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Introduction of a fast multi-soil test to field vane standards

Introduction d'un test rapide multi-sols aux normes de essai scissométrique de chantier

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ABSTRACT: In most field vane shear test (VST) standards the test method and equipment are customized to soft and sensitive fine soils and therefore unsuitable for use in firm, overconsolidated, fine soils as well as in stony and gravelly fine soils like clay tills. In addition, the test is often relatively slow to perform and therefore best described under the heading: "slow soft soil vane shear test – S-VST". In order to make the VST a robust, rapid and economic in situ test method, which can compete with other in situ tests and be used to measure vane strength in all types of soil, it is strongly advised to include a "fast multi-soil vane shear test – M-VST" in national and international test standards as a supplement/alternative to existing soft soil vane shear tests.

RÉSUMÉ: Pour la plupart des essais scissomètriques (ES) effectuée sur le terrain (norme NF P 94-112), la méthode d'essai et le matériel sont adaptés aux sols fins mous et vulnérables et ne conviennent donc pas aux sols fins surconsolidés fermes et aux sols fins pierreux et graveleux comme la moraine argileuse. En outre, le test est souvent relativement lent à réaliser et serait donc mieux décrit sous l'appelation: «Essai scissométrique lent sur sols mous – L-ES». Afin de faire du ES une méthode d'essai in situ robuste, rapide et économique, capable de concurrencer d'autres essais in situ et de mesurer la résistance dans tous types de sol, il est fortement recommandé d'introduire un «Essai scissométrique rapide multi-sols - R-ES» aux normes d'essais nationales et internationales comme complément/alternatif aux essais scissométriques de terrain existants sur sol mou.

Keywords: Soft soil field vane test; Multi soil field vane test; Robust; Rapid; Economic

1 INTRODUCTION

In vane shear tests (VST), the undrained shear strength of saturated fine soils is measured in a forced cylindrical rupture around the vane, which consist of two crossing steel plates welded to a vertical rod.

VST was originally developed to measure the undrained strength in soft and sensitive clays in Norway and Sweden, due to difficulties in obtaining undisturbed samples in these materials for laboratory tests. Such soft soil vane test (S-VST) is performed as slow as necessary to imitate the loading rate for unconfined compression tests, but so fast that partly drained conditions are avoided in all circumstances (Flodin & Broms 1981). For that reason, the rate of vane rotation is chosen somewhere between 2 and 12 degrees pr. minute in most standards which produce failure in approx. 0.5 - 3 minutes, a significantly shorter time than in traditional triaxial tests.

For completely undrained conditions the calculated vane shear strength increases as shear rate increases. Therefore, the undrained shear strength from VST should be overestimated compared with that obtained from traditional laboratory tests if nothing else was effecting the results - like soil and pore pressure disturbance during vane insertion or sample disturbance extracting and preparing samples for laboratory testing. A series of factors influence the result of the VST:

- Dimension and shape of vane blades and shaft (to minimize disturbance from insertion and geometry of failure surface).
- Waiting time between insertion and shearing (influencing excess pore pressures and consolidation of the soil from the insertion of the vane).
- Rate of rotation (time to failure).
- Unaccounted additional friction from vane shaft or friction reducer.

In most countries, the VST is still carried out in only soft (c_u < 100 kPa) fine soils, and for the same reason most commercially available equipment is rather flimsy and therefore easily damaged if the sediments contains gravel or stones and furthermore unable to measure the strength of firm (c_u > 100 kPa), overconsolidated sediments. Including waiting time before rotating the vane, a full soft soil vane test (S-VST), requires approximately 10 minutes in total. The test is therefore rather time consuming.

I some countries the S-VST has developed into an advanced soft soil vane test (AS-VST) (Peuchen & Mayne 2007):

- Torque and time is recorded continuously.
- Torque is measured downhole rather than at ground surface/sea level.

A full AS-VST procedure requires thus 20 minutes in total, which is often limiting for most commercial purposes.

Due to the time consuming test procedure the number of field vane tests is often limited to a single or few tests in soils/levels of special interest.

There is a need to shorten the test time and to customize equipment to a larger variety of soils including firm overconsolidated soils and soils with gravel and stones. In stony sediments, a test method should be preferred that compensates for both the increased variation of the measurements and the increased risk of discarding measurements. For most practical purposes, a simple and fast (inexpensive) test method that invites to carry out a large number of tests should be preferred instead of advanced and slow (expensive) methods.

With reference to (Gibbs et al 1960 - among others) the applicability of the vane shear test as a routine exploration device the following conditions should be met by the equipment:

- The equipment should be simple, flexible and strong enough to be used in a variety of field conditions.
- The test is best performed when the vane is pushed beneath the bottom of a predrilled borehole. Therefore the vane equipment should be adaptable to standard drilling equipment.
- It should be capable of enforcing a controlled rate of rotation and should permit recording of data at various stages of the test.
- It should be accurate and must have the capability to either eliminate or determine the frictional effects.
- The test should be rapid and economical and it should be reproducible in homogeneous deposits.

In order to meet the economic requirements the test should focus on need-to-have (peak field vane strength c_{fv} and remolded strength c_{rv}) and not on nice-to-have (e.g. detailed post peak behavior).

In Denmark (DK) vane evolution in the 1950's followed a different path. This is probably due to the fact that the geological conditions in DK differ significantly from the geological conditions in the other Nordic countries cf. section 2.

The Danish vane, which meet most of the conditions proposed by (Gibbs et al 1960), has been intensively used in DK very much in accordance with the guidelines originally proposed by (H. Lundgren and J. B. Hansen 1965): *Vane test is the best method known to determine the shear strength of cohesion soil in situ. Considering that it is impossible for many soils to extract truly undisturbed samples, it is obvious that any information about the in situ condition is of the utmost importance. No engineer responsible for carrying out a drilling work, should refrain from the requirement to perform vane tests simply because it is referred to that they make the fieldwork more expensive. Knowledge of the vane strength can lead to considerable savings in design, because the vane strength frequently shows that the soil is stronger and stiffer than it appears from the laboratory tests.*

2 REGIONAL GEOLOGY

Denmark is situated close to the Scandinavian Precambrian mountain area, but below most of the Danish area the old substratum has almost continuously been subsiding since the Precambrian, leaving room for deposition of several kilometers of sediments. Over time, soil layers have been eroded and re-deposited and finally, the landscape as we see it today was formed in the Quaternary period by glaciation and deglaciation processes in at least four glacial periods. Accordingly, most of the glacial and older sediments are heavily overconsolidated.

The Quaternary deposits vary in thickness between less than one meter and more than 300 meters, and that is the reason why also the Pre-quaternary deposits are of interest in some parts of the country.

Considering constructions the soil layers of interest in Denmark typically are:

- Postglacial freshwater and marine sediments of sand, organic clay, peat and gyttja.
- Lateglacial meltwater, wash down and/or solifluctional sand, silt and clay deposits.
- Glacial sand, silt and clay deposits like till, meltwater and marine arctic deposits.
- Interglacial organic freshwater and organic marine sediments.
- Neogene sand and silt deposits.
- High or very high plasticity Neogene and Palaeogene clay, most of which is fissured with slickensides.
- Limestone of early Palaeogene and Cretaceous age (firm to stiff soil/weak rock).

Due to glacial tectonic, smaller or larger parts of the Interglacial, Neogene, Paleogene and Cretaceous deposits often are deformed or moved from their original depositional place and left as floes embedded in the Quaternary deposits or maybe worked into the tills, which thereby have been more or less influenced by these materials.

Table 1. Strength range of typical Danish fine soils deposits - all of sensitivity S_t < 4 (to 8).
(Hansen 1978, slightly modified by the authors)

Soil type	w_{nat} (%)	c_u (kPa)	φ' (°)	c' (kPa)
Postgl. gyttja	50-500	5-100	25-30	0
Postglacial peat	50-1000	10-200	25-35	0
Postgl.acial clay	30-70	10-100	25-30	0
Lategl.acial clay	20-50	20-400	25-30	0-10
Clay till	8-30	20-1000	30-35	0-50
Meltwater cl.ay	8-40	100-500	30	20
Neogene clay	20-60	50-400	25	10
Paleogene cl.ay	20-80	10-400	15-22	0-20

The glacial processes imply that soil conditions within the Danish area vary enormously and often seemingly unpredictable even within short distances, both horizontally and vertically. The same applies to the strength conditions cf. Table 1 as well as content of gravels and stones. It has therefore been necessary to adapt geotechnical investigation methods, including the VST, for this particular regional geology. Thus, for example, a relatively large number of tests are required both in the horizontal plan and in depth if an investigation can reasonably be considered sufficient for a construction project.

3 THE DANISH VST SYSTEM

The Danish vane equipment and test method was developed by Professor H. Lundgren at Geo (formerly named Danish Geotechnical Institute, DGI) in the 1950's. Equipment and test methods are described in detail by the Danish Geotechnical Society (1999).

The Danish test is performed more simple and substantially faster than the S-VST, and the equipment is customized to be used in very varying soil conditions and covers the whole range from extremely soft but rather non-sensitive (sensitivity S_t < 15) organic soils to extremely firm (c_{fv} > 700 kPa) Paleogene clays, as well as gravelly and stony clay tills.

Four different dimensions of the vane blades are used to measure strengths in the range from 10 kPa to 700 kPa.

The equipment differs from the more widespread S-VST equipment by being significantly more robust in order to withstand the relatively large torque required to bring the overconsolidated soils into rupture and to limit damages when the vane blades hit gravels or stones. For this reason, and in order to minimize uncertain stress effects (singularities) at the corners during rotation, the blades have rounded corners cf. Figure 3.1, and to compensate for greater thickness of the vane blades their edges are sharpened, as friction in a rupture between steel and soil is less than in a rupture in soil.

The Danish "deep vane" equipment is applied in the bottom of a borehole in connection with execution of a geotechnical investigation boring, which usually is performed as a cased shell and auger boring. The vane shaft (Ø20 mm) is approx. 0.6 m long, and the upper end is provided with a coupling part suitable for the drilling rods used (normally Ø60 mm) for the auger. During the vane test the drilling rods are attached to the drilling rig by a ball bearing, which hold the weight of vane and drilling rods and ensures that vane and rods can rotate frictionless. The vane is pushed minimum twice the height of the vane blades into the intact ground in the bottom of the borehole with a hydraulic pressure from the drilling rig. The maximum allowable depth of penetration is approx. 0.5 m.

Figure 3.1. The Danish "deep vane" with sharpened edges, rounded corners and a friction reducer on top of the vane shaft.

Friction on the short (<0.5 m) shaft above the vane is minimized by a friction reducer which is placed just above the vane, also known from CPT-tests cf. Figure 3.1.

The vane test is performed within 1 minute after the insertion of the blades, which is the maximum delay value suggested by (Roy & Leblanc 1998) in case consolidation after penetration should be avoided.

Traditionally the torque on the rod is measured at ground level by a dial indicator spring connecting a fixed arm with the handle.

The torque is manually increased at a uniform rotation rate of 360 degrees per minute corresponding to the second hand on a clock (the slowest rate at which the load can be applied practically by hand turning without a gear) which correspond to a time of failure of approx. 6 seconds. Only the maximum force/torque value is registered, and this value is defined as the intact field vane strength (c_{fv}). Next, the vane is rotated fast around 10 times 360 degrees in approx. 10 seconds, after which the remolded vane strength (c_{rv}) is measured applying the same rotation rate as for the first part of the test. During rotation of the vane, it will normally be possible for the technician to register any irregularities (stone/gravel) or crackling noise (sand).

Typically two vane tests are performed per meter boring, and in that case the additional test is performed after the vane is pressed another twice the blade height deeper. Otherwise, the vane is pulled up, so the boring can be further elaborated by another 1 meter.

It is an obvious advantage to carry out vane test during execution of an investigation boring with extraction of soil samples as it is always documented in what kind of soil the test is performed (e.g. coarse soil or fissured fine soil).

Deriving the undrained shear strength c_u from field vane strength c_{fv} a correlation factor $\mu = c_u/c_{fv} = 1.0$ is often used for fine soils for most practical purposes (Danish Geotechnical Institute, 1978) based on plate load testing, triaxial testing and more than 60 years of experience with following exceptions:

- $\mu = 1.2/(1+0.01 \cdot I_P(\%))$ for soft, normal-consolidated, organic clay and gyttja.
- $\mu = 0.5$ for Neogene Mica-clay if it is fissured with slickensides.
- $\mu = 0.33$ for Paleogene clay (fissured with slickensides).

In Denmark, a lighter "hand-vane" equipment has been developed as well which is used without drilling rig. This equipment has a low weight and is designed to carry out tests per 0.2 m down to 1.4 meters depth below ground level within the range of c_{fv} = 20 kPa to 330 kPa. After pre-drilling by hand the test may be performed down to 2.8 meters depth using an elongated rod. The vane in inserted by pushing or hammering, and a jack has been developed, which makes it possible to pull the vane up single handed even in the most firm deposits.

In Figure 3.2 an example of an usual number of field vane tests in a traditional boring in clay is shown.

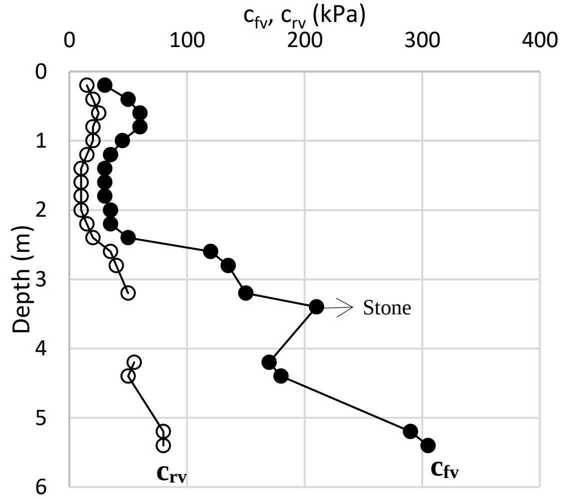

Figure 3.2. Example of results from M-FVT.

When the torque is applied to the extension rods at terrain, the rods are wrenched like a spring. As a consequence, it is difficult to achieve a constant rate of vane rotation for long thin rods, since the rotation of the vane is influenced by the build-up of elastic spring effect in the rod and of the strength of the clay (Andreasen 1981). The Danish deep vane system has the advantage over traditional S-VST systems that spring effect during rotating the rods is very small because the diameter/stiffness of drilling extension rods is much larger than normal vane extension rods.

The "deep vane" equipment is typically used for soil investigations, while the "hand vane" equipment also is used for excavation control to document that the design assumptions are met throughout the excavations, and that the construction work has not affected the strength inadmissible.

Virtually all foundation excavations in fine soil in Denmark are controlled using "hand-vane" equipment. It is the author's assessment that it is difficult to find a correspondingly suitable test type for such control work.

4 TIME EFFECTS

Most standards for S-VST prescribe a rate of vane rotation somewhere between 2 and 12 degrees per minute, depending on which rate is considered the slowest rate to perform in situ test if partly drainage should be avoided in all circumstances.

The chosen rates produce failure in about 0.5 - 3 minutes, which is a significantly shorter time than in traditional triaxial tests and direct shear tests. It is possible to perform undrained laboratory test at very slow rates because the drainage paths can be physically closed which ensure that undrained conditions prevail regardless of the strain rate. In field tests, however, a truly undrained condition is not only uncontrollable but also difficult to assess. By testing at fast rates, the likelihood of prevailing undrained conditions is increased.

It is widely accepted that the undrained strength increases with rate of strain in laboratory tests and rate of loading in vane tests. One of the most compelling documentation for this is presented by Peuchen & Mayne (2009) in Figure 4, where the normalized vane strengths versus time to failure are shown for 23 different clays. The vane strength is normalized with respect to the vane strength at a time to failure of 1 minute which is a representative value for most S-VST (t_f = 0.5 - 3.0 minutes). According to Figure 4 a logarithmic correlation exist for a long range of time span. However, at very high rates of testing (t_f < 0.1 minute) the correlation is jeopardized.

According to Figure 4 VST can be performed at rates at least one magnitude faster than the S-VST without jeopardizing the correlation with the undrained shear strength. This implies two major obvious benefits: Firstly, the likelihood of avoiding partially drained conditions is much greater and secondly, the test is much quicker to perform. Thus, the vane test becomes cheaper and much more competitive compared to alternative in situ tests.

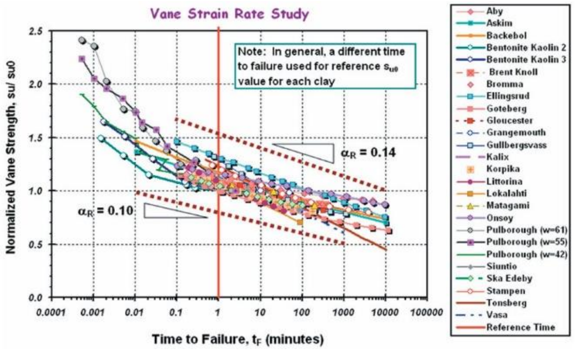

Figure 4. Normalized vane strength versus time to failure (semi-log plot) (Peuchen and Mayne, 2009).

Another important factor is the delay between insertion and testing. Insertion of the vane generates soil disturbance and excess pore pressure which leads to reduction of strength. The loss of strength may be recovered if the excess pore pressure is allowed to dissipate and the soil is allowed to regenerate. A waiting time before shearing has significant effect on the measured vane strength and the magnitude and the rate of the time effect is not the same for different types of fine soils. However, Chandler (1988) has argued that, if the waiting time before shearing is too long, the increase in strength due to consolidation could be greater than the reduction caused by vane insertion, resulting in an overestimation of the strength.

Since the rate of increase of strength is associated with the consolidation time of the soil, the degree of strength increase for a given waiting time can vary drastically between soil types. This calls for a standardization of the waiting time and of a correlation in regards of e.g. the coefficient of consolidation c_v or substitutional the plasticity index I_P.

Many standards have introduced a waiting time following insertion of the vane between 1 and 5 minutes. In a new M-VST standard waiting time is proposed limited to maximum 1 minute in order to avoid consolidation and most important to minimize time consumption.

5 DISCUSSIONS AND CONCLUSION

It is widely recognized that the vane test has the following shortcuts:

- The strength is measured in a forced rupture surface resulting in an overestimation of the strength in inhomogeneous/slickensided soils.
- Disturbance from insertion of the vane results in an underestimation of the strength. However insertion of the vane is somewhat analogous to the insertion of a sampling tube (Varathungarajan 2009).
- Unaccounted friction from vane shaft (or friction reducer) results in an overestimation of the strength.
- The undrained strength is not fully mobilized everywhere at the same time on the cylindrical rupture surface as the distribution of shear stress on the top and bottom of the cylindrical rupture surface is highly non-uniform. This result in an underestimation of the strength.
- Strength anisotropy. The VST shears soil in both horizontal and vertical planes, but the shear in the vertical plane dominates the result significantly. Therefore, the stress conditions (OCR and K_0) is of great importance for the measured strength. They are however often uncertain or even unknown.
- Vane tests only provide discrete measurements and not a fully continuous profile (as in CPT's) of the shear strength.

Benefits of the vane test:

- Most important: it is an in situ test. This ensures that the strength is measured at in situ stress conditions and at in situ temperature. The importance of the latter has recently been enligthened by Gue, Lunne & Perkins (2015).
- The M-VST is simple and easy to perform.
- Besides the peak strength the vane test may provide valuable information about post peak behavior, remolded undrained shear strength and sensitivity depending on test method and equipment.

Despite the shortcuts, the VST is a very useful test that easily can compete with more widely used in situ tests. However, current versions of the most widely accepted and recognized international standards limit the vane test to soft ($c_u \leq 100$ kPa), young fine soils. The reason for this is that S-VST equipment is not robust enough to be used in either firm ($c_u > 100$ kPa), heavily overconsolidated fine soils or in gravelly and stony fine soils like clay tills.

In addition, S-VST procedures are so very time consuming that such test is not commercially competitive compared to alternative in situ tests. Peuchen & Mayne (2007) have made suggestions on how to improve the AS-VST procedure, but these suggestions are according to the authors not sufficient to make the vane test as widely used as it deserves.

In order to make VST a robust, rapid and economic in situ test method which can compete with other in situ tests and to be used in all types of soil, it is strongly advised to include a multi-soil vane shear test (M-VST) – similar to the Danish VST - to field vane shear test standards as a supplement/alternative to the existence S-VST and AS-VST. In order to meet the requirements M-VST is recommended performed:

- Fast at a time of failure of approx. 0.1 minute. The only reason why vane test standards in the future should include a slower test is that experience in many countries may be based on such slow tests.
- With a delay between insertion and testing limited to maximum 1 minute in order to avoid consolidation and to minimize time consumption.
- With robust equipment (vane blade thickness = 3 mm and vane shaft diameter = 20 mm) in order to expand the use of vane

test to firm, heavily overconsolidated clays, so the test covers a c_{fv} range between 5 and 700 kPa and gravelly and stony fine soils as well.

- With vanes which is designed with rounded corners in order to minimize uncertain stress effects (singularities) at the corners during rotation and damages by stones and with sharpened edged in order to minimize consequences of thicker vane blades.
- From the bottom of cased boreholes (maximum penetration depth = 0.5 m) in order to minimize penetration depth and to document soil type.
- With a friction reducer on the vane shaft in order to limit unaccounted additional friction.
- With test procedure limited to need-to-have, i.e. that the standard test only measures peak vane shear strength and remolded strength. The latter measurement is need-to-have in order to check whether the maximum value are affected by gravels/stones or not.

More than 60 years of experience with the Danish VST documents that the above simplifications of the test can be done without impairing the practical application of the result crucial.

M-VST equipment and method differ so much from S-VST and AS-VST that an inclusion of M-VST in the standards makes it strictly necessary to distinguish between vane strength measured with S-VST or AS-VST method (c_{Sfv}) and strength measured with the M-VST method (c_{Mfv}).

The M-VST is extremely suitable for control investigations where the ground conditions actually encountered are verified against those predicted and assumed in the design. It is a simple and quick test that can be performed wherever you can get on foot. For instance, within 15 minutes it is possible to make six vane tests from 0.2 m to 1.2 meters depth below foundation level in one position in an excavation.

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