Numerical analyses of
field vane tests on soft clays

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Abstract – **This paper focuses on the use of field vane, a popular instrument for determining the undrained shear strength (s_u) of soft clays. In this regard, suitable corrections must be applied in order to adequately interpret the recorded measurements. Here the role played by some relevant factors (i.e., anisotropy and strain-rate effects) in influencing s_u values is investigated on the basis of FEM numerical analyses carried out via the adoption of PLAXIS-3D software.**

The results of the numerical analyses generally fit with information provided by the scientific literature using independent measurements. Moreover, they highlight a relevant effect of anisotropy for low values of the plasticity index of investigated clayey soils. On the contrary, for high values of the plasticity index, anisotropy plays a marginal role while strain rate effects prevail. All these considerations suggest the field vane tests most reliable for clayey soils with high plasticity index, although a correction is needed in order to limit strain rate effects.

I.   INTRODUCTION

Undrained shear strength (s_u) of fine-grained soils is a parameter of particular concern in total-stress analyses aimed at designing geotechnical systems, such as foundations, retaining structures, and embankments; it can be obtained by performing either laboratory or in-situ tests.

To perform laboratory tests, an undisturbed sample has to be recovered using an appropriate form of drilling and sampling, but this process and the subsequent laboratory testing are often expensive and time-consuming. Moreover, it is often difficult to recover samples of enough quality to obtain meaningful laboratory test results. Instead, in-situ tests are less expensive and quicker to perform; disturbance is participating anyway, but in a possibly less significant amount compared with laboratory tests.

Nevertheless, appropriate correlations must be developed for each in-situ test in order to successfully apply the results to a design phase.

In this paper, a focus is given to field vane tests which, in spite of the above mentioned advantages, can be carried out only on soft clays and an appropriate correction must be applied in order to interpret the recorded measurements, taking into account the role played by all relevant factors (anisotropy, progressive failure, etc.) in influencing s_u values. Among the considered factors, the role of anisotropy is mainly investigated since it may lead to significant changes in measured undrained shear strength together with strain rate effects.

II.   DEVICE AND PROCEDURE

The in-situ vane device allows to determine in situ undrained shear strength and sensitivity of a soft clay. It consists of four steel blades set at right-angles, mounted on a solid rod, pushed into soil and rotated by a constant rotation rate once arrived at the desired depth. During rotation, the torque is measured; indeed, it is possible directly to link the measured maximum torque to the undrained shear strength of soft clay. To carry out a measurement with minimized uncertainties, it is important to avoid any rotation of the vane during insertion: hence vane is surrounded by a case, which protects from any significant friction along the extension rods. Once failure has occurred and undrained shear strength has been estimated, also remoulded undrained shear strength may be obtained by rotating vane rapidly at least ten turns and by performing a new test afterwards, which is needed to record constant value of the torque at the remoulded state. This latter value is necessary to obtain remoulded undrained shear strength, used into assessment of sensitivity of the clay.

Geometric parameters of vane such as height, diameter, blade thickness, vane shaft diameter, etc., are established by ISO/DIS 22476-9 (2014) (that recommends a rectangular vane with height (H)/diameter (D) ratio of 2:1 and three vane dimensions: 100×200 mm, 40×80 mm, 33×66 mm, respectively from very low to very high undrained shear strength) and ASTM D2573 establishes the type of vane (flat or tapered) and a set of standard dimensions or rates, such as vane diameter and height, blade thickness (s), vane shaft diameter etc.

III. INTERPRETATION AND CORRECTION

A. Conventional interpretation

Conventional interpretation of field vane test assumes that the soil shears as a cylinder and that the shear stress is distributed uniformly across the horizontal planes at the top and bottom of the vane ($\tau = \tau_{m,h} = s_{uh}$), and along the vertical plane circumscribed by the vertical perimeter of the vane ($\tau = \tau_{m,v} = s_{uv}$). Moreover, isotropic behavior of undrained shear strength is often supposed, that means $s_{uv} = s_{uh}$. Hence considering at the same time conventional interpretation and isotropic behavior, and setting equilibrium between external and internal forces applied to the vane, this expression for s_u can be obtained:

$$s_u = \frac{6M}{7\pi D^3} = 0.86\frac{M}{\pi D^3} \qquad (1)$$

However, both hypothesis are not strictly valid. Indeed, it was experimentally demonstrated (Donald [1] and Menzies and Merrifield [2]) that, while the vertical distribution of shear stresses can be almost assumed uniform, the same does not result on horizontal portions of the vane, where the shear stresses distribution is highly non-uniform. This leads to different ratios between the integral of stresses on the horizontal surfaces (M_h) and the one on the vertical surface (M_v). Considering respectively uniform and non-uniform distributions on horizontal surfaces, the following ratios can be obtained:

$$\frac{M_h}{M_v} = \frac{1}{6} \qquad \text{uniform distribution}$$

$$\frac{M_h}{M_v} = \frac{1}{16} \qquad \text{non-uniform distribution}$$

In both cases it can be noticed that shear strength on the vertical plane tends to govern the undrained shear strength measured in the vane test. This suggest a primary importance of anisotropy in this kind of test, but there are other several factors which influence the test, such as disturbance, progressive failure and, mainly, viscous effects (due to strain rate). All these factors together make undrained shear strengths obtained with a field vane test in general overestimated.

B. Bjerrum's correction

During '70s, Bjerrum [3] observed the above described aspect and introduced correction factors which had to be applied before vane strength could have been used in stability analysis. By performing back-analysis of embankments, footings and excavations failures in terms of in situ vane undrained shear strength, Bjerrum plotted the factors of safety against the plasticity indices of the soils (Fig. 1). The mobilized undrained shear strength is computed from:

$$s_u^{(field)} = \mu s_u^{(FV)} \qquad (2)$$

As it is shown in the plot, the higher plasticity indices are, the more μ factors decrease; Bjerrum addressed this
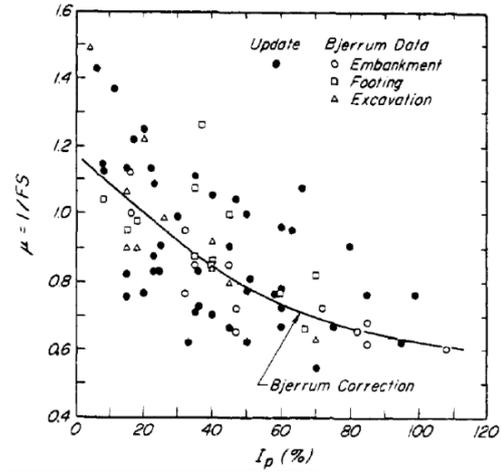

Fig. 1. Bjerrum's field vane correction factor. Reference: Terzaghi, Peck, and Mesri [4]

to the increasing effects of strain rate with the plasticity. Considering anisotropy and strain rate as main factors involved, Bjerrum suggested a more correct procedure where their effects could be considered separately:

$$s_u^{(field)} = \mu_A \mu_R s_u^{(FV)} \qquad (3)$$

being μ_A a factor correcting for the anisotropy and μ_R a factor correcting for the time effect; an expression for the last one has been proposed by Chandler [5], who also agreed with the idea of keeping separated effects of strain rate and anisotropy:

$$\mu_R = 1.05 - b(I_P)^{0.5} \qquad (4)$$

Bjerrum's factors are still today amongst the most reliable information on undrained shear strength of inorganic soft clays and silts for stability analysis of embankments, footings and excavations.

IV. 3D MODELING OF FIELD VANE

A. Geometry and materials

3D FEM simulations of the shear vane have been performed using PLAXIS in order to quantify the role of anisotropy in the interpretation of field vane test measures.

Via these simulations, two goals can be pursued: on the one hand, it can be deduced how stresses and strains distribute and evolve around the vane during rotation; on the other hand, a comparison can be made in order to verify (or not) if information gathered from numerical analyses fit well with data provided by the scientific literature (like the ones collected either by Chandler in 1988 [5] or by Gylland in 2014 [6]).

Some simplifying hypothesis are given in 3D simulations:

- disturbance due to insertion of the vane into the ground is not considered;
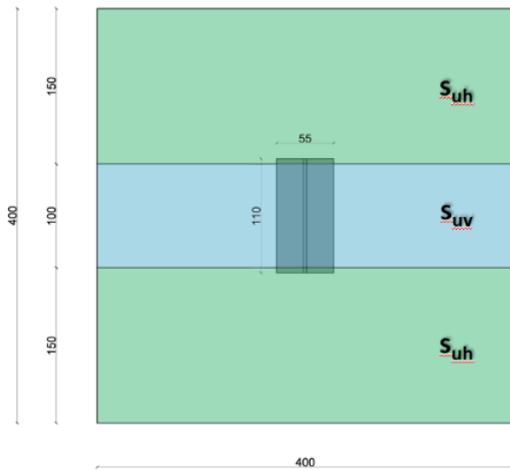- the speed rate is high enough to ensure undrained conditions;

Fig. 2. Cubic volume surrounding the vane; anisotropy is introduced by dividing the volume in three horizontal layers with different undrained shear strength.
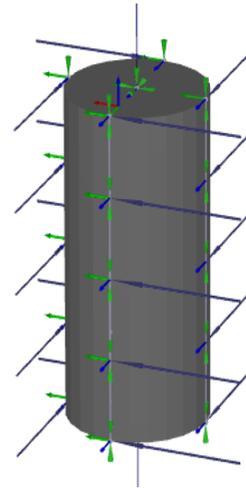

Fig. 3. Cylindrical volume around vane and distributed loads applied to vane tips; blue and green arrows respectively represent loads and fixed displacements.

- the rest period after vane insertion is low enough to make consolidation not allowed.

The whole cubic volume used ($0.4 \times 0.4 \times 0.4$ m) is composed by three clay levels with different height, namely (Fig. 2): 150 mm for top and bottom layers, 10 mm for the central layer. Different values of undrained shear strength are chosen time by time for top and bottom layers (s_{uh}); whereas for the central one it is assumed as constant and equal to 10 kPa (s_{uv}). It is clear that these strength values correspond to the ones mobilized respectively on horizontal and vertical surfaces of the vane; so anisotropy is introduced by geometry and not using a particular constitutive model. Results will be presented in terms of s_{uh}/s_{uv} ratio. It is useful to remember that widespread values of undrained shear strength for soft clays generally are from 8 to 25 kPa; so eight different values of s_{uh}/s_{uv} ratio, from 0.8 to 2.5, have been chosen to perform simulations. Material properties are the followings:

- saturated unit weight – $\gamma_{sat} = 0$ kN/m^3
- Young's modulus – $E' = 10^4$ kPa
- Poisson's coefficient – $\nu' = 0.25$

Vane (whose dimensions are 55×110 mm) is located in the centre of the whole cubic volume; this means that top and bottom part of the vane are not aligned with contact surfaces of different clays. This work hypothesis was assumed in order to be sure that values of displacements and stresses after simulations can be referred to top and bottom layers (and hence to the corresponding undrained shear strength) instead of the central one. Each blade is modeled with an artificial thickness d = 1 m (to ensure a stiffness much bigger than that pertaining to clays). Mohr-Coulomb constitutive model is adopted. Calculations were carried out with "undrained (B)" drainage type, in which stiffness is defined in terms of effective properties (E') and strength is defined as undrained shear strength (s_u). A large bulk stiffness for water is automatically applied to make the soil as a whole incompressible and (excess) pore pressures are

calculated, even above the phreatic surface. Mesh is finer around the blades and coarser for surrounding volume; indeed, more precision around the blades is needed. Conditions on clays' boundaries are set as x and y displacements FIXED while z displacements are FREE; the only exception is the bottom surfaces for which also z displacements are FIXED. Conditions are set also on cylinder boundaries; in particular, displacements along all directions are FREE. Moreover, conditions about displacements on blades are needed: while vertical displacements on tips are FIXED, x and y displacements are FREE; displacements are also FIXED on the blades' crossing vertical line. All those conditions were set to ensure the vane rotation. Furthermore, PLAXIS does not allow using a constant rotation as displacements, so that it was necessary to apply a distributed load on each tip (= 1000 N/m, that is 110 kN if concentrate load on one tip is considered) to simulate the rotation. So applying a percentage of load per every load stage, it is possible to estimate step by step tip displacements and, then, rotations for a given s_{uh}/s_{uv} ratio.

B. Results

The main results of numerical analyses consisted in estimating: the torque-rotation curves, displacements around the vane (u), relative shear stresses around the vane (τ_{rel}), plastic points.

As for the torque-rotation curves, six points (A, B, C, D, E, F) representative of six rotation values ($0.10°$, $0.13°$, $0.15°$, $0.17°$, $0.45°$ and at failure $\approx 0.90° \div 0.92°$) were considered for analysis purposes. The obtained curves, independently from the considered s_{uh}/s_{uv} ratio, show a quasi-linear trend after the point where most of strength is mobilized. For example, Fig. 4 – which deals with a s_{uh}/s_{uv} ratio equal to 1.5 – highlights that in correspondence of the D-point (where rotation equals $0.17°$) almost 94% of maximum torque is observed. Starting from this point, further torque increments are negligible.
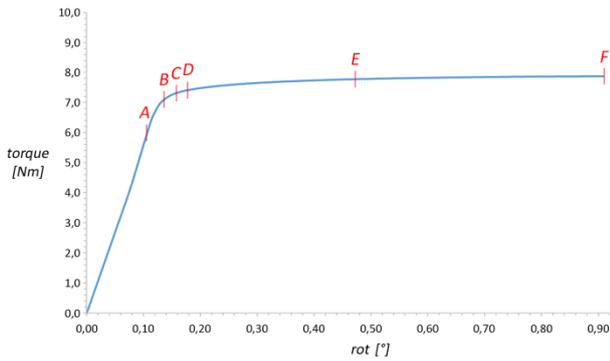
Fig. 4.   Torque–rotation plots for $s_{uh}/s_{uv} = 1.5$.

As Fig. 5 shows, while displacements at middle section are uniform, they seem to be more concentrated near tips at vane top (and bottom, for symmetry). The rounded square shape of the failure geometry around the vane is recognized in the plastic points picture referring to F-point, more emphasized at the top than at the middle of the device.

V.   PROCESS OF COMPARISON

A dataset was built starting from data obtained all over the world (especially Scandinavian countries, USA and Canada) and using mainly field vane tests. This dataset grew out of the need to obtain a measurement of the undrained shear strength which is really representative of failure mode of the soil. Indeed, field vane tests lead to two separated contributions in resistance, which symbolize resistance in horizontal and vertical planes respectively and not the actual failure in the soil. Hence, using some plots is possible to link a s_{uh}/s_{uv} ratio (typical

of each calculation) to the one which is really mobilized on the slip surface. This procedure implies three consecutive steps, in which data are strongly influenced by plasticity index and this may lead to a significant change in results. Downstream from that procedure, the dataset will represent also an useful instrument to compare results obtained by calculations with the ones provided by the literature, to be sure that the former are acceptable.

A. $1°$ step ($s_{uh}/s_{uv} - I_p$ plot)

As previously mentioned, undrained shear strengths used into the ratio s_{uh}/s_{uv} respectively correspond to resistances of upper and lower clay strata and of the central one. The used values of the ratio range between 0.8 and 2.5, which are typical values for soft clays. Dataset leaded to the plot shown in Fig. 6.

So using s_{uh}/s_{uv} ratio as input data, a corresponding plasticity index is obtained. Obviously, since data are not so much and a lot of them are concentrated about a plasticity index of 40%, a range of values (instead of a certain one) will be obtained. Range largeness has been chosen by the authors depending mainly on the data concentration in correspondence with the input value of s_{uh}/s_{uv} ratio: the more data are, the larger is the neighborhood chosen, which will be used as input in second step.

B. $2°$ step ($s_{u,DSS}/s_{u,A} - I_p$ plot)

As highlighted in the previous paragraph, a range of plasticity index is used as input. Karlsrud et al. [7] have provided a dataset, the purpose of which was to develop reliable correlations between CPTU-results and real in-
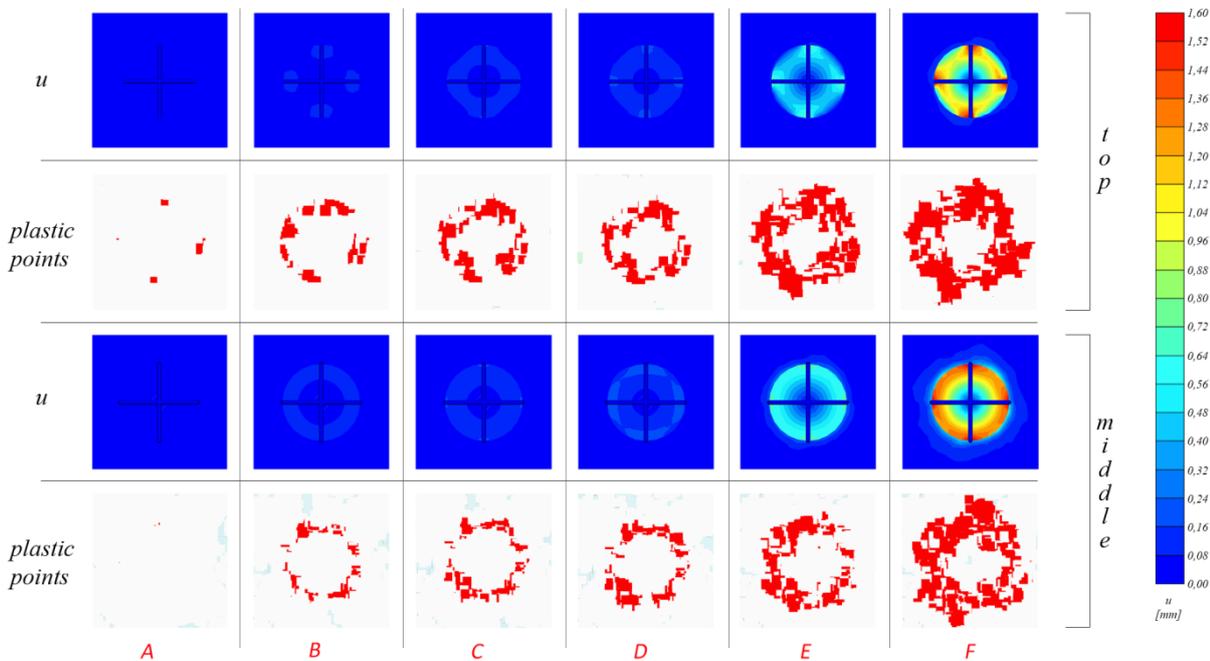

Fig. 5.   Results of 3D-calculation for $s_{uh}/s_{uv} = 1,5$; displacements (u) and evolution of plastic points around the vane during rotation; plastic points refer respectively to top and middle of the vane.
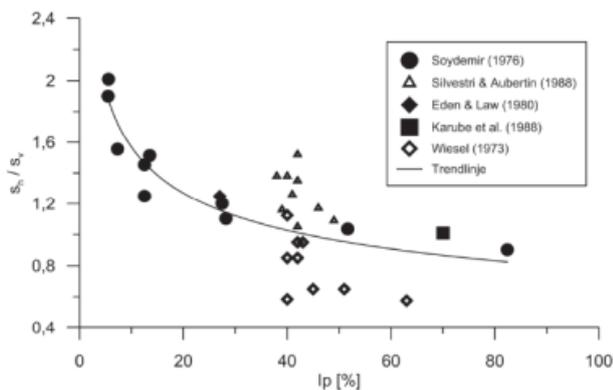
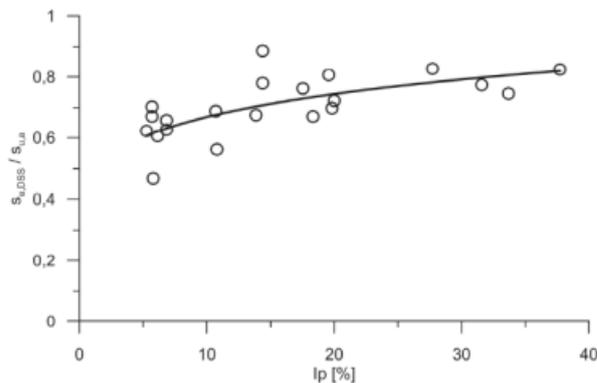*Fig. 6. s_{uh}/s_{uv} ratio against plasticity index in several soft clays. Reference: Gylland [6]*

Fig. 7. $s_{u,DSS}/s_{u,A}$ ratio against plasticity index in several relatively soft to medium stiff Norwegian clays. Reference: Gylland [6]

situ soil parameters.

As main parameter for comparison against CPTU results, undrained shear strengths obtained by triaxial tests on specimens consolidated anisotropically to actual in-situ effective stresses (hereafter defined as $s_{u,A}$) have been chosen. Moreover, on many of the block samples DSS tests have been performed and corresponding undrained shear strenghts ($s_{u,DSS}$) have been obtained. Fig. 7 compares the two different measurements of undrained shear strength. As Karlsrud et al. [7] noticed, plot suggests, among other things, that anisotropy decreases as plasticity index increases.

Using a range of plasticity index as input, a range of $s_{u,DSS}/s_{u,A}$ is obtained, but the value of each resistance is still unknown. Based on a study of Karube et al. [8], Chandler [5] suggested that failure mechanisms which occur during field vane test may be analogous to the one observed in direct simple shear. Hence, if this assumption is true, undrained shear strengths obtained by both tests, $s_{u,DSS}$ and s_{uh}, are similar, and it means that, starting from the knowledge of the ratio and replacing $s_{u,DSS}$ with s_{uh} (which is known), it is possible to obtain a value of $s_{u,A}$.

C.   3° step ($s_{u,A}/s_{uv} - I_p$ plot)

The last step is aimed at verifying if simulation results fit well with data dealing with twenty-two sites and synthesized in Fig. 8. Most of these data were collected by Chandler in 1988 [5]. Undrained shear strengths on the vertical plane s_{uv} are estimated using both conventional interpretation (i.e., uniform stress on the blade's top) and triangular distribution. The reality should show somewhat in between these two distributions. Once s_{uv} values are determined, it is possible to enter in the plot of Fig. 8 with the $s_{u,A}/s_{uv}$ ratio and the plasticity index determined in the first phase; by doing that, the eight numerical simulations provide eight different neighborhoods of values, due to the simultaneous use of the conventional interpretation and the triangular distribution. Data obtained by the described procedure are represented in red in Fig. 8.

Simulation results provide very different shear stresses on the vertical planes (middle and top sections), higher on top and bottom surfaces than in the middle; it also seems that central zone is less involved on top and bottom with respect to the middle.

Furthermore, there is a scatter between s_{uv} values estimated by considering respectively conventional interpretation and triangular distribution on top, being the first one always greater than the second one; then, results highlight that this scatter is always set within an interval ranging from 0.42 and 0.56 kPa, which is very narrow. Hence whatever distribution on vane's top does not lead to a significant difference in the calculated s_u values; accordingly, an uniform distribution can be assumed and the equation (1) is still valid.

A clear trend of reducing $s_{u,A}/s_{uv}$ ratio relationship with increasing plasticity index can be noticed. Indeed, for I_p values greater than 25% $s_{u,A}/s_{uv}$ ratio is close to constant and often included in the range 1.0-1.5; for I_p values among 4-7%, $s_{u,A}$ is larger than s_{uv} by a factor of up to about 2. All these considerations confirm that the higher plasticity index is, the lower anisotropy is. Moreover, most of data shows ratio values above 1.0; this means the vane in general shows lower undrained shear strength than the one that could be obtained by triaxial testing. In some cases, however, a lower value is noticed; this can be due to several factors, which may actually decrease $s_{u,A}$ (sample disturbance or wrong consolidation) or increase s_{uv} (rate effects, time delay between insertion and rotation, friction in equipment).

Despite of anisotropy increases when I_p is reduced, it must be considered that, for $s_{uh}/s_{uv} = 0.8$, a very high plasticity index results ($\approx 90\%$); this leads to a final value of $s_{u,A}/s_{uv}$ which is lower than 1.0 and also far from other results. This suggests that this ratio, together with high values of the plasticity index, needs to be studied more carefully. Moreover, using s_{uh}/s_{uv} ratios of 2.2 and 2.5, a very high anisotropy is registered and this leads to a significant scatter of data; this means that field vane test is less useful in low plastic clays.
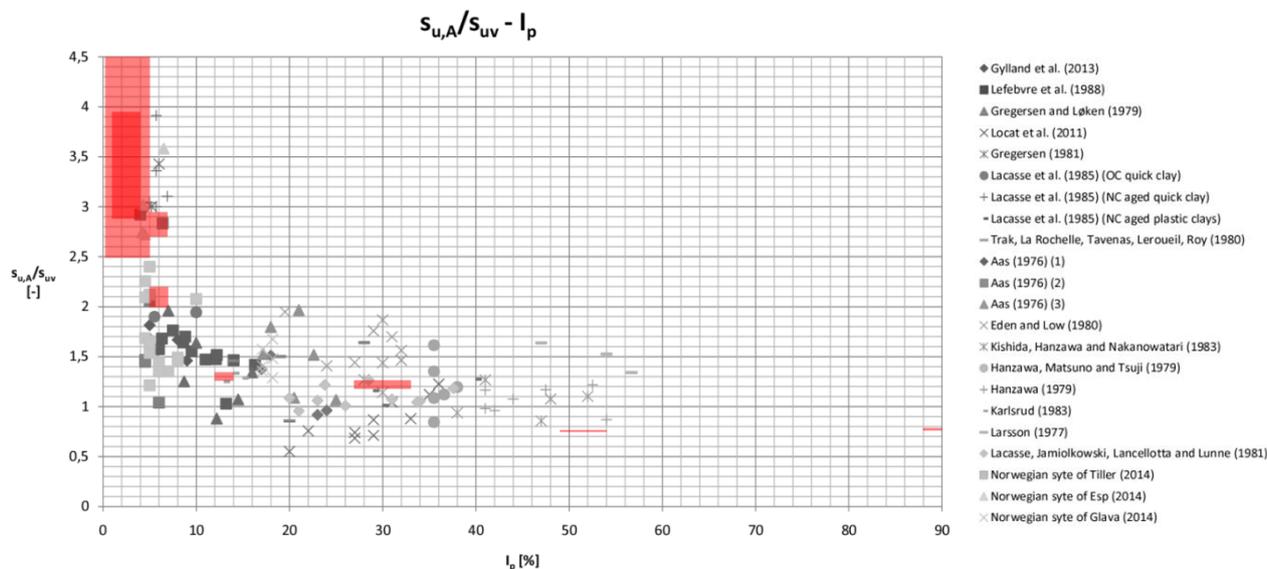
Fig. 8. $s_{u,A}/s_{uv}$ *ratio against plasticity index in 22 clays from all over the world; plot and legend. Reference: adapted from Gylland [6]*

VI. CONCLUSIONS

The work shows how to build a 3D model of a field vane aimed at estimating the stress and strain distributions in soil volumes interacting with the instrument and how they evolve during the rotation. Simulation results fit with trends from literature using independent measurements (with no interpretations involved), accordingly to the Bjerrum's correction.

According to outcomes of other research works it is confirmed that, for index of plasticity higher than 10%, field vane test is reliable for practical purposes because:

- conventional interpretations lead to well-approximated results in terms of s_u;
- anisotropy plays a marginal role while strain rate becomes a very relevant factor which can not be disregarded;
- considering the validity of the Bjerrum's correction, equations (3) and (4) have to be used to take strain rate into account and, at the same time, μ_A has to be set equal to one.

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