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Correlating q_{net} to E_{ur} of Paleogene clays of high plasticity

Corréler q_{net} à E_{ur} des argiles Paléogènes de haute plasticité

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ABSTRACT: This paper provides a practical formulation for correlating net-corrected cone resistance q_{net} to the drained unloading and reloading stiffness E_{ur} in highly overconsolidated, fissured, marine Paleogene clays of very high plasticity as observed in Aarhus, Denmark. E_{ur} is used for analysis of soil deformations using Hardening Soil models, which is particularly advantageous to use rather than more traditional Mohr-Coulomb soil models when the soil model has to handle both loading and unloading. By correlating E_{ur} from 34 drained triaxial tests to q_{net} from CPTu's near the boreholes from which the triaxial-samples are extracted, a linear correlation between these two properties is found. This formulation makes it possible to derive E_{ur} directly from CPTu for use in preliminary analysis of deformations. More importantly, the correlation supports the final derivation of E_{ur} for 3D finite element models once the results of all field and laboratory tests for the construction project are available.

RÉSUMÉ: Cet article fournit une formulation pratique pour corréler la résistance du cône corrigée nette q_{net} à la rigidité drainée de déchargement et de rechargement E_{ur} dans des argiles marines paléogènes fortement surconsolidées et fissurées de très haute plasticité, comme observé à Aarhus, au Danemark. E_{ur} est utilisé pour l'analyse des déformations du sol à l'aide de modèles de sol durcis sables, ce qui est particulièrement avantageux à utiliser plutôt que des modèles de sol Mohr-Coulomb plus traditionnels lorsque le modèle de sol doit gérer à la fois le chargement et le déchargement. En corrélant l'E_{ur} de 34 tests triaxiaux drainés avec le q_{net} des CPTu proches des forages d'où les échantillons triaxiaux sont extraits, une corrélation linéaire entre ces deux propriétés est trouvée. Cette formulation permet de dériver E_{ur} directement à partir de CPTu pour une utilisation dans l'analyse préliminaire des déformations. Plus important encore, les corrélations soutiennent le calcul final de l'E_{ur} pour les modèles d'éléments finis 3D une fois que les résultats de tous les tests sur le terrain et en laboratoire pour le projet de construction seront disponibles.

Keywords: Clay; overconsolidated; very high plasticity; cone resistance; drained unloading-reloading stiffness.

1 INTRODUCTION

It has become common practice to perform triaxial tests to determine the drained triaxial unloading and reloading stiffness for use in Hardening Soil (HS) models and Hardening Soil small strain (HSs) models when analyzing the deformations of high-rise buildings in the city of Aarhus, Denmark.

At the same time, CPTu has become the preferred investigation method because it is the most effective way to illuminate how stratigraphy, strength and stiffness varies spatially. In order to exploit this commercially, Geo has derived an Aarhus correlation between the net-corrected cone resistance q_{net} from the CPT's and the drained triaxial unloading and reloading stiffness E_{ur}.

The CPTu's are performed in a single continuous stroke from the ground surface to target depth using Geo's enhanced CPT-system, which reduce 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-crawler with a maximum push capacity of 15 ton 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, sleeve friction, pore pressure (measured behind the tip of the probe) and inclination of the probe.

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

2 THE PALEOGENE STRATIFICATION

In costal parts of Aarhus, the Paleogene stratification is found near the surface only covered by fill and/or a thin series of glacial and or postglacial layers. The following stratification is typically found, cf. figure 1:

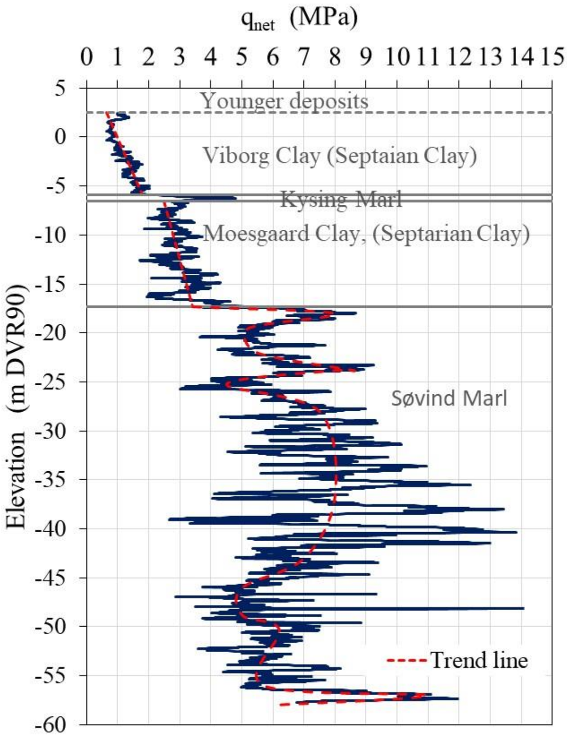

Figure 1. An example of a q_{net}-profile calculated from one of nine CPTu's included in this study.

- Topmost 5-9 meter Viborg Clay, which is an Oligocene clay of very high plasticity with mica.
- The Viborg clay is underlain by 0.5-2 meters Kysing Marl, which is a highly glauconitous, highly calcareous and high to very high plasticity clay from the top of the Eocene Søvind Marl formation. It is quite similar to the underlying Søvind Marl, but the geotechnical properties are better.
- Below the Kysing Marl typically 9 to 13 meters of Moesgaard Clay - which is an Eocene clay of very high plasticity with mica - is found. This clay is somewhat reminiscent of the overlying Viborg Clay in terms of appearance and geotechnical properties. The trivial name "Septarian Clay" is traditionally used for both clay types.
- Søvind Marl underlies Moesgaard Clay. 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.

All these clays are deposited in a deep ocean and with exception of the Kysing Marl, they are all fissured with slickensides. Due to removal of younger layers by erosion and the weight of numerous glaciers during the Quaternary period, they are also highly overconsolidated with a geological preconsolidation stress greater than two MPa.

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. If 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.

3 TEST PROCEDURES

The primary target for the triaxial tests has been to determine the drained unloading and reloading stiffness E_{ur}.

The tests are performed on nominally undisturbed specimens extracted from Shelby-tube samples with a diameter of 70 mm and a height to diameter ratio of 1. Smooth and lubricated end plates are used.

All tests are carried out isotopically consolidated with a drained failure state (CID) according to the guidelines in ISO 17892-9. De-aired tap water is used. It also applies, that a plasticity index I_P and a calcium carbonate content are determined on the specimen material itself and/or the trimming material.

Due to the swelling potential of the clays, it is necessary to set the isotropic chamber pressure during the initial flushing and water saturation of the system so high that the samples are prevented from swelling. The chamber pressure is determined corresponding to the specimen's effective in situ mean stress, which is initially estimated from the vertical effective in situ stress and a coefficient of lateral earth pressure, K_0 (between 1.3 and 2.5). If the specimen swell, the chamber pressure is increased until swelling is prevented.

Next, the specimens are isotopically pre-consolidated to a conservatively estimated pre-consolidation stress (mean stress determined from a cautious estimated vertical pre-consolidation stress and $K_0 = 0.4$ to simulate a normal consolidated state prior to the geological unloading). The consolidation phase is carried out according to Danish tradition in order to reduce the influence from the inevitable sample disturbance (Jacobsen, 1970). Finally, the specimen is isotopically unloaded to a stress corresponding to the chamber pressure found during the initial phase, from which the shearing phase starts.

The applied rate of strain during shearing is chosen according to ISO 17892-9 to ensure slow enough rates to achieve full equalization of pore water pressures in the specimen. For very high plasticity clay, this means that the applied strain rate is around 0.02-0.05%/hr. All tests are continued until failure.

$E_{ur;TX}$ is determined as the secant stiffness from the unloading and reloading loop. In the calculation, the strain is corrected for the compression of the lubricated latex sliding membranes, which are placed at both ends of the samples to ensure smooth endplates. Tests carried out with identical equipment show that the compression (strain) of the membranes can be evaluated from the following expression (for a 70 mm high specimen):

$$\epsilon_{membran} = 0.070\, ln\sigma'_V + 0.31 \qquad (1)$$

where σ'_V is the effective vertical stress acting on the specimen.

E_{ur} is stress-dependent, as it (regarding to the soil models HS or HSs) depends on the minimum principal stress σ'_3 - which initially is vertical in overconsolidated soil. For a given type of soil, the stiffness E_{ur} therefore varies with σ'_3 (typically corresponding to stiffness increasing with depth).

Only if the triaxial test is carried out at an effective chamber pressure $\sigma'_{3;TX}$, which is equal to the vertical effective in situ stress σ'_{v0} at the level where the soil sample is taken, the measured stiffness $E_{ur;TX}$ corresponds to the in situ stiffness. Due to the swelling pressure, however, the tests are typically performed at a higher chamber pressure. Therefore, it is necessary to correct the measured stiffness, if the stiffness is to be correlated with the q_{net} value measured at the same depth. This is necessary because the stiffnesses of the overconsolidated Paleogene clay types naturally fluctuate significantly with depth.

The in situ stiffness $E_{ur;insitu}$ for use in the correlation with q_{net} is calculated from equation 2 (Brinkgreve and Vermeer, 2015):

$$E_{ur;insitu} = E_{ur;TX}\left(\frac{c\,cos\varphi + \sigma'_{v0}\,sin\varphi}{c\,cos\varphi + p^{ref}\,sin\varphi}\right)^{m} \qquad (2)$$

where p^{ref} is replaced with $\sigma'_{3;TX}$. The tests indicate effective strength parameters $\varphi' = 22°$ and $c' = 40$kPa for Septarian clays and $\varphi' = 30°$ and $c' = 40$kPa for Søvind Marl. Simulations in Plaxis Soil Test indicate that the stress-dependency parameter $m \approx 0.7$. The $E_{ur;insitu}$ calculation is checked in Figure 2.

As part of commercial ground investigations, $E_{ur;TX}$ and $E_{ur;insitu}$ are derived from a total of 16 triaxial tests with Septarian Clay types and 21 triaxial tests with Søvind Marl and presented in Table 1 and 2. A total of 9 pairs of CPT's and borings are included in this study.

Table 1. Test results Septarian Clays (I_P = 56-100%).

Geo ID	**σ'_{v0}** [kPa]	**$\sigma'_{3;TX}$** [kPa]	**q_{net}** [MPa]	**$E_{ur;TX}$** [MPa]	**$E_{ur;insitu}$** [MPa]
204608$_{1;34}$	173	341	2.60	30.0	21.5
204296$_{1;37}$	170	211	3.93	38.8	35.2
205173$_{2;17}$	80	200	1.40	29.1	20.4
205173$_{2;41}$	186	246	3.50	80.2	70.2
205231$_{1;20}$	102	207	2.33	30.7	22.9
205231$_{1;12}$	70	122	1.65	20.8	17.3
204607$_{1;11}$	60	80	1.13	13.8	12.7
204607$_{1;15}$	75	23	1.45	12.3	15.7
204607$_{1;19}$	90	50	1.75	16.4	19.3
204607$_{1;27}$	125	101	2.13	22.1	23.9
206449$_{15;39}$	185	287	3.32	44.7	36.1
206449$_{15;47}$	220	485	4.00	40.9	26.8
206449$_{15;55}$	250	407	4.50	39.9	30.8
206374$_{1;25}$	131	268	1.95	50.7	36.6
206374$_{1;33}$	167	239	3.10	84.5	71.5
206385$_{4;31}$	160	247	2.25	29.9	24.4

Table 2. Test results for Søvind Marl (I_P = 67-192%).

Geo ID	**σ'_{v0}** [kPa]	**$\sigma'_{3;TX}$** [kPa]	**q_{net}** [MPa]	**$E_{ur;TX}$** [MPa]	**$E_{ur;insitu}$** [MPa]
204608$_{1;58}$	269	324	5.40	50.1	45.1
204608$_{1;66}$	301	348	6.50	67.5	62.1
204608$_{1;82}$	365	470	9.40	56.8	48.8
204296$_{1;77}$	330	331	11.0	157.7	157.4
204296$_{1;101}$	425	463	5,80	55.6	52.8
204296$_{6;53}$	240	340	6,00	41.2	33.9
204296$_{6;85}$	365	547	4.90	69.9	54.7
204296$_{6;125}$	520	621	6.10	92.5	82.8
205173$_{2;65}$	289	365	8.90	90.5	79.1
205173$_{2;81}$	457	454	8.70	86.5	86.8
205173$_{2;97}$	428	541	5.00	96.8	83.9
205231$_{1;44}$	198	265	5.75	58.0	49.6
205231$_{1;28}$	134	201	3.20	40.0	32.9
204607$_{1;35}$	157	122	3.55	37.4	42.1
204607$_{1;39}$	175	144	4.00	28.9	31.8
206374$_{1;41}$	131	281	5.00	43.9	29.7
206374$_{1;57}$	270	330	6.50	62.0	55.3
206374$_{1;81}$	372	581	6.50	52.8	40.2
206374$_{1;89}$	406	641	7.00	92.7	70.0
206385$_{4;51}$	250	294	4.70	34.5	31.5
206385$_{4;61}$	295	352	5.50	81.1	73.3

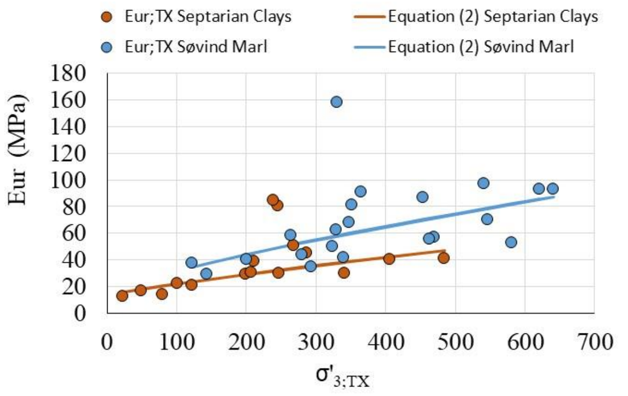

Figure 2. Check of equation (2) and the derived soil parameters.

4 CORRELATING QNET AND EUR

In commercial ground investigations about a handful or two of triaxial tests are usually carried out per site. Consequently, the soil volume with which tests are carried out is typically in the order of one billionth of the soil volume that is subsequently modelled when the settlements are to be calculated. It is therefore only possible to establish a statistically acceptable basis for deriving a valid input to a soil model if it is included the knowledge that CPTs and strength measurements in boreholes provide about the spatial variation of the stiffness. In practice, this is done by correlating the results of laboratory tests with field tests such as CPT and field vane tests.

However, the number of tests remains insufficient considering the large natural fluctuations that naturally occur in the stiffness of the overconsolidated clays cf. Figure 1. Therefore, it is necessary to improve the statistical basis by including a priori knowledge about the stiffness parameters. This is done by including corresponding correlations between measured stiffnesses and CPT-data collected in connection with previous ground investigations in the same clay types.

Only in this way is it possible to create an acceptable statistical basis for deriving a valid 3D stiffness model for use in settlement calculations.

Corresponding values of $E_{ur;insitu}$ and the net cone resistance q_{net} are plotted in Figure 3, where q_{net} is measured in a nearby CPTu at the same level as samples for the triaxial test were extracted from the boreholes (mean value of q_{net} over 0.2 m CPT).

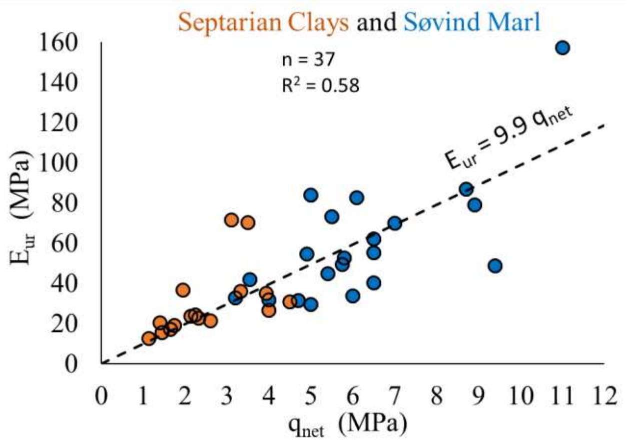

Figure 3. Correlation between q_{net} and the drained E_{ur}.

The CPTu's are typically performed approximately two meter from the borehole. However due to the inevitable deflection, the distance may be different at target depth. The distance introduces uncertainty and thus scatter when the highly fluctuating CPTu measurements are correlated with measured soil parameters from in situ testing and from laboratory testing on soil samples extracted from the boring. Therefore, a large number of tests is required to achieve a satisfactory strong correlation.

Based on available data, the following Aarhus correlation is derived for Septarian Clays and Søvind Marl:

$$E_{ur} \approx 9.9\ q_{net} \qquad (3)$$

A confidence interval for the proportionality factor was computed to be *CI(95)* = 9.9±1.4.

According to Figure 3, the deviation appears to increase as q_{net} increases. Since the overall trend is that q_{net} also increases with depth and q_{net} at the same time fluctuate violently around its overall trend cf. Figure 1, the inevitable inclination means that the distance between CPTu probe and extracted samples changes with depth and thereby deteriorates the correlation between q_{net} and E_{ur}.

5 SUMMARY AND CONCLUSION

During ground investigations for high-rise buildings in Aarhus, Geo has determined the drained unloading and reloading stiffness from 16 triaxial tests with Septarian Clays and 21 triaxial tests with Søvind Marl. On this basis, an Aarhus correlation between q_{net} the E_{ur} has been derived cf. eq. (3).

The proposed correlation makes it possible to transform CPTu-profiles into drained unloading and reloading stiffness E_{ur}-profiles for use in preliminary analysis of deformations. More importantly, the correlations support the final derivation of E_{ur} for 3D finite element models once the results of all field and laboratory tests for the construction project are available.

The derived local correlation between q_{net} and E_{ur} indicates that it is also possible to formulate similar correlations between q_{net} and other stiffness parameters such as the small strain shear modulus G_{max} and the oedometer stiffness E_{oed} for reloading in these highly overconsolidated, fissured, marine Paleogene clays of very high plasticity.

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