Problems related to field vane testing in soft soil conditions and improved reliability of measurements using an innovative field vane device

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Abstract: In Finland, undrained shear strength is commonly measured using the field vane shear test (FV). Currently, the most commonly used field vane testers are the Nilcon vane and the electrical vane with shear rotation and measuring systems located above the ground level. Vane testing is normally carried out using vanes equipped with slip coupling, while the use of casing for protecting the vane is not very common. Recent studies from Finland have shown that the undrained shear strength of clays can be significantly underestimated when casing is not used. Experimental observations suggest that the slip coupling might not always be sufficient to remove all of the rod friction effects that occur during testing. Tampere University of Technology has recently purchased an innovative field vane apparatus with a vane tester unit, where torque and rotations are measured right above the vane. In this way, the effect of rod friction is minimized and the measured stress-rotation behavior is less biased. In this study, issues related to practical applications, testing devices and interpretation methods are discussed. Then, a critical comparison between test results in soft clays from both the traditional and new field vane testers is performed.

Principle of Field Vane testing

The main advantage of the field vane test (FV) is that it gives an almost direct measurement of the in-situ undrained shear strength (s_u) (SGY 1995). In principle, the residual and remolded s_u can also be determined. The test is conducted by inserting and rotating a four-bladed vane at the desired depth, and measuring the applied torque and angular rotation (ASTM D2573-1 2007). For a successful test, the key issues are: *i)* insertion of the blade to the desired depth with as little disturbance of the soil as possible, *ii)* measurement of the actual torque produced by soil shearing.

For traditional vanes the latter goal is addressed by applying and measuring the torque above ground level (herein referred to as uphole). In this situation, it is of utmost importance to avoid any additional friction caused by the presence of soil that is pressing against the vane shear test rods. Rod friction has traditionally been avoided by using casing around the rods, which prevents direct contact between the rods and the surrounding soil. This eliminates most of the friction, even though some may still occur between the rods and the casing, especially at greater depths (Ortigao and Collet 1988). The use of a slip coupling enables measurement of rod friction so that it can be subtracted from the final result. Slip couplings are often used without casing, trusting that the total rod friction can be accurately measured. Given the mechanism of rod friction, the most accurate way to measure the torque is to place the torque sensor and the measurement unit as close as possible to the vane (herein referred to as downhole).

The applied torque, reduced when necessary by the measured rod friction, is transformed into s_u by accounting for the shape and the size of the vane. General equation for a rectangular vane and a rectangular vane with a taper at the bottom [Nilcon vane (Brand and Brenner 1981)] the relationship between torque (T) and s_u is given by Eq. (1) (Silvestri et al. 1993).

$$T = \frac{\pi D^2 H}{2}\left[1 + \frac{D}{6H}\left(1 + \frac{1}{\cos\alpha}\right)\right] s_u \quad (1)$$

Undrained conditions during testing are ensured by the high applied rate of rotation of the vane, i.e., 0.1°/sec. The failure state is thus reached in approximately one minute in soft soils. The measured values, corresponding to a relatively high shearing rate, must be corrected to account for anisotropy and rate effects, as suggested by Bjerrum (1973).

Factors influencing Field Vane test accuracy

The measurement accuracy of a given FV test can be affected by uncertainties originating from the test procedure, apparatus used and operator. In Table 1, the main problems related to FV testing are summarized, based on a review of existing literature and on experience gained from FV testing conducted in Finland by personnel from Tampere University of Technology (TUT).

Slip coupling has a major role in measurement accuracy. Lack of maintenance of the slip coupling system can lead to inaccurate evaluation of the soil-rod friction. Moreover, the rod friction behavior after free-slip of the slip coupling is quite difficult to evaluate (Ortigao and Collet 1988). Some of the uncertainties relate to the assumptions made to convert torque into shear strength. A comparison between these general assumptions and the actual soil behavior is presented in Table 2.

Table 1. Problems commonly associated with FV testing.

Soil disturbance induced by predrilling (Flaate 1966) and vane insertion (Cadling and Odenstad 1948; Flaate 1966; La Rochelle et. al. 1973; TUT).
Strain rate effects (Bjerrum 1972).
Non-uniform shear stress distribution around the vane (Donald et al. 1977; Menzies and Merrifield 1980; Gylland et al. 2012).
Uncertainties in soil-rod friction evaluations (Ortigao et al. 1988; TUT).
Influence of waiting time between vane insertion and rotation (Aas 1965; Flaate 1966; TUT)
Lack of apparatus maintenance and calibration (Flaate 1966; Kulhawy et al. 1983; TUT) [applies specially to malfunction of slip-coupling (TUT)].
Accuracy of measurement system and measurement errors (e.g. old calibration methods, non-linearity of calibration curve) (TUT).
Influence of vane size and thickness (Chandlers 1988); variability in blade thickness (TUT).
Lateral disturbance induced by vane shaft (Flaate 1966; TUT).
Malfunctioning during the test such as rods twisting, joints tightening, change of vane position (Flaate 1966; TUT).
In Finland FV testing is typically performed without centralizers, which prevents the rods from bending inside the casing (TUT).

Field Vane measurements in Finnish soft soils

In order to improve the quality of ground investigation data, various studies have been conducted recently at TUT on FV testing, piezocone testing (CPTU) and undisturbed sampling. In order to study the accuracy and repeatability of the FV test, measurements have been performed using different apparatuses such as the Nilcon FV, two different uphole electrical FV and a new downhole FV (A.P. van den Berg). The main features of the new equipment can be summarized as: *i)* torque sensor and drive are placed inside the tool itself and close to the vane, *ii)* the apparatus is equipped with a robust case and the vane is pushed out and retracted prior to and after the test, *iii)* the drive motor is electronically limited to a torque of 100 Nm.

Results from three different soft soil test sites (Perniö, Lempäälä, and Masku) are presented and discussed in this paper. Extensive field site investigation has been conducted at all sites, as partly reported by Di Buò et al. (2016).

Table 2. General assumptions made to convert torque moment into shear strength.

Assumption	Reality	Source
1. Penetration of the vane causes negligible disturbance, both in terms of changes in effective stress and shear distortion.	Disturbance of soil can cause a loss of s_u.	Cadling and Odenstad 1948; Flaate 1966; La Rochelle et. al. 1973
2. No drainage occurs before or during shearing.	Dissipation of pore pressure can occur during rotation. Thin undetected drainage layers may be present.	Roy and Leblanc 1988; Kimura and Saitoh 1983; Kulhawy et al.1983
3. The soil is isotropic and homogeneous.	Soft clays are almost always anisotropic and sometimes also layered due to sedimentation process.	Mitchell and Soga 1976; Donald et al. 1977; Silvestri and Aubertin 1988
4. The soil fails on a cylindrical shear surface.	In the beginning of the rotation, the shape of the progressing shear surface is more like a rounded square.	Roy and Leblanc 1988; Chandler 1988; Gylland et al. 2012
5. The diameter of the shear surface is equal to the width of the vane blades.	Shear surface could be a little bit larger than the diameter of the vane.	Roy and Leblanc 1988; Chandler 1988
6. At the peak and remolded strength there is a uniform shear stress distribution across the shear surface.	On horizontal planes, shear resistance is a function of the radius when the lowest mobilized shear resistance is close to the vane axle.	Donald et al. 1977; Wroth 1984
7. There is no progressive failure, so that at maximum torque the shear stress at all points on the shear surface is equal to s_u.	Numerical analyses have shown that the FV test interpretation depends upon the complete stress-strain curve of the material.	Donald et al. 1977; De Alencar 1988; Griffiths and Lane 1990

Lempäälä

This site is located in the southwest region of Finland next to the city of Tampere. The stratigraphy consists of a 3 m thick heterogeneous layer of peat and clay (possibly a fill layer), which overlies a 6-7 m thick soft sensitive clay deposit. At this site, both Nilcon and electrical vane tests were performed using the slip coupling system (Fig. 1). The raw data shown includes the effects of rotation of the slip coupling and some tightening/twisting of rods at the beginning of the test.

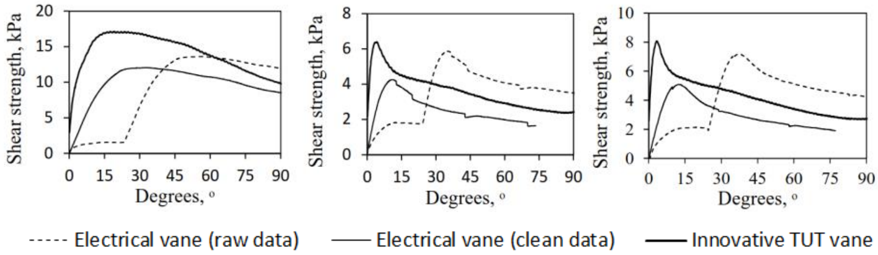

Fig. 1. Results from Lempäälä FV tests performed at depths of: a) 2.2 m, b) 4.7 m, c) 6.1 m,

The stress-strain behavior measured by the downhole FV apparatus seems to give a higher peak strength with lower deformation, indicating better quality of the test. The uphole apparatus is generally affected by higher uncertainties, since the rotating and measuring system are placed at the ground level. Therefore, the measurement seems more vulnerable to rods twisting during the test.

The uncorrected peak shear strength evaluated with the four different apparatus is shown in Fig. 2. Good repeatability can be noticed for both the electrical vanes and downhole FV, even if the data is highly influenced by the apparatus. The strength measured by the Nilcon and the electrical vane is generally lower than the one provided by the downhole FV. One possible explanation is the amount of disturbance induced into the soil since none of the apparatus are equipped with casing. Another reason is a possible malfunctioning of the slip coupling system.

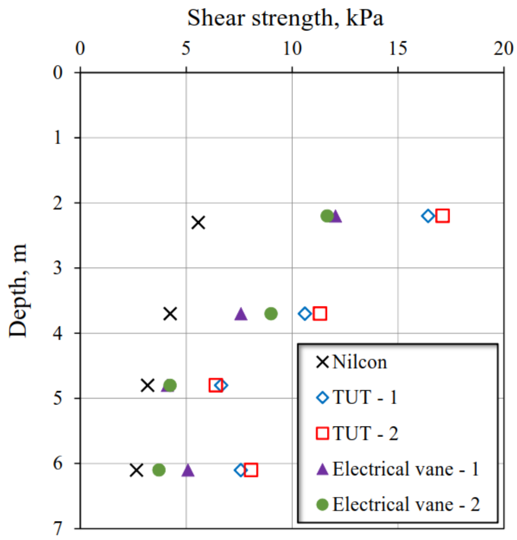

Fig. 2. Uncorrected s_u vs depth with different vane apparatuses, Lempäälä.

Perniö

The Perniö test site has been extensively investigated, as in 2009 a full-scale embankment failure test was conducted at this location (Lehtonen et al. 2015). The site is located in the southwest coast of Finland, next to the railway track connecting the cities of Helsinki and Turku. The stratigraphy consists of a 1-1.5 m of dry crust layer overlaying an 8-9 m thick soft clay layer.

The most recent field investigation has been conducted using the downhole FV apparatus. Data from other vane types are not available. Fig. 3a shows the uncorrected shear strength plotted versus depth for the Perniö site. Data clearly shows that measurements in the homogeneous soft clay layer are repeatable. Scatter can be noticed at shallow depth probably due to the presence of the dry crust layer. Tests performed at a 2.1 m depth are shown in Fig. 3b. During the vane insertion, some material from the upper layer might have entered into the casing and remained stuck to the blades, thus influencing the measurements. To avoid such a problem, pre-drilling into the dry crust layer should be performed prior to vane insertion.

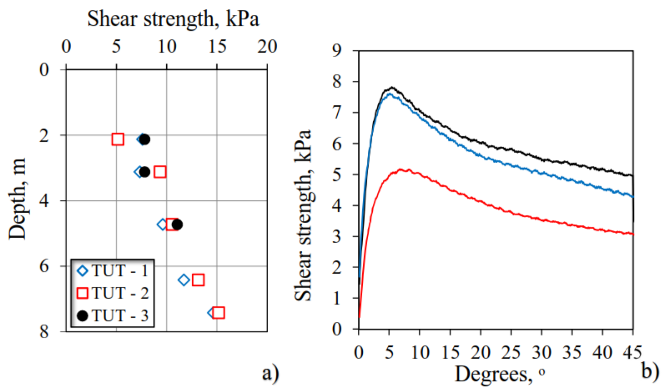

Fig. 3. a) Uncorrected undrained shear strength vs depth with downhole FV, b) FV test performed at 2,10 m depth, Perniö.

The FV is considered to be a suitable device for measuring residual and remolded shear strength. The residual strength is usually determined after a vane rotation of 180° at slow speed (0.1°/sec). To evaluate the remolded shear strength, the speed is increased up to 6 °/sec. The measurement is performed after a 3600° rotation of the vane. Measured remolded strength of Perniö clay is shown in Fig. 4a. The data shown is clearly affected by errors, which are probably due to a loose connection between the vane axle and the rotating system. The authors believe that the vane was subjected to tilt movement, which caused the “wave” effect that can be observed in the figure. Fig. 4b shows the connection between the vane and the drive unit.

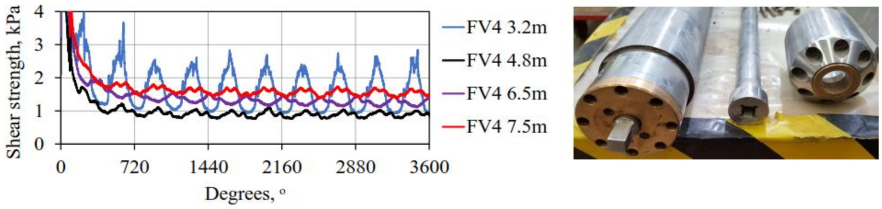

Fig. 4. a) All shear stress vs. angular rotation FV stages at different depths from Perniö. b) Connection between vane shaft and drive unit.

Fig. 5 shows remolded shear strengths measured from FV (in-situ) and fall cone test (laboratory). Higher values of remolded shear strengths measured by FV may depend on several reasons: *i)* extra movement of the vane allows the vane to cut more undisturbed soil, *ii)* the level of the vane might not stay constant, *iii)* remolded shear strength includes about 395 mm friction between soil and shaft of the vane, *iv)* pore pressure can be dissipated during the rotating (Kimura and Saitoh 1983). It should be further pointed out that the overall accuracy of the FV test device that was used is at least 0.5 Nm, which corresponds to 0.32 kPa for a vane size of 75x150 mm. The fall cone test should not be considered as an absolute reference test.

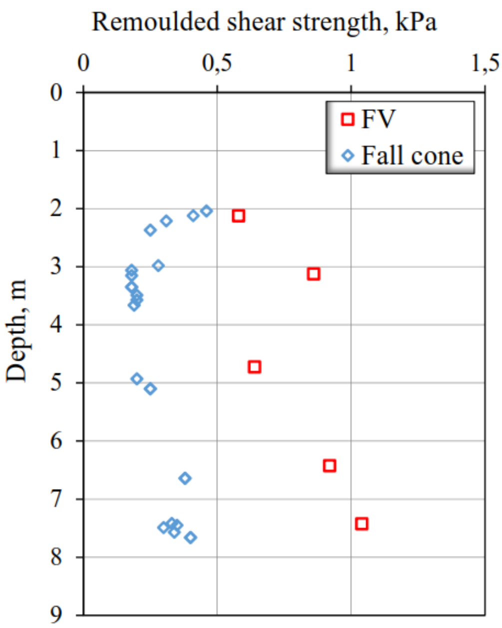

Fig. 5. Remolded s_u against depth (m) measured by FV and fall cone test, Perniö.

Masku

The Masku test site is located on the southwest coast of Finland. The stratigraphy consists of a 1.5 m thick weathered clay crust layer overlaying a 11 m thick soft clay deposit. The field investigation at this site was conducted using both a Nilcon vane equipped with casing, and the downhole FV apparatus. Measured FV results are shown in Fig. 6a. In this case, where casing was used, the difference in terms of measured shear strength between the Nilcon and the new FV downhole vane is lower than when casing was not used. The presence of the dry crust layer does not seem to affect the measurements at shallow depth, as was observed at the Perniö site. However, some scatter is noticeable at each measurement point. The scatter becomes very high at 13 m depth (Fig. 6c). This might be explained by some soil layering, as also suggested by the CPTU test (Fig. 6a).

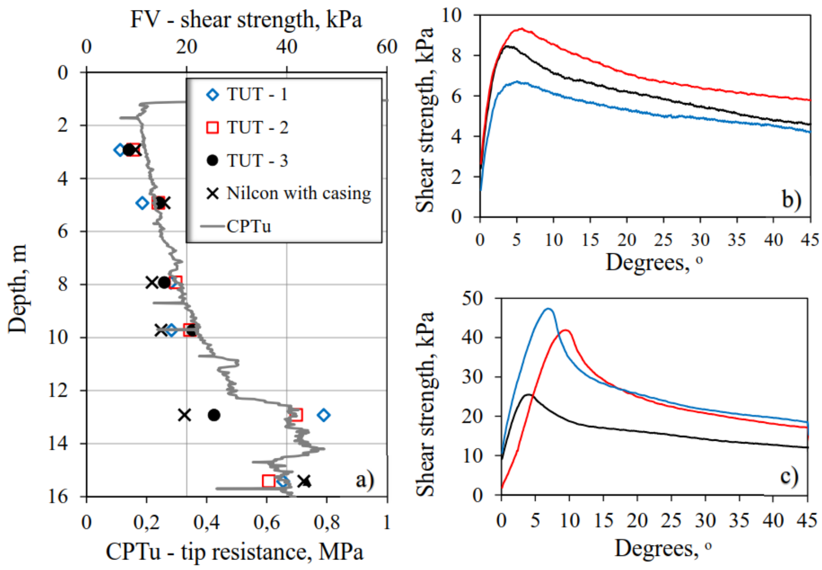

Fig. 6. a) uncorrected undrained shear strength and tip resistance vs depth, b) FV test (TUT apparatus) at 3,00 m depth, c) FV test (TUT apparatus) at 13 m depth, Masku.

Conclusions and further study

The field vane test is often seen as a rather simple and direct test to evaluate the undrained strength properties of clays. However, previous studies as well as this study have shown that many uncertainties are involved in the equipment and its maintenance, the procedure of testing and its interpretation. In recent years, there has been increasing interest to develop the FV test further. An obvious improvement is to place the measuring unit and possibly also the torque application unit right above the vane. In this study, the performance of this type of downhole equipment is compared to more traditional FV equipment. The study shows that the downhole FV gives often a very distinct stress-rotation behavior. The obtained peak strength was obtained at a smaller rotation compared to the uphole FV. Also, if no casing is used for the traditional FV, the downhole gives a clearly higher peak strength. These results emphasize the importance of using casing with traditional FV tests.

The repeatability of the new downhole FV is generally good, even though some scatter in results was observed. This can be partly avoided with improved testing procedures, e.g. by predrilling through the dry crust layer. Some of the scatter in results can also reasonably be attributed to natural soil variation, as only one measurement was performed at each given depth.

The results also show that the remolded strength obtained by the FV is generally higher than the one obtained by the fall cone test. Although some improvements can be made to the used downhole equipment, the authors think that because of the nature of the test the FV will probably always give too high values for the remolded strength, especially at larger depths.

The presented study is part of ongoing research at TUT to develop ground investigation methods. The FV results will be compared to CPTU tests and extensive laboratory tests including triaxial compression and extension tests and DSS tests on mini block samples.

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References

Aas G (1965) Study of the Effect of Vane Shape and Rate of Strain on Measured Values of In-Situ Shear Strength of Clays. Proceedings of the Conference on Shear Strength of Soils. Oslo, 1, pp 141-145

A.P. van den Berg User manual Icone vane tester Onshore http://www.apvandenberg.com/

ASTM D2573-01 (2007), Standard Test Method for Field Vane Shear Test in Cohesive Soil, ASTM International, West Conshohocken, PA, 2007, www.astm.org

Bjerrum L (1972) Embankments on Soft Ground, ASCE Specialty Conference on Performance of Earth and Earth-Supported Structures. 2, pp 1-54

Bjerrum L (1973) Problems of Soil Mechanics and Construction on Soft Clays. State-of-the-art report. Proceedings of the 8th ICSMFE, Moscow, 3, pp 111–159

Brand E W, Brenner R P (Eds) (1981) Soft clay engineering, 20, Elsevier

Cadling L, Odenstad S (1948) The Vane Borer. Proceedings of the Royal Swedish Geotechnical Institute, 2, 1-87

Chandler RJ (1988) The in-situ measurement of the undrained shear strength of clays using the field vane. Vane shear strength testing in soils: field and laboratory studies, 13-44

Clayton CRI, Simons NE, Matthews MC (1982) Site Investigation. Granada Publishing, London.

De Alencar JA, Chan DH and Morgenstern NR (1988) Progressive Failure in the Vane Test, Vane Shear Strength Testing in Soils: Field and Laboratory Studies, ASTM STP 1014, AF

Di Buò B, D'Ignazio M, Selänpää J, Länsivaara T (2016) Preliminary results from a study aiming to improve ground investigation data. Proceedings of the 17th Nordic Geotechnical Meeting, Reykjavik, 25-28 May 2016, 1, pp 187-197

Donald I B, Jordan DO, Parker RJ, Toh CT (1977) The vane test-a critical appraisal. In Proceedings of the 9th Intern. Conference on Soil Mechanics and Foundation Engineering, 1, 81-88

Flaate K (1966) Factors influencing the results of vane tests. Canadian Geotechnical Journal, 3: 18-31

Griffiths DV, Lane PA (1990) Finite element analysis of the shear vane test. Computers & Structures, 37(6): 1105-1116

Gylland AS, Jostad HP, Nordal SN (2012) Failure geometry around the shear vane in soft sensitive clay. Proceedings of the 16th Nordic Geotechnical Meeting (NGM), Copenhagen, 103-110

Kimura T, Saitoh K (1983) Effect of disturbance due to insertion on vane shear strength of normally consolidated cohesive soils. Soils and Foundations 23: 113-124

Kulhawy FH, O'Rourke TD, Stewart JP, Beech JF (1983) Transmission Line Structure Foundations for Uplift-compression Loading, Load Test Summaries: Appendix to EPRI Final Report EL-2870. Electric Power Research Institute.

La Rochelle P, Roy M, Tavenas F (1973) Field measurements of cohesion in Champlain clays. Proceedings of the 8th International Conference on Soil Mechanics and Foundation Engineering, Moscow, 1, 229-236

Lehtonen V, Meehan C, Länsivaara T, Mansikkamäki J (2015) Full-scale embankment failure test under simulated train loading. Géotechnique 65(12): 961-974

Mitchell JK, Soga K (1976) Fundamentals of soil behavior. New York: Wiley.

Menzies BK, Merrifield CM (1980) Measurements of Shear Distribution at the Edges of a Shear Vane Blade. Géotechnique 30(3): 314-318

Ortigao JAR, Collet HB (1988) Errors caused by friction in field vane tests. In Vane Shear Strength Testing in Soils: Field and Laboratory Studies. ASTM International.

Roy M, Leblanc A (1988) Factors affecting the measurements and interpretation of the vane strength in soft sensitive clays. In Vane Shear Strength Testing in Soils: Field and Laboratory Studies. ASTM International.

SGY. (1995). Kairausopas II. 2. painos, 1999. Helsinki: Suomen Geoteknillinen yhdistys r.y. Finnish Geotechnical Society

Silvestri V, Aubertin M (1988) Anisotropy and in-situ vane tests. In Vane Shear Strength Testing in Soils: Field and Laboratory Studies. ASTM International.

Silvestri V, Aubertin M, Chapuis RP (1993) A study of undrained shear strength using various vanes. Geotechnical Testing Journal, 16(2): 228-237

Wroth CP (1984) The interpretation of in-situ soil tests. Rankine Lecture. Geotéchnique 34(4): 449-489