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Relative densities and void ratios derived from CPT data using in situ field calibration

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ABSTRACT: This study shows the results of an attempt to develop a transfer function of cone resistance measured in medium over-consolidated sands (< 2 MPa) toward relative soil density and absolute porosity solely based on in-situ testing. In a sand pit, a water saturated, Late Pleistocene fluvial section of 15 m thickness with homogeneous grain size distribution and comparable e_{max} and e_{min} values, but highly variable cone resistance was selected for testing. Two ~25 m deep sampling holes, 6 CPTs and two approximately 40 m deep neighboring flush drilled holes for downhole logging with a horizontal distance of 2.5 m to the CPTs were used in this study. Relevant downhole logging parameters are wet bulk density derived from active gamma logs and porosities derived from neutron-neutron logs. The results show a straightforward stratigraphic picture with clear soil package boundaries. However, within the sand formation of interest fluvial foresets bars, top sets and incised channels with local unconformities lead to changes of stratigraphic height over short horizontal distances challenging in turn the correlation of logging and CPT data. Despite these difficulties, the project resulted in a new transfer function for glacially overconsolidated sands not only linking tip values to relative density but also directly to porosity, making sampling at least for stratigraphic equivalent sands no longer a requirement.

1 INTRODUCTION

Obtaining undisturbed sand samples in non-cohesive soils could require expensive ground freezing while conventional sampling with pushed thin walled tubes or hammered thick wall tubes usually causes densification of looser layers and loosening of densely packed layers (e.g. Fig. 1, line A). The reconstruction of the sand sample in the laboratory therefore has to rely on in-situ test results. The most common technique to estimate the relative in-situ density of sands is the application of recognized empirical correlations for cone penetration tests based on large calibration chamber tests (e.g. Baldi et al. (1986), Bolton & Gui (1993), Jamiolkowski et al. (2001), Kulhawy & Mayne (1990) see Fig. 1).

However, these correlations based on specific local test sands can provide deviant results when applied to sands of different origin, composition, grain texture, age or consolidation state.

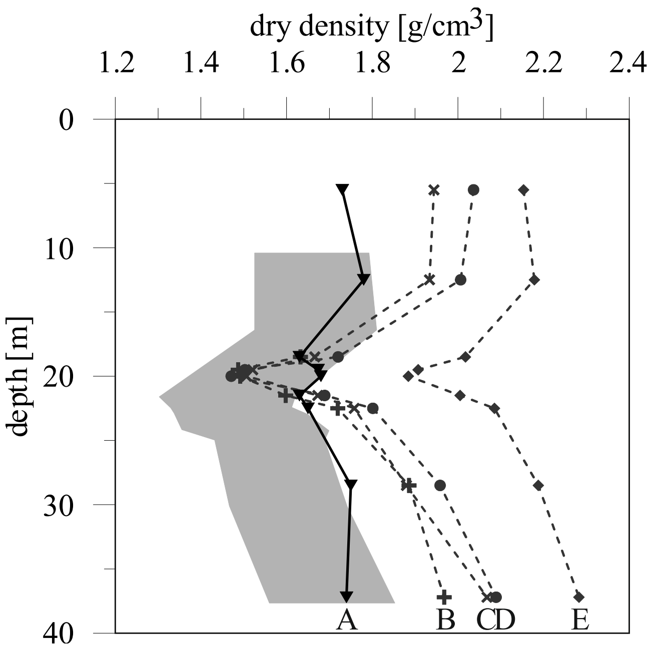

Figure 1. Offshore profile over a looser packed sand layer at around 20 m depth. Showing laboratory derived dry bulk densities from offshore taken push core samples (line A), as well as estimated dry densities using empirical CPT correlations after Bolton & Gui (1993) (B), Jamiolkowski et al. (2001) (C), Baldi et al. (1986) (D), Kulhawy & Mayne (1990) (E). Minimum and maximum compactness (according to DIN 18126) are indicated by grey shading.

So far no transfer function exists for dense, often over-consolidated Pleistocene sands of the North Sea. Establishing a new correlation in the laboratory requires comprehensive and time consuming testing and correction for equipment effects such as chamber and cone sizes. In addition freshly prepared samples in the laboratory cannot provide information on ageing or other diagenetic longer term effects.

In-situ testing and down hole logging has the advantage to account for most of the soil conditions (stress state, temperature etc..) although limitations and calibrations of the testing equipment have to be considered. In this study, a correlation among cone resistance and relative density based on in-situ CPT and gamma density measurements in dense, slightly over-consolidated Late Pleistocene sand is proposed and compared with internationally recognized correlations.

2 STUDY AREA

The study area is located south of the town Cuxhaven in Northern Germany, close to the North Sea coast (Fig. 2). The site exhibits the same sand dominated stratigraphy and related geotechnical properties as found in many offshore wind farm areas within the Danish, German and Dutch sector of the southern North Sea.

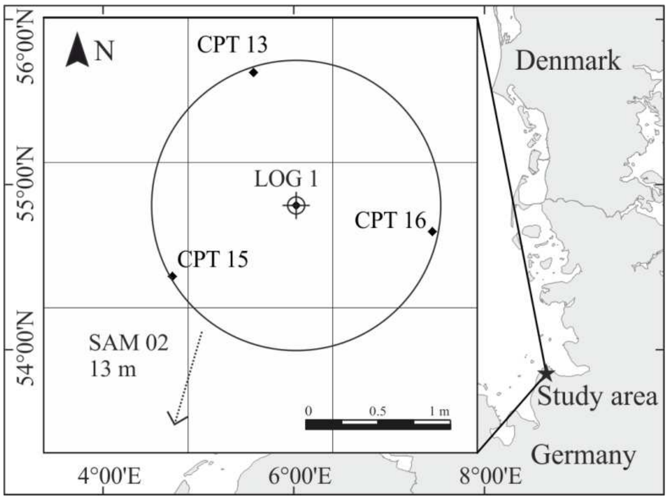

Figure 2. Study area and example of the spatial configuration of CPT, downhole logging and sampling boreholes.

In general the following requirements to the soil have to be fulfilled to consider an area suitable for in situ correlations: (i) full saturation, (ii) close to no variability in the grain size distribution and index densities ρ_{min} and ρ_{max} (iii) high variability in tip resistance and (iv) a simple horizontally layered stratigraphy with homogenous lateral soil properties.

3 METHODS

3.1 *Sampling*

A dry drilling Nordmeyer DSB 1/6 percussion hammer sampling unit has been used at the two sampling sites with a cumulative core length of 30.0 and 21.0 m respectively. A total of 41 samples have been investigated with regard to water content (DIN 18121) and soil bulk density (DIN 18125). Grain size analyses were performed according to DIN 18123, Fig. 3. Minimum and maximum void ratios (e_{min}, e_{max}) were measured according to DIN 18126 under the assumption of a grain density of ρ=2,675 g/cm^3 see Fig. 4. The derived data shows a uniformly graded deposit with consistent grain size distributions and near uniform index void ratios approximately between 6.5 and ~15 m depth. Appreciable variation in cone resistance throughout this section (Fig. 4) are ideal prerequisites in establishing an in-situ correlation function.

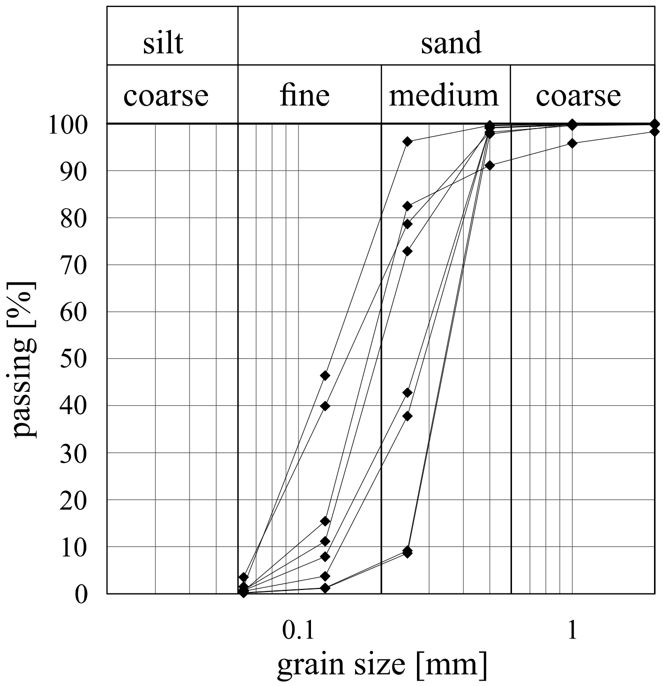

Figure 3. Fine to medium sand size grain distribution curves from the investigated sand section (6.5-15 m).

3.2 *Downhole logging*

The active gamma density with two receivers and neutron logging were carried out in uncased, open polymer mud-supported boreholes with straight bore hole geometry. More details of the logging methodology can be found in Biryaltseva et al. (2016).

The quality of the active gamma calibration, which was based on sand and water standards was tested with wet bulk densities derived from undisturbed samples of cohesive layers from the same borehole. The maximum deviation in wet bulk densities of this test is 4.5 %, proving that the gamma probe has been well calibrated delivering data well

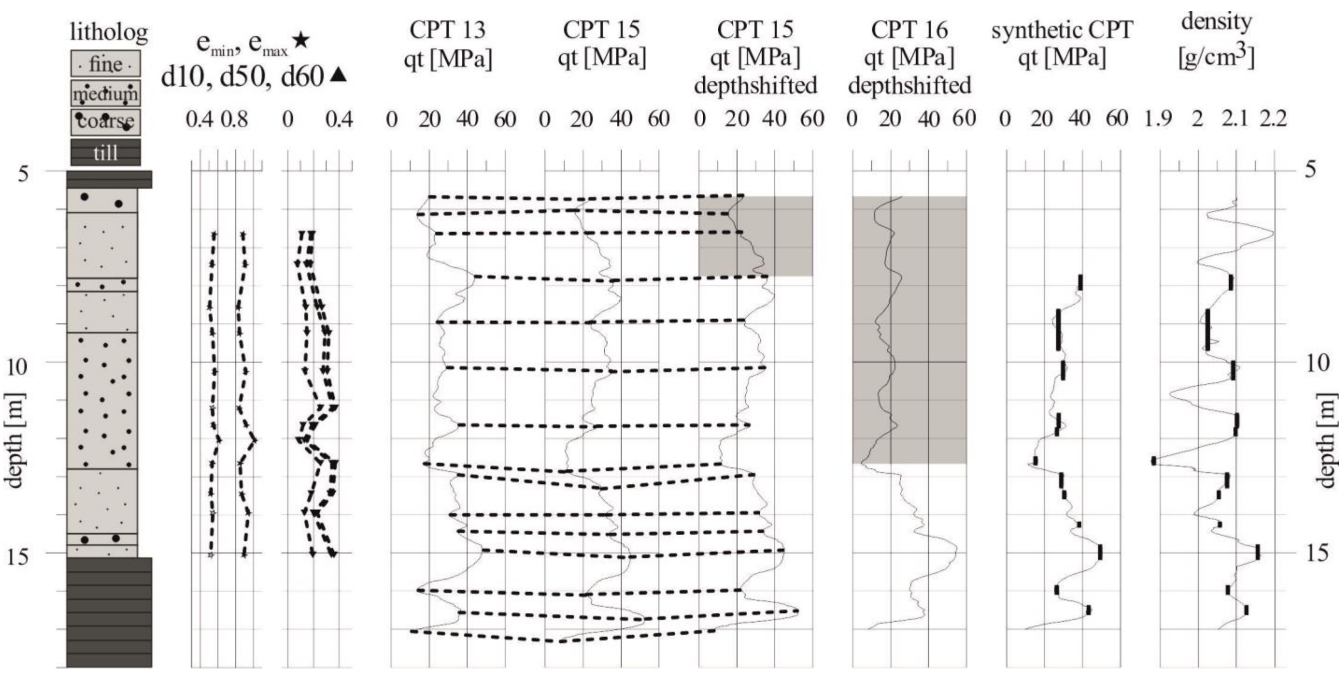

Figure 4. Data example of the investigation site LOG 1. The sequence of processing steps, correlation, depth shifting, data exclusion, establishment of a representative synthetic CPT profile and final extraction of matching averaged data pair intervals, is illustrated.

within its tool specifications. Derived wet bulk densities from the neutron porosity log showed to be less accurate and therefore were excluded from the further investigation. Averaged e_{min} and e_{max} values were used to convert wet bulk density values to relative densities (D_r).

3.3 *CPTu*

A total of 16 CPT each approximately 45 meter deep were carried out to identify and locate the soil section best suited for the study. Tests followed DIN EN ISO 22476-1, using a top driven 35 tons CPT unit and a Van den Berg 15 cm², fully digital 24 bit compression ICONE delivering data every 1 cm. Nine CPTs (including three repetitions) were carried out along a 2 m radius circle around the central logging boreholes, (Fig. 2). Two data sets of 3 CPTs and one downhole logging site each were selected and used for the further correlation process.

4 EXISTING EMPIRICAL RELATION

Equation (1) has been initially proposed by Schmertmann (1976).

$$D_r = (1/C_2) \cdot ln[q_c/(C_0 \cdot (\sigma')^{C_1})] \quad (1)$$

With σ' being effective vertical or mean stress [kPa], q_c - cone resistance [kPa] and C_0, C_1 and C_2 are empirical soil constants.

Baldi et al. (1986) established empirical constants for normally consolidated and over-consolidated sand using Ticino sand applying index densities according to ASTM. According to this formulation, an estimation of the relative density in normally consolidated sand requires only the knowledge of the vertical effective stress and the cone resistance. Soil constants are in this case given as: C_0= 157, C_1= 0.55, C_2= 2.41.Jamiolkowski et al. (2001) (cited in Mayne, 2007) proposed a correlation involving normalized cone resistance q_{tl} in in form:

$$D_r = 100 \cdot [A \ln q_{t1} - B] \quad (2)$$

With A=0.268, B= 0.675, where

$$q_{t1} = q_t/\sqrt{\sigma'_{vo} \cdot \sigma_{atm}} \quad (3)$$

In this case q_{tl} and σ_{atm} atmospheric pressure are measured in [bar], while q_t denotes cone resistance corrected for fluid pressure effects and is defined as

$$q_t = q_c + (1 - a)u_2 - \quad (4)$$

5 DEPTH CORRELATION

Due to local small scale lateral heterogeneities, e.g. dipping beds of fluvial bars, CPT data around the central logging locations were depth correlated using one of the circumference CPTs as a depth reference. The correlation made use of recognizable key points recognized in all 3 CPT profiles of each site (Fig. 4).

Afterwards, the three circumferential CPTs were combined to one depth shifted synthetic CPT profile with averaged tip values between correlation points (Fig. 4).

Intervals of strong inconsistent lateral variation marked with grey shadowed areas in Fig. 4 were excluded from the synthetic CPT forming procedure.

The density curve was smoothed and interpolated with moving average to achieve the same spatial frequency as the CPT profile. In a final step the density profile was correlated with the representative CPT profile using the same key point approach. Average values at plateaus and local maxima of q_c and ρ were calculated to form averaged matching pairs of cone resistance and density.

The final correlation step between averaged matching pairs of cone resistance and density focused on plateaus and trough to exclude the transitions zones which a higher margin of error in depth matching. The general sequence of processing steps is illustrated in Fig. 4.

6 RESULTS

The last two columns of Fig. 4 show the data intervals selected for the correlation approach, in the following referred to as the training data. The measured gamma-gamma density was converted to the relative density using averaged $e_{\min}$ and $e_{\max}$ values. In total 18 data pairs were established.

The training data were fitted to Equation (1) to determine new constants C_0, C_1, C_2. Since the horizontal stress in-situ is difficult to estimate only the vertical effective stress was used as a variable in the resulting function. The resulting relative density to cone resistance function is shown in Fig. 5.

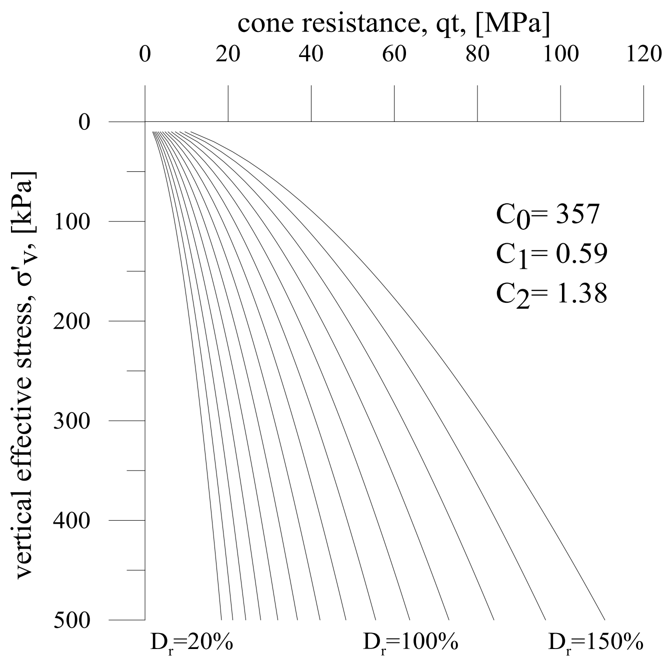

Figure 5. Relative densities as a function of vertical effective stress and cone resistance.

7 DISCUSSION

To evaluate the newly formulated relationship Fig. 6 shows established empirical relations applied to the training data. The relation by Jamiolkowski et al. (2001) seems to constantly underestimate the measured relative density values. The relation proposed in this study as well as the one by Baldi et al. (1986) provide comparable results with the new relation being more progressive in having a tendency to produce comparable higher relative densities per interval tip resistance increase.

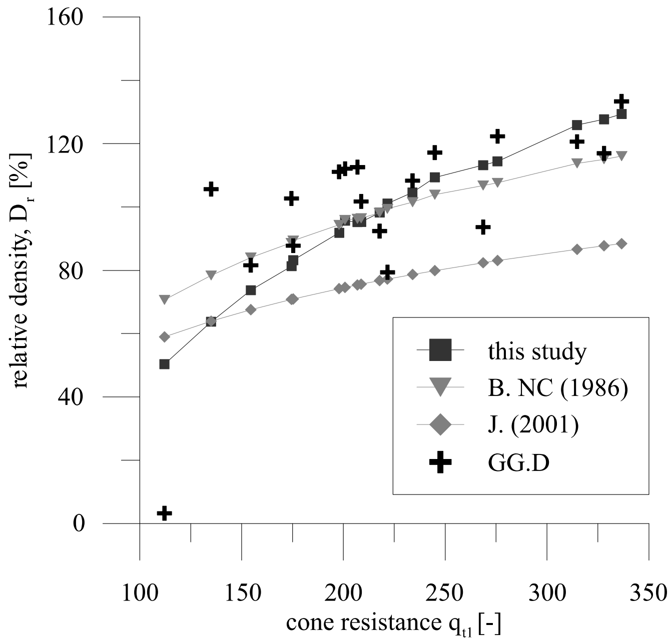

Figure 6. Relative density estimated from the measured gamma-gamma density (GG.D) (crosses) and comparison of literature transfer functions with results of this study (squares). The cone resistance is given as dimensionless q_{t1} to simplify the visual comparison. Existing empirical relations proposed by B. NC (1986) – Baldi et al. (1986) for normally consolidated sand; J. (2001) – Jamiolkowski et al. (2001).

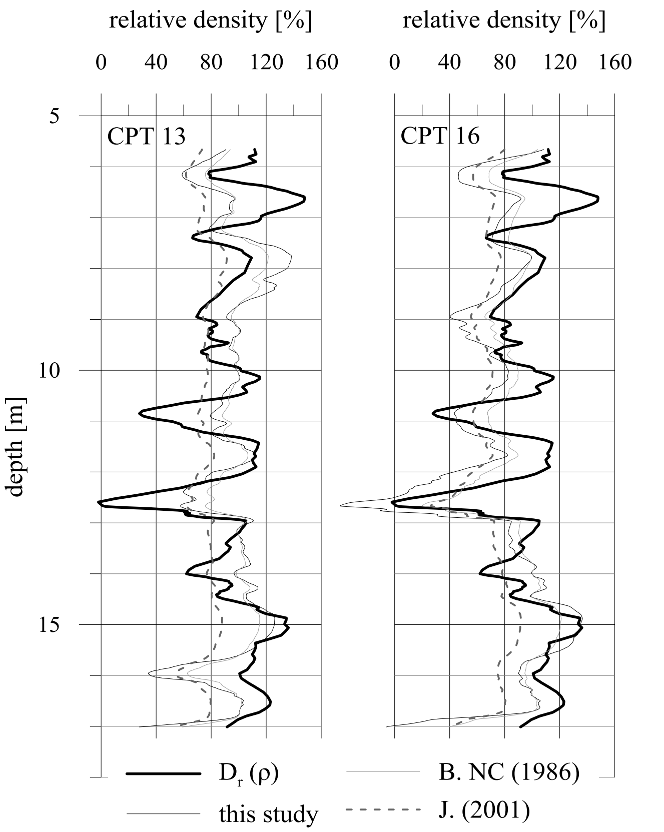

Figure 7. Application of the proposed and existing empirical relations to CPT data in comparison to logging derived relative densities D_r. B. NC – Baldi et al. (1986) for normally consolidated sand; J – Jamiolkowski et al. (2001)

The correlation by Baldi et al. (1986) seems to fit the training data better for low normalized stresses while the proposed new correlation seems to better capture the data with $q_{t1} > 200$.

Fig. 7 shows relative densities estimated from measured cone resistance profiles of the same overconsolidated strata using existing empirical relations and the empirical relation proposed in this study. Again the correlation by Jamiolkowski et al. (2001) mainly underestimates the measured values. The proposed correlation is in a good agreement with the correlation for normally consolidated sand after Baldi et al. (1986). Both correlations show a slight tendency toward a D_r - overestimation but provide an overall fairly acceptable averaged representation of the measured relative in situ densities. Local heterogeneities (extreme values) are not captured by either correlation. Both Figures (6 and 7) demonstrate that high relative densities can occur in the shallow subsurface under moderate stresses and intermediate tip resistances.

The application of this function and strictly speaking all CPT transfer functions of course are limited to the sand material used for the development of the correlation.

Blaker et al. (2015) showed that the method for determining maximum and minimum dry unit weight influences the results of laboratory testing and therefore also causes the inconsistencies when determining relative density in-situ. DIN standard may provide a broader range of possible packing densities in comparison to ASTM. In the case of the same cone resistance, this would lead to lower relative densities for loose sands and higher relative densities for dense sands when calculated according to empirical relations based on ASTM. However even in this case the ASTM-based empirical relations provide more slowly increase in relative densities per interval cone resistance increase then the new proposed correlation.

Accuracy of the density logging may strongly affect the correlation results. According to information from the subcontractor conducted the density logging the difference between two consequently repeated measurements along the same profile, may be as big as 0.05 g/cm^3. For the considered site, this would lead to the differences of about 20% of the relative density. Moreover while using the correlations the influence of the disturbed zone around the borehole should be noted. Even in case of carefully prepared boreholes density changes in the surrounding soil can be expected. In contrast the CPT method is fully non-destructive in the sense that no changes of the soil structure occur prior measurement. However as noted by e.g. Lunne et al. (1997) the soil area beneath the cone influencing the results may be as large as several cone diameters in dense soils. Therefore none of the methods provide the punctual information about the soil and the results should be considered as an averaged value around the point of interest.

The modern trend toward ground investigations with no or only a reduced numbers of sample holes results in a dilemma when it comes to complex static or cyclic soil modelling. Especially in cyclic models when using the for instance the hypoplastic soil law introduced by Kolymbas (2000) the initial void ratio e_0 is of great importance. A back calculation from CPT data is often ambiguous when no matching sample material for e_{min} and e_{max} determination was collected. By using the data of our in-situ transfer approach the latter disadvantage is overcome as it enables the direct expression of the tip resistance of CPT in terms of porosities and vertical stress. (Fig. 8).

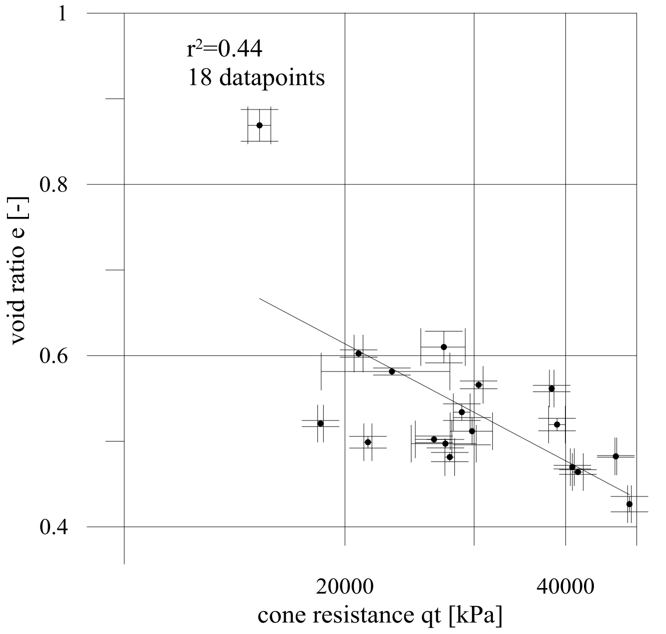

Figure 8. Measured void ratios as a function of measured cone resistance.

8 CONCLUSIONS

High variation in the relative density were measured using geophysical logging in an interval of well sorted, overconsolidated Pleistocene North Sea equivalent sands with constant relative density boundaries (e_{min}-e_{max}). An empirical relation among relative density, vertical effective stress and cone resistance was proposed based on in-situ cone resistance, gamma densities and laboratory estimations of minimum and maximum void ratios. Since in this new formulation D_r is solely related to the vertical effective stress no estimation of the horizontal stress is required. Development of the correlation based on in-situ data is an alternative and fast approach independent of boundary effects and stress state reproduction limits found in CPT test chamber studies. The relatively fast and economic approach is universal and may be applied to all sorts of settings and granular materials. The study was finished in approximately two month of work, which is way faster and more economic compared to year long experiments using CPT test chambers data to fill the D_r/stress matrix with sufficient data. However this study also shows that the complex soil physics during signal formation of cone resistance measurements is never a sole function of only packing density of the grains and construction projects with high stakes and risks should consider direct measurements using e.g. active gamma density logging giving likely far superior results in carefully prepared holes. Up to now the correlation was applied merely on the data from the same area where it was established. Application on further areas and comparison with additional density measurements will show the validity or usefulness of the newly found correlation.

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