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Cone factors from field vane and triaxial tests in Danish soils

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SYNOPSIS: Six Danish cohesive soils are investigated using Cone Penetration Test (CPT) to estimate the undrained shear strength, c_u. Field vane tests and consolidated triaxial tests are used to estimate c_u for the six soils. The tested soils all come up with cone factors very close to 10 when using c_u from the triaxial tests whereas cone factors ranging from 7 to 11 are estimated by using measurements from field vane tests. A strong correlation between the cone factor, N_{kt} and the friction ratio, f_R is obtained when the cone factor is estimated from vane tests. This relation, which is obtained using only the six thoroughly investigated soils, is tested on data from other Danish and international sites. Likewise the constant cone factor of $N_{kt} = 10$ obtained from the triaxial tests is evaluated and compared with cone factors obtained from triaxial tests in other countries.

1 INTRODUCTION

In 1991 to 1994 an investigation using CPT in Danish soils was carried out. The results from the investigation are published in Luke (1994). The main concern of the investigation was the estimation of the undrained shear strength c_u of cohesive soils applying the results from CPTs. Six test areas of $10 \times 20\ m^2$ with different types of soil were closely examined around a depth of 1.5 m.

As the field vane test in practical geotechnical engineering in Denmark is the most widely used test to determine the undrained shear strength in cohesive soils, and the consolidated triaxial test is considered as the most reliable laboratory test, these two tests were used to estimate c_u in the six test areas.

At least 15 field vane tests at two depths and 1 or 2 triaxial tests were carried out at each test area. Fig. 1 shows an example of the measurement locations on one of the investigated test areas.

The field vane tests were performed using the standard Danish hand vanes.

The triaxial tests were carried out on intact samples as Consolidated Anisotropic

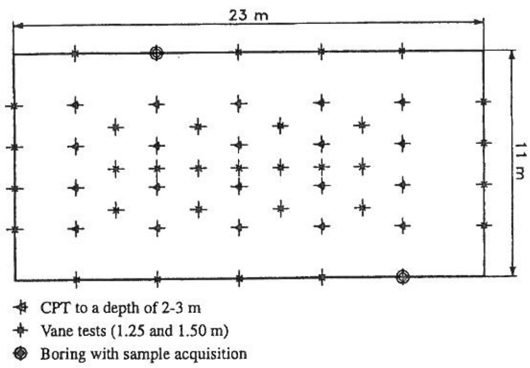

Fig. 1: Location of in situ tests on one of the test areas

(oedometric) Volume constant Compression tests (CAoeVC). The specimen height equalled the diameter, and smooth pressure heads were used according to Danish practice. The undrained test was performed at a constant rate of strain (3% of the total sample height per hour) and c_u was defined at a deformation of 10% of the total sample height. A more detailed description of the Danish triaxial test is described in Luke (1994).

The CPT cone used was the van den Berg piezo-cone. The geometry of the cone penetrometer is within the standards specified in the international guidelines, ISSMFE No 7 (1989). The cross sectional area of the cone is 10 cm^2, the cone apex angle is 60^o and a penetration velocity of 20 mm/sec was used.

1.1 Description of the six soils

The six investigated soils have very different strength, deformation and classification characteristics, and can be regarded as representative of a wide spectrum of Danish soils. The soils are as follows:

- a rather fat ice sea Yoldia clay (Aalborg).
- a soft (NC) clay till (Purhus)(clay till 1).
- a stiff (OC) clay till (Ølst)(clay till 2).
- a very plastic Tertiary clay (Ølst).
- a Holocene silty clay (Aalborg) and
- an organic mud (Kaas).

All six sites are located in the central or northern part of Jutland, Denmark. Table 1 shows a summary of the obtained classification parameters.

2 TEST RESULTS

The cone factor N_{kt} is in the present study defined as:

$$N_{kt} = \frac{q_t - \sigma_{v0}}{c_u} \quad (1)$$

where q_t is the cone resistance corrected for pore pressure effects and σ_{v0} is the total initial vertical stress.

In Fig. 2 the average value of $(q_t - \sigma_{v0})$ is plotted against **a)** the undrained shear strength $c_{u(CAoeVC)}$ and **b)** the average vane shear strength c_v.

As can be seen in Fig. 2a) the cone factors calculated using triaxial test results are all very close to the line $N_{kt} = 10$.

Compared to this the cone factors calculated using vane shear strengths differ within 7.2 and 10.6 (Fig. 2b))

The deviation between the two sets of cone factors calculated for identical soils using two different test methods must be due to the fact that the undrained soil shear strength is

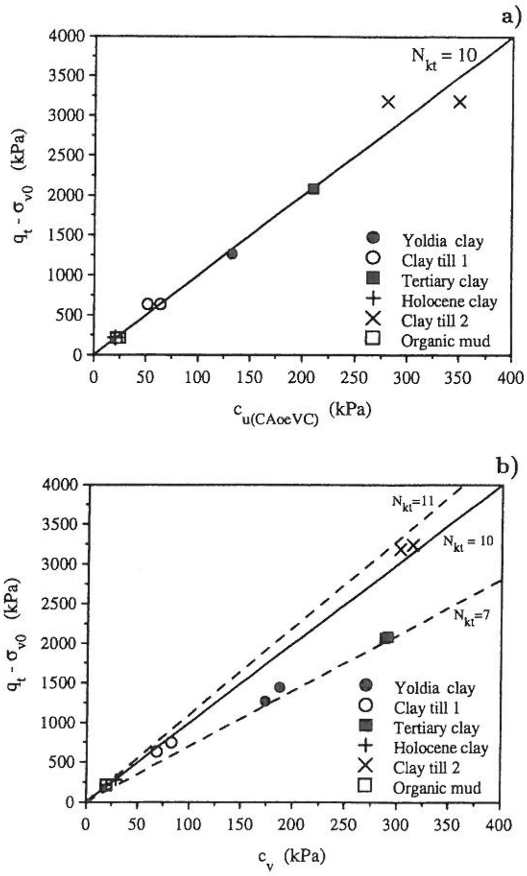

Fig. 2: Average $(q_t - \sigma_{v0})$ plotted against **a)** *$c_{u(CAoeVC)}$ and* **b)** *average c_v for the six soils.*

not unambiguous. The result is strongly dependent on which test method is used which most likely is due to rate effects and anisotropic effects.

The soils for which $c_{u(CAoeVC)}$ and c_v deviate most are the rather fat soils with high plasticity i.e the Yoldia (Aalborg) clay and the plastic Tertiary clay.

As an universal relationship between c_u obtained from different test methods do not exist cone factors have to be estimated separately for each test method. In the following the test results from the two studied test methods will be treated separately and compared with other comparable results from Denmark and other countries.

First a brief discussion on the influence of different parameters on the "vane cone factor" will be given.

Table 1: Classification parameters obtained for the Danish soils at the six test areas.

Soil	level m	w %	w_l %	w_p %	I_p %	clay cont. %	σ_{v0} kPa	σ'_{pc} kPa	OCR
Yold. clay	1.50	33	65	26	39	62	29	225	8-11
Clay till 1	1.50	17	22	15	7	15	32	110	3-4
Tert. clay	1.25	38	174	37	137	83	24	850	2-3
Holoc. clay	1.25	44	37	22	15	21	23	23	1-2
Clay till 2	1.25	14	23	13	10	32	27	700	10-11
Org. mud	2.40	110	97	44	53	35	36	25	1-2

2.1 Influence of different parameters on the vane cone factor

Luke (1994) includes an examination of the dependency of the cone factor regarding :

- classification parameters (w, w_l, w_p, I_p, I_c, A_c, k, c_k and OCR)
- drained strength parameters (ϕ' and c')
- vane parameters (c_v, c_{vr} and S_t)
- CPT parameters (q_t, f_s and f_R)

It is not possible to isolate the effect of one parameter on the cone factor as all the parameters to some degree are correlated.

In Luke (1994) the parameters listed above are plotted against the cone factor and the ones which seem to have the most dominant effect on the cone factor are:

- w_p, I_p
- content of silt, sand and clay
- friction angle ϕ'
- hydraulic conductivity k

In the analysis any clear relation between the cone factor and any of the classification parameters could not be obtained.

Though, generally N_{kt} was found to decrease when w_p, I_p and the content of clay were increased, whereas an increase in N_{kt} was obtained for increasing values of ϕ' and k. All these parameters are to some degree related; an increase in the content of silt or sand in the clay will cause (other things being equal) w_l and I_p to decrease and ϕ' and k to increase.

The parameter which appears to have the strongest correlation to the cone factor is the friction ratio $f_R = f_s/q_t$, f_s being the measured sleeve friction. Fig. 3 shows N_{kt} plotted against f_R.

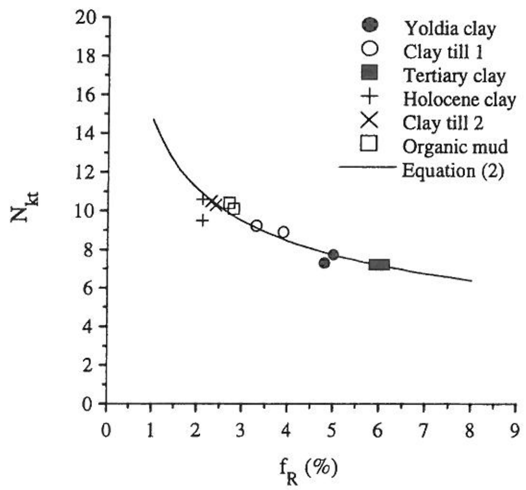

Fig. 3: N_{kt} plotted against f_R for the six soils showing the best fitting line.

The best fitting line when considering only the results from the six Danish thoroughly investigated soils is found to be:

$$N_{kt,(cv)} = 15 \cdot f_R^{-0.4} \qquad (2)$$

The friction ratio is often believed to be affected by partly the sensitivity and partly by the content of sand, silt and clay "particles" in the soil.

3 EVALUATION OF OBTAINED RESULTS

3.1 Triaxial tests

An almost constant cone factor of $N_{kt} = 10$ was obtained for the six Danish soils. Only one or two triaxial tests were carried out on each of the soils, which is unfortunate, as higher reliability would have been ensured if more tests had been performed.

For comparison reasons only consolidated triaxial tests will be used in the following as it is well known that the undrained shear strength from unconsolidated tests, is somewhat lower than those from consolidated tests, which leads to higher cone factors. Cone factors from 11 well documented clay deposits, scattered throughout the world (Lunne and Rad 1986) at which isotropic or anisotropic consolidated undrained compression triaxial tests have been used to estimate c_u will in the following be frame of reference for comparison of the general validity of the results obtained in the present study.

Fig. 4 shows large deviations of N_{kt} from the 11 sites. The cone factors are in the range of 8 to 27.

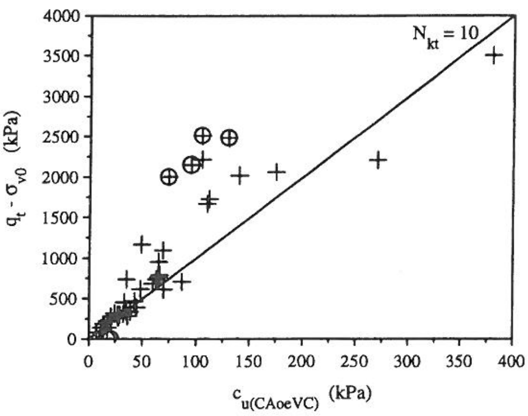

Fig. 4: c_u measured in triaxial tests plotted against $(q_t - \sigma_{v0})$ for 11 international sites, (Lunne and Rad (1986))(data sets from fissured or weathered clays are marked with a circle)

The very high cone factors (in the range of $N_{kt} = 20$) can be explained by the existence of fissures (slicken slides) in the clays, as failure in the triaxial tests is liable to happen in the fissures, whereas CPT tends to measure the intact strength between the fissures. But even when the results from the fissured or weathered clays are disregarded there is still a large number of tests which have cone factors considerably larger than 10.

It is the belief of the author that the deviating behaviour of the cone factors can be explained by applying the theory by Jacobsen (1970) on triaxial specimen size.

As pointed out by Jacobsen (1970) the differences in magnitude between c_u estimated in tests performed on H=D (smooth pressure heads) and tests performed on H=2D (rough pressure heads) can in general be summarized as follows:

$$c_{u(H=D)} \leq c_{u(H=2D)} \text{ for non-dilating soils.}$$

$$c_{u(H=D)} \geq c_{u(H=2D)} \text{ for dilating soils.}$$

The above results can be transferred to the cone factors in Fig. 4. and a close connection is seen:

Soft soils ($q_t < 500$ kPa), in which no dilation is to be expected, have cone factors very close to 10. Some of the cone factors are slightly lower than 10, which could reflect the use of rough pressure heads in connection with non-dilating soils (slightly overestimated c_u), Luke (1995). The use of triaxial specimens $H = 2D$ on non-fissured dilating soils ($q_t > 500$ kPa) may cause cone factors in the order of 15 due to non-uniform deformation of the triaxial specimen.

More research is needed in order to verify the significance of using different specimen heights in triaxial tests.

3.2 *Vane tests.*

To test the validity of Equation 2 which is obtained for the six Danish soils, available data from Danish and international sites have been analysed. These data are plotted in Fig. 5.

Very rarely f_R is stated in the CPT data published, and when it is, the data are often uncertain, especially in soft soils. In soft soils the excess pore pressure is often very high compared to f_s and unequal pore pressures acting at the ends of the sleeve can even make the measured f_s negative. A correct calculation of f_t requires control of the unequal pore

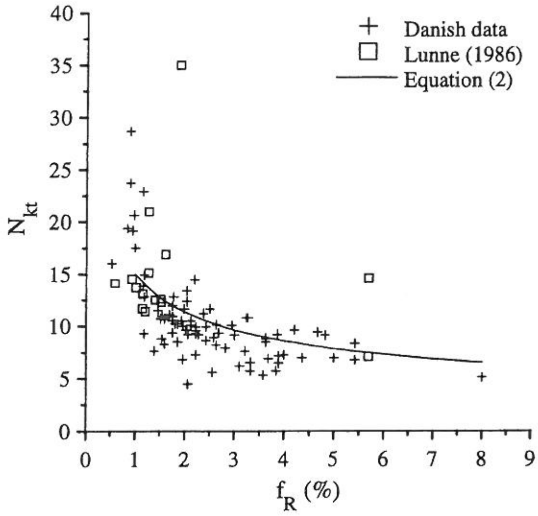

Fig. 5: N_{kt} plotted against f_R for available Danish and international data. The best fitting line for the six Danish soils is also shown.

pressures acting on the ends of the sleeve by measuring the pore pressures at both ends.

As shown in Fig. 5 there is a large variation in the data around the line fitting the Danish data.

Some of the scatter can be due to the fact that vane test results are person dependent. Small N_{kt} values (and f_R) have been estimated in large depths ($> 15\ m$) which is believed to be due to uncertainty in the measurement of c_v at these depths.

Considering the uncertainty in both the tip resistance and the vane shear strength the established relation (eq. 2) fits the data quite well. The variation of N_{kt} is especially high for soft soils ($c_v < 50\ kPa$) and it seems as if local inhomogenities in these soils (presence of sand and silt) affect the cone factor to a much higher degree than in stiffer soils.

4 CONCLUSION

In the present research study field vane tests and consolidated triaxial tests have been used to estimate c_u with the purpose of calculating the cone factor. As the undrained shear strength is not unambiguous it has proved of particular importance to carefully define and describe the test method used for the estimation of c_u if comparison of cone factors should be made possible.

Six different Danish soils have been selected for a close examination of the cone factor. The cone factors estimated using triaxial tests results were all in very close alignment with $N_{kt} = 10$.

The cone factors from international sites using (CAUC and CIUC) triaxial test results were in the range of 8 to 27. The main reasons for the deviating behaviour compared to the results from the six Danish soils are thought to be due to:

- The existence of fissures in the clays, as failure in triaxial tests is liable to happen in the fissures, whereas CPT tends to measure the intact strength in between the fissures.
- The use of different test procedures in the triaxial tests. Especially the use of specimen height twice the diameter might cause differences as the estimated undrained shear strength for certain soils can deviate significantly (mean 40% for clay till when compared to c_u values obtained from tests in which H=D is used, Jacobsen (1970)).

The cone factors calculated using the field vane shear strength varies between 7.2 and 10.6 for the six soils. It seems possible that these cone factors are affected by factors in the soil which also affect the relation between the sleeve friction and the cone resistance $f_s/q_t = f_R$ (i.e sensitivity, plasticity and content of sand and silt).

The relation obtained between N_{kt} and f_R for the six soils is expressed as:

$$N_{kt} = 15 \cdot f_R^{-0.4}$$

A large variation is observed when plotting cone factors obtained from other soils.

5 FUTURE WORK

In the following proposals for future research areas are listed.

Further investigations should be carried out to verify whether the cone factor estimated from Danish triaxial tests can be taken as $N_{kt} = 10$ for all clay soils.

The influence of specimen height when estimating the undrained shear strength in triaxial tests should be examined, especially when dealing with dilating soils.

The factors influencing the correlation between the undrained shear strength from Danish triaxial tests and field vane tests in different soils should be investigated further.

The cone factor proposed to estimate the undrained shear strength corresponding to the vane shear strength ($N_{kt} = 15 \cdot f_R^{-0.4}$) should be investigated further to see if it has a general validity.

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