Cone Penetration Testing 2022 – Gottardi & Tonni (eds)

Development of an enhanced CPT system for Dogger Bank

Tor Inge Yetginer-Tjelta
Equinor, Stavanger, Norway

Simon Bøtker-Rasmussen
Geo, Copenhagen, Denmark

Mike Rose
SSE Renewables, Perth, Scotland

Tom Lunne & Vaughan Meyer
NGI, Oslo, Norway

Callum Duffy
Logos Geoservices Ltd, Oxford, UK

ABSTRACT: An enhanced seafloor CPT system has been developed to support completion of the soil investigation campaign for Dogger Bank. This enhanced system has a demonstrable and significant performance increase over standard seafloor CPT systems; capable of pushing through dense sand layers with q_c>100 MPa and through tens of meters of very stiff clays. At Dogger Bank, this enhanced system has enabled CPT penetrations of more than 40 m below seafloor, in soils where standard systems could only average in the twenties. The system enhancement has been achieved through the application and adaption of techniques well known in the geotechnical industry (water lubrication and water injection), but which have never before been combined in an offshore seafloor CPT system. The performance of the enhanced CPT system has enabled a reliance on seafloor CPTs to acquire data to beyond monopile toe depths, therefore removing absolute reliance on boreholes to acquire data at turbine locations and facilitating the fast and efficient development of a geotechnical design basis.

1 INTRODUCTION

A challenge in offshore wind farm development is designing a soil investigation campaign that efficiently and cost effectively provides the geotechnical data required for the design of pile foundations. With many years of gradually applying in situ testing as an active part of building a design basis, it is observed that seafloor CPTs are both efficient and less expensive than boreholes, yet they are often compromised by not being able to penetrate to pile toe depths.

Monopiles are the primary foundation type for the Dogger Bank wind farm development. As outlined in the companion paper (Yetginer-Tjelta et al., 2022), the design of monopiles requires soil data to 40-45 m below seafloor. Furthermore, windfarm layouts are commonly only confirmed late in project execution, necessitating a rapid turnaround from turbine location definition, to the delivery of a geotechnical design basis. Due to these factors, seafloor CPTs would be the preferred solution provided that a penetration to greater than 40m can be achieved.

Soil conditions at Dogger Bank consist mainly of dense to very dense sands and very stiff clays. For these soils, experience has shown that for “standard” seafloor CPTs, refusal frequently happens between 20-30m below seafloor. This is due to the combined effects of high rod friction in the stiff clays and high tip resistance encountered within the dense sand layers, frequently found at the base of Dogger Bank clays, at 25 to 30m below seafloor. Consequently 40+ m penetration cannot be achieved at most locations at Dogger Bank.

The seafloor CPT penetration statistics from the two preliminary soil investigation campaigns in 2010 and 2012 illustrate these factors:

Table 1. Summary of early seafloor CPT penetration depths Dogger Bank.

		Final penetration depth (m bsf)		
Year	No. CPTs 1)	Minimum	Maximum	Average
2010	97	3.8	40.2	22.5
2012	87	8.9	40.1	27.2

DOI: 10.1201/9781003308829-34

Whilst these CPTs provide good data for the development of a ground model, the sub 40m penetrations would not enable standard seafloor CPTs to be relied on as the primary data acquisition tool for monopile design. Therefore, for the purpose of designing the turbine location specific completion soil investigation (SI) campaign, the following options were considered:

- Revisit turbine locations with seafloor CPT refusals of less than ~40m penetration with a drillship and down hole CPTs, or
- Accept high uncertainty on soil conditions below refusal depth and build trust into a good ground model, or
- Attempt to reach deeper with an improved "deep" seafloor CPT system.

Revisiting seafloor CPT refusal locations with a drillship was deemed not acceptable for reasons of cost and time. Whilst the reliance on the ground model below refusal depth was similarly rejected due to the complex geology and reworked soils. Geophysical reflectors were frequently broken and made it difficult and often impossible to follow any layer more than a few hundred meters. Furthermore, the lower sand (base of Dogger Bank) is found between 25-35m; coincident with the seabed multiple of the UHR seismic data. This resulted in very poor confidence for the ground model below this depth since all detailed information on layer thickness and general stratigraphy disappeared in the strong multiple reflection and little details were visible below.

From the above it is clear that development of equipment and procedures for achieving larger penetration with seafloor CPTs was of critical importance to support the efficient and cost-effective delivery of the Dogger Bank completion SI campaign. This became a main objective with the various CPT campaigns in the period 2018-2021. This is further detailed in Sections 3, 4 and 5 below. It became a stepwise approach where trials, results/experience and modifications were considered on a continuous basis.

As outlined by Yetginer-Tjelta et al. (2022), 3D UHRS geophysics in 2019 (and beyond) improved the resolution and capability of the ground model but were not sufficient to replace CPT data as the basis for foundation design.

2 PREVIOUS WORK TO REACH DEEPER PENETRATION

The most common way of increasing penetration is to reduce the friction along the CPT rods. Frequently a friction reducer such as an expanding coupling is used at some distance behind the cone. Thus, the diameter of the hole is expanded and the friction between the rod and the soil is reduced. According to ISO22476-8: 2012 the friction reducer must be at least 400 mm behind a 10 cm^2 cone in order not to influence the measured CPTU parameters. Offshore soil investigations with a seafloor rig often use a 15 cm^2 cone and 10 cm^2 rods, which gives good results in many cases.

Another way of reducing the rod friction is to inject water or drilling mud at some location above the friction reducer. Jefferies and Funegard (1983) reported such a system and showed that the pushing force can be reduced by up to 50 % (Figure 1). Staveren (1995) reported that in stiff overconsolidated Belgian Boom clay, normal CPTs met refusal at 5 m penetration: using mud injection, up to 62 m penetration could be achieved.

In very dense sand, high cone resistance can be a factor limiting penetration. Bayne and Tjelta (1987) and Yagi et al. (1988) reported designs of cone penetrometers where water could be injected into the soil through channels in the penetrometer tip. The cone design reported by Bayne and Tjelta (1987) was intended to be used to investigate how much skirt penetration resistance in dense dilatant sand could be reduced by water injection. High negative pore pressures and increased effective stresses, resulting in high cone resistance, may be neutralized by adding water during penetration. This cone penetrometer was unfortunately not used in practice. Yagi et al. (1988) used their cone

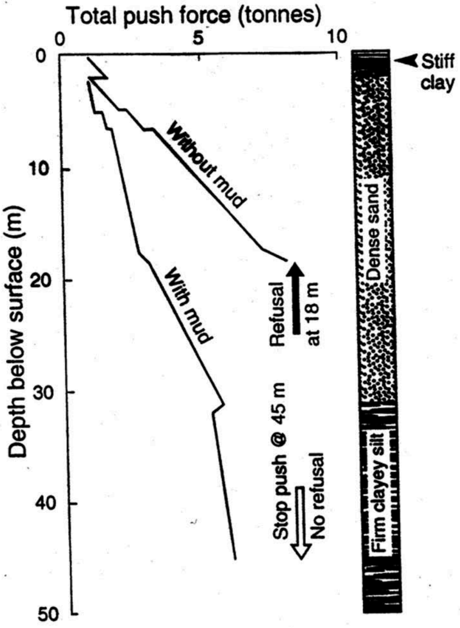

Figure 1. Total cone push force with and without mud injection (adapted from Jefferies and Funegard, 1983).

penetrometer to carry out tests at various effective stresses. They controlled this by adding water or air through the tip during cone penetration.

In summary, for further work at Dogger Bank in 2018 the ideas of rod lubrication and potentially water injection at or around the cone tip were selected for further experimenting.

3 ENHANCED CPTS USING ROD LUBRICATION

A strategic cooperation contract was agreed between the Dogger Bank project and the Danish contractor Geo with the aim to improve seafloor CPT penetration below mudline from being in the low 20m's to anything towards 40m (later changed to 45 m). In 2018 the following modifications were introduced to reach this aim:

1. Increased thrust capacity, i.e. 250 kN net thrust available at seafloor.
2. A rod lubrication system which reduced or eliminated friction accumulation in the stiff clays to enable deeper penetrations in the clays and thus enable more thrust capacity in the dense sand layers at base of Dogger Bank clay units.

These first tests improved the penetration depth below seafloor significantly, from an average of 23 m to approx. 35.8 m, and with several CPTs reaching close to 40 m (target depth at that stage) and one test meeting the target with still 5 kN thrust reserve. Figure 2 shows total thrust curves for 4 CPTs within an area of 110 x 110m with 3 standard CPTs reaching maximum thrust between 19 and 24m whilst one CPT with rod lubrication reached 35.2m including penetration through two dense sand layers.

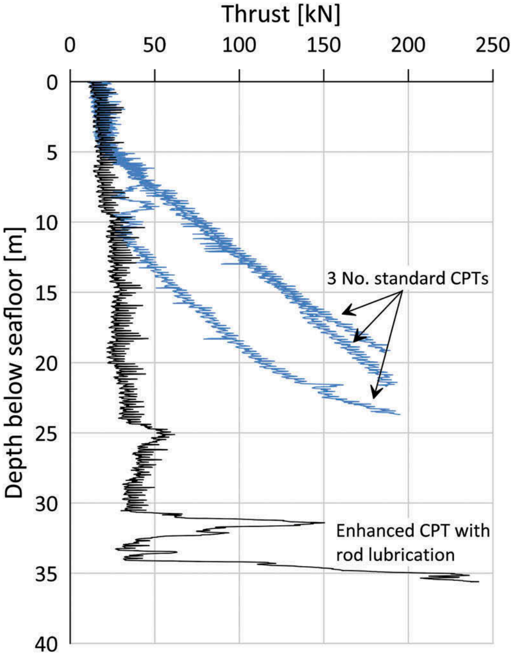

Figure 2. Thrust for Enhanced CPT with lubrication and 3 CPTs with no lubrication.

In addition to thrust, pressure and flow rate of lubrication water are measured. There is a potential for using these parameters in the interpretation of the test results.

4 DIRECT PUSH CPT WITH WATER INJECTION AT TIP, MEASURING THRUST ONLY (DCPT)

From the testing in 2018 (above) it was clear that rod lubrication worked and enabled significantly deeper penetration. It also meant when the dense sand layers were met at about thirty meters depth, only 10-15% of the thrust capacity was spent on reaching this depth (note the relatively constant thrust with depth in mostly clay down to 30m). But some of the sand layers were very dense, with q_c values of more than 100 MPa, and for some locations significantly more than 10-15% of the thrust was required to overcome layered units. Refusal was therefore still frequently encountered in dense sand layers. To deal with locations where several sand layers made the rod lubrication less efficient, and where deeper sand layers added to frequent refusals in the 30 m range, further work took part along two parallel paths.

Firstly, further improvements were made to improve the efficiency of rod lubrication. Many options were tested, including:

- variations in water injection hole diameter and location (radially and axially)
- combination with friction reducers of various thickness and length
- high and low water pressures
- variations in water volume.

Secondly, to improve the penetration of very dense sand layers, water injection at the cone was attempted in different ways. This built on experience gained over many years from projects such as Gullfaks C (Tjelta et al.,1986), Dudgeon suction anchor trials 2013 (unpublished), and the OWA Suction Anchor Trial Installation Campaign 2015 (unpublished) where significant reduction in the penetration resistance of skirts and suction anchors was observed by injecting water at the skirt tip. The effect comes from partly reducing dilation in dense sand, removing dilation completely (and reducing effective stresses) or in some cases probably by flushing away sand particles.

Various geometries of the cone with flushing through the tip, at the face and at the neck were tried, see two examples in Figure 3. These cone types were not instrumented and were named DCPTs (Direct Cone Penetration Test), with the only recording of penetration resistance being total thrust (a bit like the mechanical cones in the early days of cone testing). Water injection at these positions is expected to have some influence on a measured cone resistance, but nevertheless this system did result in deeper penetration and provided information of what was below the dense sand at which time the water injection can be reduced or halted.

Figure 3. Various cone tips with water flushing for DCPT cones.

Figure 4a shows an enhanced CPT to 45m depth (red curve) in parallel with a non-instrumented cone, DCPT (black curve). At this location it was possible to penetrate both cone types to 45 m (target depth). At many other locations the enhanced CPT met refusal at shallower depth and soil stratigraphy had to be inferred from thrust curves only (Figure 4b provides an example).

What this parallel test in Figure 4a shows is a very good correlation between q_c and thrust when rod friction is kept low and relatively constant. This test (black curve) uses combined rod lubrication and cone water injection.

Figure 4b shows an enhanced CPT meeting refusal due to max thrust and high tip resistance (114 MPa) whilst the DCPT reached 40m without any problem (40m was target depth at this test location), and clearly provides relevant information of soil strength and stratigraphy. For instance, the driveability of large monopiles can be considered feasible since the dense sand layers at 26 and 34m are proven to be relatively thin. When soil stratigraphy is very variable (less homogeneous and/or rod lubrication is less efficient) the thrust/q_c correlation is less accurate. Although the DCPT system worked well in 2019, some locations had to be covered by drilling and down-hole CPTs. This experience stimulated further development.

5 DCPT WITH MEASUREMENT OF TIP RESISTANCE (iDCPT)

To achieve improved penetration in the very dense sand layers at Dogger Bank (q_c in the range of 100-150 MPa), the S-cone was developed, as shown in Figure 5. This is a cone tip which combines the power of a 5 cm^2 cone in spearheading into dense sand, combined with large holes for water injection to reduce sand resistance on the face of the cone with enlargement following closely behind the cone tip. The early version of this S-cone was non-instrumented and only thrust was recorded. Later versions of the S-cone are instrumented, with q_c and inclination recorded (named the iDCPT), but due to robustness being prioritised and space limitations associated with water injection, the tool has less accuracy than a standard cone according to ISO specifications. However, as can be observed in Figure 6, where an enhanced CPT and an iDCPT were performed only meters apart; the enhanced CPT met refusal at 24 m whilst the iDCPT using the S-cone penetrated to 45 m. The correlation between q_c from the robust iDCPT and the enhanced CPT is good, and it is seen that the iDCPT provides useful information for layers below the depth of penetration attained by the enhanced CPT.

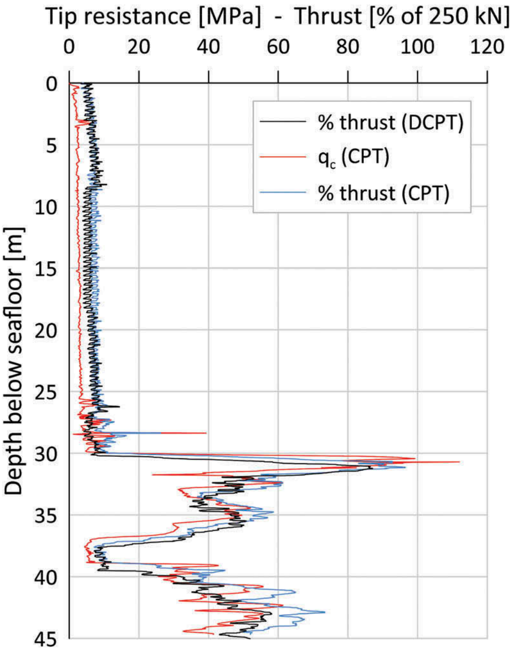

Figure 4. a) Location A (top): Comparisons between normal CPT and DCPT - enhanced CPT and DCPT both penetrate to ca. 45 m; b) Location B (bottom): Enhanced CPT refused at 26 m whilst the DCPT reached 40 m (target depth at the time, could have gone deeper).

The most efficient combination of water injection (pressure and volume), friction reducers and cone shapes may depend on the soil conditions and will invariably include some trial and error in the beginning, but the results speak for themselves (Table 2).

From pre-2018, the average CPT depth has increased from 22m to 44m in an area where dense sand layers dominate below 25-30m. These numbers do not include the iDCPT. A challenge has also been to distribute water in the most efficient way between the rod lubrication and the tip flushing.

Figure 5. Instrumented cone tip used with the iDCPT.

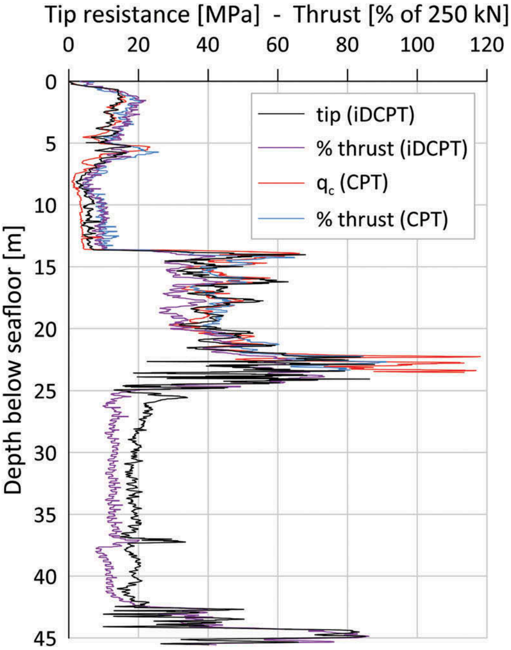

Figure 6. Enhanced CPT and iDCPT.

Table 2. Summary of Seabed CPT penetration depths Dogger Bank.

		Final penetration depth (m bsf)		
Year	No. CPTs 1)	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				
2019	100	14.3	45.6	38.8
2020	120	7.5	50.3	40.1
2021	98	23.5	58.8	44.5

6 DISCUSSION

The main objective set out at the start of 2018 was to reach sufficient penetration with seafloor CPT testing without the need for drilling and down-hole CPTs.

Two main targets were identified in these early days:

1. Reduce or "eliminate" rod friction to enable deeper penetration and have more thrust capacity available when dense sand layers appeared at base of Dogger Bank formation.
2. Improve the ability to penetrate into and through dense sand layers with tip resistances in excess of 100 MPa.

This objective has been met; seafloor penetration depth to 40-45m is now possible at Dogger Bank at most locations. The importance of this objective goes beyond the operational aspects of seafloor CPTs being more efficient than down hole CPTs in a borehole. It allows for reduced time from confirmed turbine layout to delivery of a geotechnical design basis "*by 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." quote from companion paper (Tjelta et al 2022)

On a side note, the ability to penetrate into and through dense sand layers with tip resistance in excess of 100 MPa at more than 30m below seafloor is not trivial. It requires a significant reduction of rod friction. In doing so, the combined effect of a friction reducer and water injection as described in this paper is necessary, and it has taken time and efforts to arrive at a geometry that works. The impact of altered geometry due to extreme wear on all parts in the CPT system complicates the feedback. Figure 7 indicates the changes taking place. Diameter changes, and friction reducers are ripped off by the continuous abrasion from dense quartz sand.

Figure 7. New rod with friction reducer 44mm left and to the right the wear has reduced diameter to 41 mm and in parts of the FR it is ripped off completely.

Outstanding challenges to be addressed are effective lubrication while the CPT string is being built, and effective lubrication in permeable sand layers.

The importance of the following elements has been recognized during the 3-4 years it has taken to develop a fully operational and efficient enhanced seafloor CPT system:

- Friction reduction and ideally removal along the entire rod by a combination of a friction reducer above the friction-sleeve and water injection
- Increased thrust force when stiff clays and dense sand layers are combined, like at Dogger Bank
- The importance of inclination measurement in the cone, both for operational purposes (abort the CPT if becoming excessive or to push deeper to compensate for rod inclination) and for final presentation of results with true vertical depth
- Special measures at the cone tip to tackle extremely dense sand layers with q_c above 100 MPa.

7 SUMMARY AND CONCLUSIONS

A seafloor CPT system with improved (enhanced) capabilities has been developed for the Dogger Bank field investigations in the period 2018-2021. The main objective of this development was to improve the depth range to more than 40m below seafloor in an environment where average penetration used to be in the low 20m's. This has been achieved through systematic development and adaption of techniques well known in the geotechnical industry (water lubrication and water injection). However, these techniques have never before been combined in an offshore CPT system to produce a machine capable of pushing through dense sand layers with $q_c >$ 100MPa and very stiff clays. The result has been a 100% increase in CPT penetration depth compared to a few years ago.

This performance enables fast and efficient development of a geotechnical design basis when combined with early boreholes strategically placed in geological units to build a ground model, as discussed in the companion paper (Yetginer-Tjelta et al., 2022).

ACKNOWLEDGEMENTS

The authors are grateful to Dogger Bank Wind Farm for the opportunity to create new solutions in delivering a timely and efficient design basis and for permission to publish. Colleagues in Equinor, SSE, Geo and NGI are acknowledged for their contribution to the development of an enhanced CPT tool and to this paper.

REFERENCES

Bayne, J.M. and Tjelta, T.I. (1987) "Advanced cone penetrometer development for in situ testing at Gullfaks C". Offshore Technology Conference, Richardson, Texas, Paper No. 5420.

Jefferies, M.G. and Funegard, A. (1983) "Cone penetration testing in the Beaufort Sea". Proceedings of the Conference on Geotechnical Practice in Offshore Engineering, Austin, Texas, 220–43, American Society of Engineers (ASCE).

Staveren, M. van (1995) "Advanced deep cone penetration testing and backfilling in overconsolidated clay;. Proceedings of the International Symposium on Cone Penetration Testing, CPT '95, Linkoping, Sweden, 2, 99–104, Swedish Geotechnical Society.

Tjelta, T.I., Guttormsen, T.R., Hermstad, J. (1986) "Large-Scale Penetration Test at a Deepwater Site", Offshore Technology Conference, Houston, Texas, May 1986, Paper number OTC.

Yagi, N., Enoki, M. and Yatabe, R. (1988) "Development of a penetrometer capable of applying pore pressure". Proceedings of the International Symposium on Penetration Testing, ISOPT-1, Orlando, 2, 1051–7, Balkema Pub., Rotterdam.

Yetginer-Tjelta T.I., De Sordi, J., Caferri, L.,Rose, M., Duffy, C., Lunne, T., Blaker, Ø., Strandvik,S. & Meyer, V. (2022). "The role of cone penetration testing in the Dogger Bank offshore wind farm". Proc. 5th Int. Symp. on Cone Penetration Testing, CPT'22, Bologna, Italy, 8–10 June 2022.