On the determination of the undrained shear strength from vane shear testing in soft clays

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ABSTRACT: The vane shear test is one of the most common techniques for estimating the in situ undrained shear strength of clay deposits. Despite its simple operational principle, interpretation of test results is inherently based on several assumptions regarding the interaction between the rotating blades and the deforming soil, which have not been adequately validated for soft marine clays of variable geotechnical and geochemical properties. This paper provides a brief review on the background of current interpretation methods, followed by a critical discussion of their key simplifying assumptions in the light of new experimental data from undisturbed and remoulded samples.

1 INTRODUCTION

The vane shear test is widely used for determining the undrained shear strength and sensitivity of soft clays, yet interpretation of its results is based on certain key assumptions, the validity of which is questioned by several researchers. The aim of this paper is to shed some light on the effects of insertion disturbance; vane rotation rate; soil anisotropy and structure; shape of the failure mechanism on the interpretation of the vane shear test in soft clays. A critical review of current methods and findings from the literature is presented alongside preliminary experimental results that demonstrate the influence of each one of the above parameters on the vane-measured strength. Directions for future research and opportunities for improvement of the vane shear test are identified, aimed at enhancing the accuracy of shear strength measurements, and potentially retrieving more information about the mechanical properties of the soil from vane shear tests.

2 FACTORS AFFECTING THE INTERPRETATION OF VANE TESTS

2.1 Soil disturbance during vane insertion

Strength measured via vane tests can be significantly affected by localized soil destructuration and pore pressure generation following vane insertion, with the resultant influence on the results dependent on soil and blade properties (Chandler 1988). Insertion disturbance is correlated to the perimeter ratio, defined as the ratio of the blade thickness over the vane circumference. Chandler (1988) reports that disturbance due to typical blades may result in strength degradation between 10% - 25% of the undisturbed strength. While there is a positive correlation between strength loss due to insertion disturbance and soil structure/sensitivity (Chandler 1988), insertion disturbance can variably affect both the peak and residual strength (Cerato & Lutenegger 2004), limiting the accuracy by which soil sensitivity can be measured with the vane test. Vane insertion can further result in development of a disturbed zone of uniform thickness around the perimeter of the vane (Morgenstern & Tchalenko 1967). The influence of soil structure and sensitivity on the thickness of this zone has been noted in the literature (Juneja et al. 2013), however its effect on strength measurements remains unquantified. As the disturbed zone can transect the vane failure surface with a thickness exceeding that currently considered in interpretation methods (Chandler 1988), the resultant contribution to soil resistance may vary in highly structured or sensitive soils. To depict the potential effect of soil structure on insertion disturbance, Figure 1 compares the microstructure of a typical soft marine clay against the microstructure of a consolidated kaolin sample, pre- and post- shearing. As soil destructuration and particle realignment resulted in 25% strength decrease for the artificial clay (Juneja et al. 2013), the potential influence of insertion disturbance may be extrapolated to the weakly
cemented and sensitive microstructure of natural soft marine clays.

Figure 1. Comparison of soil fabric for (a) natural Ballina clay (after Pineda et al. 2016), and (b) Pre- and post-shear 50kPa-consolidated kaolin (after Juneja et al. 2013), as viewed through scanning electron microscope (SEM) photomicrography.

Quantitative information regarding the influence of microstructural and compositional variation on the measured soil strength is provided in Figure 2, which presents laboratory mini vane shear test results performed at 6 deg/min with a 20mm square vane in soft marine Ballina clay (from the east coast of Australia) and remoulded kaolin. The plasticity index for the Ballina clay and kaolin used is 86.3 and 20.7 respectively. A clear reduction in stiffness and strength is evident between the structured (undisturbed) and remoulded Ballina clay samples, but also between the remoulded Ballina and kaolin samples.

Figure 2. Comparison of resistance to vane shearing of undisturbed Ballina clay, remoulded Ballina clay and remoulded kaolin, measured during laboratory mini vane shear tests. Undisturbed Ballina clay block samples were retrieved with a Sherbrooke sampler from the National Field Test Facility at Ballina, New South Wales, Australia (Kelly et al. 2014).

Vane insertion is associated with the generation of excess pore pressures, that can reach up to 75% of vertical effective stress (Morris & Williams 1993). These exceed by far excess pore pressures generated during the rotation of the vane (Kimura & Saitoh 1983). As the former dissipate, consolidation of the soil may compensate for the decrease in its strength due to disturbance effects (Chandler 1988). This process is illustrated in Figure 3, which presents the evolution of normalised pore pressure during insertion of a 20mm square laboratory vane, partial dissipation of insertion excess pore pressure, and subsequent undrained rotation at 200 deg/min. For regular in situ vane testing, the required time to achieve full dissipation of excess pore pressures may vary between 4 hours and 7 days, while full strength recovery can vary between 20% to 50% of the initial undisturbed strength, depending on the soil coefficient of consolidation ($c_v$) and sensitivity respectively (Chandler 1988). As full drainage conditions are difficult to assess or achieve during regular in situ vane testing, this introduces a potentially un-conservative ambiguity to the interpretation. To avoid this, a delay time no longer than 1 minute (Morris & Williams 2000) is required to ensure undrained conditions; this is in contrast to the standard delay time of 5 minutes (Chandler 1988; Morris & Williams 2000; ASTM D2573 2008).

Recent developments in numerical and analytical methods may also provide significant insight into pore pressure generation and dissipation during insertion (Kouretzis et al. 2015) and vane rotation (Puzrin & Randolph 2015). Combined with experimental results, they can lead to the proposal of a framework for quantifying disturbance and pore pressure generation.
effects on the interpreted value of undrained strength from vane tests.

Figure 3. Evolution of normalised pore pressure in Ballina clay due to vane insertion and delayed vane rotation, measured experimentally in the laboratory using a 20mm square blade at 200 deg/min rotation rate.

2.2 Shearing rate effects

The resistance to vane shearing is a function of the testing rate. There is no unique correlation between these two quantities, as it depends on soil properties and composition, shearing mechanism, and rate range under consideration. This is due to the simultaneous mechanisms of pore pressure dissipation and soil viscosity influencing the measured strength, with the conceptual diagram of Figure 4 indicating the relative rate regions in which each mechanism typically governs soil response. While standardization of the testing procedure and interpretation methodology are designed to minimize strength variation by achieving “reference” conditions, comparison between tests performed at varied strain rates requires quantification of strength dependency on shearing rate. This is necessary when comparing strength measured via alternate test procedures or alternate blade shapes and sizes, as commonly done for calibration and verification purposes respectively.

Rate effects in vane testing are commonly quantified via the comparison of normalised vane strength to the logarithm of rotation rate or time to failure. For the common range of field vane rotation rates (6 deg/min to 60 deg/min), the strength increase per log cycle increase in rotation rate is in the range of: 1% - 2% for disturbed, remoulded or partially drained soils; 10% for typical in situ soil conditions; and up to 20% - 30% for sensitive, structured or cemented soils (Chandler 1988; Biscontin & Pestana 2001). Variation in vane size and shape can alter the rate of soil shearing at constant rotation rate, which has resulted in analysis methods being generalized to consider shear rate in terms of vane peripheral velocity (Biscontin & Pestana 2001) or c_v-normalised peripheral velocity (Quinn & Brown 2011). These methods account for variation in shear surface and soil drainage velocity respectively.

The use of peripheral velocity based semi-logarithmic or power law models for vane rate effects is common, with empirical fitting parameters documented for a range of soil types (Biscontin & Pestana 2001). Figure 5a presents power law fits from mini vane tests in kaolin and bentonite, in comparison with published data for a similar bentonite-kaolin mixture tested with a full-size vane (Biscontin & Pestana 2001). Reasonable agreement is observed for tests in bentonite, despite using vanes of different size. The influence of soil structure on rate is demonstrated using mini vanes in Figure 5b, which compares rate effects from high quality, undisturbed Ballina clay to that of remoulded Ballina clay. In contrast with in situ vane results (Chandler 1988), a decrease in rate effect is evident between the remoulded and undisturbed Ballina clay samples when interpreted using peripheral velocity. This may be due to the influence of c_v between soil states. As the reduced diameter and drainage path of laboratory miniature vanes can result in partially drained test conditions (Biscontin & Pestana 2001), and a reduced c_v may be expected following remoulding (Hamblin 1985) or disturbance (Kelly 2008) of structured soils, c_v and reference rate variation due to soil state may influence measured strength significantly. This can be modelled using c_v-normalised peripheral velocity.

While the peripheral velocity and c_v can be used to normalise measurements obtained with similarly shaped blades, further research is required on modeling rate effects on measurements obtained with vane blades of varied length (Chandler 1988), a non-zero taper angle (ASTM D2573 2008) or variably inclined or elliptical edges (Menzies & Mailey 1976; Selvadurai 1979; Silvestri & Aubertin 1988). Models that can describe the variation of the shear strength with the strain rate (e.g. Quinn and Brown, 2011) can be valuable for comparison/calibration between alternate test techniques, or for the estimation of design
strength parameters in soils subjected to diverse loading rates. However, calibration of such multi-parameter models requires extensive experimental testing and parameters that cannot be readily obtained from common vane tests.

Numerical investigations exploring the influence of rate effects on measured strength have combined semi-logarithmic rate law and strength degradation models to describe localized soil softening in both pre- and post-peak failure regimes (Zhu & Randolph 2007). More recent studies (Zhu & Randolph 2011; Puzrin & Randolph 2015) consider the influence of soil rheological characteristics and pore pressure development inside shear bands with varied rotation rate. Good agreement between the abovementioned solutions and experimental results suggests that they can provide a framework for the quantification of soil parameter influence on rate effects.

2.3 Soil anisotropy and stress distribution effects

Both soil anisotropy and the distribution of stresses around the blade during shearing failure can significantly affect the estimation of soil strength from torque measurements. As these factors cannot be quantified with standard testing procedures, they are ignored in current interpretation methods: soil is assumed to be isotropic, and a simplified stress distribution along the edges of the blade is assumed.

However, various techniques are described in the literature to infer strength anisotropy from the vane test. Strength measurements from vanes of varied height or inclination angle are reported by Silvestri & Aubertin (1988), who proposed a method to obtain the contribution of each shear plane to the torsional resistance. As anisotropic soil strength can result in different rotation angle at failure between vanes featuring edges of non-standard taper angle (Morris & Williams 1993), stress conditions at failure may also vary as a function of soil softening on tapered edges (Silvestri & Aubertin 1988). These factors are ignored in practical interpretation methods. Specific to the standard blade (zero taper angle), the state-of-practice formula for deriving the undrained strength from torque measurements is based on the (conservative) assumption of uniform shear stress distribution at the edges of the blade and isotropic soil (equal horizontal to vertical stress ratio, $b = 1$ in Figure 6). A sensitivity study by Chandler (1988) suggests that considering the maximum “likely” anisotropic strength ratio of $b = 0.6$ and a more realistic polynomial stress distribution ($n = 6$, Figure 6) at the top and bottom edges will result in a variation of the calculated soil strength of the order of 6%, compared to the standard method. As the assumption of strength anisotropy results in lower strength predictions (Chandler 1988), and a polynomial stress distribution may be likely in anisotropic soils (Wroth 1984; Pérez Foguet et al. 1999), adoption of $b = 0.6$ and a polynomial stress distribution of degree $n = 5$ at the top and bottom edges may provide a more reasonable interpretation model for structured soils.

The use of blades with non-zero taper angle is not excluded from current standards (ASTM D2573 2008). However, in anisotropic soils the strength estimated with "standard" and tapered vanes under the same test conditions will vary, depending on the anisotropic strength ratio and the taper angle. Various models that can introduce the effect of soil anisotropy and taper angle in the interpretation formulas are summarized by Silvestri & Aubertin (1988), which model strength variation with shearing angle. These formulas were derived by considering anisotropic elasticity and require empirical fitting at intermediary shearing angles.
A more elaborate approach on the effect of soil anisotropy on the measured torque and stress distribution at failure is presented by Morris & Williams (1993), who proposed an effective stress framework based on the Modified Cam Clay soil model. By considering the soil effective stress state and the critical state friction angle, prediction of torque contributions from varied shear plane inclinations is made possible, facilitating the independent analysis of failure evolution with rotation angle at the horizontal and vertical shearing surfaces. While the model cannot delineate between the influence of soil anisotropy and stress distribution on the resistance torque, a modification of the method to account for varying vane geometry will enable the quantification of the contribution of soil anisotropy. Morris & Williams (1993) further demonstrate that assuming a polynomial stress distribution at the top and bottom edges of the blade may result in overestimating the available strength by up to 30% in normally and isotropically consolidated soils. This highlights the significant influence of soil anisotropy on the relative contribution of the resistance developing at the horizontal and vertical edges of the blade to the measured torque. This framework can be further evolved to consider vanes (and thus failure surfaces) of different shapes, and provide the theoretical background for obtaining additional soil properties from the vane test through measurements with diverse blade configurations.

2.4 Shape of the failure surface

The shape of the failure surface that develops in the soil as a result of vane rotation, and thus the total resistance to shearing translated to torque, depends on the shape of the vane but also on soil properties. A simplified cylindrical shear surface is assumed in current normative interpretation methods. In reality, the failure surface that develops around the vane features a square shape during the initial stages of shearing, with increased vane rotation resulting in rounding and smoothing of the shear band (Veneman & Edil 1988). In some cases, a circular failure surface may not develop until full remoulding takes place. Interpreting vane failure by assuming a simple cylindrical failure surface may result in error of up to 16% according to Veneman & Edil (1988), depending on the blade geometry, rotation rate and soil properties.

Oscillatory resistance behaviour in the post-peak region has been documented for the vane when the standard test procedure is followed (McConnell 2014), which may influence the measured residual strength considerably. McConnell (2014) attributes this effect to soil remoulding. Similar behaviour has been observed and modelled numerically for penetration-based methods of strength determination, with resistance oscillation attributed to evolving shear bands at large strains (Zhu & Randolph 2007). An example of post-peak normalised oscillatory behaviour is shown in Figure 7, which compares the resistance up to large rotations of a remoulded and a high quality block sample of Ballina clay, measured experimentally using laboratory vanes rotated at 200 deg/min.
CONCLUDING REMARKS

The presented preliminary experimental results and theoretical concepts highlight the mechanisms that influence the resistance developing during vane shear tests in soft marine clays, and how this can be correlated to the in situ undrained strength. Further research currently underway aims to collate experimental, theoretical and numerical results into a robust framework for the interpretation of vane shear tests, and for retrieving more information about the mechanical properties of the soil through vane tests.

REFERENCES


