth 1984). As a result of geometry and stress distribution, an increasing proportion of the peak stress is attributed to the resistance on the horizontal plane when the diameter increases. In turn, this reduces the measured peak undrained strength due to soil anisotropy. Further analyses using non-uniform stress distributions may provide better explanations for the trends.

Disturbance effects due to vane insertion were considered, given that the vane area ratio (described in D2573) was relatively high in the smaller diameter vanes used since the vane blade thickness remained constant. Cerato and Lutenegger (2004) have observed that a greater vane area ratio and perimeter ratio should cause a decrease in measured peak strength. However, this relationship was not observed for this testing. Vane area ratio and perimeter ratio were significantly greater in the smaller diameter vanes, yet use of the smaller vanes resulted in greater peak strengths. It is believed that soil anisotropy had a greater effect on measurement of undrained strength than vane disturbance for this testing. Further, vane disturbances were likely low given the low sensitivity of the subject material. If disturbances were in effect, the trends in the reduction of peak strength may have been more drastic if area and perimeter ratios were reduced for the smaller vanes.

3.2. Variable Vane Aspect Ratio

The results of the testing were further evaluated by varying the aspect ratio of the vanes and keeping the diameter constant. The average undrained strengths previously presented were normalized to observe relative trends when the aspect ratio was reduced. As such, the 2:1 vane was used as the basis of normalization for each vane diameter as shown in Fig. 9.

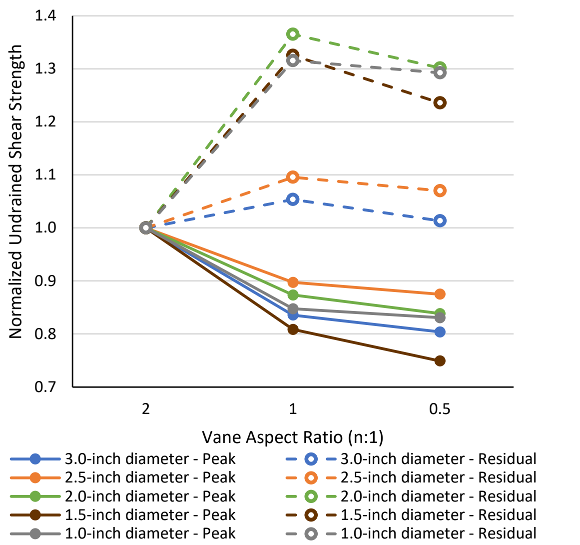

Figure 9. Normalized peak and residual undrained strength vs. vane aspect ratio for all vane diameters

There is a clear trend for all vane diameters showing that vanes of larger aspect ratios result in higher measurements of peak undrained strength compared to vanes of smaller aspect ratios. The reduction in measured peak strength from 2:1 to 1:1 vanes ranged from 10 to 19% with an average of 15%. The reduction in measured peak strength from 2:1 to 0.5:1 vanes ranged from 13 to 25% with an average of 18%. Therefore, differences between the peak strength measured with 1:1 vs. the 0.5:1 are much less significant and only averaged 3%. The reduction in peak strength showed no correlation regarding vane diameter when specifically looking at aspect ratio.

Findings presented by Donald et al. (1977) further support these results, concluding that testing with vanes of larger aspect ratios resulted in higher measurements of peak undrained strength than those with smaller aspect ratios. Further, Donald attributes these differences to compensating effects which exist between vanes of the same diameter but different heights. In these cases, the stress distribution mobilized along the vertical shear surface is greater for those vanes which have a greater height. Therefore, aspect ratio appears to have a more significant impact on the measurement of peak undrained strength than vane diameter, as supported by the data.

Disturbance effects due to vane insertion were assumed negligible when considering changes in the vane aspect ratio while maintaining constant diameter. According to Cerato and Lutenegger (2004) and guidance in D2573, soil disturbance is dependent on vane diameter, rod diameter, and vane blade thickness; all of which remained constant when comparing aspect ratio.

The normalized residual strength data shows a more inconsistent and complex trend. Overall, the data shows the opposite trend when compared to peak strength, such that residual strength increases with decreasing aspect ratio. Yet, the trend is more prominent with the smaller diameter vanes. Further, the net difference between the 1:1 and 0.5:1 vanes is negative, unlike the peak strength data. It is significant to note that the observed increase in measured residual strength was about 25 to 35% for the smaller vane diameters, when compared to the 2:1 vane data. As discussed previously when evaluating effects of vane diameter, speculation into the reasons for the trend of increasing residual strength with decreasing aspect ratio appears to be convoluted and warrants further investigation.

3.3. Other Laboratory Methods

3.3.1. Triaxial Compression

To further evaluate the results derived from the lab based VST apparatus, K_o-consolidated, undrained, triaxial compression tests with pore pressure measurements were performed on the subject material in accordance with ASTM D4767. Three compacted specimens were back pressure saturated and consolidated under Ko conditions to 1 atm vertical effective stress. Post-consolidation specimen properties were evaluated and determined to be similar to those previously described for the lab based VST testing.

When the peak obliquity (σ_1:σ_3) failure criteria was used, peak undrained strengths for the three specimens ranged from about 780 to 830 lbf/ft^2 (37 to 40 kPa) with an average of about 810 lbf/ft^2 (39 kPa). Triaxial compression test data is presented in Fig. 10.

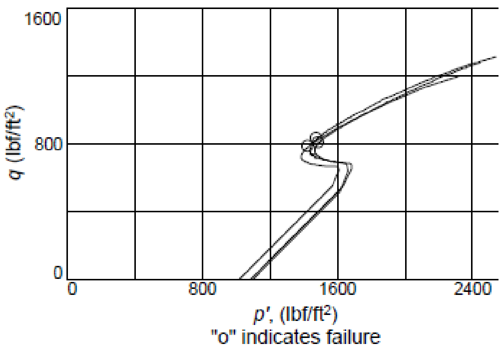

Figure 10. Stress path plot for triaxial compression testing

3.3.2. Direct Simple Shear

Additionally, K_o-consolidated, pseudo-undrained, monotonic DSS tests were performed on the subject material in accordance with ASTM D6528. Specimen preparation and post-consolidation properties were similar to those from triaxial compression testing.

Data from the DSS testing was analyzed using pore pressure behavior and the stress paths in σ'_n-τ space to select failure due to strain-hardening behavior. Peak undrained strengths for the three specimens ranged from about 600 to 660 lbf/ft^2 (29 to 32 kPa) with an average of about 640 lbf/ft^2 (31 kPa). DSS testing data is presented in Fig. 11.

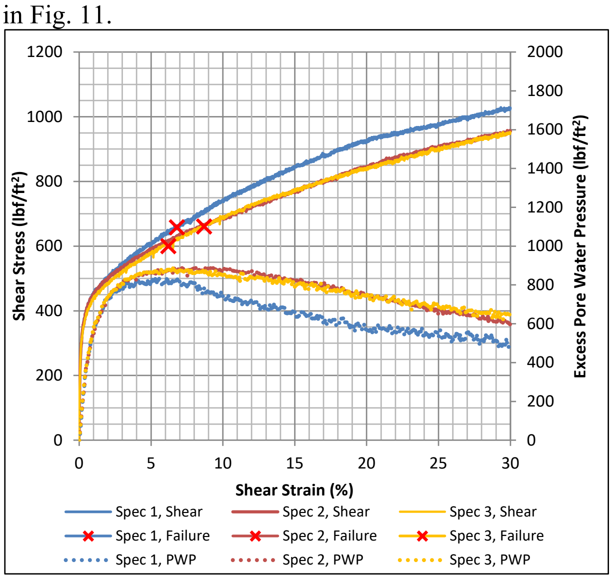

Figure 11. Shear stress and pore pressure vs. shear strain for DSS tests

3.3.3. Comparison

When comparing the various methods for measuring peak undrained strength of the subject material, it can be clearly seen in Fig. 12 that the lab based VST results were highest, followed by triaxial compression and then DSS. This pattern follows the logic of soil anisotropy such that the lab based VST is primarily testing the shear strength on the vertical plane, the triaxial compression testing on an inclined plane and the DSS testing on a horizontal plane. Decreasing the aspect ratio and increasing the vane diameter engages more of the horizontal plane in the lab based VST, bringing its results closer to the other lab methods. Yet, this anisotropy relationship is opposite of what was observed by Aas (1965) even though the clays tested were also low to moderate PI, and normally consolidated. There are likely many reasons for these differences including soil sensitivity and the effects of reconstitution of the lab based VST specimens.

Using the proposed empirical correction factor summarized by Chandler (1988) and presented in D2573, the measured lab based VST peak undrained strengths were reduced by about 14% and are shown by the open symbols (utilizing the most conservative time rate factor of 10^4 minutes). For the 1:1 and 0.5:1 vanes, this correction brings the data into relative agreement with the triaxial compression testing results.

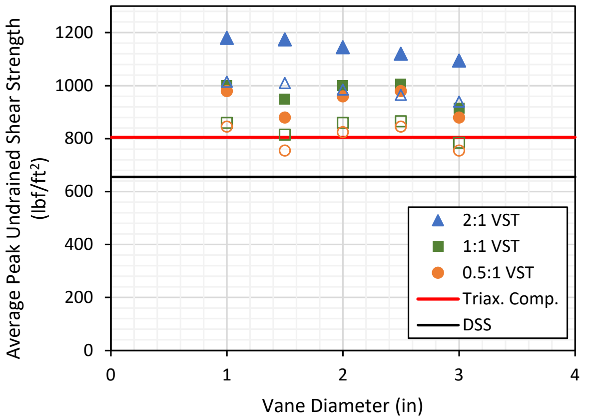

Figure 12. Average peak undrained strength for lab based VST, triaxial compression, and DSS tests

4. Conclusions

The soil tested during this study was anisotropic with respect to peak undrained strength, such that shearing resistance on the horizontal plane was inherently lower than the vertical plane. This is corroborated by the reduction in measured peak undrained strength with increasing vane diameter for a given aspect ratio. The increased diameter mobilized a greater portion of the horizontal shearing resistance. This was further corroborated by the reduction in measured peak strength when the aspect ratio of the vane was reduced, engaging more of the applied shear stress on the horizontal plane. The laboratory data also supported this by the observed reduction in peak strength in triaxial compression (inclined failure plane) and further reduction in peak strength in DSS (solely horizontal failure plane).

The use of smaller aspect ratio vanes to obtain peak undrained strength in stiffer materials during a site investigation may result in conservatism when comparing results to the conventional 2:1 vanes. None the less, the results may be inherently unconservative as compared to some laboratory methods when considering soil anisotropy and the anticipated orientation of a failure plane in stability analyses. The aspect ratio is likely more influential than vane diameter in this regard. The use of smaller aspect ratio vanes could have significant unconservative consequences when used for residual strength measurements. The trends observed on the measurement of residual strength with respect to vane diameter and aspect ratio are not well understood and warrant further investigation.

Therefore, careful consideration must be taken when selecting vane size and aspect ratio for site characterization, including the desire to measure soil anisotropy, acceptable levels of conservatism in the measurements, inferred "strain" rates of different diameter vanes and time to failure.

Further, additional testing and analysis is needed to address uncertainty in several areas including applicability of these trends to higher strength materials, reasoning behind the observed trends in residual strength, time to failure vs. vane diameter and effects related to overconsolidation and PI. Future datasets may include testing of specimens with undrained strengths in excess of 4,000 lbf/ft^2 with smaller vanes to compare strength ratios, as well as specimens that are mechanically over-consolidated and the use of subject materials with varying PI. Additional analyses may include comparisons of the data using the cylindrical failure assumption to non-linear stress distributions.

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