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Application of the PISA framework to the design of offshore wind turbine monopile foundations

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Abstract

The recently-completed **PISA** (**PI**le **S**oil **A**nalysis) research project aimed to improve the design of monopile foundations for offshore wind turbines (OWT), focusing on laterally-loaded monopiles with length-to-diameter (*L/D*) ratios between 2 and 6 [2,4]. The project resulted in a novel one-dimensional (1D) design model which overcomes certain limitations in current practice. The PISA 1D design model facilitates rapid design calculations, based on the use of Timoshenko beam theory to represent the monopile. The soil response is modelled via soil reactions, applied along the shaft and at the base of the monopile. The soil reaction curves are determined using a series of three-dimensional (3D) finite element (FE) calibration calculations, performed prior to the design process, spanning a representative design space.

A new software tool called **PLAXIS MoDeTo** (**Mo**nopile **De**sign **To**ol) has been developed based on this design procedure. This design tool facilitates the automatic generation and calculation of the 3D FE calibration models, the optimisation of the soil reaction curves and the conduct of the 1D design calculations.

Objectives

- Demonstrate the practical application of the PISA method to a design case for a clay soil profile that is typical of North Sea sites.
- Provide an indication of the efficiency and accuracy of the PISA approach.
- Demonstrate a new design framework which provides opportunities for more efficient procedures for the optimised design of monopile foundations.

Methods

A calibration set consisting of pile geometries that span a representative design space is initially established (Tab. 1). For these, 3D FE calculations are conducted, using the software PLAXIS (Fig. 1), to determine the performance of each calibration pile. Soil reaction curve data extracted from the 3D models are optimized and parameterized; they are then used to calibrate the 1D model. The calibrated model is used to conduct (rapid) design calculations to determine an optimum monopile geometry, subject to the specified design constraints. Once a final design has been obtained, the validity of the 1D model is confirmed using an additional 3D FE calculation.

Clay behaviour is modelled in the 3D FE analysis using the NGI-ADP model [1]. The assumed ground conditions correspond to an idealized offshore clay till soil deposit based on the site at Cowden, UK [4]. Loads and turbine characteristics have been assumed according to the NREL 5 MW baseline OWT [3].

Tab. 1 Calibration pile set.

3D FE models	*L* (m)	*D* (m)	*t* (mm)	*h* (m)
FEM 1	18.0	6.0	60	20.0
FEM 2	24.0	6.0	60	20.0
FEM 3	18.0	6.0	60	110.0
FEM 4	24.0	6.0	60	110.0
FEM 5	24.0	8.0	80	20.0
FEM 6	32.0	8.0	80	20.0
FEM 7	24.0	8.0	80	110.0
FEM 8	32.0	8.0	80	110.0

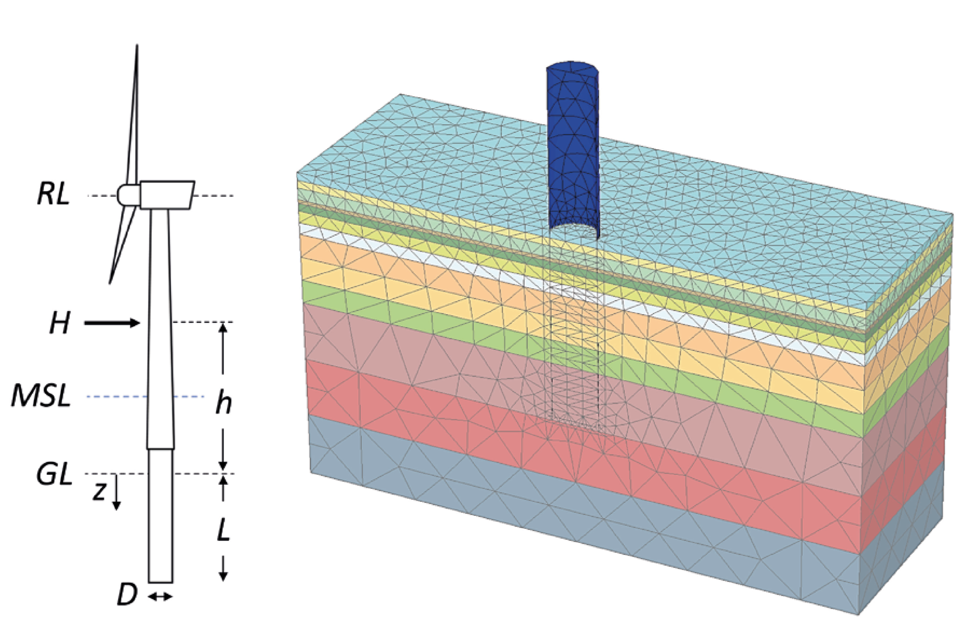

Fig. 1 Schematic representation of the NREL 5 MW OWT (left; *RL*: rotor level, *MSL*: mean sea level, *GL*: ground level, *H*: resultant horizontal load), and a 3D FE model (FEM 2) in PLAXIS (right).

The specified design criteria for the current example are (Fig. 1): monopile diameter, *D*, and loading eccentricity, *h*, are fixed at 7.5 m and 60 m respectively. The embedded length, *L*, and the wall thickness, *t*, are to be determined subject to the following constraints:

- A resultant horizontal design load, *H*, of 17 MN is applied at height *h*.
- The stress in the monopile must not exceed 325 MPa at any point when the design load is applied; the pile displacement at ground surface must be less than 0.1×*D*.
- The wall thickness of the monopile is allowed to vary along its length to minimise weight. The minimum admissible thickness is 50 mm.

After several design iterations, the dimensions of the monopile are chosen as: *L* = 30.0 m and a thickness profile divided in two sections, *t* = 0.075 m from *z* = 0 m to *z* = 15 m and *t* = 0.060 m from *z* = 15 m to *z* = 30 m.

Results

The reliability of the 3D FE calibration is checked against published numerical data [2], indicating a good match for the response of a short (*L/D* = 2) pile founded in the same ground conditions as in the current example (Fig. 2). The calibrated 1D model provides an efficient means of selecting monopile dimensions (embedded length and pile wall thickness). The depth variation of the maximum vertical normal stress in the pile (σ_z) verifies that the stress design criterion is successfully met (Fig. 3). A convergence study indicates that the 1D model is highly robust; remarkably few elements are needed to represent the embedded pile to obtain accurate results (Fig. 4). A check calculation using the final monopile design parameters – conducted using 3D FE analysis – indicates a close match with the 1D model (Fig. 5); this confirms the robustness of the design approach.

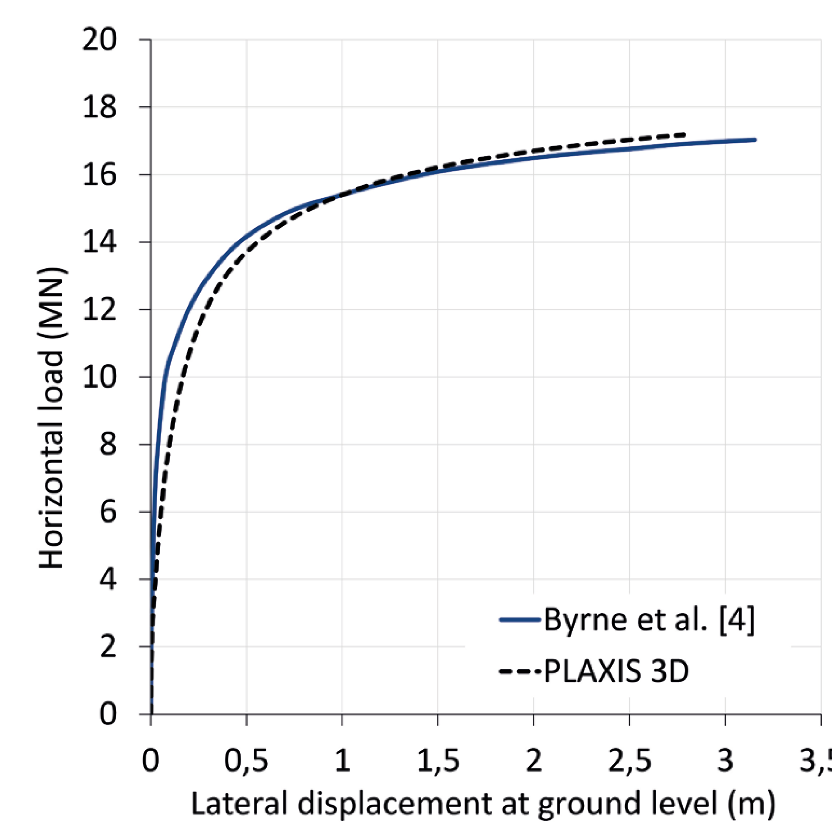

Fig. 2 Reliability check of the 3D FE calibration against published data [4].

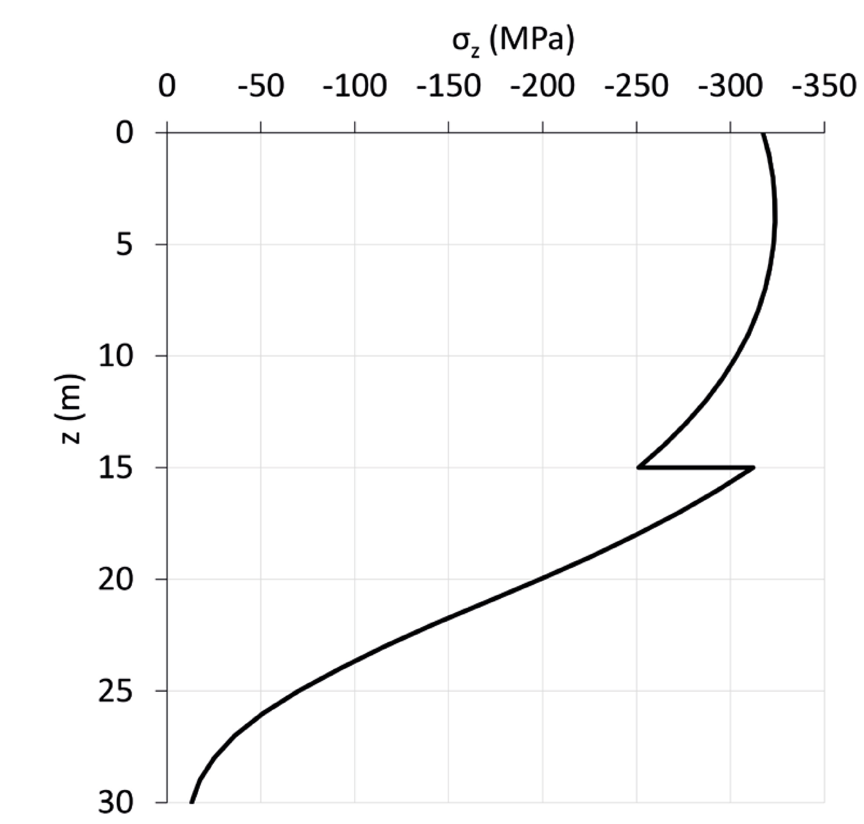

Fig. 3 Depth variation of the maximum vertical normal stress (σ_z) in the pile.

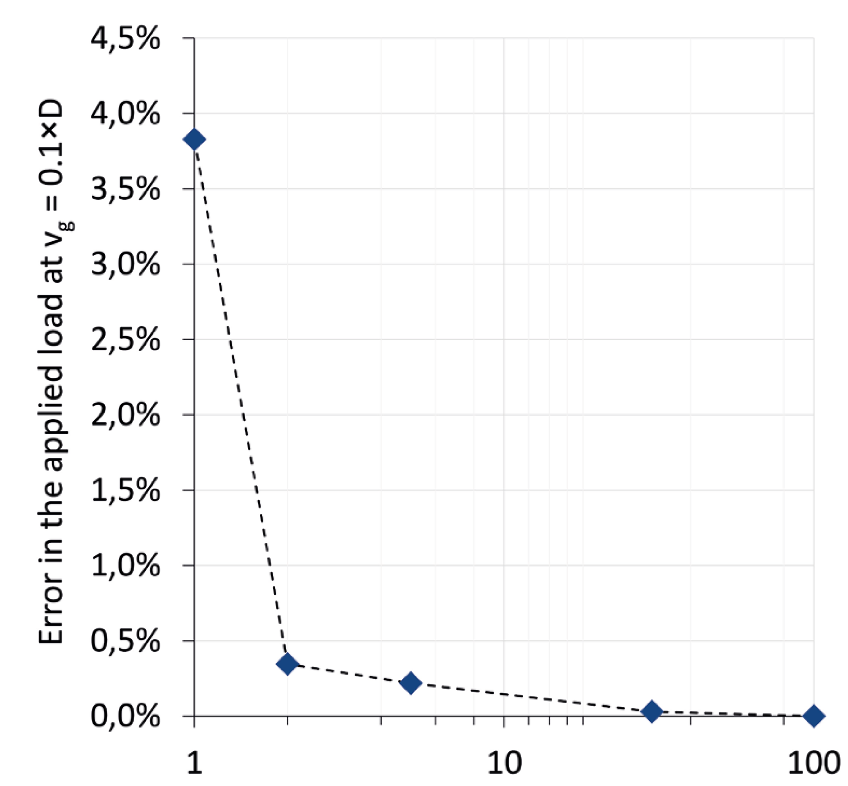

Fig. 4 1D FE model convergence study results (v_g: lateral displacement at ground level).

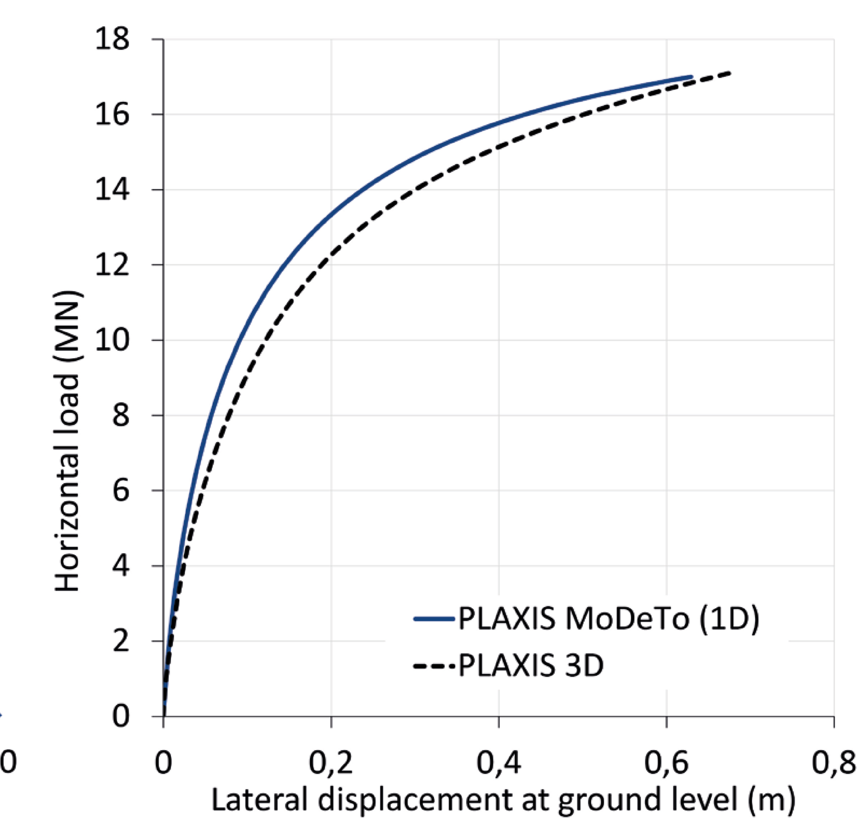

Fig. 5 Comparison between the 1D model and a 3D FE model for the final design.

Conclusions

- A novel design methodology, developed during the PISA research project, has been incorporated into a new design tool, called PLAXIS MoDeTo.
- Typical soil conditions and monopile geometries are adopted in a design study to demonstrate the capabilities of the PISA design framework.
- A small number (eight in the current case) of 3D FE calculations is needed to calibrate the 1D model in the representative design space. The 3D FE models are validated against published numerical data.
- The calibrated 1D model provides an efficient means of conducting design calculations.

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