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Comparative Concept Design Study of Laterally Loaded Monopiles

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Abstract. Offshore wind turbine generators (WTG) are commonly founded on single large diameter piles, named monopiles. These monopiles are subjected to significant lateral loads and thereby sizeable overturning bending moments mainly due to action of wind and wave forces; thus the critical geotechnical design situation for monopiles supporting WTGs is often related to lateral loading conditions. The Pile Soil Analysis (PISA) joint industry research project [1] has recently proposed a monopile design method which encompasses finite element (FE) calculations under a specific design framework. Soil reaction curves that are crucial for monopile design (i.e. lateral force and moment reactions along the shaft and at the base of the pile) are derived from FE calculations, subsequently calibrated and entered into a 1D model which is then used for design optimisation. This method is implemented within the PLAXIS MoDeTo (Monopile Design Tool) software. This paper presents results of a concept monopile design study under lateral monotonic loading with the use of the PLAXIS MoDeTo method.

1. Introduction

Planning and development of offshore wind farm parks is booming during the past few years, as they are considered a key element in meeting renewable energy and carbon emission targets. The majority of both existing and planned offshore WTGs are supported by monopiles, which are single driven foundation piles of large diameter. Monopiles supporting WTGs are subjected to significant lateral forces and overturning moments from, for example, vessel impact and environmental loads induced by wind, waves and currents. In principle, the critical geotechnical design situation for wind turbine monopile foundations is related to lateral loading conditions.

Current design standards for long slender piles [2] recommend the p-y approach for assessing pile lateral response. In this method, based on the Winkler assumption [3], the soil surrounding the pile is modelled as a set of uncoupled non-linear elasto-plastic springs, which define the lateral pressure (p) applied to the pile at a given depth, as a function of the lateral pile displacement (y). The p-y method was developed and empirically validated for piles with high aspect ratios (length L over diameter D) exceeding 15. However, monopiles usually have a low L/D aspect ratio of less than 8, and are therefore intermediate foundations, for which distributed moment along the shaft (m), base shear (H_B) and base moment (M_B) will also influence the lateral behaviour of the monopile. Historic industry practice for concept monopile design was to modify the p-y curve formulations to account for large diameter effects or to derive them from finite element (FE) calculations.

The Pile Soil Analysis (PISA) joint industry project [1] has developed and proposed a new design framework for concept monopile design. The soil reaction curves (p-y, m-ψ, H_B-y and M_B-ψ, where ψ is rotation) are extracted from 3D FE analyses and used in a 1D Timoshenko beam model representing the monopile (Figure 1). A software tool called PLAXIS MoDeTo (Monopile Design Tool) has been developed for the purpose of monopile foundation design for WTGs aiming at implementing the PISA monopile design framework for practical application [4,5].

This paper illustrates the applicability of the PISA method in engineering practice via the use of PLAXIS MoDeTo. It presents results of a concept design for monopile foundations in a stiff overconsolidated clay profile, considering monotonic loading conditions.

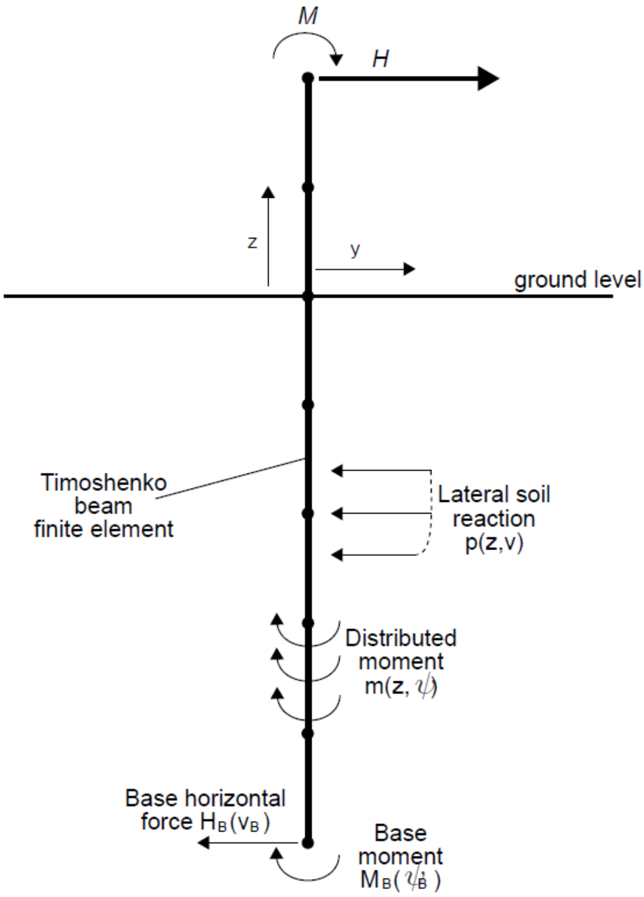

Figure 1. 1D FE model as developed in PISA project (as depicted in [4]). Note that notation v in the figure corresponds to notation y in the main text.

2. Ground Conditions

Table 1 presents the selected ground profile and soil design parameters. Profile selection included consideration of actual soil site specific investigation data including data from seismic in-situ tests and advanced laboratory tests (i.e. triaxial and direct simple shear tests with bender elements). The soil profile is idealised and does not represent or is representative of any specific location in the North Sea.

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Table 1. Summary of soil parameters.

Depth [m BSF]	Effective unit weight (γ') [kN/m^3]	Undrained shear strength (s_u) [kPa]	Small strain shear modulus (G_0) [MPa]	Coefficient of lateral earth pressure at rest (K_0) [-]	Axial strain at 50% deviatoric stress (ε_{50}) [%]
0-8	7.6	75	70	1.4	0.7
8-21	8.6	85	105	1.15	0.7
21-28	8.6	120	125	1	0.5
28-50	10.2	140	145	0.9	0.5

- BSF: below seafloor
- G_0 and K_0 are only used in the PLAXIS MoDeTo method
- ε_{50} is only used in the p-y method

3. Scope of the study

This paper considers required minimum monopile installation depth for ULS and SLS design criteria using the following methods:

- PLAXIS MoDeTo method following the PISA design framework;
- p-y method following the method by Stevens and Audibert [6].

The selected monopile (Figure 2) is modelled as an elastic beam, with an outer diameter of 9 m, wall thickness of 100 mm, to be installed by impact driving. The (unfactored) design lateral load is 9 MN resulting in an overturning moment of 594 MN at seafloor for a load eccentricity of 66 m. Table 2 presents the considered limit states and associated design criteria. Note that the presented study excludes specific considerations for scour management and the possible formation of a gap around the pile close to seafloor.

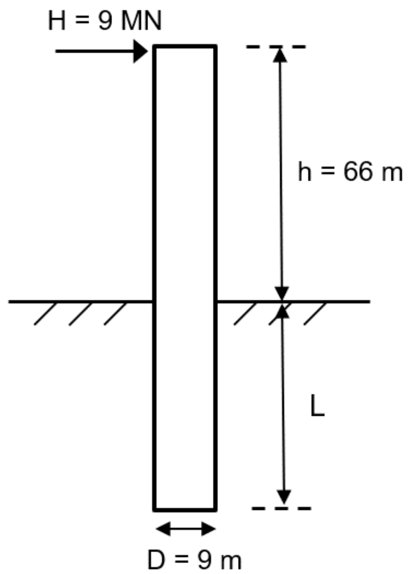

Figure 2. Schematic representation of the monopile design.

Table 2. Overview of limit states and concept design criteria.

Limit state	Design criteria
ULS	Working Stress Design (WSD) approach with a global safety factor of 1.5
SLS	Horizontal permanent rotation tolerance at seafloor of 0.25 degrees

- Note that the SLS design criterion refers to monotonic loading conditions for which the monopile rotation can be partially reversible. This is cautiously not considered for this study.

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3.1. PLAXIS MoDeTo method
The PLAXIS MoDeTo method is following the numerical-based design philosophy from the PISA project [7] and thus it entails a step-by-step procedure to be followed rather than a prescription of formulas as is the case for p-y methods. PLAXIS 3D [8] is used to define and run the 3D FE monopile models which are necessary for calibrating the soil reaction curves used in the 1D FE model. The design procedure is as follows:

- Soil stratigraphy and parameter selection;
- Definition of geometrical parameter space for calibration of soil reaction curves;
- Calculation of the 3D FE (calibration) monopile models;
- Calibration of the soil reaction curves (i.e. p-y, m-ψ, H_B-y and M_B-ψ) extracted from the 3D FE calculations;
- Run of the 1D FE model with the calibrated (site-specific) soil reaction curves;
- Optimisation of the geometry of the 1D monopile model based on ULS and SLS design criteria;
- Accuracy check of the final design with a (geometrically) equivalent 3D FE model.

3.1.1. Soil parameter selection. Soil parameters are derived to be used as input in PLAXIS 3D constitutive models. The default constitutive model for modelling undrained clay behavior (total stress analysis) within PLAXIS MoDeTo is the NGI-ADP model [9]. The more advanced parameters of the NGI-ADP model are automatically derived using empirical correlations [4] and the user-input of basic soil parameters (Table 1). This study excludes verification of the suitability of the default selection of the advanced parameters and calibration of the constitutive model.

3.1.2. Calibration parameter space. A series of 3D FE monopile models, termed calibration models, were defined in order to span the design geometrical parameters, namely the embedded pile length L, the pile outer diameter D, the pile wall thickness t and the load eccentricity h. These geometrical parameters (Table 3 and Figure 3) were selected in such a way as to ensure that the final monopile design falls within the defined design space. Reliability of the 1D model is otherwise doubtful. An initial indication of the required monopile geometry can be obtained from p-y calculations. Four, eight and twelve 3D FE models were used for calibration to investigate the influence of the number of calibration models on the outcome of the calibration of the extracted soil reaction curves (see also Section 3.1.3) and consequently on the accuracy of the 1D model. The outcome of this sensitivity analysis is presented in Section 4.1. Figure 3 also shows the final geometry of the 1D model along with the equivalent PLAXIS 3D model used for quality check.

Table 3. Summary of 3D FE calibration models.

Calibration models	Length (L) [m BSF]	Outer diameter (D) [m]	Load eccentricity (h) [m ASF]	Wall thickness (t) [mm]
GeoDS_1	20	8	48	80
GeoDS_2	42.5	8.5	76.5	90
GeoDS_3	23.75	9.5	85.5	100
GeoDS_4	50	10	60	110
GeoDS_5	42	8.4	63	85
GeoDS_6	33	8.8	79.2	90
GeoDS_7	23	9.2	69	95
GeoDS_8	36	9.6	57.6	100
GeoDS_9	64	8	72	90
GeoDS_10	80	10	60	110
GeoDS_11	40	8	96	90
GeoDS_12	25	10	120	100

- BSF: below seafloor
- ASF: above seafloor

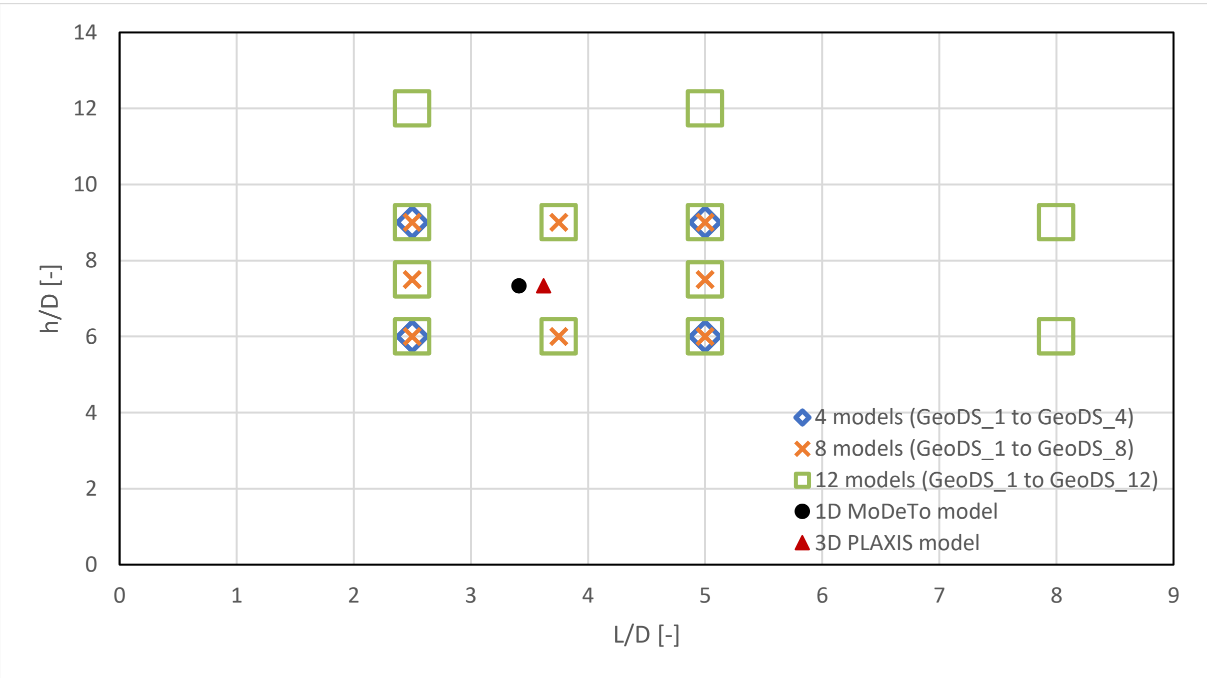


Figure 3. Calibration parameter space including the 3D calibration models, the final (optimised) 1D model and the final PLAXIS 3D model (h/D: load eccentricity ratio, L/D: aspect ratio, h: height above seafloor, L: monopile length below seafloor, D: monopile outer diameter).

The calculation of the 3D FE models is displacement-controlled; hence the prescribed value of pile head displacement should be large enough to ensure that nominal failure has occurred for all 3D models included in the calibration process. Nominal failure is presumed for pile lateral deflections at seafloor of at least 0.1D, where D is the monopile diameter [10].

3.1.3. Soil reaction curves. The soil reaction curves are extracted from the 3D FE calculations, normalised and subsequently used to calibrate the mathematical functions that will approximate the soil reaction curves in the 1D model [4]. Those functions are inherently dependent on the geometrical variations of the calibration models.

3.1.4. Design optimisation. The monopile geometry is optimised with regards to meeting the design criteria for ULS and SLS. The design parameter that has the primary focus for optimisation in this study is the embedded monopile length, since the selection of monopile diameter and wall thickness is typically driven by fatigue, buckling and natural frequency analysis. This is an iterative but fast procedure in which the embedded length of the 1D monopile model is modified (within the limits of the calibration parameter space, as presented in Figure 3) and the 1D model is ran until both ULS and SLS conditions are satisfied.

3.1.5. Accuracy check. Once the optimal monopile design is selected, an accuracy check is performed to confirm the robustness of the 1D calculation. An equivalent 3D model, of the same geometry as the final 1D model, is ran and the fitting of the resulting lateral load-deflection curves at seafloor is compared. PLAXIS MoDeTo computes an accuracy metric, termed η, which is recommended to be above 90 % [4].

3.2. p-y method
ISO suggests that the lateral behavior of long slender piles is assessed with the use of the p-y method, with the warning that large diameter piles with limited penetration may require a different formulation for the p-y relationships [2]. For this study, p-y curves were calculated according to a method proposed by Stevens and Audibert [6], based on database of pile load tests. The pile is modelled as a 1D elastic beam with no consideration of base shear, base moment and distributed moment along the shaft.

4. Results

4.1. Calibration parameter space
Figure 4 illustrates results from a sensitivity analysis carried out to check the accuracy of the 1D model calibrated with different number of 3D calibration models. Four 3D models were sufficient to calibrate the 1D model with reasonable accuracy. It was also observed that varying the pile wall thickness or the size of the calibration space had negligible influence on the calibration, as long as the final design was encompassed by the calibration space.

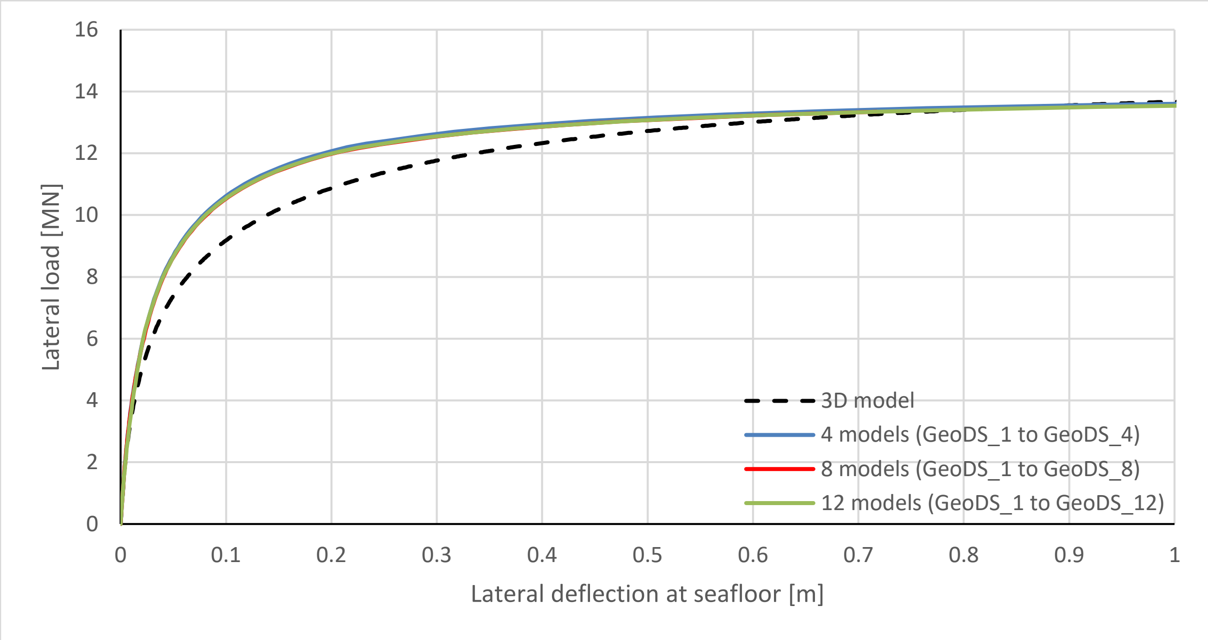


Figure 4. Comparison of resulting load-deflection curves for 1D models calibrated with different number of calibration models (see Table 3). The black dashed line represents the equivalent PLAXIS 3D model.

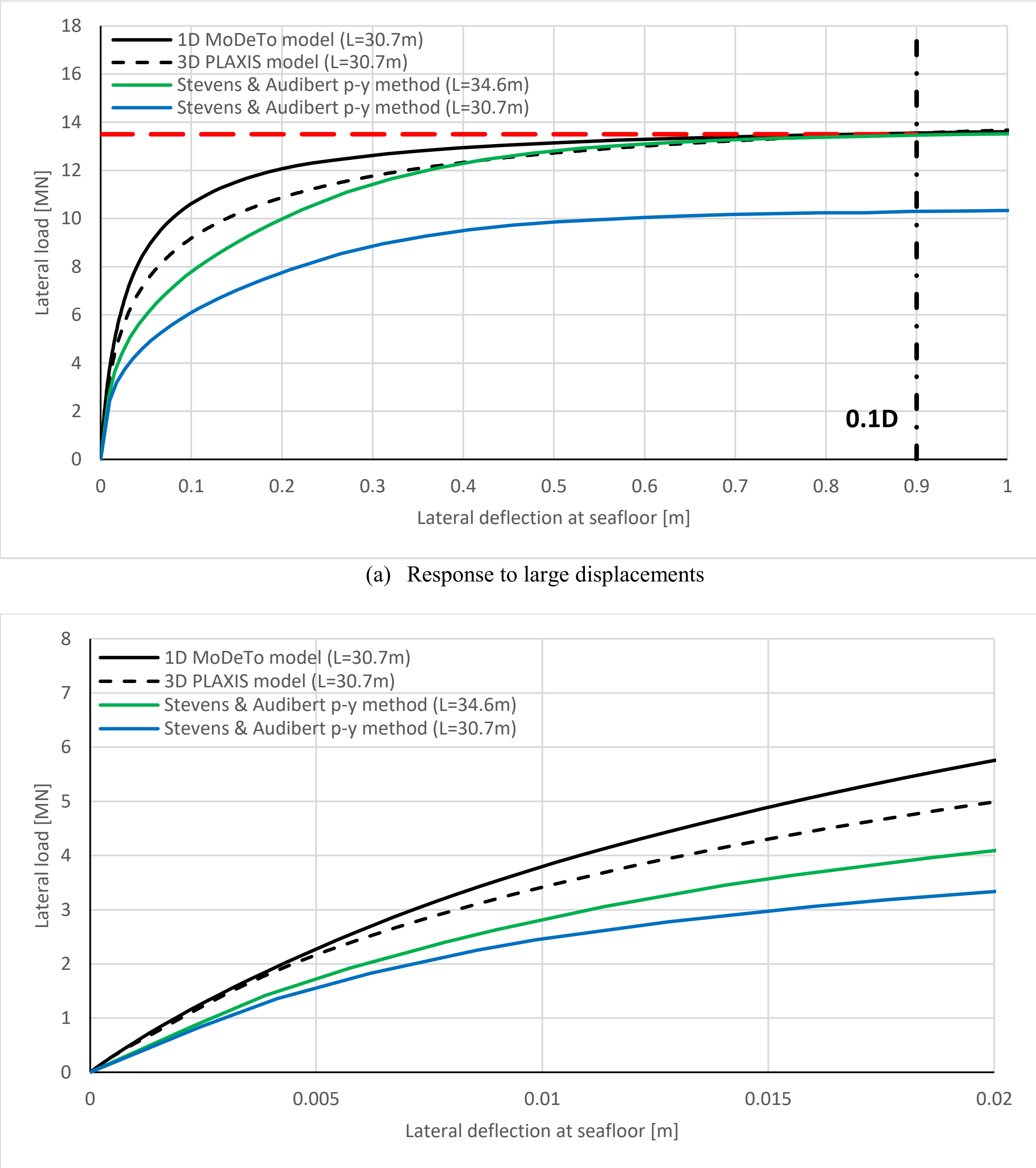
4.2. Concept monopile design

The required monopile design length according to the PLAXIS MoDeTo method is presented in Table 4. In comparison, the required monopile design lengths based on employment of a 3D FE model and the Stevens and Audibert p-y method are also displayed.

Table 4. Summary of required monopile lengths for all considered methods. The differences with the length predicted from the PLAXIS MoDeTo method (reference case) are also displayed.

Design method	Load case	Required monopile length [m BSF]	Aspect ratio [-]	Governing case	Difference
PLAXIS MoDeTo method (1D model)	ULS	30.7	3.41	✓	
	SLS	30	3.33		
PLAXIS 3D (equivalent) model	ULS	30.7	3.41		
	SLS	32.6	3.62	✓	+6%
Stevens and Audibert p-y method	ULS	34.6	3.84		
	SLS	39	4.33	✓	+27%

4.2.1. ULS. Figure 5 compares predictions of the monopile response for the ULS. For comparison purposes, load-deflection curves are also plotted for an installation depth of 30.7 m with the Stevens and Audibert p-y method. It is evident from the plots that the p-y method predicts a much lower ultimate pile capacity and considerably softer pile response compared to the other two methods. The pile would need to be 27 % longer than what the PLAXIS MoDeTo method predicts in order for the concept design to meet the ULS and SLS requirements. Furthermore, even by increasing the monopile installation depth by 13 % to meet the ULS requirement, the response is substantially softer than that determined using the PLAXIS MoDeTo approach, especially at small displacements (Figure 5b). Stiffness response is important, as design against accumulated fatigue is one of the main design drivers for the detailed monopile design in subsequent design phases. Figure 5 also presents the lateral monopile response with a PLAXIS 3D FE calculation, which can be used to check the robustness of the 1D model. The accuracy metric for the 1D model in this study was 96.8 %, although it is apparent that the 1D model shows stiffer response than its equivalent 3D model.



(a) Response to large displacements

(b) Response to small displacements

Figure 5. Monopile response in ULS.

4.2.2. SLS. The pile response for the PLAXIS MoDeTo calculation shows a stiffer behaviour than both the 3D FE calculation and the p-y method (Figure 6).

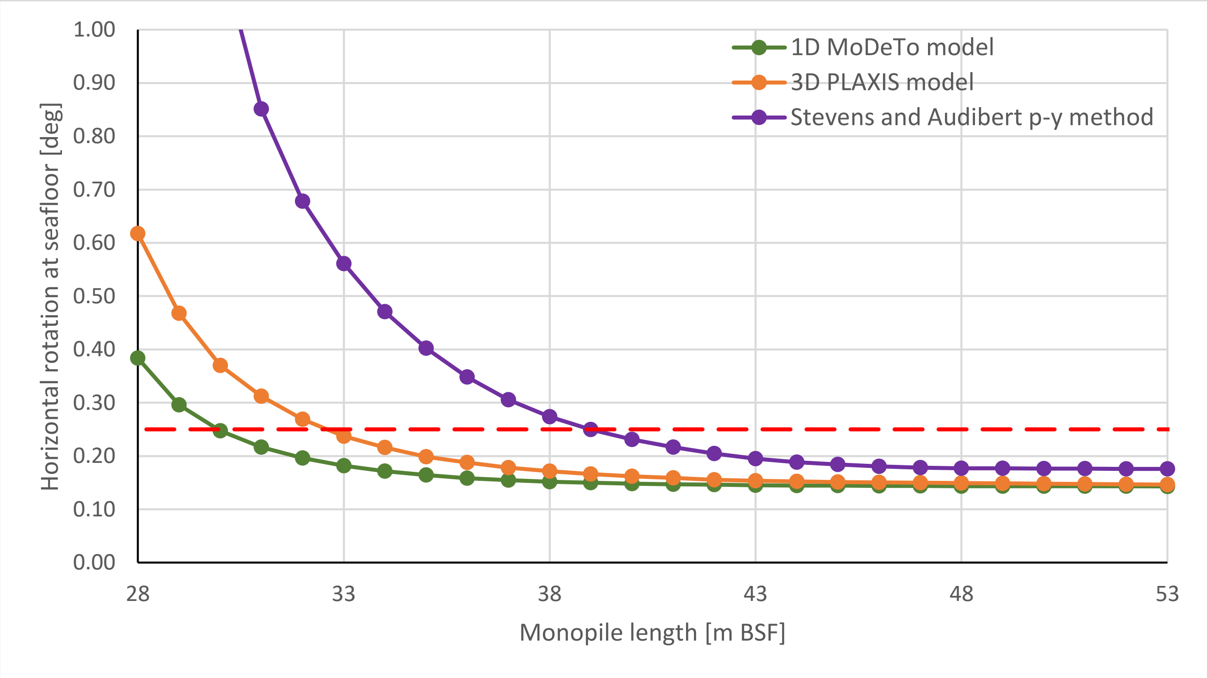


Figure 6. Horizontal monopile rotation at seafloor versus monopile length (SLS).

5. Conclusions

The PLAXIS MoDeTo method is a straightforward and easily applicable method for concept design of monopiles based on the PISA design framework. It provides a realistic representation of a typical large diameter monopile capturing the key elements of its behavior when subjected to lateral monotonic loading.

The quality check of the calibrated 1D model against its equivalent 3D model is within tolerable margins according to the accuracy metric, although in this study the calibrated 1D model was stiffer than its equivalent 3D model. This resulted in the 1D model showing a 6 % shorter monopile than the 3D model. Furthermore, the size of the calibration space did not seem to influence the calibration accuracy provided that the final design is within the defined calibration space. The MoDeTo team is working on further optimisation of the calibration procedure (i.e. calibration of the mathematical functions) to better match the 1D results with the 3D FE model results.

It was also observed that only a small number of 3D FE models (i.e. four in this study) is required for calibration of the 1D model; hence the overall computation time when employing the PLAXIS MoDeTo method is relatively limited.

Making use of a conventional p-y method for concept monopile design results in a substantially softer response and lower ultimate capacity of the pile, as anticipated.

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