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In situ cyclic degradation assessment of an offshore overconsolidated clay using the cyclic CPT

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ABSTRACT

An innovative cyclic in situ test utilising the CPT, known as the 'Cyclic CPT' or 'CPTc', has been used to assess the in situ degradation of a highly overconsolidated clay in the UK sector of the Southern North Sea. A consistent degradation of sleeve friction was observed for all tests, indicating that the test methodology may be appropriate for providing useful input to various offshore engineering applications related to foundation design.

Keywords: CPT, offshore site investigation, in situ testing, cyclic CPT, CPTc, cyclic degradation

1 INTRODUCTION

The cone penetrometer test (CPT) is used extensively for the assessment of ground conditions for offshore wind farms due its relative speed, accuracy and continuous profiling capability. As opposed to other intrusive site investigation techniques, such as boreholes, the CPT minimises the time spent offshore collecting geotechnical information whilst maximising the quality and quantity of the geotechnical data retrieved. This advantage has prompted engineers to modify and adapt the CPT to collect as much geotechnical information as possible.

In particular, there is a distinct need to understand the cyclic response of the soil due to the cyclic nature of offshore loading. Offshore wind turbines are flexible and their loading dynamic, thus a good understanding of the foundation's response to cyclic loading is critical. The cyclic response of soil is usually ascertained through advanced laboratory testing, which can be both time consuming and expensive to carry out. Therefore, an in situ method of obtaining the soil's response to cyclic loading would be highly advantageous. The 'cyclic CPT', also known as the 'CPTc', is one such test.

This paper presents the results of a CPTc campaign used to assess the in situ cyclic degradation of a highly overconsolidated low plasticity clay. The testing was completed during a geotechnical site investigation for an offshore windfarm located in the UK sector of the Southern North Sea.

2 CPT$_C$ BACKGROUND

As suggested by Puech et al. (2012), Diambra et al (2014) and Jardine et al. (2012), the CPT can be used to give a measure of the in situ cyclic degradation of soil. This can be achieved by repeated two-way cycling of the CPT (as shown in Figure 1) therefore providing a measure of the soil's cyclic degradation. During this high strain displacement controlled test, dubbed the 'CPTc' (Jardine et al, 2012) or the 'cyclic CPT' (Diambra et al, 2014), the CPT sleeve friction (f_s) is measured for each cycle (n). The degradation is then estimated for each cycle by comparing the $f_{s,n}$ on the downward stroke to the 'virgin' f_s ($f_{s,0}$) measured during the initial CPT push.

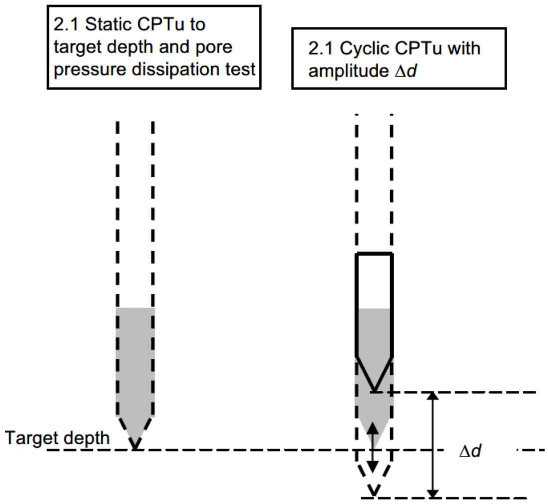

Figure 1. Cyclic CPT procedure adopted for the offshore site investigation (after Diambra et al, 2014)

A case study published by Diambra et al (2014) showed the effectiveness of using the CPTc to assess the cyclic degradation of chalk.

3 CPT$_C$ METHODOLOGY

The offshore in situ site investigation works were undertaken in 2016. The CPT cones were operated in seabed mode (using the Fugro SEACALF®) and the CPT probe utilised for the works had a cone surface area of 15 cm^2 with an apex angle of 60°. Of note, the pore water pressure measurement was made at the shoulder of the CPT in the U_2 position. Diambra et al (2014) recommended positioning the pore water pressure measurement at the U_3 position, but this was practically not feasible for this project.

Diambra et al (2014) explored two CPTc procedures, namely P1 and P2, during which the pore water dissipation tests and cyclic tests were undertaken at different times during the CPTc test. Whilst both procedures produced similar results, it was found that the P2 procedure was more suited to monitor the degradation of sleeve friction. As such, the general form of the P2 procedure, as shown in Figure 1, was utilised during the offshore site investigation works.

Irrespective of the procedure adopted, the CPTc test involves full two way cycling at very high strain levels.

4 CASE STUDY: USE OF THE CPT$_C$

4.1 Testing performed

As shallow foundations were expected to be the foundation solution for the project, CPTc tests were performed between 2 m and 7 m below mudline (bml). CPTc tests were performed at six locations. At each location, 2 tests were performed giving a total of 12 CPTc tests across the site

Table 1. CPTc test depths

Test Reference	Test 1 depth (m bml)	Test 2 depth (m bml)
1	2.6	4.6
2	2.7	5.2
3	2.2	6.7
4	2.6	4.6
5	2.7	6.7
6	2.2	5.7

4.2 Testing procedure

The CPTc test was controlled manually by the operator, with a target amplitude of 10 cm (Δd) for each cycle. The resulting penetration signal is approximately a triangular waveform with an amplitude of 10 cm. Each test consisted of 12 cycles. The methodology for each test was as follows:

i. CPT cone is stopped at the specified depth;
ii. The cone is withdrawn approximately 20 cm at a rate of 2 - 4 cm/s;
iii. Small pause to reset direction of the equipment;
iv. The cone is penetrated approximately 20 cm at a nominal rate of 2 cm/s;
v. Small pause to reset direction of the equipment before next cycle;
vi. Steps ii to v are repeated 12 times;
vii. CPT test is continued as normal.

An example of the testing procedure is provided in Figure 2 and Figure 3, which show the penetration depth and penetration rate against time respectively.

As described in numerous standards (ASTM, 2007; ISO 22476-1, 2012), the standard rate of penetration for the CPT test is 2 ± 0.5 cm/s. From Figure 3, it can be observed that the penetration rate (absolute velocity) during the penetration stages both prior to the CPTc test and during the CPTc test is relatively consistent at approximately 2 cm/s, but the rate during withdrawal varies between 2 and 4 cm/s. The effect of penetration rate on friction readings is not expected to be significant in silts (Poulsen et al, 2013) or sands, but could be significant for clayey till materials (Brown and Hyde, 2008). Brown and Hyde showed that increased penetration rates may lead to increased cone sleeve friction values, but the effect for the rates shown in Figure 3 are not expected to be large. Little research describes the effects of CPT rate on the cone sleeve friction values during CPT cycling or extraction where pore pressure values are inherently different to a virgin CPT penetration.

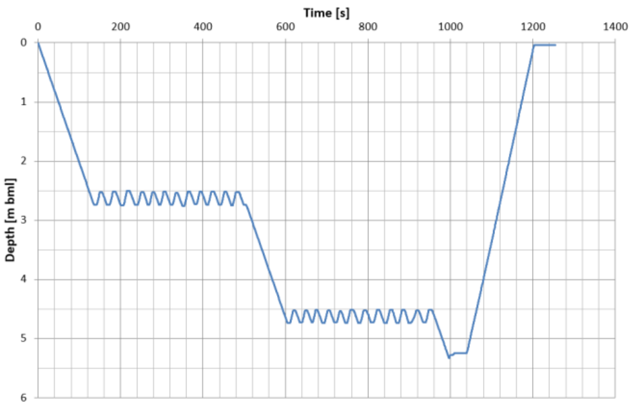

Figure 2. CPTc test procedure at one test location (2 CPTc tests)

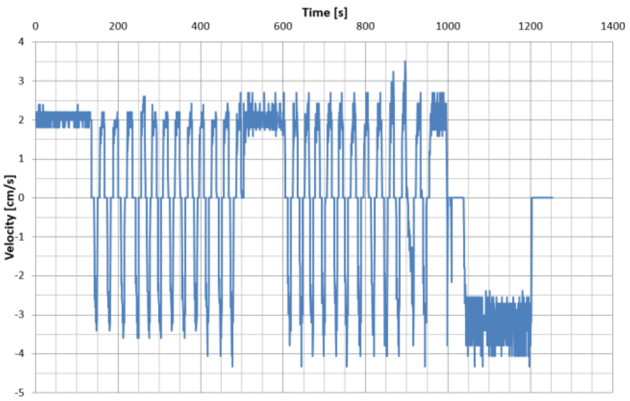

Figure 3. Velocity during the CPTc test at one test location

5 RESULTS

5.1 Typical CPTc tests

Figure 4 shows a time history of a typical CPTc test sleeve friction. At this location, two CPTc tests were undertaken at different depth below mudline. The peak sleeve friction value tends to reduce with the number of cycles, both on the downward and upward stroke of the CPT. It can be seen from Figure 4 that the CPTc is an extremely quick test with each test lasting approximately 7 minutes.

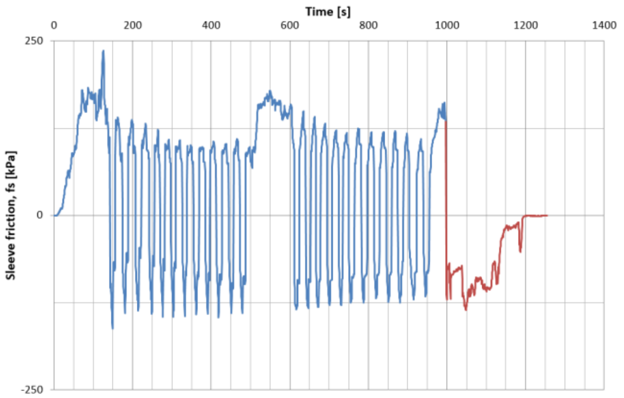

Figure 4. Example CPTc cone sleeve friction with time (two cyclic tests)

Figure 5 shows the results of a typical CPTc test in terms of depth versus sleeve friction, with the increasing darkness indicating increasing number of cycles. From Figure 5 it is evident that the peak sleeve friction reduces with the number of cycles.

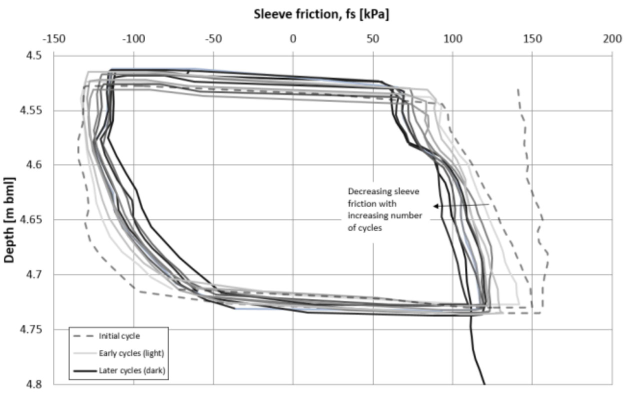

Figure 5. CPTc test showing decreasing sleeve friction with increasing cycles

5.2 Cyclic degradation from all tests

The CPTc test results from all tests undertaken at the site are shown in Figure 6, Figure 7 and Figure 8. The normalised results (Figure 6) show that a clear degradation trend exists for the in situ sleeve friction, as all the results are within a similar range of degradation (shown as dashed lines). On average, the residual sleeve friction was observed to be between 30 – 45 % lower than the initial sleeve friction. Figure 6 also shows that performing the CPTc for more than 12 cycles is not necessary for these soil conditions as cyclic 'equilibrium' was reached after approximately 8 cycles for most tests.

Figure 7 shows that residual sleeve friction values can be well predicted based on the initial sleeve friction values, providing further evidence of the consistency of the results. Assuming an intercept at the origin, the relationship between initial and residual sleeve friction can be described as per Equation 1.

$$f_{s,residual} = 0.58\, f_{s,initial} \tag{1}$$

As expected, cyclic degradation of the highly overconsolidated clay material is significantly less than the cyclic degrdataion of chalk material observed by Diambra et al (2014), where residual sleeve friction was up to a factor of 10 lower than the initial sleeve friction.

Figure 8 indicates that depth and vertical effective stress have little effect on the cyclic degradation of the highly overconsolidated clay. There is a slight trend for a reduction in the cyclic degradation with increasing depth, however the results are generally within the range of expectation given the depositional nature of the material.

The results indicate that the CPTc is a repeatable test which can provide an indication of the in situ cyclic degradation of a soil at high strain levels.

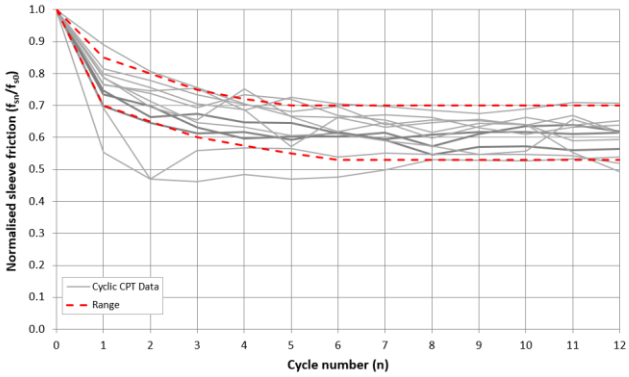

Figure 6. Normalised CPTc test results for all locations

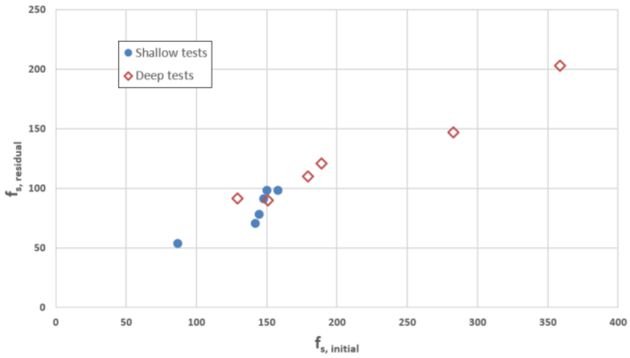

Figure 7. Initial and residual sleeve friction for all locations

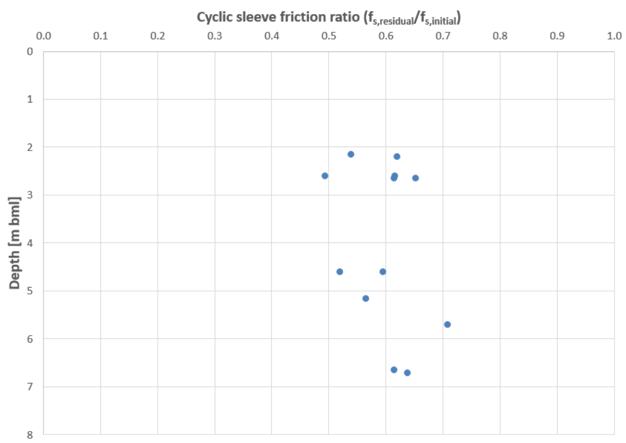

Figure 8. In situ cyclic degradation with depth

6 OTHER CONSIDERATIONS

6.1 Drainage conditions

Given the low permeability of the soil being investigated, it is highly likely that the CPTc tests were performed under undrained conditions. The effect of this on the results is unclear as a similar test rate was maintained for all tests. Whilst analysis of the pore pressure response is outside the scope of this study, the residual cone tip measurement (q_c) was between approximately 0.3 and 0.5 of the initial qc. This is a significantly different finding to that of Diambra et al (2014), who found that cone tip resistance "generally becomes negligible after about 3–4 cycles".

6.1 Large strain levels

The strain levels (both in terms of percentage and accumulated strain) during the CPTc test are significantly greater than standard 'cyclic' tests undertaken in the laboratory. Therefore, it must be considered that the results are not directly comparable with cyclic laboratory testing results but may more appropriately compared with large strain laboratory testing results (e.g. ring shear tests). However, as the test reached equilibrium, the results give an indication of the likely maximum cyclic degradation of the soil.

7 APPLICATIONS

7.1 Application for suction bucket installation

During the installation of suction buckets into highly overconsolidated clay materials, high suction pressures are generally required to overcome the friction along the suction bucket skirt (Houlsby and Byrne, 2005). As the suction pressure is limited by the cavitation limit (which is a function of water depth), a common mitigation measure in case of installation difficulties is 'cycling', whereby the pressure inside the suction bucket is cycled between the maximum differential suction pressure and an overpressure which causes the suction bucket to lift up, thus emulating two way cyclic loading. This method has been shown to significantly reduce friction between the bucket skirt and the soil, thus allowing for further installation penetration. The CPTc presents an innovative opportunity to pre-emptively explore the expected reduction in installation resistance should such mitigation measures be required.

7.2 Application for cyclic loading of foundations

Although this study does not explore the link between cyclic laboratory testing and the CPTc test, analogies exist between the representation of a soil element during cyclic loading of a pile and the CPTc test. This is discussed further by Diambra et al (2014).

Whilst scale effects must be taken into account, the CPTc test may provide an indication of the in situ reduction in shaft resistance due to two way cyclic loading and potential for the generation of porewater pressure. Further work is required to confirm the exact relationship between CPTc test results and the in situ degradation of a soil material.

8 CONCLUSIONS

Cyclic CPT, or CPTc, testing was undertaken during an offshore site investigation in a highly overconsolidated clay in the North Sea. A total of 12 CPTc tests, each lasting approximately 7 minutes, were performed across the site with relatively consistent results observed for all tests. In general, the residual sleeve friction after 8 CPTc 'cycles' was observed to be between 30 – 45 % lower than the initial sleeve friction. A linear relationship exists between the initial sleeve friction and the residual sleeve friction for this soil unit.

For this soil type, the consistent results indicate that the CPTc is a repeatable test that can provide an indication of the in situ cyclic degradation of a soil. The use of the CPTc in future offshore site investigations may be appropriate for providing useful input to various offshore engineering applications related to foundation design.

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