

Foundation optimisation for offshore wind parks

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Abstract: Larger wind turbines and increasing water depths are presenting industry with new challenges for the realisation of economical foundation systems. The issues confronting industry here are manifold and include not only the optimisation and validation of structures or soil-structure interaction models, but also the development of economical installation methods with mitigated noise levels.

A sensible alternative is provided by large-scale geotechnical tests (scale 1:15 to 1:5). Large-scale experiments allow the scale effects to be minimised and facilitate a realistic simulation of complex soil-soil and soil-structure interactions. Moreover, large-scale experiments can be drawn on to provide more reliable information about specific geotechnical issues in the design process.

The Test Center for Support Structures (Testzentrum Tragstrukturen Hannover, TTH) was inaugurated in 2014 as a cooperation project between the Fraunhofer Institute for Wind Energy and Energy System Technology IWES and the Leibniz Universität Hannover. The

1. Experimental validation of prediction models

Optimised calculation methods are required for the economical design of support or foundation structures. The engineer has a broad range of prediction models with different levels of complexity available for this purpose. During the design process, these models complement each other and can be categorised as semi-empirical models, analytical models, or numerical models.

The decision as to which of these models represents the engineering problem with sufficient accuracy is usually based on experience. All models have one thing in common though: Regardless of whether they are simple or complex, they have to be validated with the aid of physical experiments before they can be utilised.

A distinction is made here between small-scale, large-scale, and real-scale experimental tests. Since the load-bearing and deformation behaviour of the soil depends on the stress level, small-scale tests (scale 1:100 to 1:30) are often not sufficiently accurate to provide a realistic representation of the stiffness and load-bearing capacity of a foundation

system. Real-scale experiments are very cost-intensive and often not fully controllable, however, and are therefore often unable to provide an adequate statistical basis.



Figure 1: Infrastructure of the Test Center for Support Structures in Hanover

infrastructure available here, such as the geotechnical testing pit and the span field (cf. Figure 1.1), affords the possibility of validating empirical, analytical, and numerical models of support structure, sub-structure and foundation elements, developing new approaches, and transferring them into design models for offshore foundation structures.

2. Large-scale physical tests

Appropriate methods for large diameter monopiles needed

Offshore monopiles are single pile foundations which, by means of deflection, transfer the significant loads imposed by wind and waves into the soil. This type of foundation is usually designed using the well-established p-y method in the design process. This is a design model which describes the pile-soil interaction with the aid of nonlinear springs. A schematic view of the p-y method principle is given in Figure 2.1. The monopile foundation is currently the most common type of foundation for offshore wind turbines.

Wind turbines of the future with rated powers above 7.5 MW and site-related increasing water depths (> 30m) require a modification of the geometric design, however, so that pile diameters of more than eight meters become necessary.

The p-y method, which is currently used, cannot be adopted for these dimensions, because it was developed for long, thin

piles with pile diameter < 1m. It is not possible simply to transfer this method to larger diameters without a proper validation – this would result in large uncertainties for the design process. These would then have to be compensated by a conservative design, which would mean more resources would be needed for the manufacturing, logistics, and installation of the monopile foundation.

To obviate the need for this, large-scale tests under conditions similar to those found offshore are conducted on the model scale of 1:13 to 1:7. This was done by designing a monopile foundation for a 7.5 MW wind turbine in the German sector

of the North Sea.

Three model piles at different scale, pile diameter from 0.61m to 1.22m, were then defined on this basis and tested in experimental investigations. The deflection curve of the reference pile (pile diameter = 8m, penetration length = 32m) was selected as the primary model design parameter. The model piles were installed in the geotechnical testing pit by impact driving, and static lateral load tests were performed. Figure 2.2 shows the final test setup at the pile with a diameter of 1.22m by way of example.

The rotations, displacements, and strains of the pile were recorded continuously during

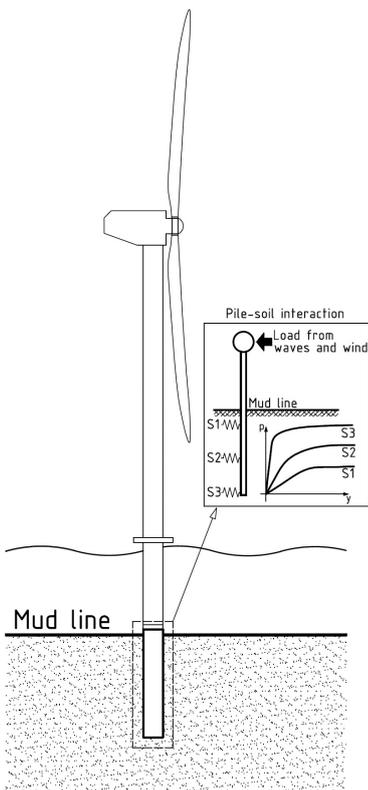


Figure 2.1: Schematic view of the p-y curves method



Figure 2.2: Static test of a large-scale monopile: pile diameter 1.22 m, pile length 7.5 m

the test. This was accomplished by means of displacement sensors at the pile head, strain gauges installed along the pile shaft, and an inclinometer chain inside the pile.

The aim in analysing and comparing pile deflection curves and load displacement curves is to provide the basis for the evaluation of the p-y method and for its potential further development to describe the structural behaviour of large-diameter monopiles.

Jacket structures – the importance of pile tensile load capacity

Jacket structures are usually used for offshore platforms, but they are also used nowadays for offshore wind turbines in water depths in excess of 30m. They are lattice support structures whereby wind and wave loads are transferred into the seabed by compression and tension piles with predominantly axial loading.

Since the dead weight of offshore wind turbines is relatively small compared to the loads resulting from wind and waves, the tensile load capacity of the pile may become the crucial design parameter for these structures.

To this end, investigations were conducted with different pile length to pile diameter ratios at the Test Center for Support Structures. The homogeneity of the model sand used here facilitated a comparison of the load-bearing capacities of six impact-driven piles. In Figure 2.3 the installation phase of the last pile is shown.

The measurements obtained could then be used to validate the semi-empirical CPT methods usually employed for estimating the axial pile load capacity. Furthermore, a range of load transfer curves were validated against the experimental results (see an example of load transfer t-z curves in Figure 2.4).

Investigation of the pile group effect

The large dead weight of offshore platforms means their pile foundations have to be designed as predominantly axially loaded compression piles which can also be arranged as a pile group, depending on the soil conditions. One example here is converter platforms, which are sometimes also constructed with two-pile groups. Unlike the situation with single piles, overlapping between the zones of influence of the piles in question and a reciprocal influence of the pile compressive load capacity cannot be excluded.

As part of an experimental campaign on the scale of 1:10 for a converter platform, the Fraunhofer IWES investigated whether and how a pile group effect makes itself felt. Both single piles and pile groups were installed in the geotechnical testing pit by impact ramming and their axial compressive load capacity was investigated.

Subsequently, the pile group effect was estimated by means of three commonly used approaches involving settlement criteria, initial and final stiffness, and creep behaviour. Figure 2.5 shows the two-pile group arrangement under compression and the qualitative experimental curves.

Testing of installation methods with mitigated noise levels

The geotechnical testing pit also offers the possibility to investigate both novel and existing installation methods. This is particularly advantageous for offshore pile foundations, since in addition to the pure material costs, factors such as time involved and installation effects also play a crucial role in the pile bearing capacity.

The wind turbine industry is looking for alternatives to pile impact driving, the most widely used system, since the noise emissions produced in this process do not comply with the BSH (German Federal Maritime and Hydrographic Agency) specifications and incur additional costs because noise mitigation measures are necessary.

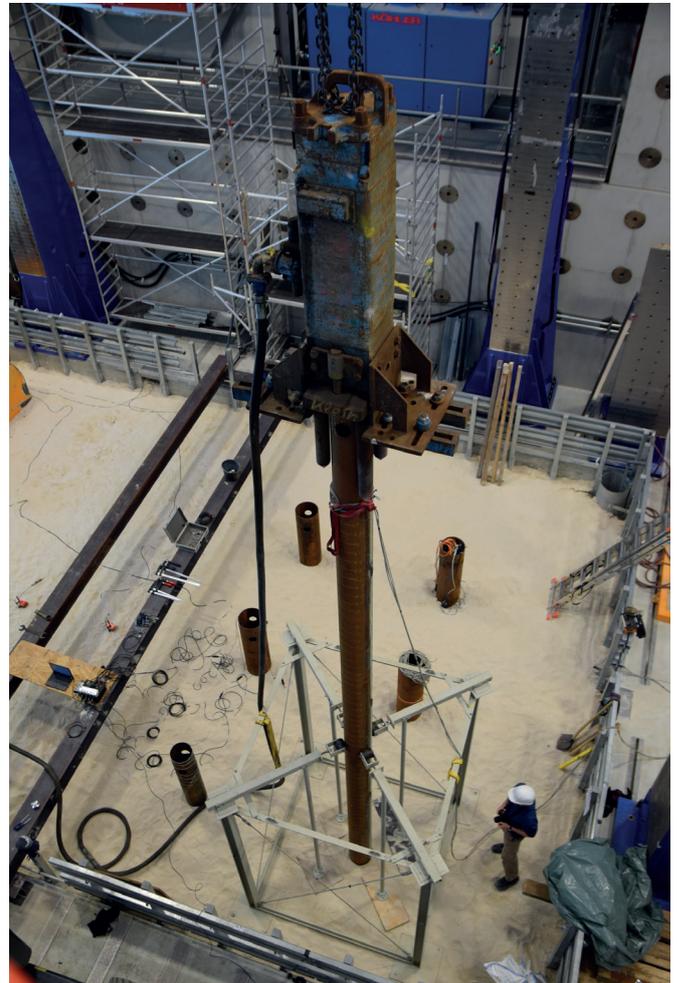


Figure 2.3: Installation of a large-scale pile foundation for jacket structures

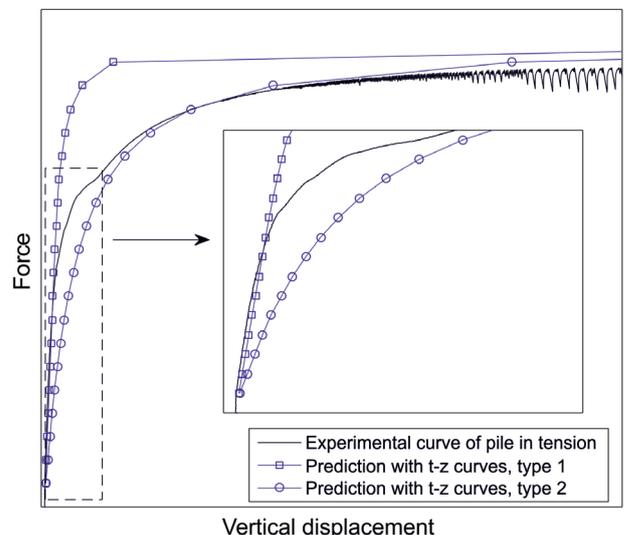


Figure 2.4: Validation of load transfer curves for axially loaded piles against experimental data

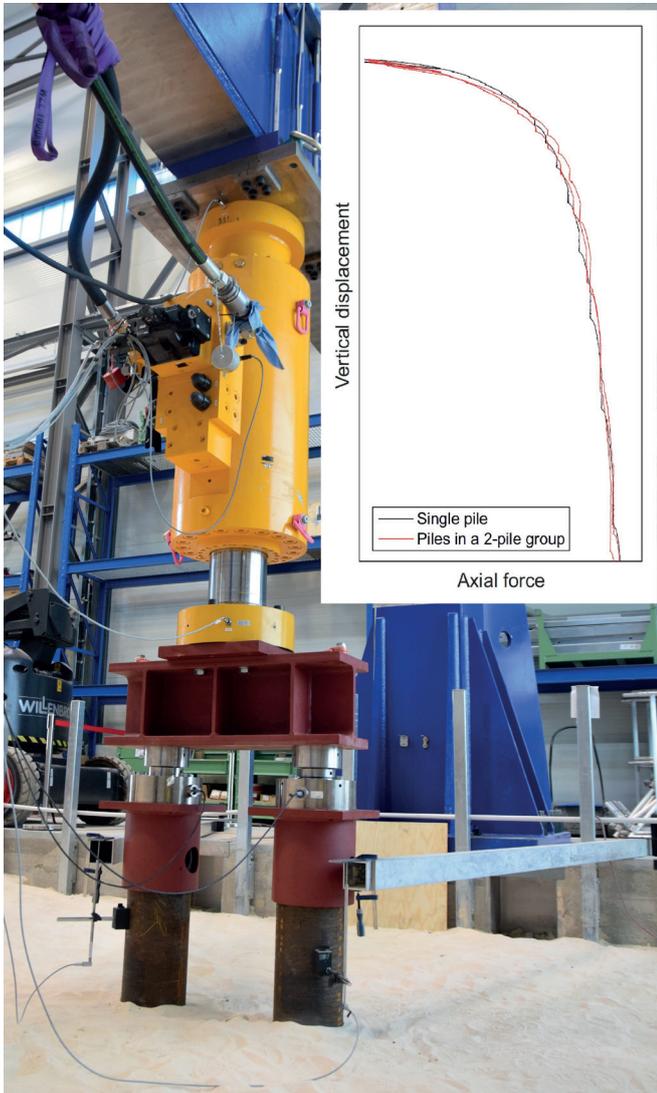


Figure 2.5: Large-scale two-pile group statically tested with qualitative load-displacement curves of single piles and pile groups

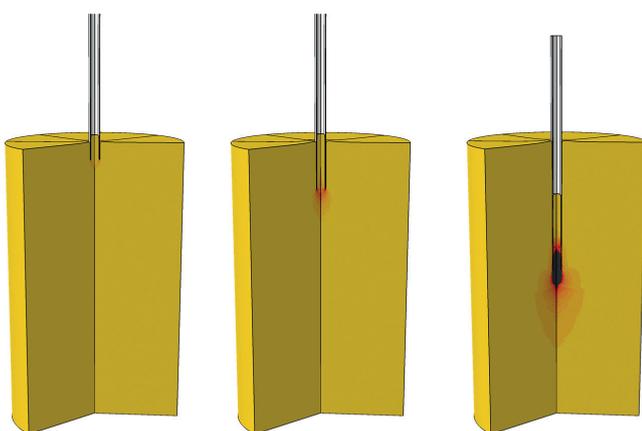


Figure 2.6: Advanced numerical model of a pile installation in sand

Vibratory-driven piles are a possible cost-effective alternative, because the time expenditure and the noise emissions here are lower than for impact pile driving. However, the effect of the installation on the load-bearing capacity has not yet been clarified for piles with lateral or vertical loading.

In order to include the effect of the installation on the load-bearing capacity of the pile accurately, a more detailed description of the soil at the particular location is required. This requires comprehensive investigations of the soil parameters through triaxial and direct shear tests, cone penetration test campaigns and pore water and soil pressure measurements to derive the local effects of the installation method under consideration.

Axial and lateral load tests conducted afterwards allow a statement to be made about the effect of the installation method on the global load-bearing capacity of the pile. With pile installation, the key is the representation of the installation process and the correct representation of the pile-soil interaction.

By simulating the stress state which exists after the pile has been installed with the aid of numerical models, the load-bearing behaviour of the pile foundations can be analysed in more detail. The simulation of the actual installation process is not trivial, however. A particular challenge here is the optimal description of the physical behaviour of the soil.

This determines which material model is suitable. Furthermore, the large deformations and the associated large distortions of the finite element mesh mean the simulation of the installation process comes up against the limits of the classical finite element method.

To avoid large element distortions, the Coupled Euler-Lagrange method (CEL) is used to simulate the installation of pile foundations. This method combines the advantages of the conventional Lagrangian formulation and those of the Eulerian formulation, which is the one usually used in fluid dynamics and allows a free motion of the continuum through the Eulerian mesh, which is fixed in space.

Combining the two viewpoints in this way allows a material flow in the soil continuum without causing mesh distortions. Figure 2.6 shows the result of a numerical simulation of a pile installation by way of example.

A comprehensive optimisation and validation of the numerical model is conducted with the aid of further large-scale tests in order to then be able to simulate the offshore installation process realistically. These results not only enter directly into the design process, but can also serve to derive, optimise, and validate design models with lower complexity level.

3. Summary and outlook

Which model approach can be used when and where in the design process depends on the project parameters and on the experience and the judgment of the engineer responsible. A semi-empirical approach may already be sufficient for an initial design, for example. If the foundation system has to have an economical design, however, a more complex approach may be needed.

Large-scale geotechnical tests are essential to examine different design approaches, validate models at different levels of complexity and obtain key information for a cost-effective design of offshore wind foundations. This is also of great interest for the issues of the future, in particular, with respect to novel developments such as anchors for floating offshore wind turbines, bucket foundations, and offshore helical piles.

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