

Field testing of large diameter piles under lateral loading for offshore wind applications

Essais sur site de pieux de large diamètre soumis à des chargements latéraux pour des applications dans le domaine de l'éolien offshore

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ABSTRACT Offshore wind power in the UK, and around Europe, has the potential to deliver significant quantities of renewable energy. The foundation is a critical element in the design. The most common foundation design is a single large diameter pile, termed a monopile. Pile diameters of between 5m and 6m are routinely used, with diameters up to 10m or more, being considered for future designs. Questions have been raised as to whether current design methods for lateral loading are relevant to these very large diameter piles. To explore this problem a joint industry project, PISA, co-ordinated by DONG Energy and the Carbon Trust, has been established. The aim of the project is to develop a new design framework for laterally loaded piles based on new theoretical developments, numerical modelling and benchmarked against a suite of large scale field pile tests. The project began in August 2013 and is scheduled to complete during 2015. This paper briefly outlines the project, focusing on the design of the field testing. The testing involves three sizes of pile, from 0.27m in diameter through to 2.0m in diameter. Two sites will be used; a stiff clay site and a dense sand site. Tests will include monotonic loading and cyclic loading. A suite of site investigation will be carried out to aid interpretation of the field tests, and will involve in-situ testing, standard laboratory testing and more advanced laboratory testing.

RÉSUMÉ L'énergie éolienne offshore, produite au Royaume-Uni ainsi qu'ailleurs en Europe, a la capacité d'offrir des quantités importantes d'énergie renouvelable. La fondation est un élément critique lors du dimensionnement. La fondation la plus utilisée est un pieu simple de large diamètre, appelé monopieu. Des pieux de 5m à 6m de diamètre sont régulièrement utilisés, et des pieux de 10m, voire plus, sont envisagés pour de futurs dimensionnements. Un certain nombre de questions ont été soulevées concernant la pertinence des méthodes de dimensionnement actuelles pour les pieux de large diamètre. Afin d'étudier ce problème, un projet mené par un regroupement d'industriels a été mis en place. Ce projet s'appelle PISA et est coordonné par DONG Energy et le Carbon Trust. L'objectif de ce projet est de développer un nouveau cadre de travail pour le dimensionnement des pieux soumis à des chargements latéraux. Ce dernier se basera sur de nouveaux développements théoriques ainsi que sur des modèles numériques développés à partir d'essais sur site de pieux de grandes dimensions. Ce projet a commencé en août 2013 et devrait s'achever courant 2015. Cet article résume les grandes lignes du projet en se concentrant sur la description des essais sur site. Le programme de tests implique trois tailles différentes de pieux allant de 0.27m de diamètre jusqu'à 2.0m de diamètre. Deux sites seront sélectionnés, un site composé d'argile raide et un site composé de sable dense. Les tests comprendront des essais sous chargement monotones et cycliques. Une étude géotechnique des sites sera menée afin de faciliter l'interprétation des essais sur site. Ils comporteront des tests in-situ, des essais classiques en laboratoire ainsi que des essais plus avancés en laboratoire.

1 INTRODUCTION

More than 1000 offshore wind turbines have been installed in European waters, and many thousands more are planned to be installed over the next decade. The most common foundation type for these turbines is the monopile, which in recent installations involve diameters of 6 m, with plans to use diameters

of 7.5 m (e.g. DONG Energy Gode Wind Offshore Wind Farm) or more, in the future. Monopiles are predominantly subject to large overturning moments, due to lateral wind and wave loads. The method typically adopted for their design is based on the Winkler model, commonly termed the p - y approach. The current offshore design guidelines (e.g. DNV 2014; API 2010) use a p - y approach that is based on field tests

of slender piles, carried out in the 1950s and 1960s, and such methods have been used successfully for oil and gas structures over many decades. However, the measured response of modern offshore wind turbines, designed using these codes, has varied significantly from the predicted response (Kallehave et al. 2012). This suggests that the traditional design methods perhaps do not accurately capture the key mechanisms by which large diameter monopiles interact with the ground.

1.1 Overview of PISA Project

To address these concerns and to develop a new design method for offshore wind turbines, a large joint industry project, PISA (**P**ile **S**oil **A**nalysis) was established. The project involves three strands of work including (a) the development of a new design methodology (see Byrne et al. 2015), (b) numerical modelling from which the design method is developed (see Zdravkovic et al. 2015) and finally (c) field testing to provide data against which new methods can be assessed and validated. The overall structure of the project is summarised in Figure 1. The numerical modelling work-stream has provided input into the design of the field testing, as well as providing the basis for development of the new design method. The new design method has been developed for a sand soil and a clay soil, both of which are representative of parts of the North Sea where offshore wind farms will be developed. The framework is developed so that it can be easily applied to other soil types, and also to layered soils. The initial focus of the work is for monotonic loading, so that the baseline pile response model is robust, but future phases of work will explore design for cyclic loading. This paper focuses on the design of the proposed field testing phase of work, which is planned for completion during the winter of 2014/2015. The final report for the PISA project will be delivered towards the end of 2015.

2 TEST SITES

The testing must provide a good representation of pile response in stiff to very stiff over-consolidated ductile Quaternary clay and dense to very dense marine Pleistocene sands. Two on-shore sites, repre-

sentative of these materials, have been identified for the field testing phase; (a) Cowden, a clay till site in the north-east England, and, (b) Dunkirk, a dense sand site in northern France. These sites represent typical soil conditions found at many North Sea wind farm sites. Both sites have been used for previous pile testing activities and, as a consequence, various field and laboratory soil data are available. This makes them ideal reference materials for the development of the new design methods. Further details of the soil profiles are given in Zdravković et al. (2015).

3 PILE TEST APPROACH

At each site it is envisaged that 14 pile tests will be carried out, each exploring different aspects of the lateral loading problem. During the field tests each test pile will be loaded against a larger reaction pile using a tension based system, as illustrated in Figure 2. This means that it will only be possible to apply one-way loading to the piles, for the cyclic loading tests. The piles will be loaded at a height, h , above

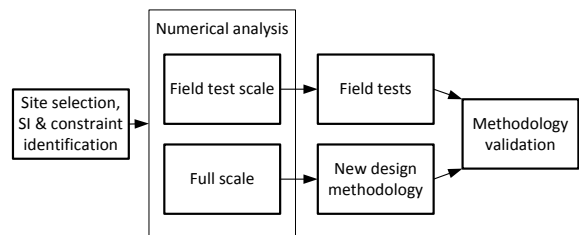


Figure 1. PISA project workflow.

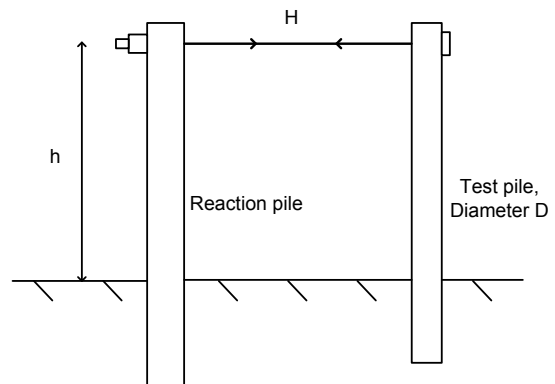


Figure 2. Pile test illustration.

ground of between 5 - 10m. The heights selected represent normalized load eccentricities, M/HD , that are representative of the wind and wave loading on full scale wind turbine structures, where H is the lateral load and M is the moment in the pile at ground level. For example a value of $M/HD \sim 5$ represents wave loading on an offshore wind turbine, whilst a value of about 15 represents more closely wind loading. Applying the loading in this way ensures that the pile kinematics is correctly simulated, so that the mobilisation of different components of soil resistance is representative. Most other lateral loading field test programmes apply the load at ground level, which in this instance is not appropriate. However, applying

the load at such height above the ground, introduces a degree of complexity, and cost, to the pile testing.

3.1 Instrumentation

The piles and areas around the pile will be instrumented to measure the response of the soil and the deflection of the piles. This will be achieved through a combination of instrumentation mounted in the buried pile section and in the above ground pile stick-up. The detailed instrument specifications take into account the physical constraints, such as size and robustness, and technical constraints such as likely displacements, stress ranges, temperature effects, shock loading and g-forces during pile installation.

3.1.1 Soil response instrumentation

The two parameters that are measured in the buried pile section are the vertical strain and the inclination of the pile. By measuring the distribution of strain on the active and passive sides of the pile, as illustrated in Figure 3, the depth-wise distribution of bending moment can be calculated. Strain will be predominantly measured using fibre optic cables etched with Bragg Gratings, which are bonded into grooves machined in the pile outer face. In the situation where a cable is damaged during installation, redundancy on the strain measurements is achieved using multi-point retrievable extensometers, mounted within tubes that are welded to the inner face of the pile.

The inclination of the pile is measured using retrievable inclinometers mounted in tubes welded to the inner face of the piles, perpendicular to the line of loading. For the calibration of a conventional p - y approach the lateral load on the pile would be calculated from the second differential of the distribution of the moment. However, for large diameter piles, the bending moment in the pile occurs due to a combina-

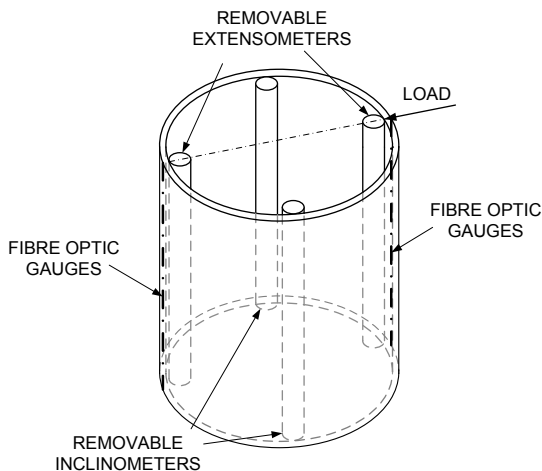


Figure 3. Illustration of soil reaction instrumentation.

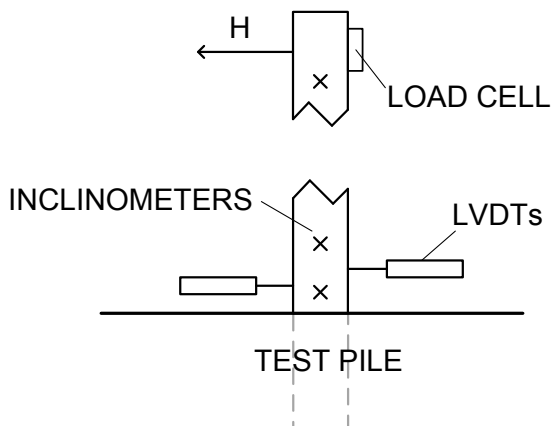


Figure 4. Illustration of stick-up instrumentation.

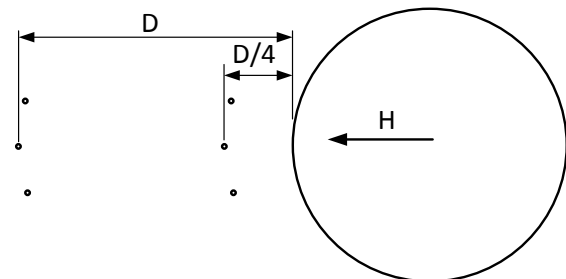


Figure 5. Plan layout of piezometers on the 2.0m diameter pile.

tion of lateral loads and vertical shear forces, as described in Section 5. This means that the bending moment distribution (determined from the strain gauges) cannot be related directly to the distribution of the lateral load.

3.1.2 Pile stick-up response instrumentation

Above the ground measurements are made of the pile displacement, inclination and load, as illustrated in Figure 4. Linear variable differential transformers (LVDTs) are used to measure displacements, from which the rotation can be calculated. These will be mounted on independent reference frames, isolated from the ground movements due to the pile. LVDTs placed either side of the pile will allow local changes in pile cross-section to be determined. Bolt-on inclinometers, mounted on the pile stick-up, will provide further validation of the LVDT measurements, offering additional redundancy to the instrumentation system, whilst also allowing horizontal displacement due to translation and rotation to be decoupled. Load cells at the pile head, within the loading system, will allow measurement of the load applied to the pile. It is expected that the loads applied will vary from 10kN for the small diameter piles up to 4000kN for the large diameter piles.

3.1.3 Pore pressure instrumentation

For a small selection of tests carried out at the clay site, the pore pressures developed in the surrounding soil, as a result of pile installation and loading, will

Table 1. Parameter space of field tests.

Geometry	Diameter	L (m)	L/D	t (mm)	D/t
1	0.273	1.4	5.25	7	39
2	0.273	2.2	8	7	39
3	0.273	2.7	10	7	39
4	0.762	2.3	3	10	76
5	0.762	4	5.25	15 – 19	40 – 51
6	0.762	4	5.25	11– 14	54 – 69
7	0.762	6.1 – 7.6	8 – 10	25	30
8	2.0	10.5	5.25	25 – 38	53 – 80

be measured using vibrating wire push-in piezometers. On those instrumented piles, piezometers are located at two radial distances from the pile wall, on both the active and passive sides of the pile, an example is shown in Figure 5. At each radial distance, three piezometers are used to capture data at depths of approximately 0.3L, 0.5L and 0.9L.

3.2 Site Investigation

Although the two sites have been highly characterised, through previous testing programmes, it has still been necessary to collect new data for each site. A programme of in-situ testing has been carried out including CPT, Pressuremeter, SDMT and Magcone testing. The testing is broadly aligned with previous measurements taken at the sites. In addition soil sampling has been carried out with additional laboratory testing planned to assist with the further development of the numerical modelling, particularly for the cyclic loading analysis. Robust information on the site characteristics is an important input into the new design methods.

4 TEST PARAMETER SPACE

The field tests cover a range of pile geometries, including relatively long and short piles. The displacement of these piles is anticipated to be due to a combination of bending and rigid body rotation. Based on this assumption, two metrics for the target threshold on pile response have been chosen; a ground level lateral displacement of $0.1D$ or a ground level rotation of 2 degrees.

For each test in which the piles are monotonically loaded, the piles would ideally pass both target thresholds, developing high strains in the pile, which can provide a high resolution approximation of the bending moment distribution and the resulting distri-

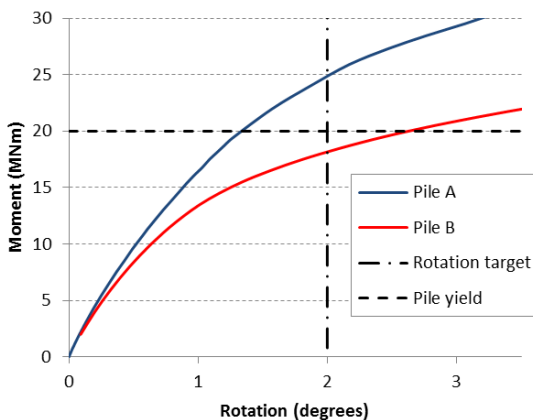


Figure 6. Example plot of pile displacement and failure.

bution of loads. However, to ensure that the response of the pile remains linear elastic, the stresses in the pile should not exceed the yield stress. The geometry of the piles must therefore be selected to maximize the pile strains up to the desired threshold load. Figure 6 illustrates the design problem; a pile that is inappropriately sized (such as Pile A) will yield before the target rotation and displacement thresholds are reached. Conversely, Pile B is able to reach these thresholds without yielding.

Piles of eight different geometries have been chosen, as shown in Table 1. These piles are scaled representative of the geometry of current and future offshore wind turbine foundations. Due to the stiffer response of the Dunkirk soil a greater load is generally required to achieve the target rotation or displacement. Where there is a range of geometry shown in Table 1, the piles in Dunkirk are those of greatest thickness or shorter length to resist these increased loads. Figure 7 and 8 show dimensionless pile geometries for the test piles at Cowden and Dunkirk, compared against geometries considered to be representa-

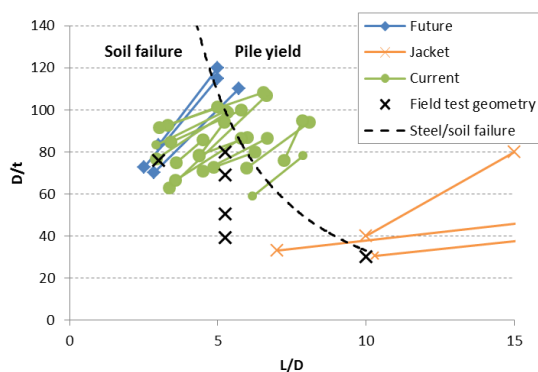


Figure 7. Geometry space in glacial till clay at Cowden.

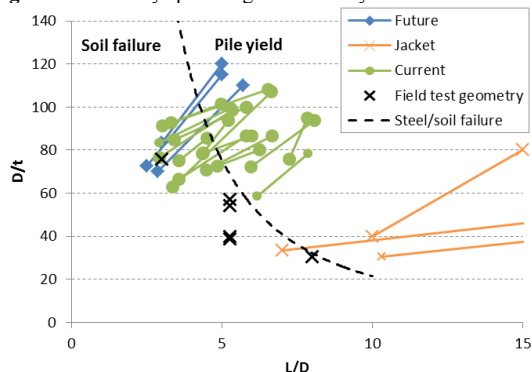


Figure 8. Geometry space in Flandrian sand at Dunkirk.

tive of monopiles and jacket piles. Also plotted is a line that represents the boundary between pile yield and soil failure. This line is determined for the pile geometries, loading conditions and soil conditions that are relevant to the pile tests.

4.1 Test types

The testing will consist mostly of monotonic loading events. This is essential for definition of the baseline response of the pile, and for comparison against the predictions made by the numerical analyses. The monotonic tests will incorporate unload-reload events so that the evolution of stiffness and hysteresis can be identified. For example Figure 9 shows a schematic of a typical monotonic test. A small number of tests will be devoted to cyclic loading, such as the one-way loading events shown in Figure 9. This information will provide the basis for developing methods that can predict the accumulation of rotation (or displacement) and the stiffening or degradation of the response. In addition, such events provide very important detail on the hysteresis that might be expected. This is needed for developing design guidance on damping from the foundation, which will mainly be derived from the hysteretic response. The assessment of damping is critical for determining the applied loads due to turbine operation, wave and wind loading and so consequently for fatigue design.

5 FIELD TEST DATA ANALYSIS

The field tests are designed to provide a high quality

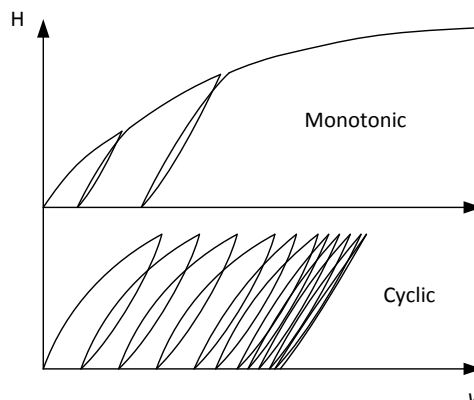


Figure 9. Illustration of test types.

data set for benchmarking new design methods for laterally loaded piles. Pile-head load displacement data will be an important indicator of the accuracy of the numerical modelling that has been carried out (Zdravković et al. 2015). Based on the modelling Byrne et al. (2015) describe a new design method that builds on the existing p - y approach, but which allows for additional components of the soil resistance. These additional components are shown in Figure 10. The importance of each component depends on the pile geometry, and pile kinematics under loading. For longer small diameter piles the inferred p - y relationship will be a good approximation to the pile response. However, for many of the tests it will be necessary to carry out additional numerical simulations, to properly extract the contribution from the different soil reactions. The instrumentation will allow detailed analysis of bending strains down the pile, of the pile deflected shape, as well as any pore pressures that develop in the soil around the pile. There is a degree of instrumentation redundancy to ensure the success of the programme. A small number of tests will explore cyclic loading. Instrumentation allows the cycle by cycle behaviour to be resolved, as well as any accumulation or stiffening.

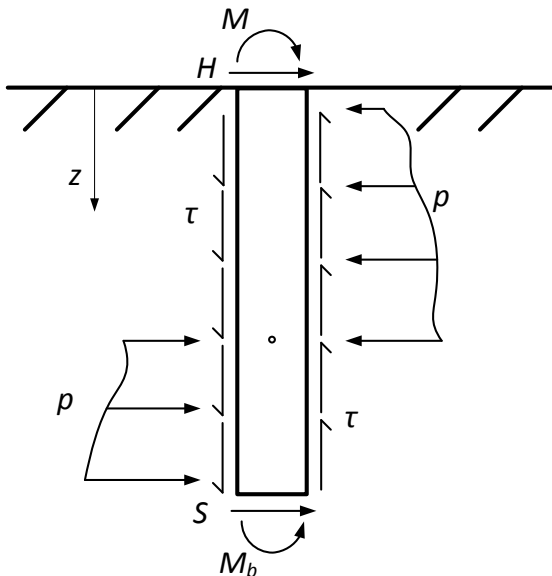


Figure 10. Diagrammatic indication of the soil reaction components applied to a monopile (based on the modelling assumptions outlined in Byrne et al. 2015).

6 CONCLUSIONS

This paper describes a field testing programme to explore the monotonic and cyclic lateral load response of piles for offshore wind applications. A large number of highly instrumented and appropriately loaded piles will be tested at a stiff clay site and a dense sand site. The resulting data will be used to benchmark numerical modelling that has been carried out (Zdravković et al. 2015), and the new design methods that have been developed (Byrne et al. 2015). The initial focus of the work is for monotonic loading, but data will be collected from cyclic tests, to aid development of cyclic load design guidance.

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