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CSi – a joint industry project into CPTUs in silty soils

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ABSTRACT: The CPTU constitutes the main *in situ* offshore investigation tool for geotechnical site characterisation and provision of soil input for the design of wind turbine foundations. CPTUs are typically performed at all foundation positions. Thus, all obtained results of supporting geotechnical *in situ*, model and laboratory testing need to be confidently correlated to the CPTU parameters. Most of the interpretation methodologies available for industry practice consider the soil behaviour around the cone either as fully drained or undrained, and acknowledged and well-proven correlations between CPTU parameters and classification and engineering properties exist for sand and clay. However, for transitional soils, e.g. silty soils, which may exhibit partial drainage during standardized cone penetration, such robust interpretation schemes do not exist. This paper presents the background, the objectives, setup and early field results of a joint industry project into CPTUs in silty soils for developing schemes for planning, execution and interpretation.

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1 INTRODUCTION

The Offshore Wind Industry is rapidly expanding across the globe. This expansion leads to the exploration of offshore wind sites that are characterized by thick layers of silty sand and silt mixtures. In contrast to sampling boreholes, CPTUs are performed on all wind turbine positions, which in many cases can be more than 100 positions covering large areas. The CPTU parameters must be confidently correlated to all supporting geotechnical tests to mitigate the following risks: a) site characterization and establishing facility position-specific soil parameters for foundation design, b) choice of foundation concept and relevant design methodologies, c) installation predictions, d) cable design and e) increased project maturation times and site investigation scopes. However, as opposed to sand and clays, the Industry finds it generally challenging to properly identify and capture the behaviour of transitional soil, e.g. silty sand, silts and silt mixtures, with standardized CPTUs. No simple, robust, and standardized testing approaches and interpretation methodologies have been calibrated to these types of soils.

A Joint Industry Project (CSi – CPTUs in Silty soils) is currently being executed within the Carbon Trust Offshore Wind Accelerator programme with the main objective to develop robust guidelines targeting the industry for planning, specification, execution, and interpretation of CPTUs in silty soils. Focus is especially paid to

- Soil classification and mechanical behaviour
  - New and/or revised soil classification and soil behaviour type charts
  - Identification of transition between drainage conditions including rate effects, i.e. of drained to partially drained to undrained conditions
- Correlations to engineering properties
  - Strength and stiffness.
- Guidelines for specifying and executing CPTUs for identifying silty soils and their behaviour.

The project targets mainly silty and transitional soils with low plasticity. This paper presents the background of the CSi project as well as the overall project set-up and early findings from a test site in Halden, Norway.

2 BACKGROUND

CPTUs carried out at a standard constant penetration rate (20 mm/s ± 5 mm/s according to ISO 2012) generally result in an undrained response in clay and a drained response in sand (Lunne et al. 1997). However, for silty soils partially drained conditions may prevail at the standard penetration rate, see DeJong et al. (2013). Understanding the drainage conditions around the penetrating cone is key to interpret CPTUs in silty soils (correlation with engineering parameters and classification charts).

2.1 *Drainage conditions*

In recent years the normalized penetration velocity V represents an often-used framework to indicate the drainage conditions around the penetrometer and to demonstrate how CPTU parameters change with penetration rate v, soil properties (horizontal coefficient of consolidation of the soil c_h) and cone penetrometer diameter d, see e.g. Randolph & Hope (2004), Kim et al. (2008) and Schneider et al. (2008). The normalized penetration velocity is defined as:

$$V = \frac{v\, d}{c_h} \tag{1}$$

For contractive soils and a given cone diameter, the cone shoulder pore pressure u_2 increases, and the cone resistance decreases with increasing V, whereas the opposite may be observed for u_2 for dilative soils (Schneider et al. 2007 and Krage & DeJong 2016). Drained penetration is observed to occur for $V < 0.01\text{-}0.3$ and undrained penetration for $V > 20\text{-}100$ (Randolph 2004, Bihs 2021). v and d are parameters, which can be fully controlled and specified. Therefore, an accurate determination of c_h is important in the estimation of V. c_h depends on stress history, density and grain composition.

Determination of the operational value of the coefficient of consolidation of the soil is not straight forward, especially not for the more coarse-grained transitional soils. Most of the work to date, numerically and experimentally, is anchored in contractive clay-like soils and undrained conditions.

c_h can be determined from piezocone dissipation tests (PPDT) accounting for partial consolidation during cone penetration, and hence penetration rate, in the interpretation of the tests (DeJong & Randolph 2012). However, for transitional soils, the excess pore pressure measured at the cone shoulder u_2 does not always decay monotonically over time during dissipation and a dilatory response can be observed. Burns & Mayne (1998) and Paniagua et al. (2016) discuss different approaches to determine t_{50}, the time associated for 50% dissipation, dealing with both standard and non-standard (dilatory) dissipation curves. Carrol and Paniagua (2018) note that different interpretation methods can lead to significant differences in the estimated t_{50} and hence c_h.

The rigidity index I_r is required to interpret dissipation tests. However, the concept of I_r, developed for fully undrained conditions, may not be appropriate for partially drained conditions. Krage et al. (2014) provide guidance on how to determine I_r.

To overcome some of the challenges with the estimation of c_h, Schnaid et al. (2020) propose a modified version of the normalized penetration velocity depending on v, t_{50}, d and I_r.

CPTUs at variable penetration rates (VRCPTU) are traditionally performed to investigate the drainage conditions around the cone. Even with a robust methodology to estimate *V*, a link between *V* and engineering properties and soil classification need to be developed – also for engineering practice.

2.2 *Soil classification*

Soil behaviour type (SBT) charts, like Robertson (1990) and later updates or Schneider et al. (2008), are often used for classification purposes. The charts are based on standard CPTU geometries and a penetration rate of 20 mm/s.

Research (e.g. Schneider et al. 2008, Bradshaw et al. 2012) and practice support that silty soils can plot on a large range of zones in the SBT charts and thus the SBT charts alone can, at present, not be used to robustly identify grain composition or plasticity for a silt deposit. The reason is that the position in the SBT chart is a function of several parameters, including grain size, plasticity, *in situ* density, stress history and local geological history. Furthermore, partial drainage conditions affect where data plots on the SBT charts (DeJong & Randolph 2012) and use of additional data from dissipation tests and VRCPTUs may aid the identification of silty soils.

2.3 *Strength and stiffness*

Current practice in the offshore wind industry for assessing silty soils is to apply methods anchored in either clean sand (drained conditions, effective stress approach) or pure clay (undrained conditions, total stress approach).

The relation between cone resistance and the undrained shear strength through the cone factor N_{kt} has been investigated in the literature, e.g. Senneset et al. (1988), Blaker et al. (2019), Naeini & Moayed (2017) and Huang et al. (2021). For the effective stress friction angle Senneset et al. (1988) suggested an approach, which considers pore pressure build-up and is relevant for partially drained conditions. Bihs (2021) reports that both the drained and undrained strength depends on the choice of penetration rate. Senneset et al. (1988), Lunne et al. (1997), Robertson (2009) and Tonni & Simonini (2013) discuss constrained and small strain shear modulus.

Correlations between CPTU parameters and engineering properties are dependent on the quality of the samples tested in the laboratory for calibration purposes. Furthermore, for the strength correlations a unique failure criterion may not exist for undrained shear of especially dilative transitional soils (Blaker & DeGroot 2020). It is complicated to retrieve and prepare intact samples for testing and currently no robust and well-proved criterion for evaluating sample disturbance exists. Sampling and handling of silty samples are thus of importance to the CSi project.

3 CSI PROJECT SETUP

3.1 *CSi project scope and approach*

The CSi project includes a comprehensive scope of work, see Figure 1, on different scales and platforms to meet the project objectives and to exploit current and new methodologies and hypotheses for addressing the project challenges, cf. Sections 1, 2.

Initial studies in terms of a literature review and a project plan provides the background and detail the other activities. The guidelines, addressing the project objectives, are based on analyses of high-quality factual data gathered in a database. The data are extracted from different sources.

In situ tests, and parallel laboratory tests, will be performed on aged natural silty soils at two complementary onshore test sites (Halden, Norway and Voorne-Putten, the Netherlands). VRCPTUs with different cone sizes, dissipation tests, seismic CPTUs and sampling (the static hydraulic piston sampler and the static gel-push sampler) will be undertaken. The onshore test site data are supplemented by Partners' data from offshore projects across the world as well as data from other silt sites published in the literature, thereby increasing the applicability of the database.

Calibration chamber testing, centrifuge testing and associated standard element laboratory tests complement the onshore test site data by providing test results under well-defined and controlled conditions. Furthermore, they are also relevant for benchmarking to existing interpretation schemes for clean sand. VRCPTUs and dissipation tests are performed at different densities and consolidation stresses with full-scale and miniature cones in unaged non-plastic silty sand and reconstituted clean sands (Fioravante et al. 2022).

A state-of-the-art numerical model will expand the general applicability of the guidelines by validating and extrapolating the design space offered by the experimental data. Furthermore, recommendations with respect to numerical models for predicting CPTUs in transitional soils will be provided. The critical state based Norsand constitutive model along with large-deformation finite element and cavity expansion analyses will be used to calibrate and validate the model based on field, laboratory and model tests (calibration and centrifuge testing).

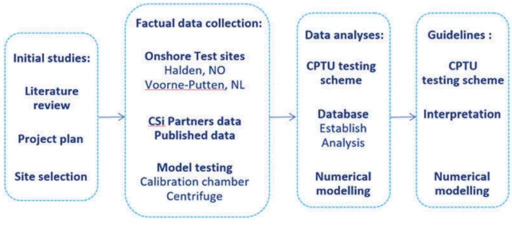

Figure 1. High-level strategy adopted during the CSi project.

3.2 *CSi organisation*

The CSi project is developed and led by Ørsted in partnership with five other offshore wind developers. The project is run as a discretionary project through the Carbon Trust's Offshore Wind Accelerator programme. The technical activities are managed and executed by the Norwegian Geotechnical Institute (NGI), supported by Fugro and ISMGEO. Selected activities are reviewed by an independent technical review panel to substantiate the developed methodologies. A certification body (DNV) ensures that the outcome is practically, applicable and relevant for industry practice and future standardization. Figure 2 illustrates the CSi organizational setup.

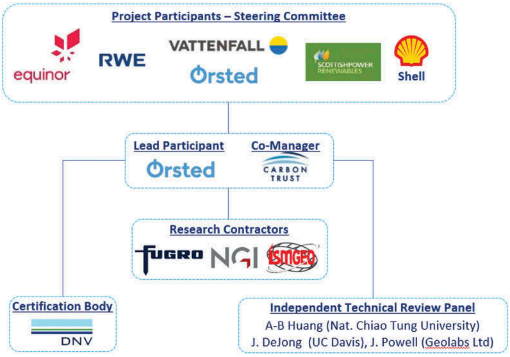

Figure 2. Schematic view of the CSi project setup.

4 FIELD TESTING AT HALDEN, NORWAY

4.1 *Test site and test programme*

The Halden site is located in southern Norway and is one of five sites within the Norwegian Geo-Test Sites program (NGTS). Extensive geophysical, *in situ* and laboratory testing have been carried out as part of the site characterization (see Blaker et al. 2019) and for subsequent research. Normally consolidated clayey silt is deposited between depths of five and 16 m and divided into two units, Unit II and Unit III, which are homogenous across the site.

The *in situ* testing programme (CPTUs and a borehole) was carried out in September 2021 and is summarized in Table 1 and Figure 3. The CPTUs were performed according to ISO (2012), except that non-standard penetration rates were also adopted. All tests were closely spaced but ensuring no interference with each other.

Efforts were made to ensure good saturation of the filters and cone chamber. At fast rate, the u_2 sensor must respond quickly and at slow rates, it shall ensure accurate measurements due to the small values of excess pore pressures measured. Plastic, bronze and HPDE filters were used for the 5, 10 and 15 cm^2 cones, respectively. All filters and cones chambers were saturated with silicon oil. The filters were saturated under vacuum and placed in a container of saturation fluid before mobilization and until assembling with the cone. The cone chamber was first saturated with syringes and hereafter left submerged in a chamber with silicon oil along with the filters. Vacuum was also applied for up to 90 minutes for the 5 and 10 cm^2 cones. The penetrometer was assembled in submerged conditions and covered in a rubber membrane. The filters were replaced after each test.

Table 1. In situ testing scope, Halden campaign.

Item	Description
Cones	10 cm^2 single element (u_2)
	15 cm^2 dual element (u_1 and u_2)
	5 cm^2 single element (u_2)**
Scope per cone	1 CPTU benchmark*, 20 mm/s rate
	1 VRCPTU, 0.2 mm/s rate, 2 PPDT
	1 VRCPTU, 2.0 mm/s rate, 2 PPDT
	1 VRCPTU,200 mm/s rate, 2 PPDT

* 2 benchmark tests carried out for the 10 cm^2 cone
** Additional scope funded by the NGTS project
*** Dissipation tests (PPDT) as per Figure 3

Attention was also given to monitor the ground water table and thus the hydrostatic pressure (u_0-profile), since u_0 enters the calculation of e.g. B_q and is the baseline for dissipation tests. The ground water pressure was continuously monitored at four depths by means of standpipes permanently installed at the site, indicating hydrostatic conditions with the water table at 1.85 m depth.

To investigate the drainage conditions around the cone through the normalized penetration velocity V, the chosen penetration rates cover four orders of magnitude (from 0.2 mm/s to 200 mm/s). The aim was to span from drained to undrained response during penetration. Furthermore, three cone sizes were used to investigate the effect of diameter. The u_1 sensor (located at the cone face) was used in addition to u_2 to study the differences in response during both variable rate penetration and during dissipation. The approach of having one long stroke at variable rate per soil unit at each location was preferred to the alternative twitch tests (see e.g. DeJong et al. 2013) because: (a) from VRCPTU tests performed earlier at Halden it was found that after changes in rate or dissipation tests, the length required to build up u_2 was in several cases up to 1.0 m and (b) shorter strokes can be affected by vertical variability and hence are thought to be less robust for future recommendations for offshore site investigations.

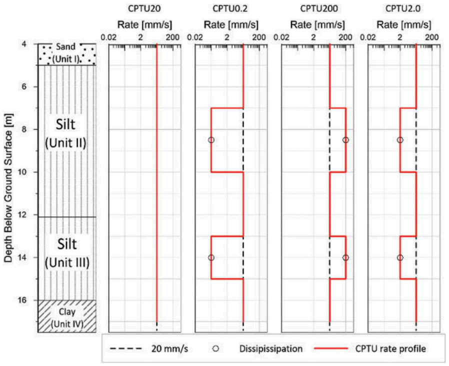

Figure 3. Specified penetration rate profiles for VRCPTUs.

4.2 *Test results*

Figure 4 shows selected results of standard rate CPTUs and VRCPTUs carried out with the 10 cm^2 and 15 cm^2 cones. The penetration rate profiles indicate that the rig accurately controls the speed in all tests.

At depths of 10-12/13m all CPTUs are performed at standard rate. There is generally a good match of q_t, f_s and u_2 between the location with the CPTU at standard rate and the VRCPTU locations for both cones (10 cm^2 and 15 cm^2), respectively, indicating that (a) adjacent locations have similar soil conditions and hence the profiles at different rates at different locations can be directly compared and (b) the cones are performing consistently among different

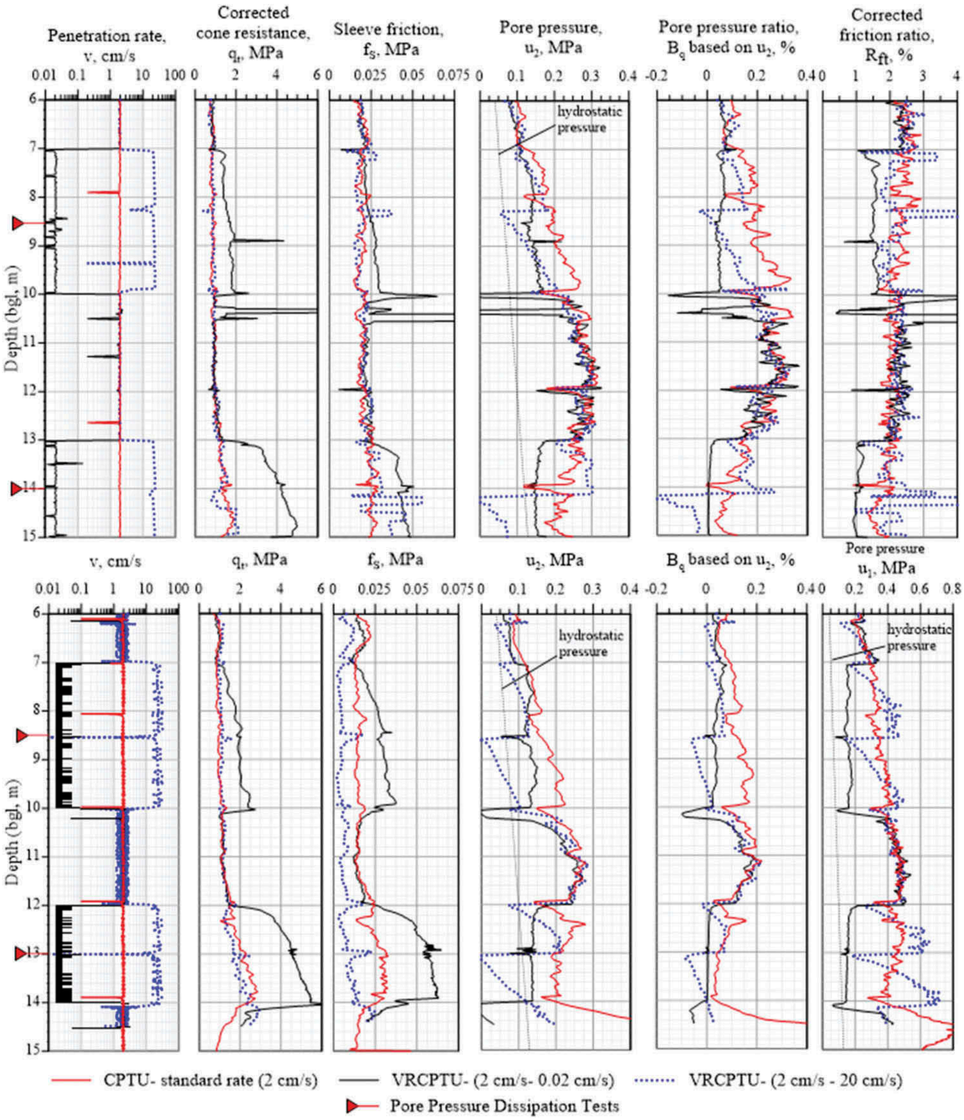

Figure 4. Selected in situ test results, CSi Halden campaign. 10 cm^2 cone (upper figures) and 15 cm^2 cone (lower figures).

locations. The long strokes (up to 1.5 m before any stop, cf. Figure 3) allow for a clear identification of the changes in q_t, f_s and u_2 for penetrations at 0.2 mm/s compared to the standard rate. These aspects provide robustness to the VRCPTU interpretation approach.

During penetration at 0.2 mm/s both cones show an increase in q_t and f_s and a reduction in u_2 compared to the tests with standard rate. For example, q_t increases on average from 1.0 MPa to 1.6 MPa and B_q decreases from 0.2 % to 0.05 % for the 10 cm^2 cone in Unit II. In Unit III, the impact of a slower rate appears more markedly with q_t increasing from 1.5 MPa to 4.2 MPa and B_q decreasing from 0.08% to zero. This may be due to the less plastic and coarser nature of the lower unit.

In contrast, the VRCPTUs at 200 mm/s do not appear to affect q_t or f_s compared to CPTUs at standard rate (though for the 15 cm^2 cone the entire f_s profile is shifted at the location). Generally, after a prolonged stop in penetration, either for dissipation testing or for change in rate, u_2 increases smoothly and linearly with depth often starting with an abrupt negative increment in the pore pressure. These results will be further scrutinized during the project.

The u_1 profile for the 15 cm^2 cone shows similar trends to the u_2 sensor for both the highest and lowest rates noting that (a) the drop in pore pressure during slow penetration is more distinct and (b) at high rates u_1 appears to exceed u_1 for the standard rate CPTU after typically 50-70 cm of penetration after having changed rate or after a dissipation test.

Figure 5 shows the results of a representative dissipation tests performed with the 15 cm^2 cone. u_1 decays monotonically over time whereas u_2 exhibits a dilatory response. This response is similar to what has been reported for cases in overconsolidated clays (e.g. Lunne et al. 1997). The effect of this difference on the estimated coefficient of consolidation will be investigated.

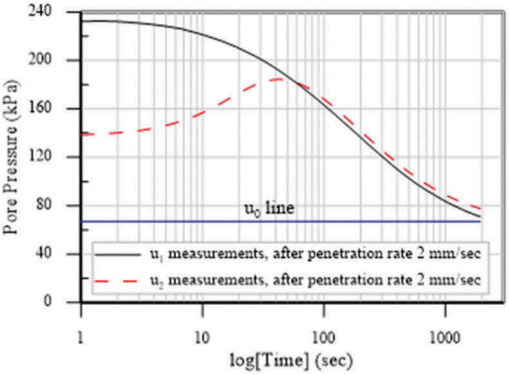

Figure 5. Dissipation test at 8.5 m depth, 15 cm^2 cone.

5 CONCLUSIONS

Even with the landmark research undertaken over the last decades on CPTUs in silty soils, more research is needed to establish robust guidelines for use in engineering practice. The objective of the Joint Industry Project CSi is to provide such guidelines. The background, objectives, setup, and approach of the CSi project are described in this paper along with some initial results from the Halden test site. Field testing at the Voorne-Putten test site as well as centrifuge and calibration chamber testing are currently being performed in parallel with laboratory testing and numerical modelling. More Partners and Contractors are invited to join the project for the opportunity of investigating more innovative equipment and methods, such as partially drained triaxial testing and selected CPTU add-on sensors. Furthermore, field trials for validating the project outcome are essential and will add to the robustness and broaden the applicability of the project.

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