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The ICP Design Method and Application to a North Sea Offshore Wind Farm

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ABSTRACT: This paper outlines the Imperial College Pile (ICP) approach for developing reliable predictions for the axial capacity of driven piles. The ICP's advantages over traditional design methods have led to widespread use in offshore oil and gas developments. The methods are now playing a critical role in major Northern European offshore wind projects. Hundreds of large steel tubular piles are being driven in the North and Baltic seas and improving design efficiency is crucial to the industry's economic success. This paper provides an overview of the development of the ICP design methods and summarizes their key features, together with experience-based guidance on their application. Their application is illustrated by reference to the North Sea Borkum West II wind farm, where 40 turbines have been installed on steel tripods founded on large diameter steel piles driven in very dense sands. The paper reports how the significant effects of axial and lateral cyclic loading were addressed for Borkum West II through the ICP design methodology.

INTRODUCTION

The ICP design methods for estimating the axial resistance of driven piles in sands and clays were developed from research between 1980 and 2005 by Imperial College London. The research included field tests in the UK and France that covered a wide range of soil conditions and demonstrated the fundamental mechanisms controlling the axial resistance of displacement piles. Pile load test database studies presented in Jardine et al (2005) and Lehane et al (2005) have shown that the ICP design methods are more accurate and reliable than traditional design approaches such as the 'Main Text' methods in the API RP2GEO (2011) offshore foundation guidance. The CPT-based design method for driven piles in sand is included in the current API guidance and has been used internationally to design piles for offshore oil, gas and wind turbine installations. Onshore practitioners have made less use of these effective stress and CPT based approaches, although Williams et al (1997) report on their successful application to mainstream civil engineering projects.

This paper summarizes the design methods' key features and adds experience-based guidance on the interpretation of the geotechnical parameters for efficient and

safe design. The recent use of the methods in a large offshore wind farm development at a sand dominated site in the North Sea is reported. The steps taken to optimize foundation designs while incorporating important aspects such as cyclic loading, lateral interactions and time effects while mitigating pile driving risks are outlined. The economies that can be achieved in pile design are also discussed and it is suggested that greater use could be made of the approach in onshore applications.

THE ICP PILE DESIGN METHOD

Research programmes

The ICP design methods were developed from research projects that aimed to find a more fundamental and thorough understanding of pile behavior. Field tests were performed with instrumented piles at six onshore UK and French test sites covering two sands (one loose dune, one dense marine), stiff to very stiff lean glacial till, a high OCR plastic marine clay, soft Holocene marine clay and laminated glacio-lacustrine clays, as reported by Bond (1989), Lehane (1992) and Chow (1997). The 102mm diameter closed-ended heavily instrumented piles employed allowed direct measurement of local interface shear stresses, pore water pressures and radial total stresses at multiple levels along their shafts during installation by fast cyclic jacking, long-term equalization and load testing to failure. These ‘ICP’ tests provided the most accurate measurements to date of the effective stresses around displacement piles. Parallel site investigation and theoretical studies were undertaken, as were:

- Analyses of parallel tests on driven open-ended piles (up to 760mm diameter) to assess the effects of scale, installation methods and pile-end conditions;
- Field pile group tests in clays;
- Full-scale driven pile tests to assess cyclic loading, pile age, base grouting;
- Analyses of field tests on piles of different shape and material;
- Laboratory research into the interface shearing properties of clays and sands;
- Database studies to calibrate and validate the new design methods for open- and closed-ended driven piles in different ground conditions.

The background research and design methods developed from it are summarized by Jardine et al (2005), who cite multiple earlier references including Jardine et al (1998), Saldivar and Jardine (2005) and Jardine et al (2006) which present full details of the methods. Further investigations of the effects of time on the axial capacity of piles driven in sand are described by Jardine et al (2006) and those concerning cyclic loading effects by Jardine & Standing (2012). The main considerations in sands and clays are summarized below.

Basic Mechanisms and Axial Pile Capacity in Sand

The external shaft capacity for the pile is calculated in the ICP procedures by integrating local shaft shear stresses τ_f over the external pile area, with the pile length divided into typically 30 or more subsections to capture the soil layering and soil parameter variations. The ICP field tests confirmed that the Coulomb criterion

$\tau_f = \sigma'_{rf} \tan \delta$ governs local shaft shear failure in both sands and clays. The governing effective angle of interface shearing resistance δ can be found reliably from ring-shear interface tests. Jardine et al (2005) also give guidance charts that are most applicable for sands.

The shaft radial effective stress at failure σ'_{rf} is the sum of σ'_{rc} , the local radial effective stress set up by installation, and $\Delta\sigma'_{rd}$, the dilatant increase in σ'_r that develops during loading. In sands $\Delta\sigma'_{rd} = G \Delta R/R$ where G is the local shear stiffness (related to the CPT resistances q_c), ΔR is the pile's surface roughness and R is the pile radius. The local radial effective stresses set up by installation are strongly affected by the soils' local in-situ state and in sands the ICP makes direct use of the CPT tip resistance (q_c) profiles to predict design profiles of both σ'_{rc} and $\Delta\sigma'_{rd}$.

Another key feature observed in the field research was the marked dependency of the σ'_{rc} profiles on the relative pile tip depth, as defined and illustrated in Figure 1. The shaft radial effective stress developed at any particular depth below ground level reduces rapidly as the pile tip is driven past that level and the relative tip depth (h) increases. Equation (1) predicts with good accuracy how σ'_{rc} profiles depend on local q_c , relative tip depth h/R and are affected by the 'free-field' vertical effective stress σ'_{v0} . With closed ended piles, $R^* = R$. Open-ended conditions are considered by allowing for a more rapid reduction of σ'_{rc} with h/R which is achieved by substituting $R^* = (R_{\text{outer}}^2 - R_{\text{inner}}^2)^{0.5}$ into the same key function.

$$\sigma'_{rc} = 0.029 q_c (\sigma'_{v0}/P_a)^{0.13} (h/R^*)^{-0.38} \quad (1)$$

Piles loaded in tension were seen to develop lower shaft friction and radial effective stresses, principally due to 'Poisson' radial contractions of the shaft and principal stress axis rotation effects that are accounted for through simple modifications incorporated into the ICP methodology.

FIG. 1. Definition of relative pile tip depth (h) and variation of local radial effective stress with depth and relative pile tip depth observed in dense sand at Dunkirk (after Chow, 1997).

The base capacities of closed-ended and open-ended driven piles in sand are also directly related to the CPT tip resistance in the ICP method. For open-ended tubular piles the base capacity represents the combination of internal shaft friction and end bearing on the annular area of the pile. Simple criteria are given to define whether a rigid basal plug may develop, and for fully plugged or unplugged piles which have different end bearing conditions. The internal shaft friction for open-ended piles is concentrated near the pile tip due to arching effects (particularly for smaller diameter piles in dense sands), and for simplicity this component is considered as part of the pile base capacity rather than being explicitly calculated as in other design methods.

Basic Mechanisms and Axial Pile Capacity in Clay

The shaft radial effective stress at failure in clays can be defined as $\sigma'_{rf} = (K_f/K_c) \sigma'_{rc}$. The loading factor K_f/K_c is constant and may be assumed equal to 0.8. The field research in clays showed that pile installation and equalization leads to local radial effective stress profiles that can be expressed as $\sigma'_{rc} = K_c \sigma'_{v0}$ with σ'_{v0} being the free-field vertical effective stress. K_c is not constant, but depends on the clay's local Yield Stress Ratio (YSR, apparent over-consolidation ratio) and sensitivity. As with sands, the relative pile tip depth is also critically important. Clays tend to show negative dilatancy on shaft loading, and this is accounted for with a simple factor. Shaft friction can be brittle and ring shear interface tests that follow a specified procedure allow both peak and ultimate angles to be assessed, that depend on pile roughness and clay type. The degree of progressive failure depends on the extent of local pile-soil slip displacement and may be assessed by 'falling-branch' T-Z analysis or other simplified methods. As with the ICP sand method, the modified radius (R^*) is applied in the open-ended K_c design function. However, no modification was found necessary when addressing tension loading cases in clays.

Base resistance provides a relatively small contribution in most clay cases and is usually mobilized at larger displacements than the shaft capacity. The ICP field tests showed that base capacity correlates closely with local CPT q_c and the ICP design rules offer simple expressions that apply to closed- and open-ended piles with various geometries under both undrained and drained loading conditions.

Geotechnical Parameters for ICP Design Methods

The key geotechnical parameters required to use the ICP design methods are:

- Continuous CPT / PCPT tip resistance profiles
- Soil-steel interface friction angles for sands and clays from ring shear tests
- Sand shear stiffness
- Yield Stress Ratio of clays determined from in-situ tests (e.g. CPTs or field vane tests), laboratory triaxial or oedometer tests
- Clay sensitivities determined from laboratory oedometer tests or undrained triaxial tests on undisturbed intact and remolded samples

Routine classification tests are also required in well-planned site characterization studies that record ground water conditions, unit weights, grading curves, Atterberg limits and water contents. The latter can also be substituted into expressions that help

check, for example, interface friction angles. Relationships with average particle size (d_{50}) can be instructive with sands. Similar relationships with I_p for clays are subject to much greater scatter and there is a greater need for site specific ring-shear testing.

As noted above, site-specific CPTs or PCPTs are essential to ICP application. High capacity cones that can measure tip resistances up to 100MPa are required with very dense sands. CPTs that ‘max-out’ at lower resistances make capacity calculation difficult and may not identify adequately the potential risks of pile refusal or tip buckling. CPT interpretation affects pile capacity assessment and care is needed to distinguish clays, sands and silts, identify any thin layers and edit out unrepresentative measurements made at the ‘disturbed’ starts of pushes and the unloading data recorded at the end of pushes. The calculations must discretize the CPT traces with sufficient accuracy to capture the layering and trends within layers. It is also appropriate in mixed profiles to reduce the δ angle assumed in the first metre (or more) of sand that may have experienced clay down-drag during driving.

A ‘cautious mean trend’ CPT profile interpretation that eliminates any minor spikes is appropriate when considering shaft resistance in sands. Jardine et al (2005) discuss approaches for selecting base capacity q_c values and suggest averaging 1.5 pile diameters above and below the tip. However, it may be more appropriate to adopt the lowest values recorded within 2 diameters of the pile tip level in order to reduce the relatively high probability that variations in layering could leave the pile tips in the weakest layers that might be feasibly encountered.

Time Effects on Pile Capacity

It is well known that the axial capacity of piles in sands and clays generally increase over time after driving. Changes continue after full pore pressure equalization that may relate to radial effective stresses increasing due to creep processes relaxing circumferential arching around the pile shaft. The effects are most pronounced for sensitive low YSR clays; reductions in pile capacity over time can occur in insensitive high YSR clays. Pile end bearing capacity is not thought to change significantly with time. Pile load tests performed at different times after driving in dense sands at Dunkirk, northern France, are reported by Jardine et al (2006). The multiple ‘first-time’ loading tests demonstrated marked increases in capacity over the months following installation, and multiple re-tests revealed a brittle failure mode applied to the aged piles. Figure 2 shows the increase in pile shaft capacity over time (normalized by the values expected one day after driving) from the ‘first-time’ tests at Dunkirk, along with others from the literature. Capacities measured at the end of driving usually fall substantially below the ICP capacities, and it typically takes 10 to 30 days for these values to be reached. Site specific pile set up behavior is variable and requires a pile load test programme during the early stages of a project to assess for design purposes. Thus, pile set up is not often considered in design predictions of pile axial resistance, but substantial practical benefits follow if set up can be relied upon in service, as capacities can build to values 2 to 3 times those calculated by the ICP. Time effects are central to interpreting fitness-for-purpose from driving and re-strike tests.

FIG. 2. Normalized trends in shaft capacity with time for driven piles in sand (from Jardine et al, 2006); $Q_s(t)$ is capacity at time t $Q_s(t=1)$ is value at day 1.

Cyclic Loading Effects

Foundations that have to sustain considerable cyclic loading should be assessed by the methods set out by Jardine et al (2005, 2012). The effects can be particularly important for offshore wind turbines as the magnitude of cyclic loads can be a large proportion of the static loads. Substantial research involving laboratory, model and field testing has recently been undertaken on the effects of cyclic loading on axial pile capacity, as summarized in Jardine et al (2012). The impact depends on the amplitude and number of load cycles, which control whether the response will be stable, meta-stable or unstable. Large amplitude cyclic loads can degrade axial capacity rapidly, whereas small amplitude loads may be beneficial and potentially increase axial capacity; Jardine and Standing (2012), Rimoy et al (2012).

Cyclic assessments can make use of prior field loading tests, as described by Merritt et al (2012), or employ results from cyclic triaxial or simple shear laboratory tests. Assessment first requires characterization of the cyclic loading. With offshore foundations this involves considering a design storm, typically the 50 or 100 year recurrence event, developed from specific met-ocean data. Representative wave heights and wind speeds are given over the buildup, peak and dissipation periods of the storm. Hydrodynamic-structural analysis is performed to transform these data into axial pile-load variations. The expected succession of non-uniformly distributed irregular amplitude load cycles is usually sorted into 'binned' groups of idealized uniform axial load cycles with a given cyclic load amplitude (Q_{cyc}), average load (Q_{avg}) and number of cycles (N), as illustrated in Figure 3.

The ICP method provides an approach for assessing the effects of the derived cyclic axial loads on axial pile capacity based on effective stress principles. The reduction in shaft capacity is related to changes in local σ'_r , which are determined from the number of load cycles and the normalized cyclic shear stress amplitude ($\tau_{cyc}/\tau_{max\ stat}$) according to Equation (2) or an equivalent logarithmic expression. The parameters A , B and C are material coefficients determined from laboratory or field tests and the model can be used for both sands and clays.

FIG. 3. Transformation of non-uniform load cycles to idealized uniform cycles.

$$\frac{\Delta\sigma'_r}{\sigma'_{r0}} = A \left(B + \frac{\tau_{cyc}}{\tau_{max stat}} \right) N^C \quad (2)$$

The degradation of overall shaft resistance can be determined by integrating local radial stress changes along the length of the pile (e.g. Jardine et al, 2012), or by a simplified global approach (e.g. Merritt et al, 2012). Cyclic lateral loading can also influence the axial capacity of piles by reducing the stiffness of the soil and local stresses over a certain depth below the ground surface. This is an area of active research and new design methods are under development; Jardine et al (2012).

PILE DESIGN FOR THE BORKUM WEST II OFFSHORE WIND FARM

The Borkum West II offshore wind farm lies 45km off the German North Sea coast. The first phase of the project includes 40 wind turbines in water depths of 26 to 33m, supported on steel tripod structures founded on 2.48m dia. tubular driven steel piles. Ground conditions consist principally of dense to very dense, fine to medium grained sand, with some layers of medium dense silt and stiff to very stiff clay. The high quality site characterization provided continuous PCPT profiles at each turbine location as well as the laboratory soil-steel ring shear interface friction data and clay YSR and sensitivity values required to apply the ICP in pile design.

The project's pile design methodology addressed the risks associated with driving piles in very dense sands and used the ICP approach for assessment of static axial pile capacity and cyclic loading effects; Merritt et al (2012). Driving piles in very dense sand poses the risk of local pile tip damage by extrusion buckling related to out-of-roundness. The CPT profiles frequently showed $q_c > 50\text{MPa}$, with $q_c > 110\text{MPa}$ at a number of locations: see Figure 4. Qualitative risk assessment identified turbine locations with thick layers of very dense sand with $q_c > 80\text{MPa}$ as requiring pile wall thickness increases to mitigate the risk of driving damage.

The static axial pile capacity was assessed for each turbine location applying the ICP method with site specific geotechnical design profiles. The PCPT data helped to distinguish sand, clay and silt layers and design profiles were discretized on a metre-by-metre (or finer) basis to capture the q_c traces and soil layering. The shaft q_c values reflected average values, while the base capacity values represented lower bound assessments as described above. Examples of the measured and interpreted design

CPT profiles for two turbine locations are shown in Figure 4. The other necessary geotechnical parameters were interpreted from laboratory test data. Where clay layers were identified, reduced values for the interface friction angle were used over a length of approximately one pile diameter into the underlying sand layers to account for effects of down-drag of the clay into the sand during pile driving.

FIG. 4. Measured and design CPT profiles for two turbine locations.

Figure 5 shows examples of the static axial pile capacity profiles determined using the ICP method for the locations with design profiles shown in Figure 4 (including allowance for global and local scour effects). Also shown are the pile capacity profiles based on the standard Main Text methods in API RP2GEO (2011).

The effects of cyclic lateral and axial loading under the 50 year design storm were assessed and applied. The storm was discretized into $\approx 15,000$ load cycles binned, as described above, into groups with ascending average and cyclic load amplitudes. The impact on axial pile capacity was assessed using a simplified global approach based on field tests at Dunkirk in North Sea sands. Following Jardine and Standing (2012), only cycles with amplitudes greater than a defined cyclic damage limit were considered in the analysis and an ‘equivalent number’ approach applied with Equation 2. Cyclic axial loading was found to reduce the static axial pile capacity by up to 25% at the locations with the lowest shaft capacities. It appears possible to eliminate the risk of cyclic capacity losses by designing piles with sufficiently high static capacity, although this may not be the most economical solution. The effects of lateral cyclic loading on axial pile capacity were also assessed, taking Dührkop’s (2010) proposal that, in sands, soil stiffness and local stress reductions extend to a depth of 2.6 pile diameters below ground level. Lateral cyclic loading was found to cause a potential further 5% reduction in static axial pile capacity.

Even after applying the conservative steps outlined above the ICP approach led to shorter pile lengths than Main Text API methods and direct cost savings in excess of US\$15m to the Borkum West II project.

FIG. 5. ICP and API pile capacity profiles for two turbine locations.

SUMMARY AND CONCLUSIONS

This paper summarizes the ICP axial capacity driven pile methods, that were developed from highly instrumented tests at several onshore sites, covering their background, formulation and site investigations requirements, together with experience-based guidance on their application in practice. The key conclusions are:

- The effective stress based ICP methods provide practical design tools that offer more reliable predictions of axial capacity than conventional methods;
- The method addresses often neglected but important phenomena such as ageing and cyclic loading effects;
- It was possible to address the above features in an ICP-based design process for a large offshore wind farm and still achieve economies in design;
- The ICP design methods have an 18 year track record of widespread application in offshore engineering resulting in considerable economies as well as enabling development of otherwise marginal oil and gas fields (Overy and Sayer, 2007);
- It is possible that onshore piling specialists may not be as aware of the significant advantages the methods offer in avoiding both costly problems resulting from under-predictions of capacity (see Williams et al 1997) and expensive over-design (see Merritt et al 2012).

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