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PISA: Recent Developments in Offshore Wind Turbine Monopile Design

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Abstract. This paper provides a brief overview of the Pile Soil Analysis (PISA) project, recently completed in the UK. The research was aimed at developing new design methods for laterally loaded monopile foundations, such as those supporting offshore wind turbine structures. The paper first describes the background to the project and briefly outlines the key research elements completed. The paper concludes with a brief description of the anticipated impact of the work and describes initiatives that have followed since.

Keywords: Offshore wind · PISA project · Monopiles · Finite element model

1 Background to PISA Project

Offshore wind energy is a major component of the energy mix for the UK, with 2000 offshore turbines either operational or being constructed, and many more to be constructed over the next few decades [1]. There are ambitious plans for Europe, USA and East Asia. Driving down the Levelised Cost of Electricity (LCOE) is critical for wind as a sustainable long-term energy business. The application of advanced, less conservative, geotechnical engineering is critical as the wind turbine foundation contributes significantly to the installed capital cost.

The PISA (Pile Soil Analysis) Project, run as a £3.5 m joint industry research project, has produced new practical geotechnical design methods that significantly reduce the dimensions and costs for laterally loaded offshore wind turbine monopile foundations [1–3]. The work proposes revisions to conservative design approaches that date back 50 years, such as the American Petroleum Institute (API) *p-y* method [4] typically adopted for monopile design in the UK, with new and innovative ideas.

The work has been developed by an Academic Work Group (AWG) in collaboration with an industry consortium led by Ørsted, including developers, contractors and consultants. The project included a significant construction and testing component, with Socotec UK (formerly ESG) undertaking one of the largest and most

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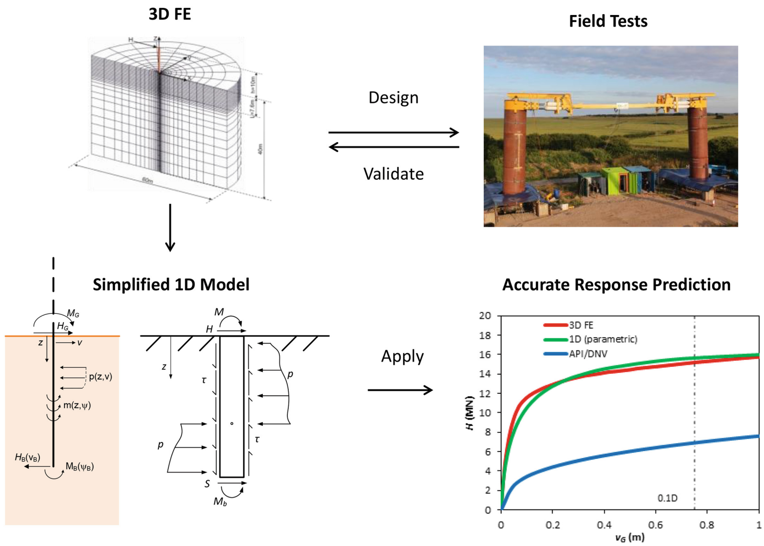

Fig. 1. The relationship between different elements of the PISA Project.

comprehensive pile testing campaigns exploring monopile behaviour under monotonic and cyclic loading [5]. The pile tests provide high quality benchmark data against which numerical modelling and other design approaches can be validated.

2 Overview of PISA Project Work Packages

Figure 1 provides a summary of the key elements in the PISA Project and how they relate to each other (see also [1, 2]). This figure shows a suite of 3D finite element (3D FE) analyses benchmarked against medium scale field tests (a total of 28 completed) which are then used to inform simplified and improved computational models of pile response. These simplified models encode the fidelity of the finite element calculation within a computationally efficient 1D formulation.

2.1 Structure and Timetable

PISA was commercially led by Ørsted, as lead partner of a discretionary project through the Carbon Trust's Offshore Wind Accelerator. The project formally commenced in August 2013 and concluded with the Final Report in May 2016. The field testing program was completed in the first half of 2015. By the completion of the project 10 additional funding partners had joined the consortium, representing major offshore wind developers and stakeholders in UK and Europe.

The funding partners contributed valuable advice to a Steering Committee and Expert Panel, providing oversight and review of technical developments. The core of the scientific activities was executed by the AWG, led by Oxford University with Imperial College London and University College Dublin. The AWG were appointed by

Ørsted following a tender process, with responsibilities to develop the new design method and demonstrate application. An Independent Technical Review Panel (ITRP) was established, comprised of experts external to the AWG, including from certification authority DNVGL. The ITRP and Expert Panel provided feedback on written deliverables throughout the project, through workshops and written commentary.

The field testing program was executed by Socotec UK under contract to Ørsted, with the scientific direction set by the AWG. The focus of the work was determined principally by available test sites, and their relationship with North Sea soil conditions. Hence stiff glacial clay till, such as found at Cowden UK, and dense marine sand, as found Dunkirk France, were targeted during the project. A very close collaboration between the three parties ensured the high quality of testing achieved, and the subsequent test data obtained. Additional consultants and contractors were appointed to provide specialist advice and assistance through the project, to expedite the work, and providing additional resource as required. During the project more than 100 people contributed to technical elements and assisted in the execution of the work.

2.2 Finite Element Modelling

The basis for the new design method comes from state-of-the-art 3D FE analyses of laterally loaded piles under loading typical for offshore wind foundations, using the software ICFEP and the modelling approach laid out in [6]. Analyses were performed for clay (Cowden clay) and sand soils (Dunkirk sand), felt to be representative of North Sea wind farm sites, following their advanced characterisation through laboratory and field investigations. The results indicate that current design methods (e.g. API *p-y* [4]) consistently under-predict ultimate capacity and initial stiffness for typical stiff clays [3], and do not accurately predict initial stiffness for sands.

The new design method is derived from the 3D FE results, drawing on existing techniques (the *p-y* approach) but with distinctly improved formulation of the soil reaction responses. The process demonstrates that for long piles a (modified) *p-y* approach may be suitable for design, however, for large diameter short monopiles, the *p-y* approach alone will never successfully predict the response, even if appropriately re-calibrated. Three additional soil reaction components are identified, accounting for the base shear and moment, and a distributed moment down the pile [3]. If these are used to extend the *p-y* approach, the pile response is more accurately computed [2]. Detailed calibration of all four soil reaction components was facilitated by the ability to extract detailed numerical information from the 3D FE results [1, 3].

2.3 Field Testing

A campaign of 28 medium scale field trials, with diameters 0.273 m, 0.762 m and 2.0 m, was designed, procured, constructed and executed to test the new design methods [1, 2, 5]. The tests were carefully planned, based on 3D FE analyses (see Sect. 2.2) covering a range of appropriate loading conditions. For many of the pile tests this involved loading to failure at 10 m above ground level (a significant innovation over previous testing). The field tests were carefully supervised during execution, leading to very high quality results obtained from the numerous instruments deployed.

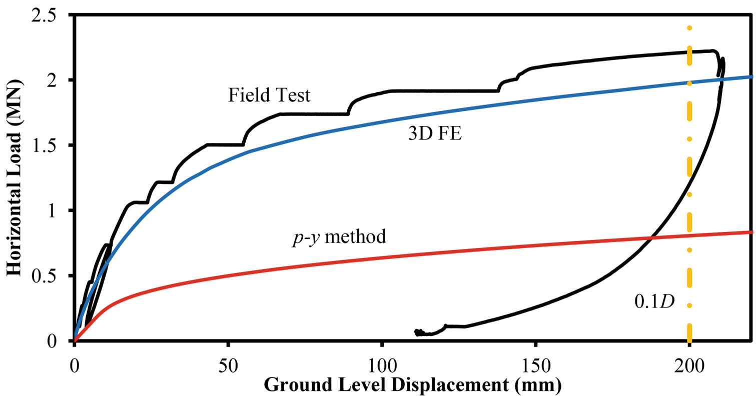

Fig. 2. Field test results from 2 m diameter, *L*/*D* = 5.25, pile installed at the Cowden test site.

The field tests validated the 3D FE calculations, providing high confidence that the developed computational approach can be used to predict the performance of full scale large diameter monopiles. For example, Fig. 2 shows a comparison of the results from the 2 m diameter pile test at Cowden. The 3D FE computation was completed in advance of the testing, to aid design of the tests. Had the *p-y* method been used for test design then it is likely that the field testing program would have failed, as the loading system would have been under-designed. Of interest, the PISA Project is the first known instance of successful instrumentation of impact driven piles with bonded fibre optic strain gauges [7] – this provided high resolution measurement of strain through both monotonic and cyclic testing. It is probable that this type of instrumentation will find further use for field monitoring of full scale offshore wind turbine structures.

2.4 1D Model

A key advance in the project is the development of a 1D FE model of the monopile; an extension of the *p-y* approach in which additional soil reaction curves (described in 2.2 and in Fig. 1) are implemented. The model is ideally suited to computational requirements for monopile optimisation and offshore wind farm design, where there can be many load cases to consider, along with many individual foundations to design. It is critical that each calculation captures the site specific response, as determined by the 3D FE, but computationally efficiently, similar to the *p-y* approach.

Two alternative approaches are proposed for determining the soil reaction curves required in the model [1]. The first is a ‘rule based method’, using lookup tables to derive appropriate inputs for the model, determined by basic strength and stiffness parameters, similar to current codified procedures. The second, more detailed approach, involves bespoke finite element modelling to determine site specific soil reaction functions. This is achieved by completing a systematic 3D FE study of pile response across an appropriate parameter space (e.g. *L*/*D*, *M*/*HD*, *D*/*t* etc.) from which the 1D model is calibrated. New calculations representing likely 3D FE responses can then be computed within the parameter space, but in greatly reduced time.

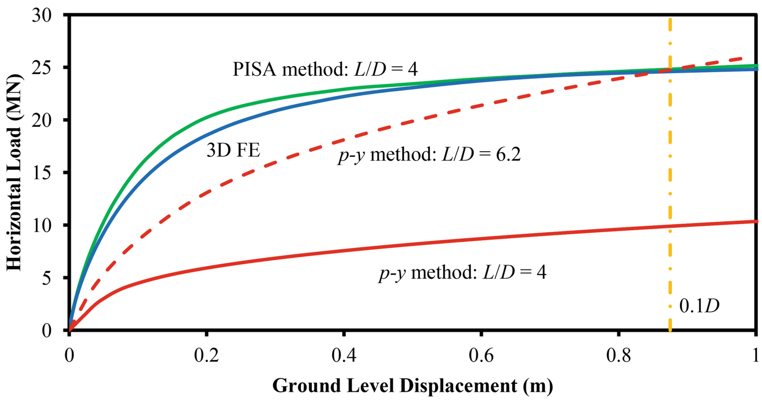

Fig. 3. Comparison of calculations for a test case with $L/D = 4$, $M/HD = 10$ and $D = 8.75$ m embedded in a Cowden clay soil.

2.5 Potential Impact

PISA demonstrates that substantial direct savings can be made for each monopile foundation if a site-specific approach is taken. For example, Fig. 3 shows results for a monopile of diameter 8.75 m in Cowden clay. The PISA method shows that a pile with *L*/*D* of 4 achieves a capacity of 25 MN. The result of the 1D calculation, interpolated in the parameter space, compares closely to an independent 3D FE calculation. If the *p*-*y* method is used this pile yields an apparent capacity of 10 MN; the pile length would need to be increased by 2.2*D* to achieve the same capacity as PISA. This indicates a potential saving of about 35%, which is considerable, particularly when multiplied across the entire wind farm. It is apparent that the small displacement response, important for natural frequency calculations, is not well predicted by the *p*-*y* method. Improved assessment of this through PISA will lead to better estimates of fatigue life. There are other likely indirect savings with smaller vessels being required for transportation and installation. By reducing the monopile length, the installation schedule can be reduced, leading to savings in the installation costs. Additionally, the monopile foundation can be feasible for larger turbines and deeper water than hitherto anticipated, increasing the pace at which wind farm sites can be developed.

3 Next Steps

Publications describing the PISA Project are in progress, and the PISA design approach is being implemented into commercial software by PLAXIS for release in 2018 [8]. The success of PISA has led to the PISA2 "Layered Soils Extension" Project, which is a computational study exploring the application of PISA to a wider range of soils including layered soil profiles. The same successful PISA framework has been adopted with the AWG comprising Oxford University and Imperial College. PISA was focused on clay till (Cowden clay) and dense marine sand (Dunkirk sand). PISA2 widens this to additional sand densities (loose, medium and very dense) as well stiff brittle clay (London clay) and soft clay (Bothkennar clay). The layered soil component addresses the layering effects by exploring the hypothesis; *soil reaction curves calibrated using homogeneous soil profiles can be employed, directly, to conduct 1D analyses of monopiles embedded in a layered soil*. The project completed in March 2018, involving more than 100 advanced 3D FE computations exploring homogeneous and layered soil pile response, probably the largest database of such calculations.

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References

1. Byrne, B.W., et al.: PISA: new design method for offshore wind turbine monopiles. In: SUT OSIG 8th International Conference, London, UK (2017)
2. Burd, H.J., et al.: Design aspects for monopile foundations. In: Proceedings of TC209 Workshop: Foundation Design of Offshore Wind Structures, 19th ICSMGE, Seoul Korea (2017)
3. Byrne, B.W., et al.: New design methods for large diameter piles under lateral loading for offshore wind applications. In: Proceedings of 3rd International Symposium of Frontiers in Offshore Geotechnics (ISFOG 2015), Oslo, Norway (2015)
4. API: RP 2A-WD—Recommended Practice for planning, Designing and Constructing Fixed Offshore Platforms. American Petroleum Institute, Washington (2010)
5. Byrne, B.W., et al.: Field testing of large diameter piles under lateral loading for offshore wind applications. In: Proceedings of 15th European Conference Soil Mechanics and Geotechnical Engineering (XVECSMGE), Edinburgh, United Kingdom (2015)
6. Zdravković, L., et al.: Numerical modelling of large diameter piles under lateral loading for offshore wind applications. In: Proceedings of 3rd International Symposium of Frontiers in Offshore Geotechnics (ISFOG2015), Oslo, Norway (2015)
7. Doherty, P., et al.: Field validation of fibre Bragg grating sensors for measuring strain on driven steel piles. Géotech. Lett. **5**, 74–79 (2015)
8. PLAXIS MoDeTo. https://www.plaxis.com/software/plaxis-modeto/. Accessed Mar 2018