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The role of cone penetration testing in the Dogger Bank offshore wind farm

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ABSTRACT: The cone penetration test is the preferred tool for measuring the in-situ soil conditions for offshore wind farm developments. This preference stems from the consistent and reliable data quality, low relative cost, and speed of data acquisition which enables developers to characterise large areas with numerous structure locations to support foundation concept feasibility studies, installation risk assessments and geotechnical engineering analyses to optimise the foundation design by reducing the uncertainty in soil input parameters. However, the interpretation of CPT data is largely dependent on site-specific or published correlations, which can present challenges when relying on the CPT as the primary tool for stratigraphic profiling, interpretation of soil behaviour and for defining geotechnical parameters for engineering design. This paper presents recent developments and processes that enabled the delivery of an optimised CPT based geotechnical design basis for the Dogger Bank Wind Farm. The processes and tools that enabled this approach comprised a novel SI strategy, focussed CPT interpretation and CPT tool development. The strategic approach for the novel SI strategy is presented and the individual elements described. Challenges and limitations associated with the interpretation of CPT data are discussed, including size and scale effects, resolution, calibration with laboratory and large-scale field test data and rate effects. Finally, the challenges with using statistical methods to derive design values from CPT records are briefly discussed.

1 INTRODUCTION

The Dogger Bank offshore wind farm comprises three project areas (Dogger Bank A, B and C) within the Dogger Bank Offshore Development Zone, located 125 to 290 km off the east coast of Yorkshire, UK. The development zone covers ca. 8660 km² and water depths range from 18 to 63 m (Dogger Bank Wind Farm, 2022).

Dogger Bank has a complex geology, resulting from the different depositional environments and post-depositional processes that have formed it over the last 120 000 years (Cotterill, et al., 2017a & b). Dogger Bank is generally accepted to be a complex of highly deformed glacial till, created as the ice sheets from Britain and Scandinavia oscillated across the area, bringing eroded soils with them that were often left in ridges (terminal moraines) at the front of the ice. As the ice moved backwards and forwards these soils were “rucked up” forming features known as push-moraines, which were then overridden and eroded by later glacial advances. Between these ridges shallow lakes developed. The soils are therefore typically non-sedimented and have been deposited and reshaped by a number of different environments ranging from tundra, permafrost, subglacial, pro-glacial - through to temperate - including lacustrine, fluvial and estuarine or lagoonal and to changes as the sea level rose and flooded the Dogger Bank about 7000 years ago. Thus, desiccation due to drying, evapotranspiration and freezing are considered to be important post-depositional processes in the geologic history of the Dogger Bank soils. The resulting variability in the soil conditions are significant for the ground investigations and the ensuing characteristic values of soil properties derived for geotechnical design of the monopile foundations. At Dogger Bank, seafloor CPTs were the primary intrusive ground investigation tool performed at each wind turbine generator (WTG) location. The CPT

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data were a key input to the ground model developed for the site, which combined high quality 3D seismic profiling and targeted borehole locations from which site-specific CPT correlations were developed.

2 CHALLENGES AND LIMITATIONS ASSOCIATED WITH INTERPRETATION OF CPT DATA

The soils present at Dogger Bank are, in general, not classic sedimented clays and sands, or conventional glacial lodgement tills or glaciomarine tills. The Dogger Bank soils must therefore not be forced into a classical framework for sedimented soils nor the correlations that have been developed for such soils. It follows that a key challenge with the Dogger Bank site is the natural variability encountered in the geotechnical parameters, especially for the clays of the Dogger Bank Formation. This variability is primarily attributed to the different depositional environments and varying post-depositional processes to which the soils have been subjected, as discussed above. Consequently, the soils vary in composition (particle size distribution and plasticity), stress and strain histories, and in their current state (in situ stresses, density) and fabric. Coupled with this natural variability are possible sample disturbance effects (including effects of dissolved gas coming out of solution when sample is recovered to deck (Lunne et al. 2001), uncertainty with in situ stress conditions, limitations with laboratory testing, and scale effects. A further complication when using CPT data to develop site-specific correlations, is that these data are invariably noncoincident with the other test data used to develop the correlation. Examples of the variability in geotechnical parameters are given below.

For low to medium overconsolidation (OCR) ratio clays, it has been shown that the preconsolidation stress (p_c') assessed from oedometer tests usually correlates well with the undrained shear strength from anisotropically consolidated triaxial compression (CAUC) tests (s_{uC}), as shown in Figure 1. The post-depositional processes to which the Dogger Bank clays have been subjected have imposed stress histories that are very different to simple vertical loading, unloading and reloading. Consequently, very large scatter is evident in the $s_{uC} - p_c'$ dataset shown in Figure 1 for the Dogger Bank clays.

It should be emphasized that the p_c' and OCR values derived from oedometer tests performed on these soils are “apparent” values. Correlations developed from loading-unloading-reloading data, such as those linking p_c' and s_{uC} and those linking OCR and in situ horizontal stress (or the later earth pressure at rest, K_0), therefore do not apply to the Dogger Bank clays. As noted by Yetginer & Tjelta (2021), the inability to reliably estimate p_c', OCR and K_0 increases the uncertainty in laboratory test results for these soils.

Figure 2 presents plots of corrected cone resistance (q_t) versus depth for Upper Dogger Bank clay. The cone resistance data have been filtered to remove sand-like layers based on expected Soil Behaviour Type (SBT), however some spikes in the q_t data are still present. It is seen that q_t increases with depth, but that there is variability in the cone resistance. This variability leads to challenges and uncertainties when developing cone resistance based geotechnical parameter correlations.

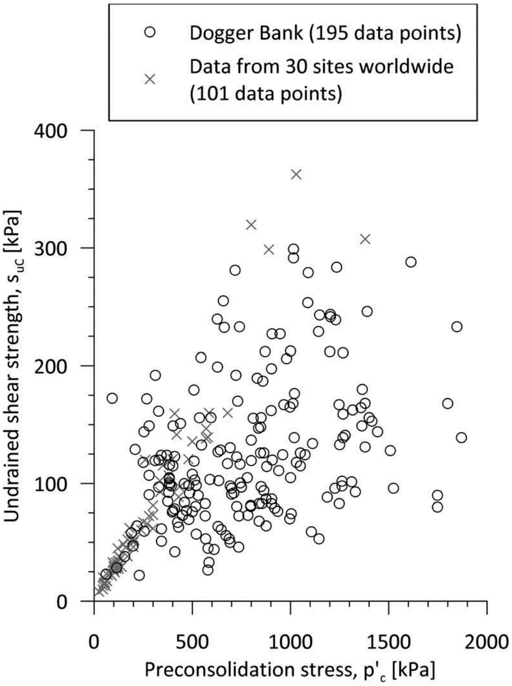

Figure 1. Preconsolidation stresses from odeometer tests compared with undrained shear strengths from anisotropically consolidated triaxial compression tests (updated from DeGroot et al., 2019).

Figure 3 shows considerable variation of N_{kt}-factor versus depth (where $N_{kt} = q_{net}/s_{uC}$), despite efforts to filter the data based on sample quality and sampling techniques. Possible explanations for this scatter include:

1) The presence of fissures and planes of weakness in the clay fabric which influence the measured undrained shear strength.
2) Sample disturbance effects which are difficult to quantify in overconsolidated/non-sedimented clays and possibly includes dissolved gas coming out of solution.
3) Uncertainties in the selected q_t value due to noncoincident borehole and CPT data (i.e. the physical inability to measure q_t on the soil sample tested in the laboratory).
4) Limitations in laboratory testing procedures, including the inability to reliably estimate p_c', OCR and K_0, as noted previously.

3 EVOLVEMENT OF A NOVEL SOIL INVESTIGATION STRATEGY

Soil investigation (SI) for the Dogger Bank offshore wind farm has been conducted in three principal phases. These phases were not conceived entirely at the outset but developed organically to address arising challenges and constraints.

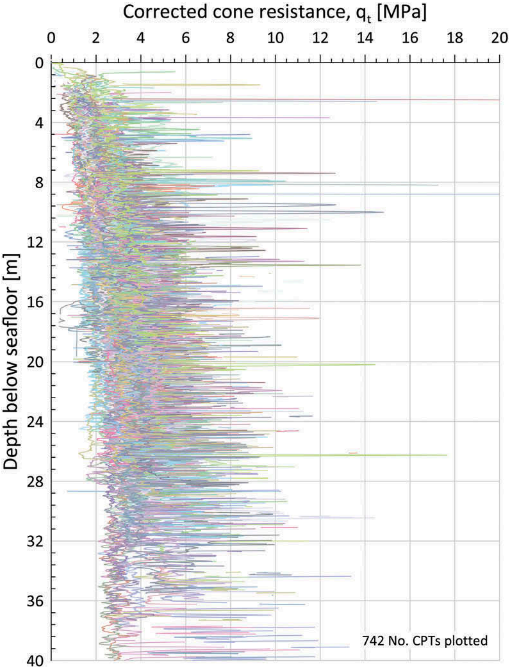

Figure 2. Corrected cone resistance versus depth for Upper Dogger Bank clay.

Phase I:
An initial phase with regional geophysical and geotechnical investigations (incorporating boreholes and CPTUs) and including study of geological information. All information was integrated into a regional ground model that was used for wind farm layout and foundation feasibility studies. Routines to provide "synthetic CPT data" from the ground model at untested locations were also developed (Forsberg et al. 2017).

Development of site-specific correlations between CPT data and geotechnical parameters started during this phase. Two of the most important challenges were:

1) Available seafloor CPT equipment did not give sufficiently deep penetrations for the expected monopile embedment's.
2) The "normal" approach of correlating corrected cone resistance (q_t) to undrained shear strength (s_u) resulted in exceptionally large scatter in the derived N_{kt} factors.

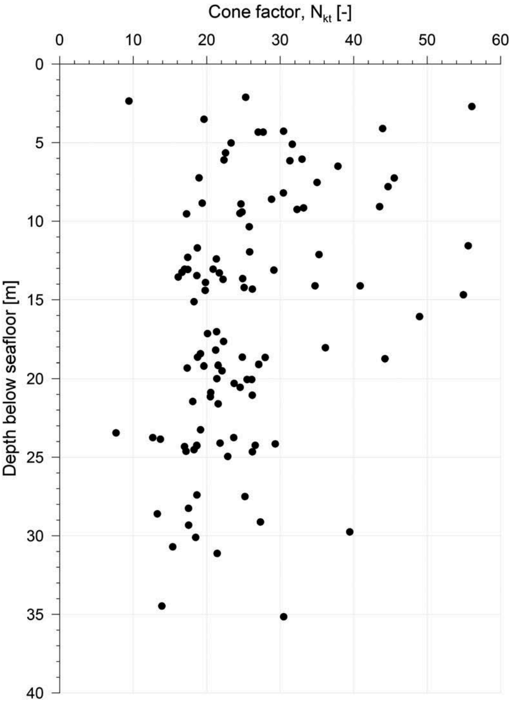

Figure 3. Example variation in N_{kt}-factor versus depth for clay from the Dogger Bank Formation.

Phase II
A hypothesis that the scatter in apparent p_c', s_{uC} and N_{kt} data is a function of sampling, testing, and/or scale (fabric) effects was tested by deployment of spudcan penetration tests (see Section 5.1) and detailed soil characterization, including seismic CPTs at a small number of carefully selected "focus" locations. These focus locations provided detailed information on the soils, including the depositional and post-depositional regimes, for the various geological units identified at each location. CPT correlations were then developed using the data gathered at the focus locations. Phase II also included the trialling of enhanced seafloor CPT equipment with the aim to achieve penetrations beyond the expected monopile embedment's, and finalization of the CPT interpretation scheme.

Phase III
In order to optimise project execution, the Phase III SI and final Geotechnical Design Basis (GBD) production were squeezed into a 10-month period.

The final phase of SI comprised at least one enhanced (deep) seafloor CPTU at each WTG location. Seismic CPTs and soil borings were performed at selected locations identified from the updated ground model.

Due to the lack of soil sampling at turbine locations, a complementary 3D Ultra High Resolution Seismic (UHRS) survey was also conducted. This survey and associated detailed geological interpretation provided a high reliability of regional geological unitisation, which was critical given the lack of sampling at WTG locations.

The key elements to the success of the soil investigation strategy are:

1) Enhanced CPTs extending below monopile embedment depths, enabling reliance on CPTs as the primary WTG location specific dataset, and thereby minimising the final survey campaign period and laboratory testing period;
2) Integration of CPT, borehole and interpreted 3D UHRS geophysical survey data;
3) A geological model developed by the BGS (Cotterill, et al., 2017a & b);
4) Site- and unit-specific CPT-correlations for geotechnical parameters;
5) Spudcan penetration tests to validate the 'operational shear strength' and application of regional unit specific N_{kt}-factors.

4 RECENT DEVELOPMENTS WITH CPT EQUIPMENT

For monopile foundations it is generally necessary to obtain soil parameter data to a depth of 40 – 50 m bsf. Using seafloor CPTs to obtain the required data is approximately 10 times more efficient than using combined down-hole sampling and CPT boreholes. Thus, there is a significant productivity gain in being able to penetrate to 45-50 m bsf with seafloor CPTs. However, from a CPT and monopile design perspective, the very dense sands of the Eem Formation, present at a depth of 30 – 40 m bsf at the Dogger Bank site are important. Seafloor CPT refusal was invariably encountered in the upper few metres of this unit, with q_c values of up to 150 MPa being recorded. This presented a challenge for the project and led to enhancements of the standard CPT equipment, such as using lubrication behind the cone to reduce rod friction. However, even with lubrication, it can be difficult, or even impossible, to penetrate a deep very dense sand layer. A new approach where water is flushed through holes near the cone tip has been developed and successfully used at the Dogger Bank Offshore Wind Farm. The development of these enhanced CPTs for Dogger Bank project has been successful due to close cooperation between the soil investigation contractor and the wind farm developer, as presented in Tjelta et al. (2022).

These enhancements increased the seafloor CPT penetration depth, as indicated in Table 1 and thus permitted efficient use of the CPT data to derive full depth geotechnical design parameter profiles at each WTG location.

Table 1. Summary of seafloor CPT penetration depths for the Dogger Bank project area.

		Final penetration depth (m bsf)		
Year	No. CPTs*	Minimum	Maximum	Average
2010	97	3.8	40.2	22.5
2012	87	8.9	40.1	27.2
CPT equipment enhancements from 2018 onwards				
2018	35	12.4	40.0	27.5
2019	100	14.3	45.6	38.8
2020	120	7.5	50.3	40.1
2021	98	23.5	58.8	44.5

* excluding tests with premature refusal and seismic CPTs

5 IMPROVEMENTS IN CPT INTERPRETATION

5.1 *Giant "CPTs"*

A novel feature of the Dogger Bank SI strategy was the use of large scale plate loading tests in the form of spudcans from a jack-up unit to assess the mass *operational* undrained shear strengths for the clay units at selected focus locations (Yetginer & Tjelta, 2021). Back-analysis of spudcan penetrations recorded from these jacking trials resulted N_{kt}^{*1} factors for most clay units in the range 18-22 with a best estimate of 20. The corresponding reduced range in undrained shear strengths avoided designing foundations for a potentially unrealistic low strength for capacity, yielding large foundations, and then an equally unrealistic high strength for installation, resulting in high refusal risk.

Corrected CPT cone resistance measurements were interpreted both individually and collectively (over the wider jacking footprint area) to derive design undrained shear strength profiles for input into the back-analysis calculations. Location specific average operational N_{kt}* factors were fine-tuned to best match the predicted spudcan penetration behaviour with the observed offshore penetration record. Spudcan penetration predictions were made by means of both traditional bearing capacity calculations using NGI's in-house SPLAT software (Zhang et al., 2015) and Large Deformation Finite Element (LDFE) analyses using Abaqus. Example details from a back-analysis are shown in Figure 4.

Results from the spudcan penetration tests help to highlight that scale and fabric effects are an important consideration for the Dogger Bank clays. Comparison of the laboratory CAUC

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[1] Herein N_{kt}^* denotes the factor used to infer the mass operational shear strength, whereas N_{kt} denotes the factor used to estimate the undrained shear strength in triaxial compression, s_{uC}.

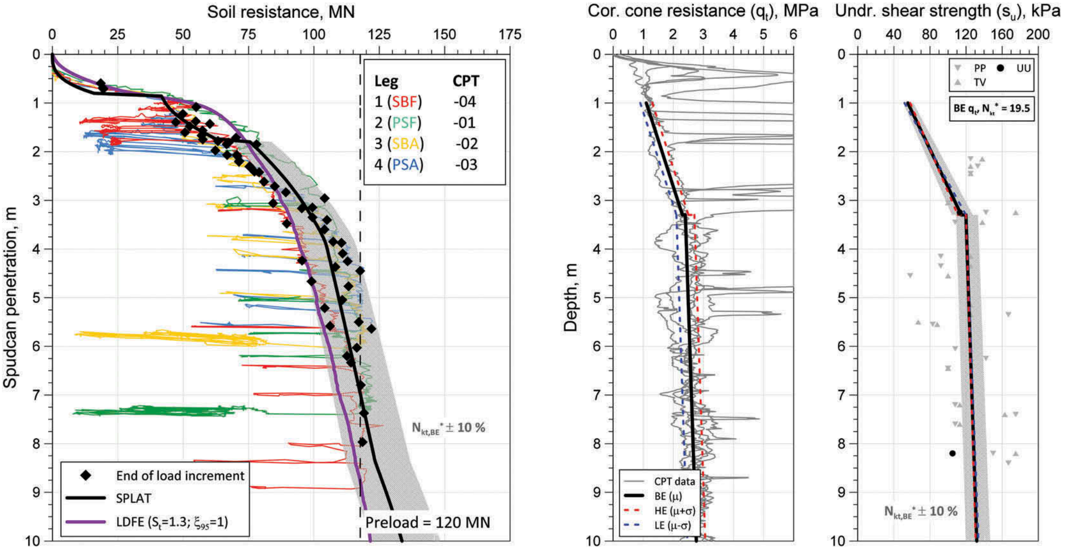

Figure 4. Example details from back analysis of recorded spudcan penetrations using SPLAT and large deformation finite element (LDFE) analyses.

strengths and the mass operational undrained shear strengths determined from back-analysis of spudcan penetration records at Dogger Bank, suggests the data shows a positive scale effect, with undrained strength increasing with increasing sample size. The size of the spudcans are comparable to the diameter of a monopile and the scale of the penetration tests is such that the varying responses due to natural variability and to different behaviour patterns in undrained shear (e.g. Hight et al., 2003) are integrated to some extent. The resulting range in N_{kt} values applicable to back-calculated strengths are lower than for the laboratory tests.

Differences in the kinematic restraints between the field and laboratory tests as well as rate-effects are noted to contribute to this observation.

The cost of performing the spudcan penetration tests were comparable to those for an SI vessel, particularly when these tests could be timed with existing operations. Such tests also have the advantage of providing valuable information for future WTG installation operations.

5.2 *V_s and G_{max} correlations*

Soil unit specific correlations for shear wave velocity (v_s) were developed in terms of net cone resistance (q_{net}) and in situ effective vertical stress (σ_{v0}'):

$$v_s = \beta_0 \cdot q_{net}{}^{\beta_1} \cdot \sigma'_{v0}{}^{\beta 2} \tag{4.1}$$

where β_0, β_1 and β_2 are best-fit empirical factors. The unit for q_{net} and $\sigma_{v0'}$ is kPa and that for v_s is m/s. The small strain shear modulus (G_{max}) is evaluated from:

$$G_{max} = \rho \cdot v_s^2 \tag{4.2}$$

where ρ is the soil density.

The correlations are primarily developed from seafloor and downhole seismic CPTs (SCPTs). Data from borehole suspension logging as well as bender element measurements performed during triaxial, direct simple shear and resonant column laboratory tests were also considered. Figure 5 presents a comparison of measured versus calculated shear wave velocity for Upper and Lower Dogger Bank clay. As with the N_{kt} dataset, there is also variability in the v_s data. This suggests that factors such as the depositional environment and varying post-depositional processes to which the soils have been subjected also influence the shear stiffness of the soil.

Shear wave velocities determined at the end of consolidation in triaxial tests using bender elements typically give v_s values which are lower than those determined in situ (Figure 6). Such observations are not uncommon and highlight the importance of in situ shear wave velocity measurements for structures, such as monopiles, which are sensitive to the small strain stiffness response of the soil.

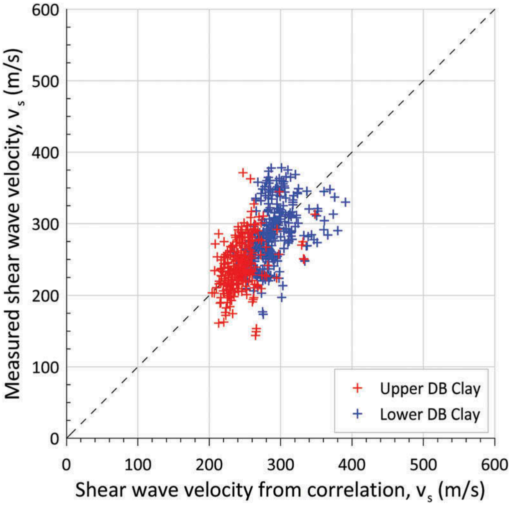

Figure 5. Measured versus calculated shear wave velocity for Upper and Lower Dogger Bank clay.

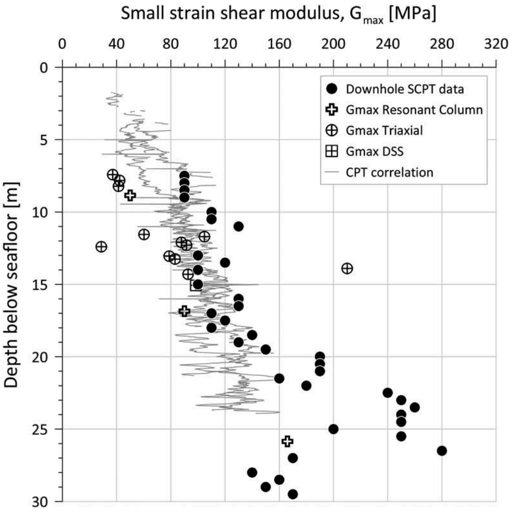

Figure 6. Example G_{max} data from investigations at a focus location.

6 FINAL CPT DATA INTERPRETATION SCHEME

A key advantage with CPT testing is the speed with which the data can be acquired, processed and interpreted to provide geotechnical engineering parameters. This is advantageous for the development of offshore wind farm projects which may have 100 or more WTGs. For the Dogger Bank WTG locations, continuous seafloor CPT data permitted semi-automatic processing and analysis of data and thus:

1) Rapid development of geotechnical design profiles (preliminary profiles available in a matter of minutes);
2) Early phase monopile driveability predictions for identifying the potential risk of refusal during installation.

The geotechnical design profiles can also be used in automated routines for monopile design, such as those presented by Klinkvort et al. (2020).

Design parameter profiles for each WTG monopile foundation were developed from the site-specific CPT data acquired at each location coupled with the ground model developed for the Dogger Bank site. Figure 7 presents an example design parameter profile, showing q_t together with interpreted parameter profiles for undrained shear strength (s_u), relative density (D_r), peak drained effective stress friction angle (ϕ'), small strain shear modulus (G_{max}) and soil behaviour type (SBT).

Figure 8 presents example soil resistance to driving (SRD) and blow count predictions derived automatically from the site-specific CPT data. These predictions proved very valuable and indicated that monopile installation should be nonproblematic (earlier estimations made using composite CPT profiles gave strong indications for driving refusal).

7 INTEGRATION OF 3D UHRS SURVEY DATA

At each WTG location, refined interpretation of the 3D UHRS seismic data was performed to validate the variations in the CPT data accounted for in the characteristic design profiles. These detailed interpretations focused primarily on the continuity of soil layers within a 40 × 40 m box surrounding each CPT position, as shown in Figure 9. Such interpretations provide confidence that the CPT-derived stratigraphic profiles are representative for the much larger scale application of monopile foundation design.

8 STATISTICAL INTERPRETATION OF CPT DATA

The continuous nature of seafloor CPT data lends itself towards the development of design parameter profiles using statistical methods. However, this approach has some challenges, as discussed below.

Linear regression can be used to derive a best estimate (i.e. central estimation) trend for q_t data over a specified depth interval. For such data, which can be considered to have a single independent variable, the confidence on the mean value, $\overline{q_t}$, together with the predictive interval (e.g. 5 and 95% percentiles) can be estimated from DNV (2012).

It is important to emphasise that the formulations in DNV (2012) only apply where there is a single independent variable. Where multiple variables are present, such as when geotechnical parameters are derived from CPT-based correlations (e.g. s_u or G_{max}), an

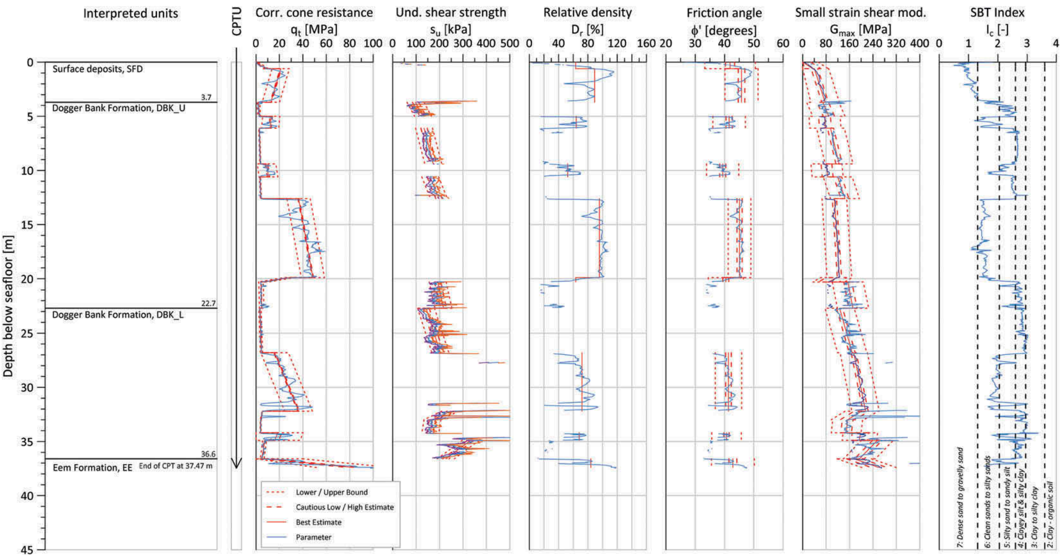

Figure 7. Example design parameter profile for a WTG location.

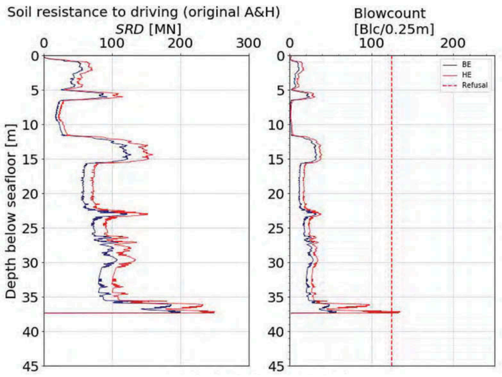

Figure 8. Example SRD and blow count predictions.

alternative methodology needs to be adopted which also considers the uncertainty in the correlation itself. One such method is the first-order second-moment (FOSM) method, which determines the stochastic moments of a function with random input variables using a first-order Taylor series (Haldar & Mahadevan, 2000). However, this approach is also not without its challenges and limitations, which include:

1) Assessment of the statistical uncertainty associated with each coefficient and exponent in the correlation formula. Such information may not be readily available.
2) Assessment of the equivalent number of independent data points for CPT data.

Coupled with this are how the design parameter profiles should be defined. Treatment of these topics is beyond the scope of this paper, but it is emphasized that these are important topics which the industry should address.

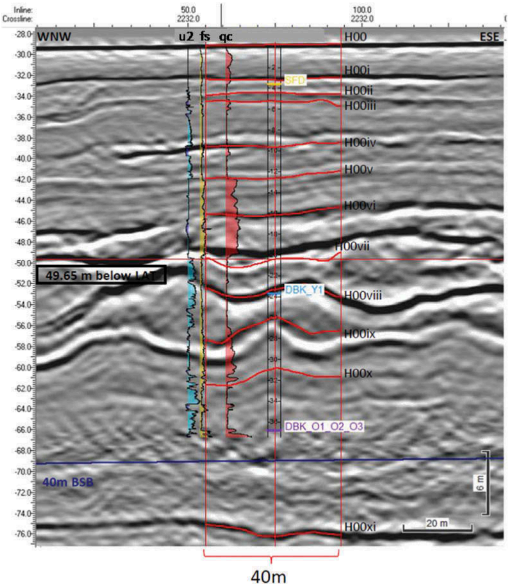

Figure 9. Example showing correlation between interpreted geophysical profile and CPT data (image courtesy of Geosurveys /MMT).

9 CONCLUDING REMARKS

The Dogger Bank project has demonstrated that the CPT can be used as the primary intrusive site investigation tool for offshore wind farm projects despite complex geology and challenging ground conditions comprising stiff clays and very dense sands. A novel soil investigation strategy evolved for the project which addressed these challenges as they arose and had the following key elements:

1) Enhanced CPTs extending below monopile embedment depths. This enabled CPTs to be the primary intrusive SI dataset for each monopile location which had significant project timeline benefits. In order to attain target CPT penetration depths, innovative technical developments comprising rod lubrication and/or water injection at the cone tip were developed. The developments were the result of close collaboration between the SI contractor and the project developer.
2) Development of a reliable ground model which integrated CPT and borehole information with interpreted 3D UHRS geophysical survey data and the regional geological model for the site.
3) Development of site- and unit-specific CPT correlations for geotechnical parameters. Laboratory testing necessary for the development of these correlations was programmed early in the project timeline, where possible.
4) Innovative use of spudcan penetration tests to validate the operational undrained shear strength of the clays and enable application of regional unit specific N_{kt}-factors. Such tests highlight the value of large scale in situ testing of soils.

The CPT tool developments outlined in this paper, together with the novel site investigation strategy developed for the Dogger Bank wind farm, indicate the CPT will continue to have a central role in future offshore wind projects. However, it is contended that CPT tool development now probably lies in front of CPT interpretation, especially when it comes to the determination of design parameter profiles inferred from CPT data and associated coupling with statistical analysis.

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