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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.

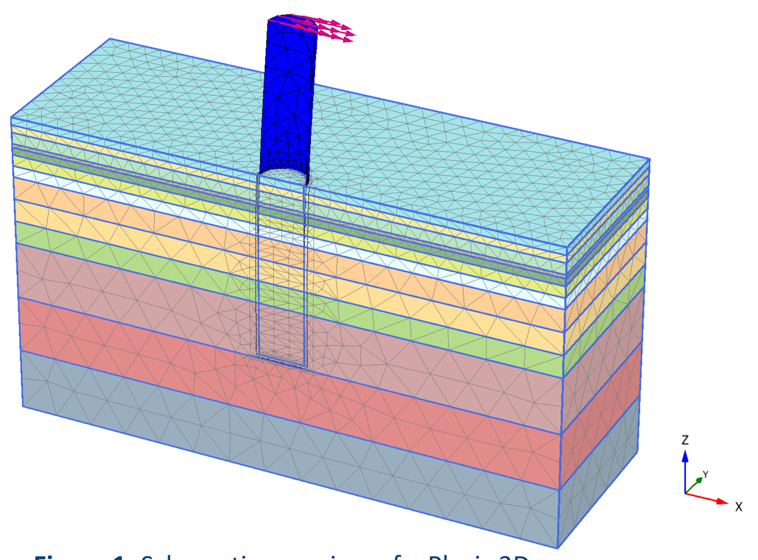

Figure 1. Schematic overview of a Plaxis 3D monopile model created via Plaxis MoDeTo.

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 [2]. This poster presents results of a concept monopile design study under lateral monotonic loading with the use of the Plaxis MoDeTo method.

Objectives

- Demonstrate the applicability of the PISA method in standard engineering practice via the use of Plaxis MoDeTo.
- Showcase comparative results for concept design of a laterally loaded large diameter monopile.

Methods

Design Basis

- Driven open-ended tubular monopile of 9 m outer diameter and 100 mm wall thickness.
- Static monotonic loading conditions (horizontal load at seafloor of 9 MN with load eccentricity of 66 m).
- Two limit states, namely:
  - Ultimate Limit State (ULS): working stress design approach (general safety factor of 1.5);
  - Service Limit State (SLS): horizontal rotation tolerance at seafloor of 0.25 degrees.
- Stiff overconsolidated clay profile (Table 1).

Plaxis MoDeTo method

PISA design framework

- Derivation of soil reaction curves from finite element calculations to be used within a 1D framework (Timoshenko beam).
- Four types of soil reaction curves are defined, namely:
  - Distributed lateral load along pile (i.e. p-y);
  - Distributed moment along pile (i.e. m-ψ, where ψ is rotation);
  - Horizontal force at pile base (i.e. H_B-γ);
  - Moment at pile base (i.e. M_B- ψ).
- Validated against data from pile load field testing.

Design procedure

- Soil stratigraphy and parameter selection for the Plaxis 3D constitutive model (i.e. NGI-ADP model, [3]);
- Definition of geometrical parameter space for calibration of soil reaction curves;
- Calculation of the 3D FE (calibration) models;
- Calibration of the 1D model from extracted soil reaction curves from the 3D FE calculations;
- Run of the calibrated 1D model with the site-specific soil reaction curves;
- Optimisation of the monopile geometry based on ULS and SLS design criteria;
- Robustness check of the final design (1D model) with a (geometrically) equivalent 3D FE model.

P-y method

- Based on ISO guidance for lateral behavior of long slender piles [4];
- Derivation of p-y curves according to Matlock [5] with modified stiffness according to method by Stevens and Audibert [6] based on database of pile load tests.

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 horizontal 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

Notes:
- 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

Results

Calibration Parameter Space

A series of 3D FE models with varying geometric configurations is defined to calibrate the 1D model (Figure 2). A sensitivity check was carried out to study the influence of the number of 3D FE calibration models on the accuracy of the 1D model (Figure 3).

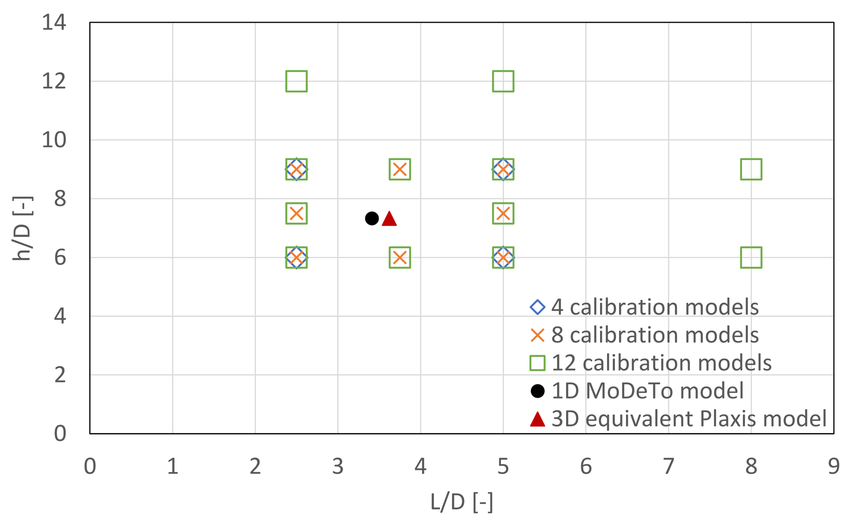

Figure 2. Parameter space including the 3D calibration models, the final (optimised) 1D model and the final 3D model (h/D: load eccentricity ratio, L/D: aspect ratio, h: height above seafloor, L: monopile length below seafloor, D: monopile outer diameter).

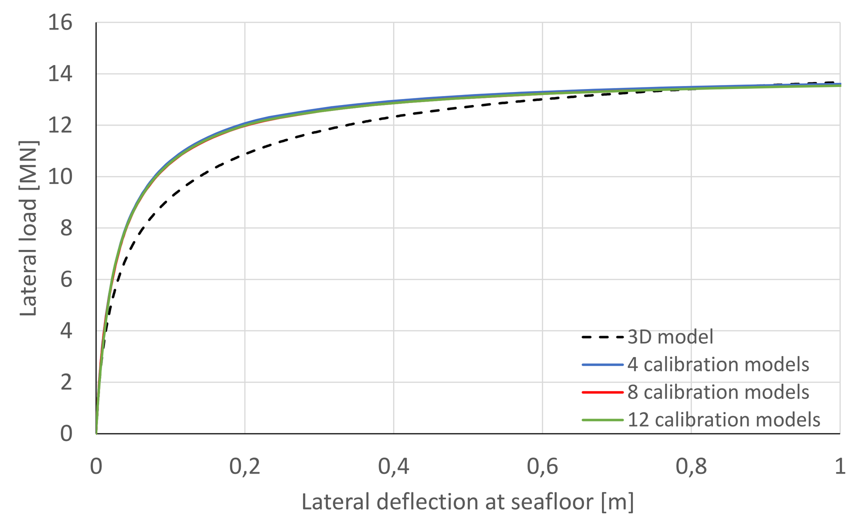

Figure 3. Comparison of resulting load-deflection curves for 1D models calibrated with different number of calibration models. The black dashed line represents the (geometrically) equivalent Plaxis 3D model.

Monopile Concept Design

ULS

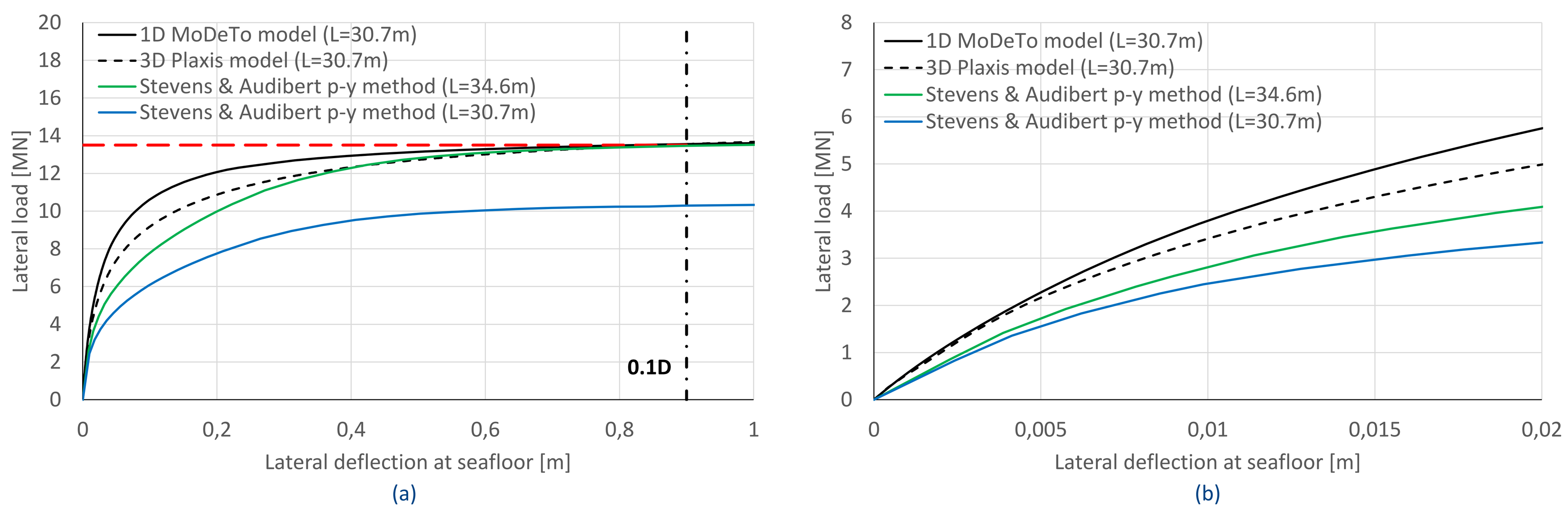

Figure 4. Monopile response in ULS at (a) large horizontal displacements and at (b) small horizontal displacements

SLS

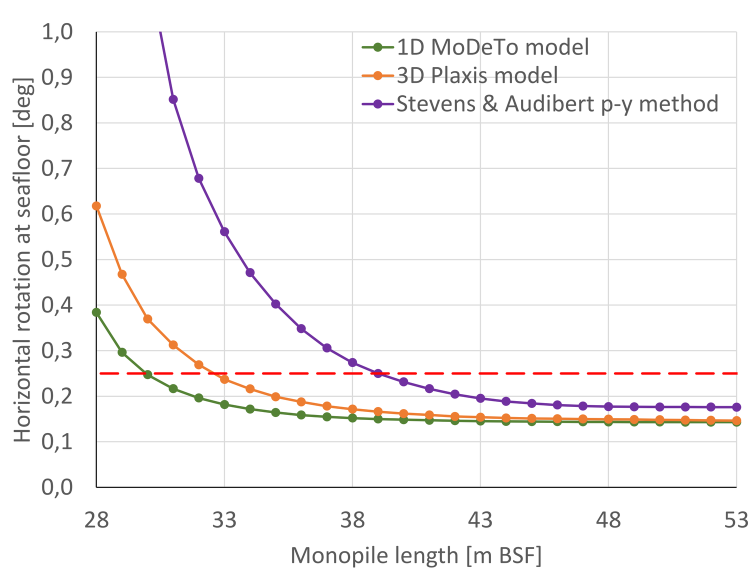

Figure 5. Horizontal rotation at seafloor versus monopile length for the SLS.

Results

Table 2. Summary of required monopile lengths. 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%

Conclusions

- The Plaxis MoDeTo method is a straightforward and easily applicable method for concept design of monopiles. 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. In this study, the calibrated 1D model was stiffer than its equivalent 3D model. 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 to better match the 1D results with the 3D FE model results.
- Only a small number of 3D FE models (i.e. 4 in this study) is required for calibration of the 1D model; thus overall computation time is relatively limited.
- Making use of a conventional p-y method (i.e. Stevens and Audibert method in this study) for concept monopile design results in a substantially softer response and lower ultimate capacity of the pile, as anticipated.

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