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Potential of the Cone Pressuremeter Test for obtaining stiffness degradation for offshore wind turbine monopile foundations

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ABSTRACT: The piezocone (CPTU) offers a quick and repeatable investigation tool with instantly available high-resolution data. For these reasons it is both technically and commercially attractive to further instrument the CPTU to acquire additional measurements with more sensors either within the cone itself or as add-on modules behind the cone. Many ideas for further instrumentation of the CPTU have been conceptualised or tested but one that could offer direct benefit for offshore wind turbine foundation design is the Cone Pressuremeter (CPM). This in situ tool includes a pressuremeter module behind the standard cone that can measure ground displacement or expansion as a function of pressure applied during the loading, unloading and reloading of the surrounding soil when penetration is paused. From these measurements a number of soil parameters may be interpreted including the stiffness degradation (G/G_0) of the soil when combined with reliable in situ or laboratory measured G_0 values. With increasingly larger wind turbines being used and deeper water sites selected for construction, soil stiffness is an increasingly critical input for the design of many offshore wind turbine foundations. CPM testing has been trialed in the field onshore at a glacial till site and a medium to very dense sand site. The results of the CPM are compared in this paper to site specific results for the self-boring pressuremeter and advanced laboratory-based alternatives. The practical considerations of using the CPM offshore in seafloor mode are also reviewed.

1 INTRODUCTION

The piezocone (CPTU) is the main in situ tool for offshore geotechnical site investigations related to the design of offshore wind turbine foundations. It is a relatively fast test to perform and process, particularly in seafloor (non-drilling) mode, that provides continuous data for the entire investigation depth. These advantages inspire continuous development of the CPTU where many add on modules are considered and developed to investigate specific soil properties.

Following the general trends in offshore wind of increasing turbine sizes and larger water depths the soil stiffness becomes increasingly important for laterally loaded foundation design, for example the initial stiffness (G_0) and the stiffness degradation (G/G_0) required for the PISA design method (e.g. Byrne et al, 2017).

Current practice allows determination of initial stiffness in situ by seismic cone piezometer (SCPTU) and P-S logging and in the laboratory by use of advanced tests like the resonant column test and the bender element add on to triaxial tests. The knowledge on stiffness degradation can be derived from in situ pressuremeter tests and testing in the laboratory by use of resonant column tests and direct simple shear tests.

An onshore research campaign has been carried out to investigate the use of a cone pressuremeter (CPM), a CPTU with a pressuremeter module, with the objectives of investigating its practical application and benchmarking its results to the self-boring pressuremeter (SBP) and advanced laboratory tests. With the assumption that G_0 is known from other in situ tests (e.g. SCPTU) the applicability of the CPM for offshore use is explored. This assessment also assumes the requirement to deploy the CPM in seafloor mode to maximise the associated operational benefits.

2 BACKGROUND

The concept of mounting a pressuremeter module behind a cone penetrometer was first applied in the early 1980s. Jezequel et al. (1982) developed

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a pressio penetrometer for shallow offshore surveys. The device had a diameter of 89 mm and was installed using a vibrating hammer device. Robertson et al. (1984) placed a 60° solid cone on to the base of a 75 mm diameter SBP. Due to the large diameter of these devices, special equipment was required for their installation. The pressuremeter data proved to be successful for the design of laterally loaded piles.

These early devices were superseded by smaller diameter devices known as CPMs, which comprised of a pressuremeter module mounted behind a standard electrical cone penetrometer. These devices could be installed by CPTU jacking equipment, either cone truck or seafloor frame, and enable pressuremeter tests to be performed as part of the CPTU operations. The first CPM, for which the most results have been published, was designed and built by Cambridge In Situ, originally to a specification of Fugro Netherlands. This device was described by Withers et al. (1986) and has been slightly modified afterwards to improve the operation.

Considerable research and development was carried out on the use of the CPM and the interpretation of the results in the late 1980s and the 1990s. Work was carried out by Powell & Shields (1995) and others. Over the last 20 years the CPM has not been used so much but its use may prove useful in the near future with an application in offshore wind foundation design.

3 TESTING

3.1 *Equipment and method*

The CPM considered here (Figure 1) comprises of a cylindrical 47 mm diameter pressuremeter module placed behind either a 46.7 mm diameter (15 cm²) or a 36 mm diameter (10 cm²) instrumented CPTU cone. This configuration can record live data during penetration through the soil, as well as being able to undertake a pressuremeter test and dissipation test when pushing is temporarily paused.

Figure 1. CPM equipment.

The combined CPM module is approximately 1.30 m in length. It has a central expanding section which is covered by a tough rubber membrane 250 mm in length and its centre point being 630 mm behind the instrumented cone tip. The expanding section can be pressurised internally by oil using a manual hydraulic pump or compressed air using cylinder stored gas and a manual control unit. Oil is typically only used for marine surveys, whereby the complex internal electronics are more protected from the ingress of saltwater in the event of a membrane burst.

Testing is generally carried out in accordance with ISO 22476-6. Pressure applied to the inside of the instrument forces the membrane to expand against the test pocket wall. The radial displacement of the inside boundary of the membrane is measured at three points equally distributed at 120^{O} around the centre of the expanding section by free moving arms. This displacement and the pressure necessary to cause the movement is continuously monitored by electronic transducers contained within the instrument.

Testing trials were performed in the field with the CPM either by pushing the instrument in from ground level, or by undertaking a pre-push using a 63 mm diameter dummy cone to approximately 1.00 m above each pressuremeter test depth. The CPM was inserted using a 20 tonne track mounted CPTU rig with 36 mm diameter push rods. The rods were then released from the top drive hydraulic pushing clamps at which point a pressuremeter test was simultaneously initiated. The pressuremeter tests were carried out in a nominal stress-controlled manner using a manually operated gas control box to pressurise the instrument at an appropriate rate for the ground conditions.

During the tests a number of pressuremeter unload-reload loops were performed in order to provide data for determining shear modulus. Loading was continued until uneven expansion around the probe occurred such that the operator deemed the risk of damage to the probe via a membrane burst too high if loading was continued, or the strain capacity of the CPM was approached, typically around 60 %. Upon full unloading and deflation of the membrane, the dissipation test was terminated, and the CPM was either pushed to the next pressuremeter test depth further down or withdrawn from the ground.

The CPM is classed as a full displacement pressuremeter as it increases the state of stress in the test material as it is inserted. The early stages of the pressuremeter test should therefore always be treated with a degree of caution as the material has already been partially disturbed from its original state.

The SBP used (Figure 2) for comparison purposes to the CPM comprises of a cylindrical instrument with an integral cutter, of the same diameter as the main body of the instrument, that is drilled into the ground using a top drive rotary drilling rig. The rotary rig provides rotation to the SBP cutter through RW size 27.8 mm diameter inner rods and thrust to advance the pressuremeter via non-rotating 50.8 mm diameter outer rods. Water or drilling mud is flushed by the rig pump down the inner rods and returns up through the annulus between the inner and outer rods to remove the cuttings and provide lubrication and cooling to the cutter. The outside of the pressuremeter remains in contact with the ground relatively undisturbed during insertion.

Figure 2. SBP equipment.

The SBP probe is approximately 1.20 m in length. It has a central section 493 mm in length covered by a rubber membrane. Pressure applied to the inside of the instrument, via compressed air, forces the membrane to expand against the test pocket wall.

The larger diameter of the SBP (63.1 mm) compared to the CPM (47 mm) means that the radial displacement of the inside boundary of the membrane can be measured by six free moving arms, equally distributed at 60^O around the centre of the expanding section. Analysis using a greater number of measured points generally increases the reliability of pressuremeter test results. The radial displacement and pressure necessary for the expansion of the membrane are continuously monitored by transducers contained within the instrument body.

The SBP is also equipped with pore water pressure transducers, which are opposite facing, positioned at the midpoint of the membrane.

3.2 *Site details and scope*

Trials were performed with the CPM at two test sites with ground conditions similar to some commonly encountered at offshore wind farm developments.

The first site was located in Cowden, England and was selected to test overconsolidated clays within glacial tills. Groundwater level was estimated to be at 3.0 m below ground level (bgl) based on piezometer readings and CPTU dissipation tests. In total seven pressuremeter tests were performed using the CPM at three locations between 6.7 m bgl and 18.2 m bgl. For comparison purposes, a further seven pressuremeter tests were performed using the SBP at two locations between 7.0 m bgl and 18.7 m bgl. In addition, borehole samples were taken to perform a suite of laboratory testing for classification of the site and further comparison to the CPM.

The second site was located in Cuxhaven, Germany and comprised mainly of medium dense to very dense fine to medium sands. Groundwater level was estimated to be at 2.75 m bgl based on falling head tests in standpipes with time (slug tests). At this site six pressuremeter tests were performed using the CPM between 3.0 m bgl and 7.0 m bgl at three locations. A further six SBP tests were performed at three locations between 3.0 m bgl and 7.5 m bgl.

4 RESULTS AND ANALYSIS

4.1 *Reliability of test data*

The maximum distances between CPM and SBP test locations at both sites are summarised in Table 1.

Table 1. Maximum distance between CPM locations, between SBP locations and between all (CPM and SBP) locations.

Site	CPM only	SBP only	All
Cowden (CO)	2.8 m	1.5 m	5.0 m
Cuxhaven (CU)	1.5 m	3.0 m	5.0 m

For each site, the cone resistance (q_c), sleeve friction (f_s) and penetration pore water pressure (u_2) profiles with depth at each CPM location were compared to evaluate the similarity of soil conditions, as shown in Figure 3 and Figure 4. Pre-pushing was performed using a dummy cone, at Cowden to 15.1 m bgl and 15.5 m bgl for Tests CO-CPM-1A and CO-CPM-2A respectively and at Cuxhaven to 3.9 m bgl for Test CU-CPM-1, so it was not possible to compare these CPTU profiles to the others. Overall the ground conditions were comparable for the two sets of tests and hence not considered a major uncertainty for evaluating the repeatability of the CPM test results.

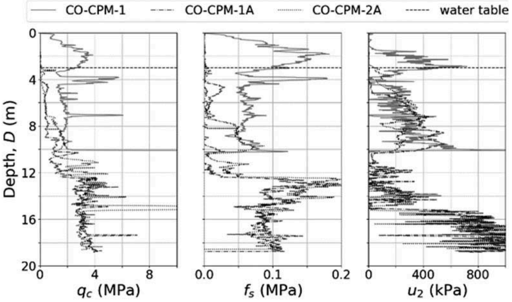

Figure 3. CPTU profiles with depth at CPM positions for the Cowden site.

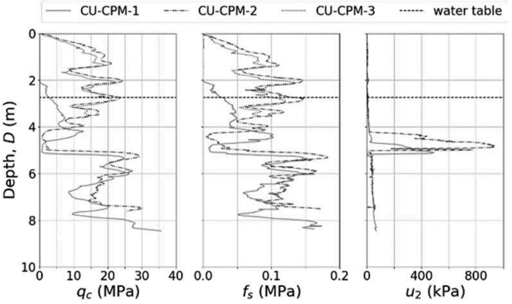

Figure 4. CPTU profiles with depth at CPM positions for the Cuxhaven site.

For the interpretation of stiffness degradation, average arm displacements from the CPM and SBP data were used as per standard practice. A review of the datasets confirmed that average arm displacements were generally representative of the response for each individual pressuremeter arm with applied pressure. Examples of this are shown in Figure 5 for the CPM and Figure 6 for the SBP for Cowden.

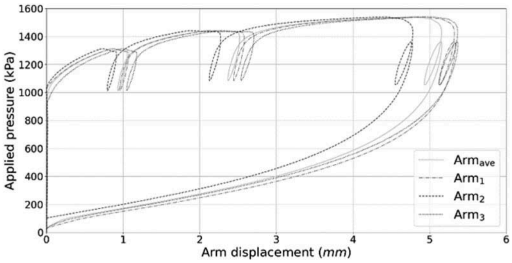

Figure 5. Comparison of individual and average arm displacements for a representative CPM (CO-CPM-1A, 15.5 m bgl).

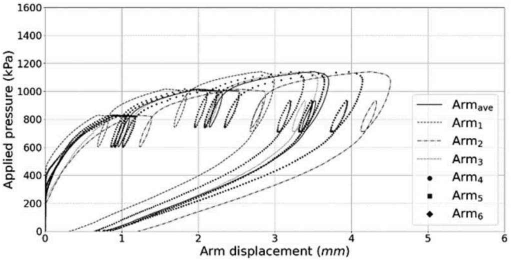

Figure 6. Comparison of individual and average arm displacements for a representative SBP (CO-SBP-1, 15.5 m bgl).

The repeatability of the applied pressure versus average arm displacement plots was reviewed to further evaluate the reliability of the data. Examples from Cowden are shown for pairs of CPM tests and pairs of SBP tests at similar depths in Figure 7 and Figure 8 respectively.

The 'lift off' pressures at the start of the CPM tests in Figure 7 were within approximately 10 % of each other. This was also found to be the case for the other pair of CPM tests available at Cowden. The difference in maximum pressure at the end of the two pairs of CPM tests were 3 % and 8 % respectively. For Cuxhaven, three pairs of CPM tests were available for comparison and the difference in 'lift off' pressures typically differed by approximately 200 kPa to 300 kPa and maximum pressures differed by between approximately 10 % and 35 %.

The only pair of SBP tests available from Cowden were within 7 % of the maximum pressure of each other while there was a nominal difference in 'lift off' pressures. Unfortunately, the SBP tests performed at Cuxhaven were significantly influenced by disturbance of the test pocket.

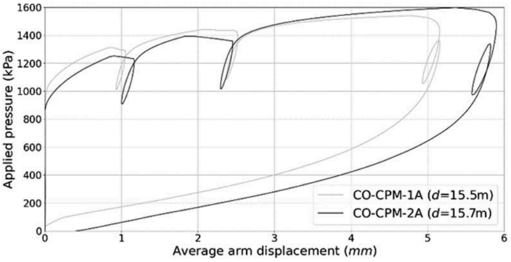

Figure 7. Comparison of applied pressure versus average arm displacement for CPM tests.

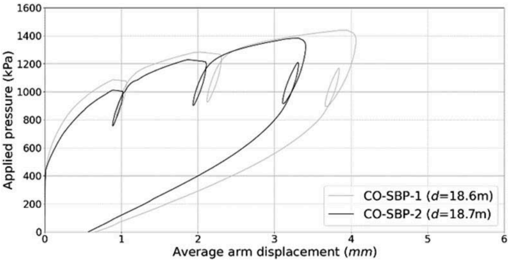

Figure 8. Comparison of applied pressure versus average arm displacement for SBP tests.

An additional comparison was made for CPM tests from Cowden with historical CPM tests at similar depths performed by Building Research Establishment (1996) where ground conditions were broadly similar enough for comparison purposes. It was found that plots of applied pressure versus average arm displacement were consistent between the two sites.

Finally, applied pressure versus average arm displacement plots for CPM tests were compared to SBP tests at the same depth to benchmark the CPM data against the SBP data. An example from Cowden is shown in Figure 9.

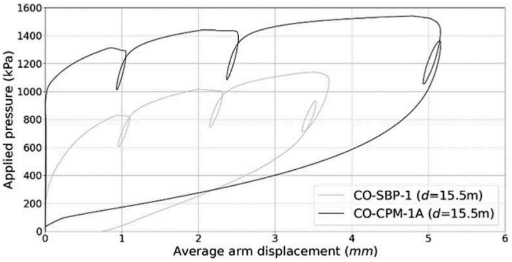

Figure 9. Comparison of applied pressure versus average arm displacement for CPM and SBP tests.

It was consistently observed across both sites that the CPM recorded a higher 'lift off' pressure and maximum applied pressure than the SBP, as was reported by Powell & Shields (1995). As the CPTU displaces the surrounding soil during penetration before the pressuremeter test is performed, the applied pressure at a given displacement is higher than would be expected for the in situ conditions. In theory the SBP insertion method does not displace any soil and hence in situ conditions should not be disturbed, however in practice this requires a high degree of operator control, and so may be considered a disadvantage compared to the CPM. It was observed from the results of Cuxhaven that inserting the SBP in coarser grained soils is very challenging. These differences in measurements between the CPM and SBP may influence the reliability of other interpreted parameters but not the G/G_0 curves.

4.2 *Stiffness degradation*

Shear modulus was interpreted from the average gradient of the unload-reload loops performed during each CPM and SBP test using Bolton and Whittle (1999).

At Cowden interpreted shear modulus with shear strain was very similar for unload-reload loops from the same CPM test, and for pairs of CPM tests at the same depth. Figure 10 shows three stiffness degradation curves per pressuremeter test derived from the three corresponding unload-reload loops performed (loop 1-3). Very good repeatability was seen for loops from three pairs of CPM and SBP tests at similar depths. A fourth pair at 15.5 m bgl (CO-CPM-1A and CO-SBP-1), had very similar stiffness degradation profiles to CO-CPM-1A at 17.0 m and CO-SBP-1 at 17.7 m bgl. The only instance with poor repeatability was at 7.0 m bgl comparing CO-CPM-1 to CO-SBP-1, where the latter experienced leakage of the pressuremeter membrane.

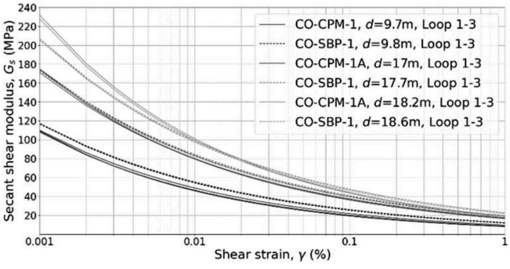

Figure 10. Comparison of shear modulus versus shear strain for CPM and SBP tests at the Cowden Site.

Figure 11 shows that at Cuxhaven the repeatability of unload-reload loops from the same CPM test was still good, except for CU-CPM-2 at 5.5 m bgl. However, repeatability between loops from different CPM locations at the same depth and between loops from CPM and SBP locations at the same depth were comparatively poorer than at Cowden, with stiffness at a given strain differing by up to a factor of two approximately. The difference in performance at the two sites was deemed to be influenced by the quality of the CPM test pocket that could be achieved in this instance, where considerable disturbance was observed for the coarser soils.

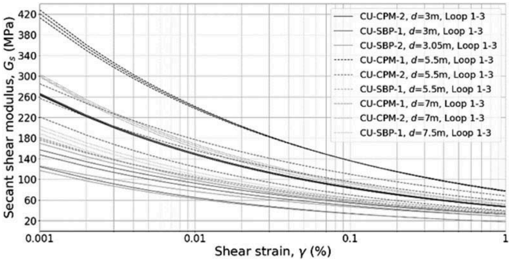

Figure 11. Comparison of shear modulus versus shear strain for CPM and SBP tests at the Cuxhaven Site.

For use in the design of laterally loaded foundations, shear modulus versus shear strain is normalised by G_0. As an example, data from Cowden was normalised using G_0 values from laboratory bender element and resonant column tests. The outcome was compared to historical pressuremeter and laboratory data presented by Powell & Butcher (2003) as shown in the example in Figure 12. Good agreement was found between the Cowden CPM data and the historical pressuremeter data. Relationships proposed by Vucetic & Dobry (1991) and Hardin & Drnevitch (1972) were not found be good fits.

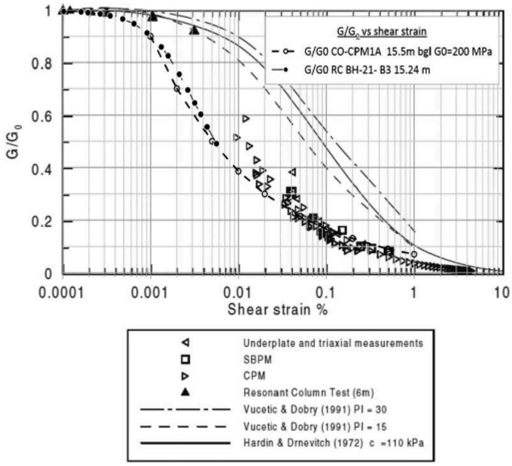

Figure 12. G/G_0 from CPM and resonant column tests at 15.5 m bgl compared with data from Powell & Butcher (2003).

In practice the sensitivity of the measurement by the pressuremeter arms are considered accurate only to 0.01 % shear strain. However, the interpreted curve has been presented to 0.001 % shear strain for information and does not appear unreasonable compared to resonant column data. Verification work is needed to confirm if the method for establishing the

G/G_0 curve is representative of the lateral deformation experienced by the monopile.

5 APPLICABILITY FOR OFFSHORE USE

The CPM pressuremeter module is primarily designed for testing in superficial deposits, such as loose to medium dense sands and soft to very stiff clays. The CPM was found to be easily susceptible to damage if pushing through dense granular material or till deposits containing coarse gravel or cobble size fragments. In general, it is not recommended to advance the instrument in its current design through granular material that is dense to very dense (q_c > 18 MPa), or very high strength cohesive material (typically q_c > 4 MPa), as there is increased risk of damaging the membrane, or in the worst case bending the instrument body. Pre-pushing using a dummy cone was often required to advance the instrument to the required test depths, however this will not be practical for offshore testing.

For deployment offshore in seafloor mode, the body of the instrument would require strengthening and the electronics module made more robust with improved watertight sealing. The deployment and operation of the instrument would also need careful consideration if it is to be combined with currently available seafloor pushing systems, especially the control umbilical and instrument inflation system.

6 CONCLUSIONS

CPM tests have been carried out at two very different sites to investigate the use of the add on tool.

Analysis of the obtained stiffness results for overconsolidated clays showed very good repeatability in the CPM tests, and a direct comparison of the results from CPM and SBP tests showed good compliance for the unload-reload loops.

CPM testing in medium to very dense sands showed a fair repeatability for stiffness based on unload-reload loops from the same CPM test but much less so when loops were compared from different locations. The granular nature of the soils presented operational challenges with forming the test pocket which affected test quality and generally being able to insert the CPM in these soils.

The two sites that were tested represent the typical range of fine to coarse soils encountered offshore. The equipment presently available for CPM testing appears to be susceptible to damage in these soils and measures to ease the penetration (i.e. use of dummy cone) would not be compatible in seafloor mode. Thus, there is potential for further exploring the instrument and its development, including increasing its robustness.

A G/G_0 curve has been established from CPM and laboratory tests at Cowden and comparison with historical data shows a very good compliance, though deviating from the general relationships proposed in literature. Overall, the results show the potential of the CPM for offshore wind turbine foundation design. Further investigation and validation of reliable G/G_0 curves from the CPM when combined with other in situ tests used to estimate G_0 may help mature the CPM for this application in the future.

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