Cone Penetration Testing 2018 – Hicks, Pisanò & Peuchen (Eds)

ISBN 978-1-138-58449-5

Shallow depth characterisation and stress history assessment of an over-consolidated sand in Cuxhaven, Germany

V.S. Quinteros & T. Lunne
Norwegian Geotechnical Institute, NGI, Oslo, Norway

L. Krogh & R. Bøgelund-Pedersen
Ørsted Wind Power (formerly DONG Energy Wind Power), Copenhagen, Denmark

J. Brink Clausen
Geo, Copenhagen, Denmark

ABSTRACT: A comprehensive field campaign was carried out on an aged, dense, over-consolidated sand in Cuxhaven, Germany. CPTs along with a suite of additional in-situ tests, including DMTs, PLTs, shear wave velocity measurements (SDMT and MASW), nuclear densometer, manual drive-in cylinder, temperature, suction and volumetric water content testing were performed on a clean sand to a depth of about four meters. Aim of this field-testing program was to characterize *in-situ* a clean North-Sea sand and by doing so overcome calibration chamber effects (like reconstitution, ageing, and imposed boundary conditions). The field campaign forms part of an effort for the determination of *in-situ* stress history as well as engineering strength and stiffness properties within the 'low' stress regime (< 50 kPa vertical effective stresses). Details of the field results together with an assessment of OCR and K_0 values are introductory presented in this paper. The background of this study is the soil characterisation at 'shallow depths' for subsea structures such as suction buckets, cables, pipelines, satellites and light gravity base structures.

1 INTRODUCTION

Interpretation of CPT results on dense-very dense marine sands at shallow depths in terms of relative density, D_r, is commonly done using either empirical or semi-empirical methods developed based on calibration chamber testing, CC, and/or centrifuge tests involving measurements on freshly reconstituted sand. Hence, some important features like layering, fabric, ageing, cementation, bonding and over-consolidation, OC, effects resulting from glaciation and potential wave loading cannot be replicated in the laboratory. Obviously, CPT profiles obtained in CC may differ significantly from field CPT profiles.

In order to overcome the issues of analysing CPTs from laboratory testing conditions, and with the long-term purpose of creating a field database of shallow CPTs on over-consolidated dense sands, Ørsted Wind Power, Geo and NGI joined efforts to characterise the upper sand layer of a research site in Cuxhaven, Germany. The site was chosen because of its relatively homogeneous sand unit of dense over-consolidated state, and since the deposition conditions resemble offshore sands around the North Sea. The characterization of Cuxhaven sand is part of an R&D project with the aim of developing a framework for interpretation of OCR, K_0 and ultimately relative density, strength and stiffness properties of over-consolidated marine sands.

2 THE SITE

2.1 *Description and general location*

The test field is located around 5 km south of Cuxhaven, Germany, approximately 6 km east of the North Sea coast (see Fig. 1). The test site is part of a sand/gravel pit, which is owned by Plambeck Erd- und Tiefbau GmbH. The pit started operations in1980 and soil has been excavated from the area since then. Approximately 16 m to 20 m of sand has been excavated at site within the last ca. 35 years. The exact overburden height is uncertain, but based on the information provided by Plambeck, about 18 m can be assumed as representative. Moreover, the Cuxhaven test field has also been used for research studies related to monopile installations and thus, several monopiles of 4.3 m diameter and 21 m buried length placed with 26 m distance in between (see Fig. 2) are located in the vicinity of the testing area. The specific field location chosen for testing is expected to be influenced

Figure 1. Location of Cuxhaven research site (google\maps).

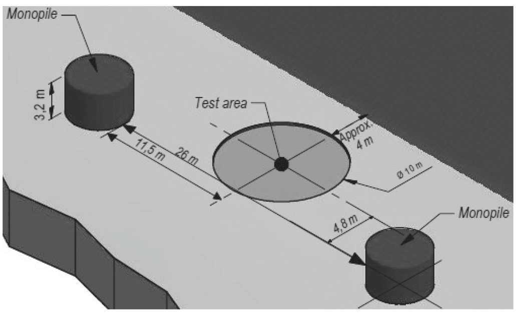

Figure 2. Schematic overview of field tests locations.

by the monopile installations to a minor degree. An adjacent 7 m high embankment lies approximately 4 meters west of the testing area. Testing near the embankment was avoided. As seen in Figure 2, the testing area tested was circular with a diameter of 10 m. Several tests were carried out, including: CPTs, dilatometer tests, DMTs, seismic dilatometer, SDMTs, plate load tests, PLTs, nuclear densometer, ND, manual drive-in cylinder density tests, MD, as well as sampling, suction, volumetric water content and temperature. Multichannel analysis of surface waves, MASW, were performed right outside the circular testing area. The upper soil at the site is characterized by a 4.7 m thick marine fine to medium sand, overlying clay. The ground water table, GWT, was measured at 3.1 m.

2.2 *Depositional environment and material source*

Before the glaciations, thick layers of sands were deposited by ancient rivers in large parts of the North Sea area. During the earlier glaciations (Saale and Elster) the area closest to present day shore line was ice-covered, whereas in the latest glaciation thick fluvial or deltaic sediments were deposited in a cold environment without vegetation. Deposition, erosion and re-deposition during the glaciations sorted and packed the sediments but also contributed with silt and clay sediments. Deltaic deposits formed along the ancient shorelines and fluvial deposits continued in braided streams with numerous channels. The different cycles of sand deposits are difficult to distinguish when looking at isolated samples.

The clean upper sand unit of Cuxhaven was observed in the field to be homogeneous (similar grain size), but the unit weight of the layers varied significantly. This variation is believed to be a consequence of the depositional environment and impact of wave loading.

3 FIELD TESTING PROGRAM

3.1 *Overview of results*

A summary of the field tests performed are given in Table 1, together with information about the number of tests and respective depths. During testing, the site was carefully dug in 0.5 m intervals using an excavator for the first 0.4 m, whereas the remaining 0.1 m was cautiously manually excavated. Measurements were carried out at each excavated depth, on a levelled surface, to obtain a dissected profile of index parameters.

3.2 *Excavation log*

Shallow surface stratigraphy of the site, measurements of water content, wc, unit weight,γ, and dry unit weight, γ_d, are presented in Figure 3. As seen in Figure 3a, the sand thickness is about 4.7 m, and GWT lies at about 3.1 m depth and the zone saturated by capillarity (above GWT) was about 0.3 m.

Table 1. Summary of field tests in Cuxhaven sand.

Test type	No.	Depth (m)
CPT*	7	0 to 5.5
DMT†	2	0 to 5.5
SDMT‡	2	0 to 5.5, V_s from 1 to 5
MASW§	4	0 (from the surface)
Plate load test (PLT)	5	0; 0.5; 1; 2; 3
Nuclear densom. (ND)	34	0; 0.5; 1; 1.5; 2; 2.5; 3; 3.5; 3.67
Manual densom. (MD)	40	0; 0.5; 1; 1.5; 2; 2.5; 3; 3.5; 3.67
Sampling (–)	6	0; 0.5; 1; 1.5; 2; 2.5; 3; 3.5; 4
Temperature (t)	5	0; 0.5; 1; 2; 3
Suction (ψ)	5	0; 0.5; 1; 2; 3
Vol. water content (θ)	5	0; 0.5; 1; 2; 3

* Cone Penetration Test, † Dilatometer, ‡ Seismic Dilatometer, § Multichannel Analysis of Surface Waves.

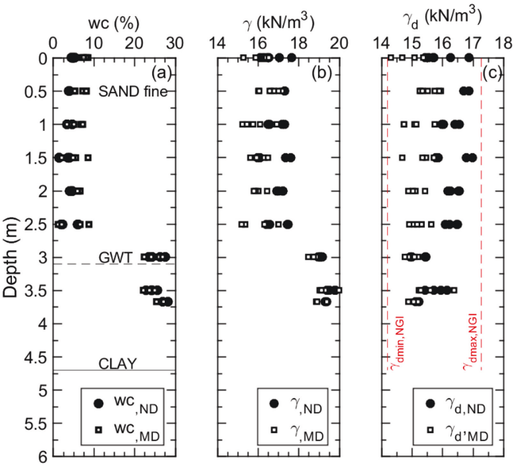

Figure 3. Excavation log: (a) stratigraphy, (b) water content, (c) unit weight, and (d) dry unit weight.

Water content was determined from samples sent to the NGI laboratory in Oslo, Norway, while values of γ and γ_d were obtained manually, with great care, using the drive-in cylinder technique, MD, and nuclear densometer, ND. MD measurements were performed using cylinders of 70.4 mm diameter and two different heights, namely 50 mm and 100 mm, following ASTM D-2937-10 recommendations. Significant scatter of results was observed during MD tests despite the great care exerted during sampling. ND measurements were done in parallel using a calibrated nuclear density gauge (model Troxler 3440). Measurements were complying with ASTM D-2922, using the 'direct transmission mode' by inserting the nuclear source into the ground. Less scatter of ND results was observed. Given the fact, that MD measurements are more susceptible to errors (dilation or contraction of sand while pushing the cylinder) and systematically lower than the ND measurements, they are considered less trustworthy.

Decagon 5TM soil moisture and temperature probes were used to estimate the volumetric water content, θ, which was about 0.1 m³/m³ from 0 m to 2 m depth and 0.2 m³/m³ at 3.0 m depth. Suction was measured using MP-6 calibrated ceramic disks. A suction of about 10 ± 2 kPa was measured.

4 OVERVIEW OF TEST RESULTS

4.1 *CPT results*

CPT tests were performed using Geo's CPT-truck and a standard AP van den Berg 10 cm² cone. Profiles of cone resistance, q_c, sleeve friction, f_s, and

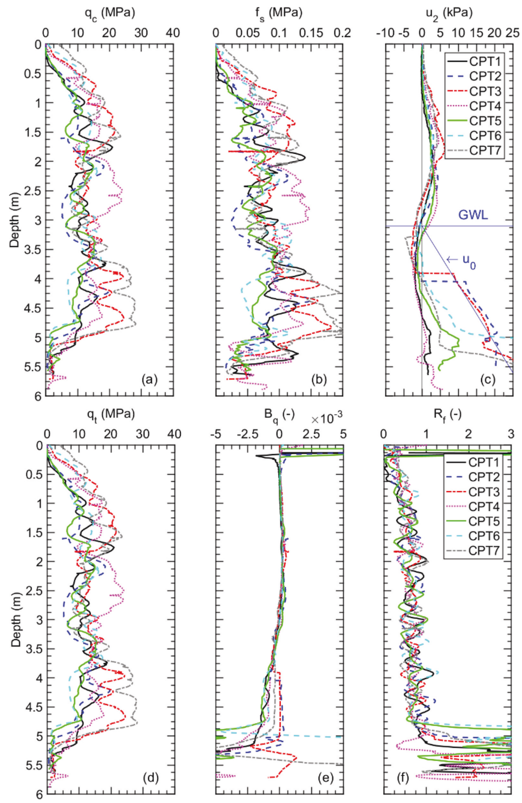

Figure 4. CPT: (a) q_c, (b) f_s, (c) u_2, (d) q_t, (e) B_q, (f) R_f.

pore water pressure, u_2, vary considerable with depth inferring layering within the sand unit (see Fig. 4). Scatter of the CPT measurements was observed within the relatively small circular testing area of 10 m. A distinctive "S" shape of u_2 is observed in Figure 4c, which is attributed to the unsaturated soil conditions as well as uncertainties while measuring small values of u_2. Two dissipation tests were performed at about 4 m depth, the results verified GWT level.

For Cuxhaven sand, q_c reached its full value (also called quasi stationary value q_{st}), at about 0.7 m (see Fig. 4a) indicating the sand being OC, since NC sand usually reaches q_{st} much deeper at values of > 1.0 m, depending on sand density and its characteristics. As seen in Figure 4d q_t is equal to q_c, as expected for a clean sand. R_f shown in Figure 4e is 0.5, in average for the entire sand layer, though significant scatter is observed due to soil layering. B_q, shown in Figure 4f, is almost constant in the unsaturated zone above GWL, with small variations as expected from the u_2 measurements. B_q values decrease as soon as the CPT reaches ground water.

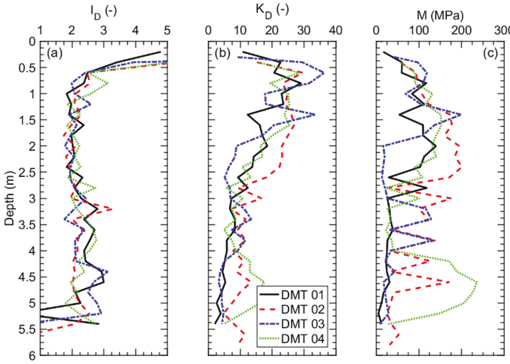

Figure 5. DMT: (a) I_D, (b) K_D, and (c) M.

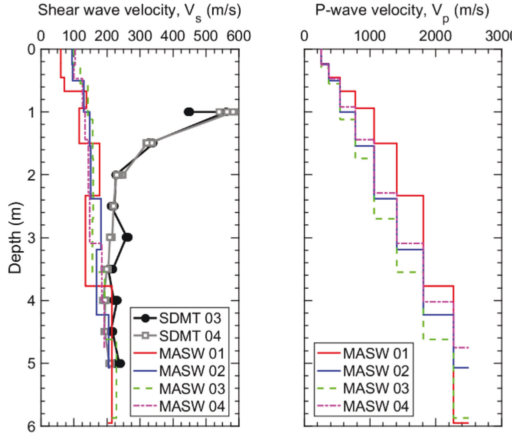

Figure 6. (a) V_s from SDMT and MASW, (b) V_p from MASW.

4.2 *DMT results*

DMT tests were performed following ASTM D6635–01 (2007) procedures. Results are presented in terms of Material index, I_D, Horizontal stress index, K_D, and Dilatometer modulus, M, (see Fig. 5). Almost constant I_D values were obtained from 0.5 m to ca. 4.7 m depth. However, K_D and E_D results were affected by soil layering, especially because these parameters are not normalized as I_D.

4.3 *Shear and P-wave velocities*

Shear wave velocities, V_s, were obtained using SDMT and MASW equipment. Two test pairs were performed on top of each other, while two additional MASW were performed outside the tested perimeter. The SDMT probe consisted of two sensors spaced 0.5 m, and a falling hammer system with a wooden beam mounted on the CPT truck was used to generate shear waves. The beam and the SDMT probe distance was 0.95 m. The hammer weight was 18.8 kg and four falling heights, namely 40, 80, 160 and 360 mm, were used to determine the energy giving the best signal. Results are given in Figure 6a. From MASW readings, V_s and P-wave velocities, V_p, were derived (see Figs. 6a and 6b).

High resolution 1D MASW were performed using a 24 channel Geode digital seismograph, 48 no. 10HZ vertical geophones. Details of the MASW technique are found in Park et al. 1999. Data processing was performed using NGI *in-house* software.

V_s values from SDMT are deemed unreliable at depths between 0 m to ca. 3.5 m depth, even though a geometrical depth correction was applied. Hence, $V_{s,MASW}$ values were considered more credible than $V_{s,SDMT}$. Note though that $V_{s,SDMT}$ and $V_{s,MASW}$ cannot be directly compared since they differ in terms of travel path and polarisation. $V_{s,SDMT}$ is an invasive method where the tool is deployed in downhole mode, and $V_{s,MASW}$ is non-invasive surficial method.

4.4 *PLT results*

Plate loading tests, PLTs, were performed at the same location at meter-intervals using a 0.3 m diameter plate. Figure 7 shows the average load measured, P, relative to plate settlement. The ultimate bearing capacity, P_{ult}, varied between 35 kN and 70 kN. At first glance, the variation of P_{ult} seems to be quite high, but the variation is reasonable given the layering of the soil. P_{ult} compares quite well with the corresponding distributions of q_c and K_D from CPT and DMT respectively. Nevertheless, note that P_{ult} at 3 m depth was affected by the GWL and a lower P_{ult} value was expected.

4.5 *Material composition and index tests*

Grain size distribution curves, GSD, were determined at each excavated depth (see Fig. 8). Because of the homogeneity of the GSDs, the sand was mixed to a batch. Hence, almost all index and advanced tests (except wc) were performed on the batched sand. Results of triaxial testing are presented in Quinteros et al. (2017). Values of d_{10} and d_{60} are given in Figure 8; C_U and C_C are 2.3 and 1.1 respectively. The fines content was less than 3%. Unit weight of solid particles, γ_s, is 26.2 kN/m³. Maximum and minimum dry unit weights, $\gamma_{d,max}$ = 17.27 kN/m³ and $\gamma_{d,min}$ = 14.19 kN/m³, were obtained using NGI *in-house* methods.

A scanning electro-micrograph, SEM, is shown also in Figure 8. From the SEM, particle roundness, R = 0.75, sphericity, S = 0.90, and regularity,

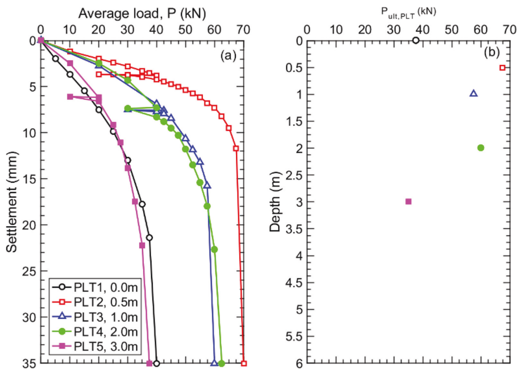

Figure 7. PLT: (a) Load vs. settlements, (b) P_{ult} vs. depth.

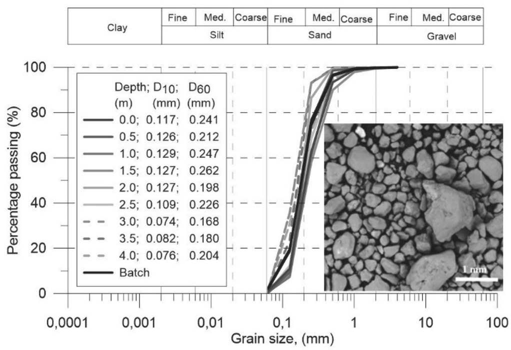

Figure 8. GSDs and SEM image of Cuxhaven sand.

ρ = 0.82, were obtained. Grains angularity was determined on a selected 500 g batched sample resulting in 0.4% angular, 12.4% sub-angular, 59.6% sub-rounded, 26.4% rounded and 1.2% rounded particles. Mineralogy of grains was assessed using the X-ray diffraction method, XRD. The main minerals being quartz (93%), alkali-feldspar (4%) and plagioclase (3%).

5 ASSESSMENT OF STRESS HISTORY

5.1 *Estimation of OCR*

The mechanically over-consolidation ratio, OCR, is defined as the maximum past effective consolidation stress, σ'_p, over the present effective overburden stress, σ'_{vo}, as:

$$OCR = \sigma'_p / \sigma'_{vo} \tag{1}$$

As discussed in Chapter 2, the Cuxhaven site has been excavated by around 18 m ± 2 m. Hence OCR can be calculated using Equation 1 (see Fig. 9).

Mayne et al. (2009) presented a so-called unified-approach, for a first-order estimation of the yield stress from CPT results:

$$\sigma'_p = 0.33\,(q_t - \sigma_{vo})^{m'} \tag{2}$$

where q_t = corrected cone resistance ($q_t = q_c + u_2(1 - a)$) in kPa, σ_{vo} = vertical total stress in kPa, and m' is a fitting exponent ($m' \approx 0.72$ for clean quartz to silica sand).

Using Equations 1 and 2, OCR profiles were estimated reasonably well from CPT results (see Fig. 9a).

Monaco et al. (2014) proposed a multi-parameter approach in terms of the empirical equation for homogeneous soils:

$$OCR = 0.0344\,(M_{DMT}/q_c)^2 - 0.4174\,(M_{DMT}/q_c) + 2.2914 \tag{3}$$

Figure 9b shows calculated OCR profiles using Equation 3 from combined close-by CPTs and DMTs. Note that Equation 3 does not predict OCR from CPT-DMT at shallow depths. OCR estimation based on DMT alone (Marchetti, 1980) was also tried, but unreliable estimates were obtained here as well.

5.2 *Estimation of K_0*

The coefficient of lateral earth pressure at rest is defined as the ratio of effective horizontal stress over the effective vertical stress, $K_0 = \sigma'_{h0}/\sigma'_{vo}$. Typical values of K_0 reported in the literature are 0.4 for loose and 0.6 for dense NC sands. For wave-densified OC sands a constant $K_0 = 1$ is often assumed. Jaky (1944) proposed the well-known formula

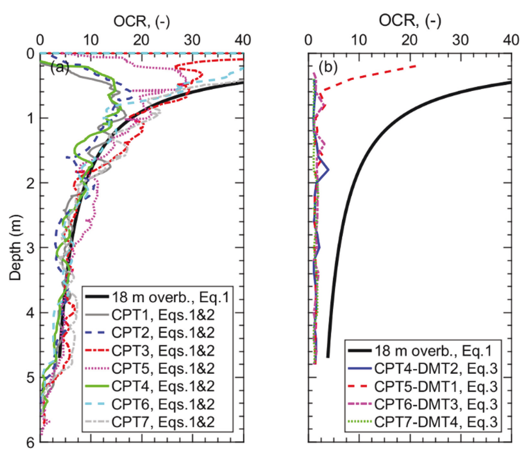

Figure 9. OCR based on: (a) CPT after Mayne et al. (2009), and (b) CPT-DMT after Monaco et al. (2014).

$K_0 = (1 - \sin\phi')$. Wroth (1973) stated that K_0 of OC sand is higher than K_0 of NC sand; hence, reflecting the effect of OCR on K_0, Kulhawy & Mayne (1990) proposed an equation based on the effective friction angle of soil ϕ' and OCR:

$$K_0 = (1 - \sin\phi')\cdot(\mathrm{OCR})^{\sin\phi'} \tag{4}$$

Using Equation 4, K_0 was estimated using $\phi'_{cv} \approx 32°$ (from triaxial tests) as recommended by Lee et al. (2013) for dense sands, while OCR was obtained from Equation 1, see Figure 10. As seen in this figure, K_0 changes significantly with depth and is obviously not constant as often assumed in practice. Hence, standard K_0 equations (derived for clayey soils) seem to be applicable for estimating K_0 in the case of the unloaded OC Cuxhaven sand site. In Figure 10a, K_0 is calculated using Equations 4, 1 and 2 for CPT tests.

A CPT-DMT multi-parameter approach, as proposed by Marchetti (1985), was also used to estimate K_0, namely:

$$K_0 = 0.376 + 0.095\ K_D - D_3 \cdot (q_c/\sigma'_v) \tag{5}$$

where: D_3 = fitting parameter equal to 0.0017 for CC data, 0.0046 for Po river sand, or 0.005 for seasoned sand and 0.002 for freshly deposited sand after Baldi et al. (1986). Given the range of possible values of D_3, the multi-parameter approach will return rough estimations of K_0 only. For Cuxhaven sand D_3 = 0.005 was used. Figure 10b shows the K_0 assessment based also on CPT-DMT Equation 5. As seen in this figure, the multi-parameter approach seems to follow the theoretical K_0 calculated after Kulhawy & Mayne (1990) as per Equation 4, but significant scatter is observed.

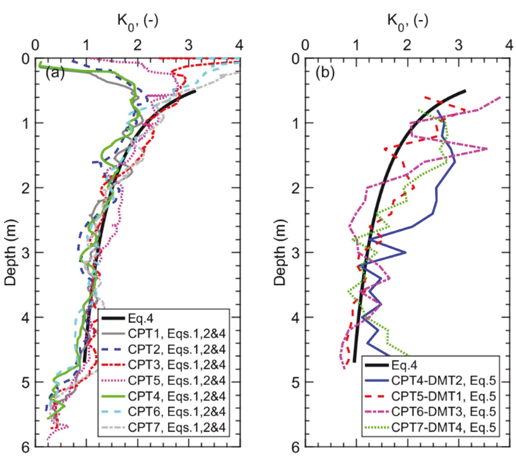

Figure 10. Assessment of K_0 from CPT after Kulhawy & Mayne (1990) and from CPT-DMT after Marchetti (1985).

6 CONCLUSIONS

A comprehensive site characterization program carried out on Cuxhaven sand has been presented. The clean, quartzitic, aged, dense sand of Cuxhaven is a typical North Sea sand. Aim of the field campaign was to obtain data from a natural OC sand in contrast to calibration chamber test results on freshly deposited sand. This research is part of an overall study to develop appropriate correlations for estimating OCR, K_0 and ultimately D_r in an OC sand at shallow depths. Based on the field results and subsequent site stress history assessment, the following initial conclusions were drawn:

- Nuclear density measurements of unit weights are higher than manual density measurements using the drive-in cylinders. Large scatter is related to the results in spite of the great care exerted during sampling with drive-in cylinders.
- From CPT, DMT and PLT results significant variability is observed as a result of the geological depositional history of the site. However, the sand unit is quite homogeneous in terms of grain sizes.
- CPT gives a more detailed profile than DMT. However, due to the rate of change of q_c, local peaks of q_c may be underestimated, since q_c may not be fully developed to a quasi-stationary value.
- V_s results from SCPT are unreliable at shallow depths (< 3.5 m). Hence, MASW is considered to give more realistic results at shallow depths.
- OCR was reasonably estimated from CPT readings using Mayne et al. (2009) method. While the multi-parameter approach (CPT-DMT combined) as proposed by Monaco et al. (2014) did not provide reliable estimations at shallow depth.
- K_0 was estimated using Kulhawy & Mayne (1990) approach as well as the multi-parameter approach after Marchetti (1985). Both methods returned similar results.

ACKNOWLEDGEMENTS

The research presented herein was performed as a Joint Industry Project carried out between: Ørsted Wind Power, Geo and NGI. The efforts of all parties are highly appreciated. The support of other involved companies during the fieldwork, such as GEO-Engineering, Plambeck Gmbh and Apex Geoservices is gratefully acknowledged.

REFERENCES

ASTM D2922–05. 2005. Standard Test Methods for Density of Soil and Soil-Aggregate in Place by Nuclear Methods (Shallow Depth). *ASTM International*. West Conshohocken, PA.

ASTM D2937–10. 2010. Standard Test Method for Density of Soil in Place by the Drive-Cylinder Method. *ASTM International*. West Conshohocken, PA.

ASTM D6635–01. 2007. Standard Test Method for Performing the Flat Plate Dilatometer. *ASTM International*. West Conshohocken, PA.

Baldi, G., Bellotti, R., Ghionna, V., Jamiolkowski, M., & Pasqualini, E. 1986. Interpretation of CPTs and CPTUs; 2nd part: drained penetration of sands. *Proc. 4th Int. Geotech. Seminar*, Singapore, pp 143–156.

Jaky, J. 1944. The coefficient of earth pressure at rest. In Hungarian (A nyugalmi nyomas tenyezoje). *Journal of the Society of Hungarian Architects and Engineering*, 355–358.

Kulhawy, F.H. & Mayne, P.W. 1990. Manual on estimating soil properties for foundation design. Report EPRI EL-6800, *Electric Power Research Institute*, Palo Alto, 306 p.

Marchetti, S. 1985. On the Field Determination of K_0 in Sand. *Proc. 11th Int. Conf. Soil Mech. Found. Eng.* S. Francisco, Vol. 5: 2667–2672.

Mayne, P.W., Coop, M.R., Springman, S., Huang, A-B., & Zornberg, J. 2009. State-of-the-Art Paper (SOA-1): GeoMaterial Behavior and Testing. *Proc. 17th Intl. Conf. Soil Mech. Geotech. Eng.*, Vol. 4. Alexandria, Egypt, Millpress/IOS Press Rotterdam: 2777–2872.

Monaco P.; Amoroso S.; Marchetti S.; Marchetti D.; Totani. G. Cola, S. & Simonini, P. 2014. Overconsolidation and Stiffness of Venice Lagoon Sands and Silts from SDMT and CPTU. *J. Geotech. Geoenviron. Eng.* ASCE, v. 140:1, p. 215–227.

Lee, J., Park, D. Kyung, D. and Lee, D. 2013. Effect of Particle characteristics on K0 Behavior for Granular Materials. *Proc. 18th Int. Conf. Soil Mech. & Geotech. Eng.*, Paris 2013. pp 337–380.

Park, C.B., Miller, R.D., & Xia, J. 1999. Multi-channel analysis of surface waves (MASW): *Geophysics*, May-June issue.

Quinteros, V.S., Lunne, T., Dyvik, R., Krogh, L., Bøgelund-Pedersen, R., & Bøtker-Rasmussen, S. 2017. Influence of Pre-Shearing on the Drained Strength and Stiffness of a Marine North Sea Sand. *Proc. 8th Int. Offshore Site Invest. Geotech. Conf*. Sep. 12–14. London.

Wroth, C.P. 1973. General theories of earth pressure and deformation. *Proc. 5th Eur. Conf. Soil Mech. Found. Eng.* Vol. 2, Madrid, Spain, 33–52.