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Correlating q_c and q_{net} with $c_{fv\text{-}f}$ of Paleogene clays of very high plasticity

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ABSTRACT: This paper provides practical formulations for correlating CPTu cone resistance q_c and net corrected cone resistance q_{net} to fast field vane strengths $c_{fv\text{-}f}$ (FVT-F) in highly overconsolidated, fissured, marine Paleogene clays of very high plasticity, from late Eocene and early Oligocene as observed in Aarhus, Denmark. In the Danish geotechnical industry, it has been a tradition for more than half a century to derive the undrained strength in all types of cohesive deposits from FVT-F. By comparing $c_{fv\text{-}f}$ carried out in boreholes with associated q_c and q_{net} values from CPTu's carried out in the immediate proximity of the boreholes, correlations between these properties have been derived. The correlations allow $c_{fv\text{-}f}$ to be derived from q_c and q_{net} and vice versa, but they also make it possible to transform existing correlations between CPTu data and soil parameters into correlations with $c_{fv\text{-}f}$ and vice versa. Most importantly, the correlations document that FVT-F is useful for measuring the undrained shear strength.

KEYWORDS: Correlating, Cone resistance, Net corrected cone resistance, Fast field vane strength, Paleogene clay.

1 INTRODUCTION

In the Danish geotechnical industry, it has been a tradition for more than half a century to derive the undrained strength in all types of cohesive deposits from fast field vane tests (FVT-F) performed in geotechnical boreholes.

Nowadays, CPTu has become an important and indispensable investigation method in Denmark because it is an effective way to explore how stratigraphy, strength, and stiffness vary spatially. However, CPT investigations are always supplemented with geotechnical boreholes, which due to tradition are performed with FVT-F. This practice calls for a method to correlate the undrained strength derived from the two field test types.

For this reason, the subject of this study is to correlate CPTu cone resistance q_c and net corrected cone resistance q_{net} to fast field vane strengths $c_{fv\text{-}f}$. However, the scope is limited to highly over-consolidated, fissured, marine Paleogene clays of very high plasticity, from late Eocene and early Oligocene as observed in Aarhus, Denmark.

All tests have been conducted to solve urgent technical problems, but in this article, the collected data are used in a more fundamental study of the correlation between $c_{fv\text{-}f}$ and cone resistance.

2 THE PALEOGENE STRATIFICATION

In coastal parts of Aarhus, the Paleogene stratification is found near the surface only covered by a thin layer of younger deposits. The stratification typically found is:

- Topmost 0-20 m Septarian clays of very high plasticity. On some construction sites, a 0.5 – 2.0 meter thick layer of Kysing Marl is embedded, which separates the upper Oligocene part (Viborg Clay) from the lower Eocene part (Moesgaard Clay). However, the Septarian clays are not present everywhere.
- Søvind Marl underlies the Septarian clays. Søvind Marl is a clay of very high plasticity that makes up the majority of the Søvind Marl formation. It is predominantly very calcareous. However, calcareous-free or slightly calcareous zones frequently alternate with more calcareous ones.

The Paleogene Clays are additionally characterized by the classification parameters in Table 1.

All these clays are deposited in a deep ocean, except for Kysing Marl; they are all fissured with slickensides. Due to the removal of younger layers by erosion and the weight of numerous glaciers during the Quaternary period, they are also highly over-consolidated with a geological pre-consolidation pressure greater than two MPa.

Table 1. Classification parameters of the Paleogene Clays.

Clay type	Parameter	Range
Septarian clays	Natural water content [%]	30-49
	Bulk unit weight [kN/m^3]	17-19
	Plastic limit [%]	29-38
	Plasticity index [%]	55-84
	Calcium carbonate content [%]	3-18
Søvind Marl	Natural water content [%]	29-58
	Bulk unit weight [kN/m^3]	17-19
	Plastic limit [%]	28-50
	Plasticity index [%]	65-250
	Calcium carbonate content [%]	1-65

Large variations in plasticity and calcium carbonate content indicate that also strength and deformation properties vary a lot down through the formations. Variability in CPTu cone resistance confirms this, cf. Figure 1.

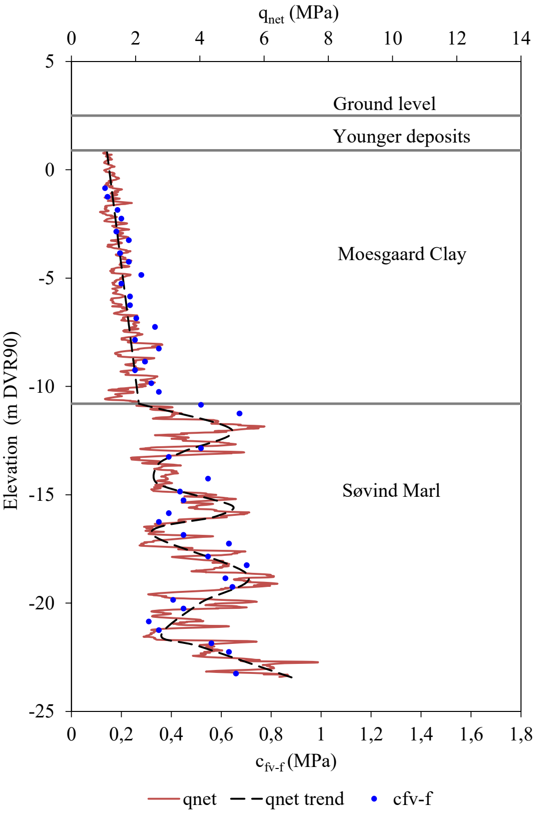


Figure 1. An example of a q_{net}-profile calculated from a CPTu in the Paleogene stratification in Aarhus and FVT-F measurements from a nearby borehole.

If the cone resistance is decomposed into a trend component and a fluctuating component, the CPTu's show that the fluctuating component is characterized by frequent and violent fluctuations around a trend line. Through the Septarian clays, the trend line is directly proportional to depth, but in the Søvind Marl, it varies in large irregular cycles. The main trend can usually traceable in the CPTu's across the construction site, while it is more difficult to trace the individual fluctuations.

According to Larsen 2017 the variations in calcite content in the Søvind Marl is due to climate changes, which are caused by Milankovitch cycles during the approximately 10-15 million years long sedimentation period. We suspect that Milankovitch cycles could be the underlying reason for the cyclic strength variations.

3 CPTU

The CPTu's are performed in a single continuous stroke from the ground surface to the target depth using Geo's enhanced CPT-system, which reduces the friction on the rod and makes it possible to push the cone through more than 80 meters of very firm clays.

Geo's CPT with a maximum push capacity of 15 tons is used together with a 10 or 15 cm^2 piezoelectric cone from the manufacturer A.P. van den Berg. The equipment and the execution are in agreement with ISO 22476-1 with continuous measurement of tip resistance (q_c), sleeve friction, pore pressure (u_2) as measured behind the tip of the probe), and inclination of the probe. From this data the corrected cone resistance $q_{net} = q_c + 0{,}25u_2 - \sigma_{v0}$ is computed, where σ_{v0} is the vertical total stress.

The CPTu's are supplemented with geotechnical boreholes performed with fast field vane tests for use in interpreting the CPTu's and for extracting soil samples for classification and advanced laboratory tests.

4 FAST FIELD VANE TESTS

In Denmark, fast field vane tests are traditionally performed in cohesive soils in all geotechnical boreholes. Typically, two FVT-F's are performed per meter per boring often supplemented with extra tests near the ground surface. In excavations for buildings and construction sites, FVT-F's are also carried out as control investigations to verify the design assumptions by performing the test with light, hand-held equipment. Andersen, 2020 presents some guidance for deriving the undrained shear strength c_u from the FVT-F ($c_u \approx c_{fv}/3$ for fissured, Paleogene clays of very high plasticity).

The equipment of the FVT-F is very robust and thus customized to Danish soil conditions, i.e. stony tills and firm, overconsolidated clays cf. Okkels 2019. Furthermore, the test is simple and quick to perform compared to the internationally well-known field vane test types (FVT).

A reference standard of the Danish Geotechnical Society (1999) describes the equipment and execution, which is in agreement with ISO 22476-1. The only deviation from this is that strengths greater than 0.7 MPa are measured with an extended moment arm.

5 DATA COLLECTION

Data is collected from paired boreholes and CPTs typically spaced two meters apart. For each fast field vane test, the cone resistance q_c and the associated calculated q_{net} value are read as an average value over a 0,1 m zone at the same depth, which in the case of the CPTs has been corrected for the inevitable deflection of the CPT rod. In most cases, the deflection increases the distance to the borehole and thus to the field vane tests which increase scatter. All vane tests that max out are discarded.

In the Septarian clays, CPT data is collected for 194 FVT-F's from 11-paired boreholes and CPTs distributed over seven building sites in Aarhus. The deflection of the CPT probe increases with depth from between 0.1-1.0 meters on the top of the layer 3-17 meters below ground, and up to between 0.1-2.8 meters when 9-32 meters below ground. The average deflection is approximately 0.6 meters for the collected data.

In the Søvind Marl down below, CPT data is collected for 458 FVT-F's from 16-paired boreholes and CPTs distributed over seven sites in Aarhus. The deflection of the CPT probe increases with depth from between 0.1-4.5 meters on the top of the layer 10-33 meters below ground, and up to between 0.5-8.8 meters when 25-50 meters below ground. In this case, the average deflection is in the order of two meters for the collected data.

6 DATA PROCESSING

From the collected data, the following proportionality factors are calculated for each field vane test:

$$N_k = q_c / c_{fv-f} \qquad (1)$$

$$N_{kt} = q_{net} / c_{fv-f} \qquad (2)$$

Next, the mean and standard deviation of both N_k and N_{kt} for both clay types are calculated. Assuming that the proportionality factors are normally distributed, values greater/lower than the mean plus/minus three times the standard deviation are considered outliers and discarded. Afterwards, both the mean and standard deviation are calculated for the remaining values and summarized in Table 2.

Table 2. Parameters characterizing the normal distributions.

Clay type	Parameter	N_k	N_{kt}
Septarian clays	Mean	7.11	6.58
	Median	6.98	6.37
	Standard deviation	1.91	1.88
	No. of data sets	192	194
	No. of discarded outliers	2	0
Søvind Marl	Mean	8.09	7.50
	Median	7.86	7.27
	Standard deviation	2.27	2.25
	No. of data sets	440	440
	No. of discarded outliers	18	16

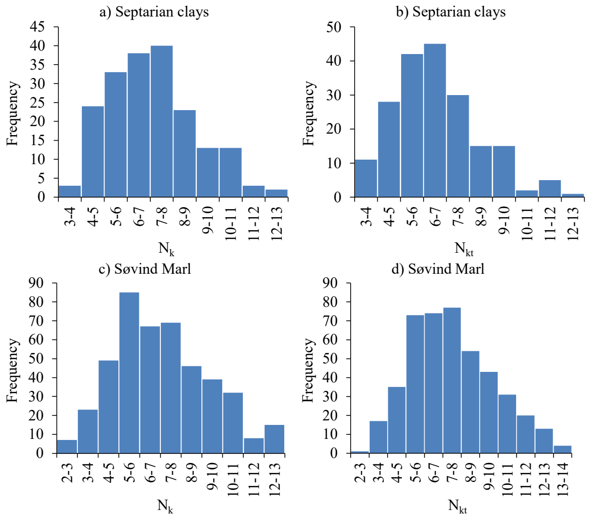


Figure 2. a) – d) shows histograms for the filtered data.

Table 3. Calculated and derived correlation parameters. Figure 3 presents the derived parameters.

Origin	Septarian Clay		Søvind Marl	
	N_k	R^2	N_k	R^2
Calculated from $q_c=f(c_{fv\text{-}f})$	6.64	0.67	7.64	0.32
Calculated from $c_{fv\text{-}f}=f(q_c)$	7.01	0.65	8.22	0.20
Derived for $q_c=f(c_{fv\text{-}f})$	**6.83**	0.66	**7.93**	0.31
Derived for $c_{fv\text{-}f}=f(q_c)$	**6.83**	0.65	**7.93**	0.18
	N_{kt}	R^2	N_{kt}	R^2
Calculated from $q_{net}=f(c_{fv\text{-}f})$	6.08	0.63	7.12	0.32
Calculated from $c_{fv\text{-}f}=f(q_{net})$	6.44	0.63	7.75	0.08
Derived for $q_{net}=f(c_{fv\text{-}f})$	**6.26**	0.62	**7.44**	0.30
Derived for $c_{fv\text{-}f}=f(q_{net})$	**6.26**	0.63	**7.44**	0.07

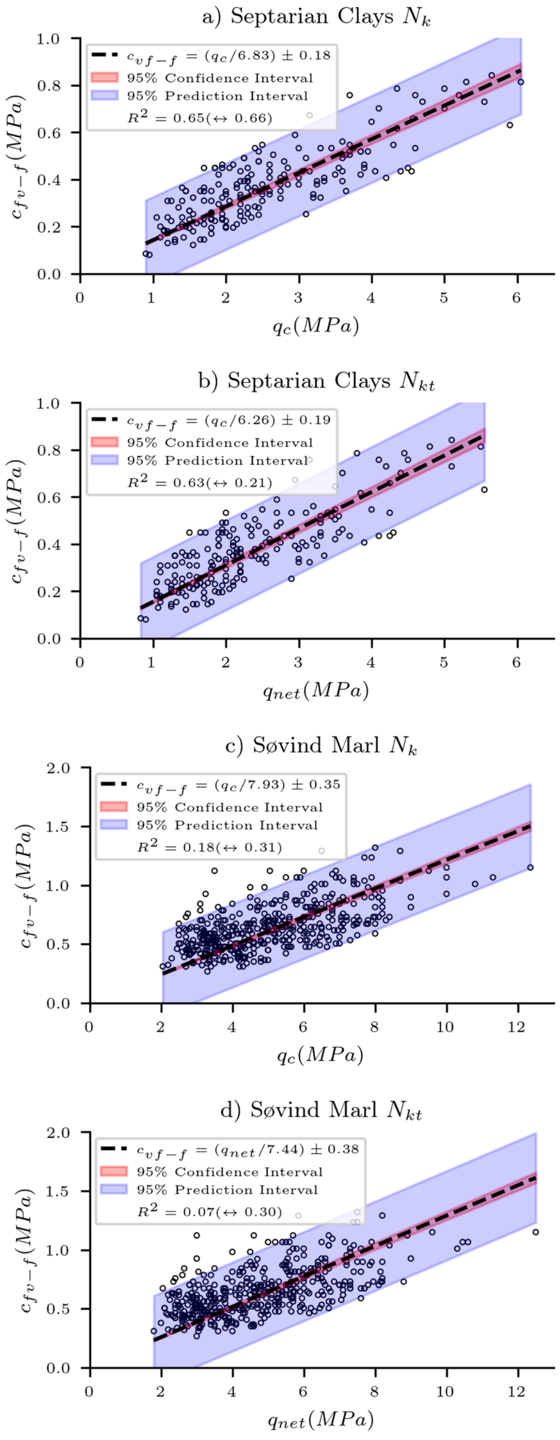


Figure 3. a) – d) shows four scatter plots for $c_{fv\text{-}f}$ vs. q_c and for $c_{fv\text{-}f}$ vs. q_{net} for the Septarian clays and Søvind Marl, respectively. Derived trend lines, confidence intervals and predictions intervals are shown as well.

Figure 2 shows histograms for the filtered data. All four distributions are roughly bell-shaped, and a Gaussian distribution appears to be a good approximation. However, the distributions are skewed right.

The correlations are determined in the following by simple linear regression, which do not account for errors in both variables. For this reason different regression lines and thus also different constants (N_k or N_{kt}) are calculated when the cone resistance is plotted as a function of the fast field vane strength, q = f(c_{fv}), and when it is plotted as the inverse function, c_{fv} = f(q) i.e. Table 3. This is inappropriate for many practical applications and is compensated for by using the mean value of each pair of correlations.

Figure 3 presents scatter plots for $c_{fv\text{-}f}$ vs. q_c and for $c_{fv\text{-}f}$ vs. q_{net} for the Septarian clays and Søvind Marl, respectively. For each plot, straight trend lines forced through the origin is calculated using simple linear regression. The forced binding simplifies the correlation model, but gives a slightly worse fitting model. As can be seen, the derived correlation coefficients are slightly less than the means in Table 2.

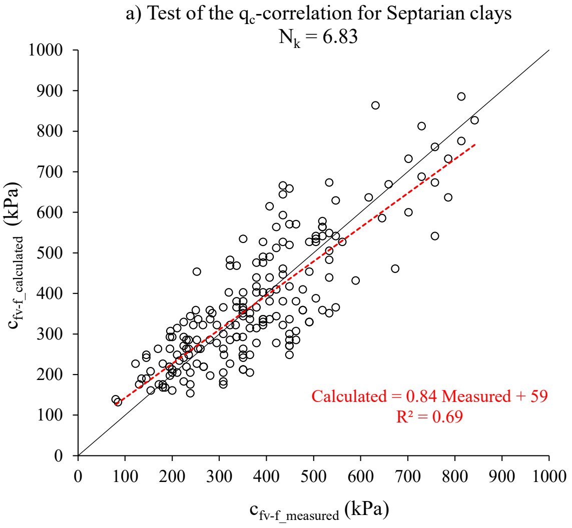
The correlations for the Septarian clays are derived for $c_{fv\text{-}f}$ between 80-850 kPa and cone resistance between 0.8-6.0 MPa. The correlations for the Søvind Marl are derived for $c_{fv\text{-}f}$ between 250-1300 kPa and cone resistance between 2-12 MPa.

The test of the correlations in Figure 4 shows that the variation is large – not least for the Søvind Marl. The difference between the two clay types indicates that the variation is largely due to the violent fluctuations discussed in section 2, combined with the inevitable deflection of the CPT probe, both of which are most pronounced in the Søvind Marl. This means that the correlation between CPT-data and FVT-F is stronger than it seems at first glance.

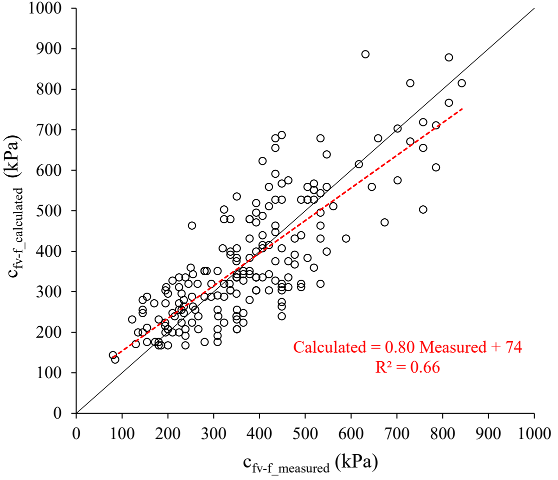
The test plots also reveals that the correlations are not symmetrical. They thus tend to overestimate low field vane strengths and underestimate high field vane strengths. The asymmetric trend, which is most dominant for Søvind Marl, is, however, secondary to the general scatter.

7 TEST OF THE CORRELATIONS

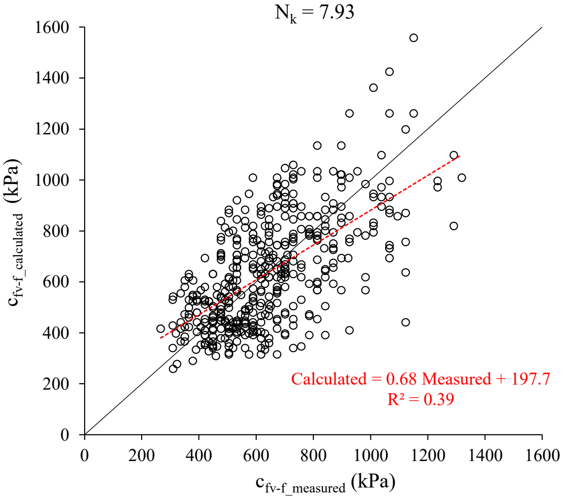
The correlations are tested in Figure 4 by comparing measured fast field vane strengths with fast field vane strengths calculated from cone resistance and net corrected cone resistance using the derived correlation coefficients.



b) Test of the q_{net}-correlation for Septarian clays
N_{kt} = 6.26



c) Test of the q_c-correlation for Søvind Marl
N_k = 7.93



d) Test of Søvind Marl correlation with q_{net}
N_{kt} = 7.44

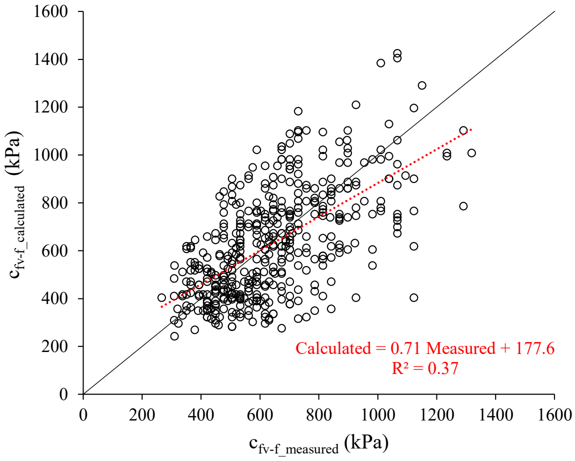


Figure 4. a) – d) shows four test plots comparing the measured values with the calculated values using the derived correlations.

In Figure 5, $c_{fv\text{-}f}$ calculated with the correlation for q_c is compared with $c_{fv\text{-}f}$ calculated with the correlation for q_{net}. As can be seen, the difference between the two correlations is of no practical significance concerning the uncertainties in the correlations. This result is of course not surprising since q_c and q_{net} are in all cases correlated with the same field vane strength.

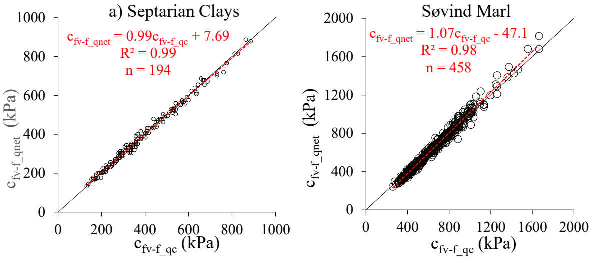


Figure 5. Two test plots comparing calculated values of fast field vane strength using the derived correlations with q_c and q_{net}.

8 DISCUSSION

The authors would expect that the Søvind Marl would have smaller correlation coefficients than the Septarian clays due to higher plasticity. However, it is the experience of the authors that the Søvind Marl generally has better strength and stiffness properties than the plasticity indicate (see e.g. Okkels, 2024). This deviation from the expected plasticity trend is probably due to the predominantly high calcium carbonate content in the Søvind Marl, which originates from silt-sized coccoliths (Sorensen, 2023).

An important consideration is the heterogeneous nature of geological units in Denmark, which in large have undergone glaciotectonic deformation. The spatial positions of the CPT test and geotechnical boreholes used for vane tests do not coincide. This increases the uncertainty of the linear models presented in this study. A possible solution is to place two or three boreholes in close proximity around the CPT test, making it possible to account for the geological heterogeneity. Alternatively, another possible solution could be to place two or more CPTs closely around a single borehole. The q_c and q_{net} values could then be estimated at the position of the borehole.

9 CONCLUSIONS

By comparing $c_{fv\text{-}f}$ carried out in boreholes with associated q_c and q_{net} values from CPTu's carried out in the immediate proximity of the boreholes, linear correlations between these properties have been derived for Septarian clays and Søvind Marl cf. Table 3.

The correlations allows $c_{fv\text{-}f}$ to be derived from q_c and q_{net} values and vice versa, but they also make it possible to transform existing correlations between CPTu data and soil parameters into correlations with $c_{fv\text{-}f}$ and vice versa. The q_c and q_{net} correlations are equivalent because the two parameters in all cases are correlated with the same fast field vane strength.

Very importantly, the correlations document that FVT-F is useful for measuring the undrained shear strength.

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