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

Panagoulias, Stavros; Brinkgreve, Ronald; Minga, Elini; Burd, Harvey; McAdam, R.

Important note
To cite this publication, please use the final published version (if applicable).
Please check the document version above.

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

S. Panagoulias[1], R.B.J. Brinkgreve[2], E. Minga[3], H.J. Burd[4], R.A. McAdam[5]

Abstract

The recently-completed PISA (PIle Soil Analysis) 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. 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 (Monopile Design Tool) 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.

Keywords: PISA, PLAXIS MoDeTo, offshore wind, offshore foundations, monopile design

1. Introduction

As recently announced by the Commission, the European Parliament and the Council, the European Union has set the renewable energy target to 32% by 2030. Apart from the global need for decarbonisation of heating, transportation and any industrial applications, another driving factor for this decision was the significant recent advances in the cost reduction of technologies and processes related to renewables. As part of this endeavour towards a more sustainable energy system, the PISA (PIle Soil Analysis) joint industry research project [4, 5, 6, 9, 11], run through the Carbon Trust's Wind Accelerator Programme in the United Kingdom, and primarily coordinated by Ørsted (formerly DONG Energy), aimed to develop a new design framework for offshore wind monopile foundations subjected to lateral loading. The project focused on large-diameter monopiles of low length-to-diameter (L/D) ratios (between 2 and 6), to represent the expected dimensions of monopile foundations for the 10MW+ next generation wind turbines.

The design method currently being used by the conventional design practice, on the basis of the recommendations of the offshore design codes [2, 7], referred to as the '*p-y*' method, has been

---

[1] Researcher, Plaxis bv, Delft, the Netherlands, s.panagoulias@plaxis.com
[2] Associate Professor, Delft University of Technology, Delft, the Netherlands, R.B.J.Brinkgreve@tudelft.nl
[3] Postdoctoral Research Assistant, University of Oxford, Oxford, United Kingdom, eleni.minga@gmail.com
[4] Associate Professor, University of Oxford, Oxford, United Kingdom, harvey.burd@eng.ox.ac.uk
[5] Associate Professor, University of Oxford, Oxford, United Kingdom, ross.mcadam@eng.ox.ac.uk

shown to have limitations when used to design large diameter monopiles. This is mainly because the *p-y* method was developed from field test results of long slender piles [6]. The PISA project resulted in a novel design methodology which makes use of a one-dimensional (1D) finite element (FE) model to simulate monopiles under lateral loading. This new design approach has been validated via a series of field tests and is shown to have considerable benefits over the conventional *p-y* design method [4, 5, 6].

This innovative design method has been implemented in a software tool, the PLAXIS MoDeTo (Monopile Design Tool). The main objective of the current study is to demonstrate the practical application of the PISA method, via PLAXIS MoDeTo, to a design case for a clay soil profile that is representative of North Sea sites. The new design framework, which provides opportunities for more efficient procedures for the optimised design of monopile foundations, is discussed, providing an indication of the efficiency and accuracy of the PISA design methodology.

2. Design methodology

The PISA design methodology is based on rapid 1D FE design calculations. Timoshenko beam theory is employed to model the response of the monopile under lateral loading [10]; this type of formulation allows for shear strains to be considered in the overall pile response. Shear strains are likely to be significant for low L/D [4, 6]. In addition to the distributed lateral reaction forces (p) developed between the monopile and the soil along the shaft (which forms the basis of the conventional *p-y* method), three additional soil reaction components are considered in the 1D FE framework, namely the distributed moment along the shaft (m), the horizontal reaction force at the base (H_B) and the moment reaction at the base (M_B). The term 'soil reaction curves' is employed to represent the functions that relate each one of the non-linear soil reaction component (force or moment) to the local pile deformation (displacement v or rotation ψ). Fig. 1 illustrates the four soil reaction components, under a horizontal force (H) and a moment (M) applied at a certain height (h) above the ground level. Recent research has shown that the lower the value of L/D, the more significant the effect of the three additional components becomes [4, 6].

The suggested design methodology consists of two distinctive approaches, namely the 'rule-based design' and the 'numerical-based design'. Geotechnical professionals may follow one of these two approaches, depending on the phase of the project and the required level of detail in the design. Both approaches are discussed in the following sections. In the present study, the numerical-based design approach is adopted to demonstrate the full potential of this novel design methodology.

2.1 Rule-based design

The rule-based design approach is principally intended for concept or preliminary design. In this approach, the 1D model is calibrated with data that are published in literature, retrieved from existing numerical-based calibrations or provided by consultants. If using this approach, it is of considerable importance that the selected 1D model calibration data correspond to a soil profile that resembles the soil conditions for which the monopile is to be designed. For that purpose, standard soil investigation data may be used. Attention should also be paid to the various loading conditions and monopile geometries to be considered in the design. The original calibration data needs to cover the anticipated design space to obtain a robust design.

2.2 Numerical-based design

The numerical-based design approach is more likely to be applicable for detailed design. It could also be part of the preliminary design phase if the required soil and load data are available. In this approach, a series of detailed 3D FE analyses is employed to calibrate the 1D FE model. High quality soil data, obtained via site investigation and/or laboratory testing, should be used to calibrate the soil constitutive models employed in the 3D FE calculations. Each 3D FE calibration model represents a separate design scenario. A variation of the main monopile geometrical components (*D, L, t, h*) should be considered to cover the expected range of values for the design study. The resulting parameter variation is referred to as the 'design space'. Relevant experience indicates that eight to ten geometrical variations (i.e. calibration models) are sufficient to calibrate the 1D model for a typical design space.

The results of the 3D FE analyses are used to calibrate the 1D FE model. The latter is then used to conduct rapid 1D analyses to optimise the monopile design based on the assumed design criteria and constraints. Once the design optimisation has been completed, usually after multiple 1D FE runs, the 1D analysis for the chosen final design should be compared with a separate detailed 3D FE calculation to confirm the 1D numerical results and finalise the design procedure.
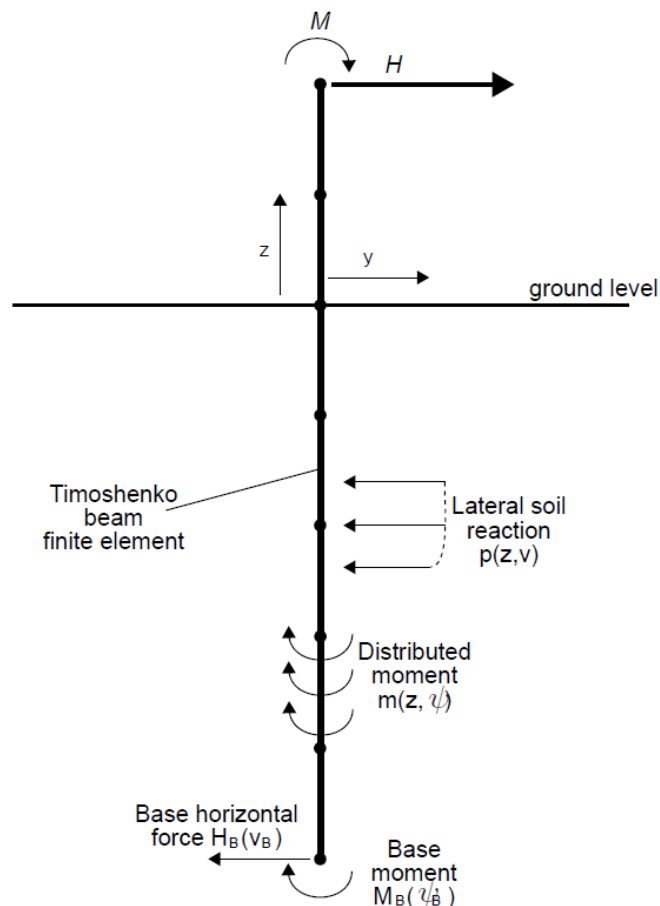

Fig. 1 Components of the 1D FE model (based on [10]).

The numerical-based design approach offers the opportunity to develop a global database of calibration data sets which could be accessed and used by the geotechnical engineering

community around the globe. Each calibration data set should have a unique signature, based on the encountered soil and load conditions, and the design space employed during its generation. The database should also be expandable, such that newly derived data sets can be added and used. Quality assurance procedures could be applied to ensure that the imported data suffice certain quality criteria.

3. Design aspects

An example application of the numerical-based design approach, for a representative offshore clay site, is discussed below. First the soil conditions are established based on literature (Sec. 3.1). A set of 3D FE calibration models is the defined to span the design space (Sec. 3.2). The 3D numerical results are the used to calibrate the 1D FE model and optimise the final design, based on certain specified design criteria (Sec. 3.3).

3.1 Soil conditions

Soil conditions representative of an offshore North Sea glacial till site are employed in the present study. Specifically, the adopted soil profile is based on the site at Cowden, United Kingdom, and soil data published in literature [11] are used to calibrate the 3D FE models. The Cowden site mainly consists of stiff over-consolidated glacial clay tills deposits. The idealised clay till profile presented by Zdravković et al. [11] is considered to be a characteristic North Sea clay site, based on these data.

Clay behaviour is modelled in the 3D FE calibration analyses using the NGI-ADP model [1] under undrained loading conditions. To simulate the variation of the main soil parameters as reported in [11], thirteen soil (sub) layers are used. Fig. 2 depicts the adopted idealised clay till profiles of the lateral earth pressure coefficient at rest (K_0), the undrained shear strength in triaxial compression ($s_{u,TXC}$) and the small-strain stiffness shear modulus (G_0). The corresponding profiles in PLAXIS MoDeTo are also plotted for comparison.
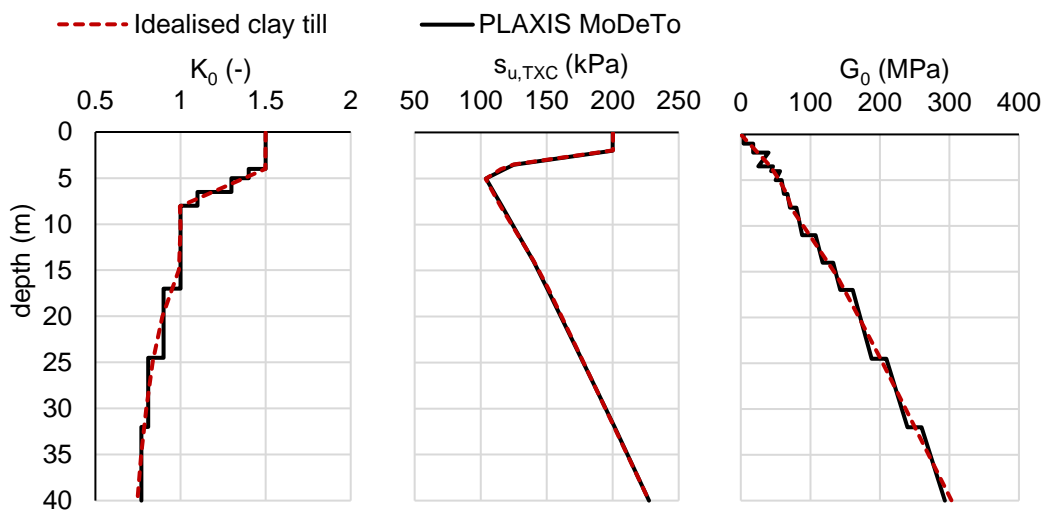

Fig. 2 Idealised clay till [11] and the corresponding PLAXIS MoDeTo profiles for the lateral earth pressure coefficient at rest (a), the undrained shear strength in triaxial compression (b) and the small-strain stiffness shear modulus (c).

3.2 Calibration models

A calibration set consisting of eight pile geometries that span a representative design space is initially established (Tab. 1). The variation of the monopile embedded length (L) and outer diameter (D) is based on preliminary design calculations, considering the soil profile in Sec. 3.1. The monopile wall thickness (t) is chosen to vary as a constant ratio (1/100) of the selected outer diameter. The height above ground level (h) at which the horizontal excitation is applied, is determined based on the assumed load conditions. The mean sea level (MSL) is set at 20.0 m above the ground level (Fig. 3a). Two values of h are considered to simulate the minimum and the maximum elevation of the lateral loading, considering the wave (h equals 20.0 m) and the wind (h equals 110.0 m) actions correspondingly. It is noted that the load eccentricity, h, for typical design analyses will likely fall within these two bounds. Loads and turbine characteristics have been assumed according to the NREL 5 MW baseline offshore wind turbine [8]. This turbine support structure is defined by the National Renewable Energy Laboratories (NREL) specifically for use in research.

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

For each of the calibration pile geometries, 3D FE calculations are conducted to compute the performance of the monopile in PLAXIS 3D (2018 version). Fig. 3b illustrates the model geometry and the finite element mesh of the calibration model FEM 2, which is concerned as a typical example of the analysed cases. Only half the 3D model is simulated, taking advantage of the model symmetry. The finite element mesh consists of 10-noded (quadratic) tetrahedral finite elements [3]. To enhance results accuracy, mesh refinement is applied to an area which is extended to 0.30 diameters around and below the monopile. In total about 40000 mesh elements are used for the depicted case.

The pile is modelled with 5-noded plate elements, on the basis of Mindlin's theory [3]. Conventional values of steel material properties are assigned to the plate elements. Poisson's ratio equals 0.3, while Young's modulus equals 210 GPa. The monopile is weightless as the design procedure focuses on the response under lateral loading. Also, installation effects are not taken into account. Interface elements are used at the outer monopile surface and at the bottom to model the pile-soil interaction. Soil reactions – required to calibrate the 1D FE model - are extracted directly from these interface elements.

Soil reaction data extracted from the 3D FE models are optimized and parameterised; they are then used to calibrate the 1D FE model [10]. The calibrated model is used to conduct (rapid) design calculations to determine an optimum monopile geometry, subject to the specified design constraints (Sec 3.3). Once a final design has been obtained, the validity of the 1D model is confirmed using an additional 3D FE calculation (Sec. 5).
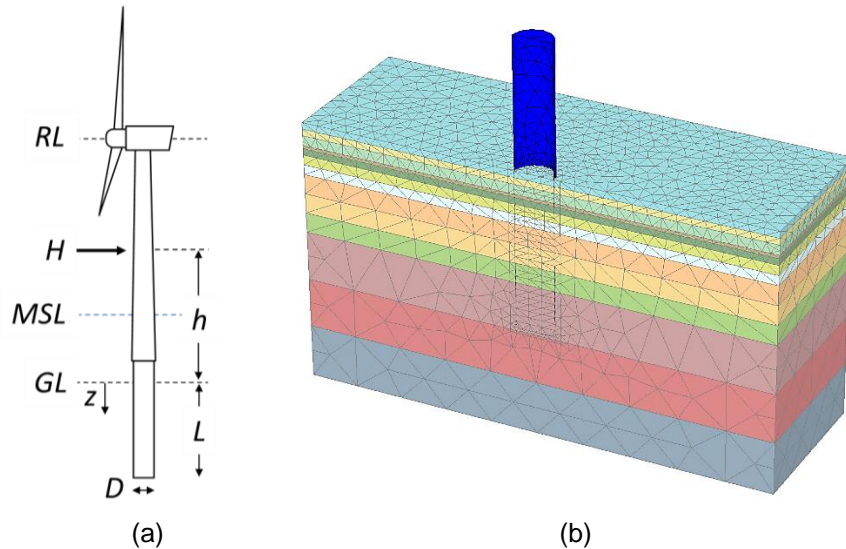

Fig. 3 Schematic representation of the NREL 5 MW OWT (a); RL: rotor level, MSL: mean sea level, GL: ground level, H: resultant horizontal load, and the 3D calibration model FEM 2 (b).

3.3 Design criteria

To illustrate the application of the 1D model in design, a single monopile design scenario is considered for the following conditions:

- Monopile outer diameter (D) equal to 7.5 m;
- Loading eccentricity (h) equal to 60.0 m.

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 equal to 60.0 m above the ground level;
- The stress in the monopile must not exceed 325 MPa at any point when the design load is applied;
- The pile displacement at ground level (v_g) must be less than 0.1D when the design load is applied;
- The wall thickness (t) of the monopile may vary along its length to minimise weight. The minimum acceptable thickness is 50 mm.

4. Numerical validation

The reliability of the 3D FE calibration is checked against published numerical data [6]. The comparison in terms of horizontal reaction force (H) versus mean lateral displacement at

mudline (v_g), indicates a very good match for the response of a short (D = 10.0 m, L/D = 2) pile founded in the same ground conditions as in the current example (Fig. 4a). The differences in the response of the long pile (D = 10.0 m, L/D = 6), presented in Fig. 4b, may be attributed to potential mismatch between the assumed stiffness and strength profiles. Additionally, it is noted that the soil constitutive model employed in the current study has a different framework to the extended Modified Cam Clay model employed in [11].
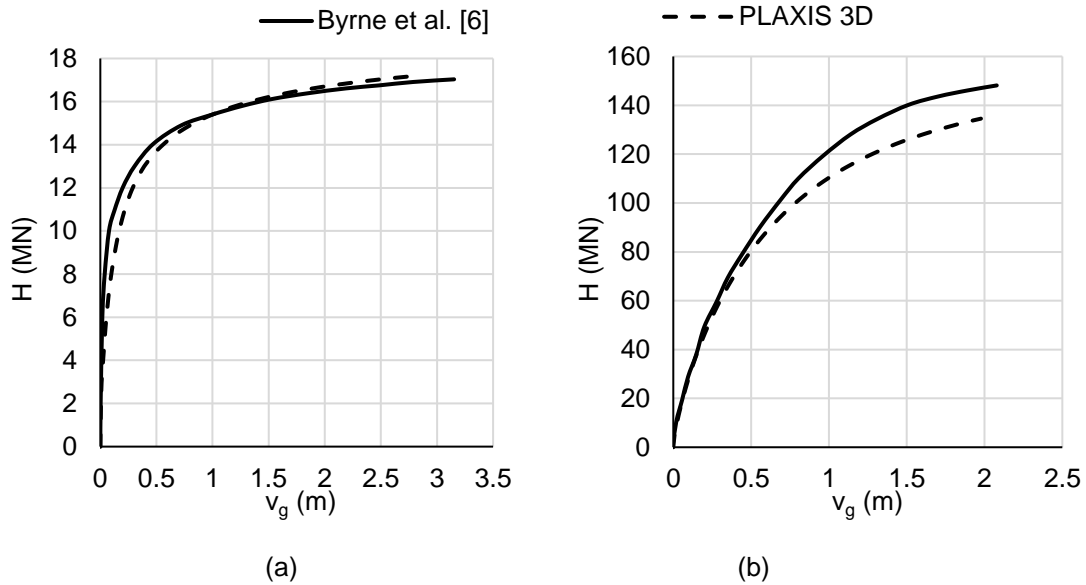

(a)

(b)

Fig. 4 Reliability check of the 3D FE calibration against published data [6] for a short (D = 10.0 m, L/D = 2) (a) and a long (D = 10.0 m, L/D = 6) (b) monopile.

5. Design optimisation

The set of eight 3D calibration models presented in Tab. 1 was used to calibrate the 1D FE model. The latter was used to obtain a final design configuration, given the design criteria presented in Sec. 3.3. After several design iterations, the dimensions of the monopile are chosen as:

- Embedded length (L) equal to 30 m and
- Thickness profile divided in two sections:
    o t = 0.075 m from z = 0 m to z = 15 m;
    o t = 0.060 m from z = 15 m to z = 30 m.

Fig. 5a depicts the dimensionless design space (L/D against h/L) of the 3D FE models used for calibration. The final monopile geometry selected via 1D analyses falls within the employed design space. A check calculation using the final monopile design parameters, conducted via 3D FE analysis, indicates a close match with the 1D model (Fig. 5b). This confirms the validity of the 1D analysis and the robustness of the applied design approach.

The depth variation of the maximum vertical normal stress in the pile (σ_z) verifies that the stress design criterion is successfully met (Fig. 5c). In addition, a convergence study indicates that the 1D model is highly robust as remarkably few elements (less than 2) are needed to represent the embedded pile to obtain accurate results (Fig. 5d).

The calibrated 1D model provides an efficient means of selecting monopile dimensions (embedded length and pile wall thickness). Each 1D FE calculation lasts few seconds, whereas, if the design optimisation was to be done via 3D modelling, a single 3D FE calculation may take up to several hours.
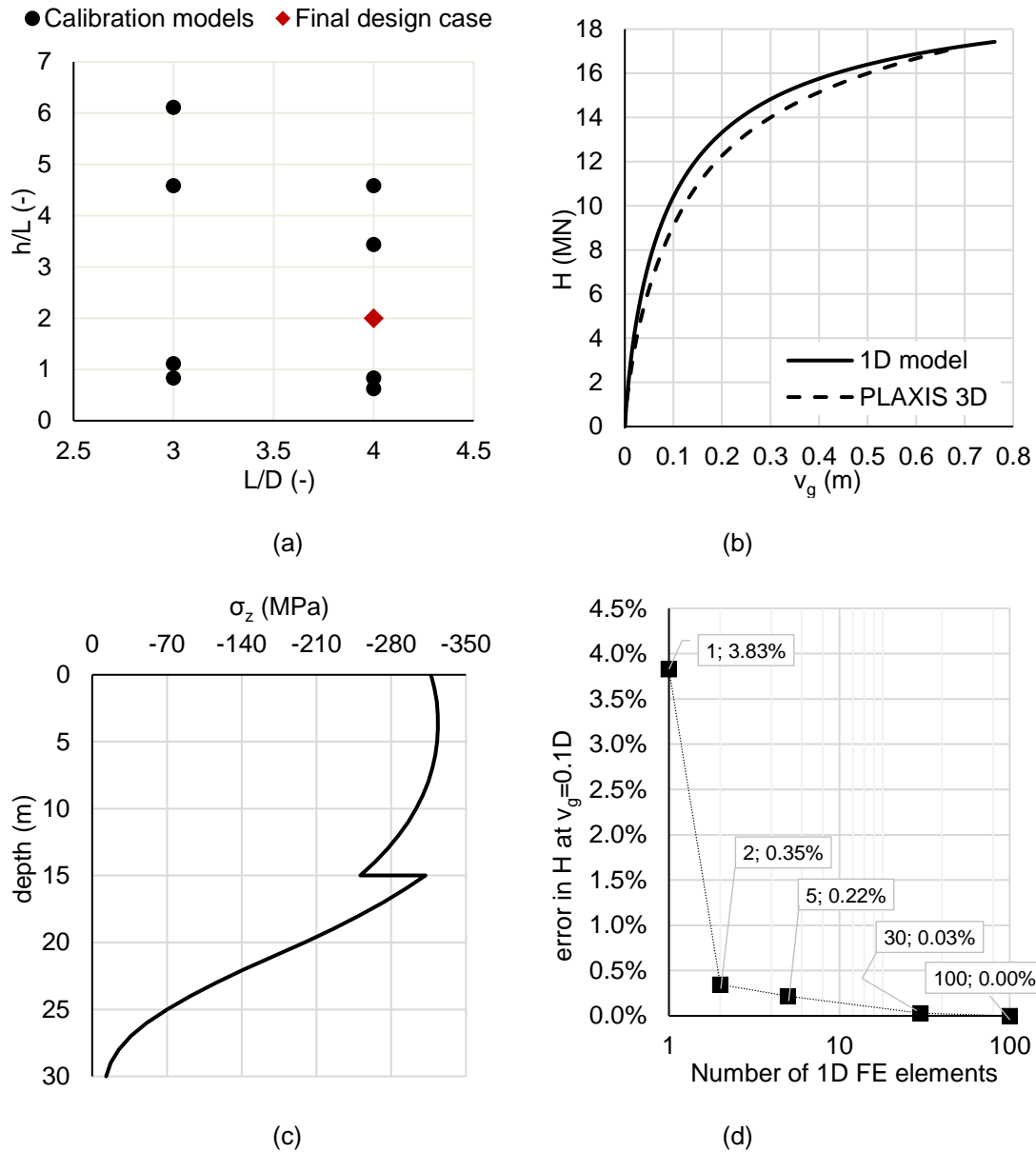

(a)

(b)

(c)

(d)

Fig. 5 Final design case against the used calibration cases within the *h/L* versus *L/D* design space (a); comparison between the 1D FE model results and a 3D FE model for the final design (b); depth variation of the maximum vertical normal stress (σ_z) in the pile (c); 1D FE model convergence study results (d).

6. Conclusions

A novel design methodology, developed during the PISA joint industry research project, has been incorporated into a new design tool, called PLAXIS MoDeTo. The new design approach is proven to be advantageous against the conventional *p-y* method, considering the design of

monopile foundations under lateral loading. Two distinctive design approaches (rule-based and numerical-based) may be followed based on the level of detail required at the certain phase of a project. Following the numerical-based design, typical soil conditions and monopile geometries are adopted in this 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. As indicated by the results of the design process, the calibrated 1D model provides an efficient means of conducting design calculations.

7. References

[1]. Andersen L, Jostad HP. Application of an anisotropic hardening model for undrained response of saturated clay. In Proc. *Numerical Models in Geomechanics - NUMOG VII*. Graz, Austria, 1999.

[2]. API. *RP 2A-WSD - Recommended practice for planning, designing and constructing fixed offshore platforms*. American Petroleum Institute, Washington, United States of America, 2010.

[3]. Brinkgreve RBJ, Kumarswamy S, Swolfs WM. *PLAXIS manual 2018*. Plaxis bv, Delft, the Netherlands, 2018.

[4]. Burd HJ, Byrne BW, Mcadam RA, Houlsby GT, Martin CM, Beuckelaers WJAP, Zdravković L, Taborda DMG, Potts DM, Jardine RJ, Gavin K, Doherty P, Igoe D, Skov Gretlund J, Pacheco Andrade JM, Muir Wood A. Design aspects for monopile foundations. In Proc. *TC209 Workshop, 19th International Conference on Soil Mechanics and Geotechnical Engineering (ICSMGE)*, pp. 35-44, Seoul, Korea, 2017.

[5]. Byrne BW, Mcadam RA, Burd HJ, Houlsby GT, Martin CM, Beuckelaers WJAP, Zdravković L, Taborda DMG., Potts DM, Jardine RJ, Ushev E, Liu T, Abadias D, Gavin K, Igoe D, Doherty P, Skov Gretlund J, Pacheco Andrade M, Muir Wood A, Schroeder FC, Turner S, Plummer MAL. PISA: new design methods for offshore wind turbine monopiles. In Proc. *Offshore Site Investigation and Geotechnics, SUT*, vol. 1, pp. 142-161, London, United Kingdom, 2017.

[6]. Byrne BW, McAdam R, Burd HJ, Houlsby G, Martin C, Zdravković L, Taborda DMG, Potts DM, Jardine RJ, Sideri M, Schroeder FC. New design methods for large diameter piles under lateral loading for offshore wind applications. In Proc. *3rd International Symposium on Frontiers in Offshore Geotechnics (ISFOG 2015)*, Oslo, Norway, 2015.

[7]. DNVGL-ST. *DNVGL-ST-0126: Support structure for wind turbines*. Det Norske Veritas Germanischer Lloyd, Oslo, Norway, 2016.

[8]. Jonkman J, Butterfield S, Musial W, Scott G. *Definition of a 5-MW reference wind turbine for offshore system development*. National Renewable Energy Laboratory, Golden, CO, Technical Report No. NREL/TP-500-38060, 2009.

[9]. Panagoulias S, Hosseini S, Brinkgreve RBJ. An innovative design methodology for offshore wind monopile foundations. In Proc. *26th European Young Geotechnical Engineers Conference*, Graz, Austria, 2018.

[10]. Panagoulias S, Brinkgreve RBJ, Zampich L. *PLAXIS MoDeTo manual 2018*. Plaxis bv, Delft, the Netherlands, 2018.

[11]. Zdravković L, Taborda DMG, Potts DM, Jardine RJ, Sideri M, Schroeder FC, Byrne BW, McAdam R, Burd HJ, Houlsby GT, Martin CM. Numerical modelling of large diameter piles under lateral loading for offshore wind applications. In Proc. *3rd International Symposium on Frontiers in Offshore Geotechnics (ISFOG 2015)*, vol. 1, pp. 759-764, Oslo, Norway, 2015.