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Application of the PISA framework for slender jacket piles

Application du cadre PISA pour les pieux à jaquette minces

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ABSTRACT: For a typical offshore pile design, it is industry practice to assess the lateral response of jacket piles using *p-y* curves. These prescribed *p-y* curves (for example, as described by DNV-GL (2019)), are generally limited to use for piles with diameters (*D*) of up to approximately 2.5 m and should be validated for piles with diameters of more than 1 m, e.g. by finite element analysis (FEA). A jacket pile foundation was selected as the support structure for an offshore wind farm where ground investigations identified soils which require large deformations to mobilize their peak strength. The presence of these soils results in large pile diameters and therefore the empirical *p-y* curves are not considered appropriate for assessing the lateral soil-structure response. To accurately capture this response, the recently developed PISA framework for site-specific calibration of 1D soil reaction curves (SRCs) is applied. The PISA project established a novel procedure for deriving the site-specific SRCs from 3D FEA calibrated using high-quality site investigation and laboratory testing data. This paper presents the application of the PISA framework for long slender piles and a comparison of calibrated SRC and "traditional" *p-y* curve predictions against 3D FEA results. The comparison reveals that the calibrated SRCs result in more accurate predictions of the pile's lateral response and bending moment with depth. The results also suggest that the *p-y* curves may lead to non-conservative predictions for this pile geometry and ground conditions.

RÉSUMÉ: Pour de nombreuses conceptions de fondations d'éoliennes offshore, le standard industriel est d'évaluer le chargement latéral des pieux type jacket à l'aide de courbes *p-y* (DNV-GL, 2019). Ces courbes p-y sont généralement limitées à une utilisation pour les pieux type jacket dont le diamètre (*D*) ne dépasse pas environ 2.5 m et doivent être validées pour les pieux dont le diamètre est supérieur à 1 m, par exemple par une analyse par éléments finis (AEF). Une fondation de pieux type jacket a été choisie comme structure de support pour un parc éolien offshore où les études de terrain ont identifié des sols qui nécessitent de grandes déformations pour optimiser leur résistance maximale. La présence de ces sols a demandé de grands diamètres de pieux et par conséquent les courbes *p-y* expérimentales n'ont pas été considérées appropriées pour évaluer le chargement latéral du sol et de la structure. Pour évaluer ce chargement avec précision, le cadre PISA, récemment développé pour l'étalonnage des courbes de réaction des sols (CRS) en une dimension et spécifique à chaque site, a été appliqué. A partir de données de terrain et de tests en laboratoire, le projet PISA a établi une nouvelle procédure pour étalonner les courbes de réaction des sols en utilisant une analyse par éléments finis (AEF 3D). Cette publication présente l'application du cadre PISA pour des pieux type « jacket » longs et fins ainsi qu'une comparaison des CRS étalonnées avec des prédictions de la courbe *p-y* "traditionnelle" selon ces résultats de l'AEF 3D. La comparaison révèle que les CRS étalonnées fournissent des prédictions plus précises du chargement latéral du pieu et du moment de flexion par rapport à la profondeur. Les résultats suggèrent également que les courbes *p-y* peuvent conduire à des prédictions risquées pour cette combinaison de géométrie de pieu et de conditions de sol.

KEYWORDS: jacket piles, p-y curves, PISA, offshore wind farms, geotechnics.

1 INTRODUCTION

The power output and rotor size of Wind Turbine Generators (WTG's) is growing. In 2024, Siemens Gamesa and Vestas MHI will begin producing 14 and 15 MW turbines respectively (Siemens Gamesa, 2020 & Vestas MHI, 2021), in comparison to the 8-10 MW turbines currently in production. These increasing WTG sizes increase the loads on the foundations, and thereby the foundation sizes.

At offshore windfarms with challenging site characteristics, such as poor ground conditions, deep water or extraordinary load conditions, jacket piles can be used as the foundation type. Jacket piles have been used extensively in the oil and gas industry and generally provide a robust foundation for typical offshore structures. The jacket pile foundation type consists of a lattice structure supporting the turbine tower on three or four legs, where each leg is founded on one or more piles in the ground.

The lateral loads on the jacket structure lead to moments and shear forces at seabed, which are transferred to the soil by axial and lateral soil reactions. In areas with poor ground conditions, the pile diameter can be increased to gain axial and lateral capacity by increasing the pile surface area.

The lateral soil-structure interaction of a driven steel pile is typically modelled using a beam model with non-linear Winkler springs (*p-y* springs) to model the soil response. Cox et al (1974) reported the results of lateral pile tests in clean sand performed at Mustang Island, Texas, on two 61 cm diameter piles with a length to diameter ratio (*L/D*) of 34. Based on these tests, Reese et al. (1974) developed expressions for *p-y* curves in sand. Murchison and O'Neill (1984) investigated a number of pile tests and developed on the *p-y* curve formulation by Reese et al. (1974) to the formulation currently presented for sands in DNV-GL (2019) and API, 2014.

The *p-y* formulations have been developed for long and slender piles with diameters up to 1 m and extrapolating these formulations to larger, and potentially more rigid, jacket piles with diameters over 2.5 m is not recommended by DNV-GL (2019). The shortcomings of the *p-y* formulations have been presented in multiple papers, see e.g. Doherty and Gavin (2012), Lam (2013) and more recently Duroska et al. (2020).

1.1 *The PISA framework*

The PISA joint-industry project (JIP) aimed to capture the response of large-diameter (with low *L/D* ratio) monopiles to quasi-static monotonic lateral and moment loading. This project resulted in the development of the 'PISA design framework" (Byrne et al., 2017). The framework proposes two possible applications of the design method. These are often referred to as 'numerical-based method' and 'rule-based method'.

The PISA design framework builds upon the *p*-*y* approach by introducing three additional soil reaction components. This results in the four reaction components; distributed load *p*-*v* (*y* is replaced by *v* as the lateral displacement in the *y*-direction) and distributed moment springs down the pile shaft along with base shear and base moment springs located at the pile toe.

The numerical-based method proposes a basis for the development of Soil Reaction Curves (SRC's) calibrated for a particular offshore site. A high-quality site investigation and laboratory testing campaign to determine the strength and non-linear stiffness parameters of the soil for the site is required to calibrate advanced constitutive models for 3D Finite Element Analysis (FEA). The outcome of the 3D FEA is used to calibrate the SRC's for a simpler 1D model to provide a highly accurate and computationally efficient method for position-specific design.

The rule-based method proposes the use of previously derived SRC calibrations, where only basic soil strength and stiffness parameters obtained from standard site investigation are required. The accuracy of this method when used for a new site depends on the similarity of the ground conditions and pile geometries to those employed in the original calibration exercise.

1.2 *Approach for the present study*

In this paper, the predicted response of large-diameter piles is compared with the predictions of the standard lateral SRC's proposed by design standards (DNV-GL, 2019) and site-specific SRC's calibrated using 3D FEA. The site-specific SRC calibration consists of only the PISA *p*-*v* component calibrated to a series of 3D FEAs.

The results show that the site-specific SRC calibration compares more accurately against the 3D FEA predictions than the lateral SRCs proposed by design standards. The results also indicate that application of the lateral SRCs proposed by design standards can lead to non-conservative predictions.

2 APPLICATION OF PISA FRAMEWORK

A three-legged jacket supported by a single pile at each leg is proposed as a foundation type for a wind farm project with the water depth at the site ranging between roughly 25 m to 45 m. The outer diameter of the piles is more than 3 m and the approximate penetration lengths range from 50 m to 80 m, i.e. *L/D* of roughly 15 to 25.

A comprehensive geological and geotechnical site investigation identified soils which require large deformations to mobilize their peak strength. The ground conditions are characterised to consist of Holocene and Pleistocene formations and the Geotechnical Soil Units (GSU's) present at the site are shown in Table 1.

The lateral response of the piles may have a large influence on the jacket design and therefore it is important to accurately capture the response of the individual piles to lateral loading. The standard lateral SRC's proposed by design standards (DNV-GL, 2019) are limited to use for pile with diameters up to 2.5 m and for larger pile diameters require support from alternative analyses such as 3D FEA. This combined with the site-specific soil conditions leads to a need for an alternative method to accurately capture the response of the large-diameter piles to lateral loading.

Table 1. Classification of the geotechnical soil units at the site.

Geotechnical Soil Unit	Geological reference	Classified soil Unit
GSU I	Holocene	GSU I – Sand
GSU II	Holocene	GSU II – Clay
GSU III	Pleistocene	GSU III – Sand GSU III – Clay
GSU IV	Pleistocene	GSUI IV – Sand

To accurately capture the lateral response of the piles, the numerical-based method is applied to GSU I and GSU II, which are considered the most influential for the lateral pile response. The methodology of the SRC calibration framework is based on the PISA design framework (Byrne et al., 2017). It is acknowledged that the PISA framework is specifically aimed at capturing the response of large diameter monopiles, with low *L/D* ratios, subjected to quasi-static monotonic lateral and moment loading. The bespoke pile geometries are outside of the geometry space used in the PISA project (Burd et al., 2020 and Byron et al., 2018); however, as noted in the PISA work and outlined by Byrne et al. (2015), the PISA approach is capable of operating over the full range of geometries from long slender piles with large *L/D* ratios to monopiles with low *L/D* ratios. This suggests that the proposed PISA design framework comprises a process applicable to piles outside the pile geometry space considered in the PISA JIP project.

The numerical-based approach is applied to derive the site-specific SRC formulations, involving the use of 3D FEA. The objective is to obtain calibrated lateral distributed load *p*-*v* springs, as they are the governing SRC component considering the *L/D* ratios in question.

Four positions, P1, P2, P3 and P4 are selected as representative of the various stratigraphic scenarios and pile penetration lengths across the site. The simplified stratigraphy of the representative positions is presented in Figure 1.

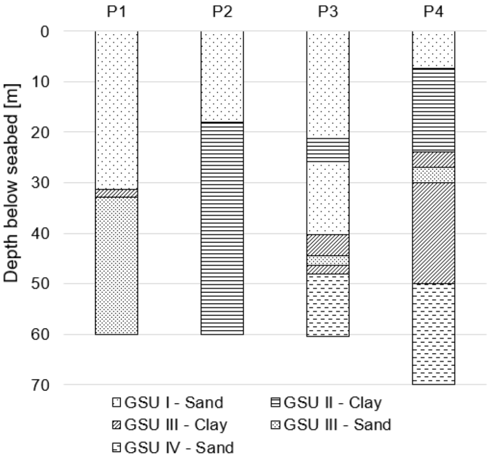

Figure 1. Simplified stratigraphy of selected positions at the site.

The piles at the selected positions have an outer pile diameter equal to 3.9 m and their respective penetration lengths are listed in Table 2.

2.1 *Finite element analysis*

For the correct modelling of the lateral pile response at the site, a series of 3D FEA analyses at the four selected representative positions were performed by the Geotechnical Consulting Group (GCG, 2019). All FE analyses were carried out using the finite element code ICFEP (Potts & Zdravkovic, 1999), which was also used to perform all FE analyses for the PISA project.

GCG (2019) provides further detail on the 3D FEA, such as the derivation of geotechnical parameters, calibration of constitutive models, modelling of selected positions, pile geometries and extraction of SRC's.

Table 2. List of positions for calibration of SRCs.

Position	Pile penetration length	Pile total length including stick-up
P1	60 m	65 m
P2	60 m	65 m
P3	60.5 m	65.5 m
P4	70 m	75 m

2.1.1 *Modelling approach*

Appropriate constitutive models were selected to capture the response of the GSU's and calibrated based on the results from available laboratory tests performed on the samples from the site.

The stratigraphy and pile geometries of the four representative positions is shown in Figure 1 and Table 2. The pile and the stick-up were incorporated in the FE models as hollow tubes and modelled using shell elements. The FE mesh for all piles extended to 60 m below seabed at which level full fixity was assumed. As such, the analyses did not cover the full pile penetration in all cases and did not attempt to accurately model the behaviour at the pile toes. This assumption was shown to have negligible effects on the overall lateral pile response. The lateral extent of the FE mesh was modelled to be approximately 25 *D* from the pile centre which was considered sufficiently far not to significantly influence the results of the analyses.

The weight of the structure above design seabed level was neglected and no vertical load was applied prior to the application of lateral and moment loading. The aim of FE analysis is to accurately capture the lateral response of the piles up to maximum load level corresponding to the representative load levels expected at the site. Therefore, the vertical loading is considered to have little effect on the outcome of the analysis.

A displacement-controlled approach was chosen for the application of the horizontal and moment loading. In this approach, lateral displacements are applied to the structure at an elevation above seabed equivalent to the ratio between the lateral load and moment.

2.1.2 *Modelling the pile-soil interface*

The interface between the pile and the surrounding soil was modelled using specially formulated interface elements. Interface elements are not used on the inside face of the pile; an assumption not considered to influence the results significantly.

The interface within the predominantly sandy materials was assumed to behave in a drained manner and a Mohr-Coulomb yield surface with non-associated plasticity was used. In the clayey materials, the interface was assumed to behave in an undrained manner using a Tresca yield surface with undrained strength values equivalent to the initial values of undrained strength in the surrounding soil. The interface elements were allowed to open, given appropriate stress conditions, and the analyses accounted for presence of water in these cases.

2.1.3 Finite element analyses results

For all positions, the 3D FEA suggests reasonably similar patterns of pile deformation against depth as the load levels increase. As expected, the slender piles are bending in response to lateral load application, with the largest displacements observed close to the seabed.

A wide range of results from the 3D FEA was obtained for the selected four positions. Among the results are lateral load-displacement pile responses at seabed level, SRC's for distributed lateral load with depth and the distribution of pile internal forces (i.e. axial force, bending moment and shear force) with depth for various load levels. The shaft lateral load SRCs are generally calculated in accordance with the procedures established in the PISA project by systematically extracting and processing the stresses from the interface elements around the pile shaft and nodal displacements from the 3D FEA models. These results are used for calibration of the site specific SRC's.

2.2 *Calibration of soil reaction curves*

The procedure to derive parameterised the SRC's from the 3D FEA results follows the normalization and calibration procedure established in the PISA project (Burd et al., 2020 and Byrne et al., 2020). This allows the SRC's obtained from a relatively small number of calibration positions to be applied across the entire windfarm site accounting for variations in key soil input parameters, e.g. undrained strength.

2.3 *Application of soil reaction curves*

The SRC's, both the derived site-specific SRC's and standard lateral SRC's proposed by design standards (DNV-GL, 2019), are applied as non-linear Winkler springs on a laterally loaded Timoshenko beam. The 1D FE model is identical between the two SRC models and only the soil response modelling approach differs.

3 RESULTS

The performance of the calibrated SRCs is benchmarked against the 3D FEA results and also compared with the results of the SRCs proposed by industry design standards (DNV-GL, 2019). The performance of these methods is compared in terms of the normalized load-displacement response to static lateral loading (Figure 2 and Figure 3) and the normalized distribution of bending moment along the pile for various load levels (see Figure 4). The maximum load levels presented in Figure 2, 3, and 4 are representative for the lateral loads expected at the site. They do not represent the ultimate capacity of the jacket pile, which would occur at very large and unrealistic displacement levels.

The predictions based on the SRC's proposed by the design standard are denoted as *DNV-GL p-y* and predictions obtained using the calibrate site-specific SRC's are denoted as *Calibrated p-v*. The 3D FEA results are simply denoted as *3D FEA*. The *DNV-GL p-y* and *Calibrated p-v* predictions are obtained using Ørsted's in-house developed 1D beam model. The *Calibrated p-v* predictions are based on the calibrated site-specific *p-v* springs for GSU I and II, which are governing the lateral response. GSU III and IV are modelled using the traditional *p-y* formulations proposed by the design standards (DNV-GL, 2019).

3.1 *Lateral load-displacement response*

The lateral pile response at positions P1, P2 and P3 is governed by the thick top layer of GSU I and their responses are generally similar. Thus, in Figure 2 the load-displacement responses from *DNV-GL p-y*, *Calibrated p-v* and *3D FEA* are compared only for position P2. As expected, the *Calibrated p-v* predictions match well with the *3D FEA* predictions, but both are significantly different to the *DNV-GL p-y* predictions. The *DNV-GL p-y* prediction is considerably stiffer and predicts approximately half the lateral displacement at seabed for the maximum applied lateral load when compared to the other two predictions. It is well-documented (Duroska et al., 2020) that SRC's proposed by design standards can lead to non-conservative predictions of lateral large-diameter pile response in ground conditions dominated by sand.

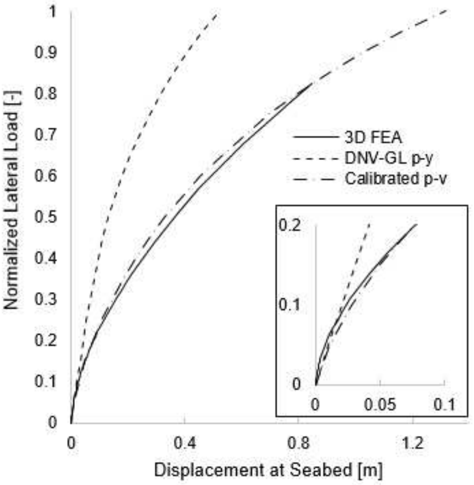

Figure 2. Comparison of the load-displacement response using the DNV-GL *p-y*, and calibrated *p-v* springs against the 3D FEA response from position P2.

In Figure 3 the load-displacement responses from *DNV-GL p-y*, *Calibrated p-v* and *3D FEA* are compared for position P4. At position P4, the top layer of GSU I is underlain by a significantly thicker layer of GSU II. The *Calibrated p-v* predictions again match well with the *3D FEA* predictions but the divergence between the results based on the PISA framework and those from *DNV-GL p-y* predictions is less systematic. The use of *DNV-GL p-y* results still predicts a stiffer response; however, the overall response is closer to the other two than in the case of position P2 presented in Figure 2. At the largest load level, the *DNV-GL p-y* prediction underestimates the lateral displacement at seabed by approximately 20 % compared to the other predictions.

The zoom-in windows in Figure 2 and Figure 3 focus on the very small displacement range of the pile response. The *Calibrated p-v* prediction matches better the *3D FEA* predictions compared to the *DNV-GL p-y* predictions.

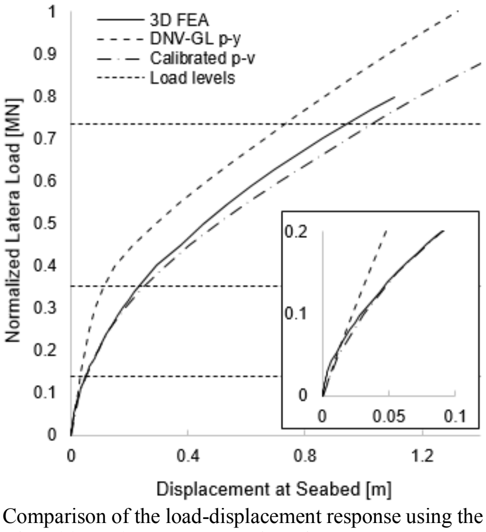

Figure 3. Comparison of the load-displacement response using the *DNV-GL p-y* and *Calibrated p-v* SRC's against the *3D FEA* response from position P4.

3.1 *Pile internal forces*

The bending moment is often governing the structural design of the jacket pile top sections and is considered as the most relevant structural force for comparison in this study. The comparison of the bending moment along the pile at three different load levels (using the different methods) is shown in Figure 4. The three different load levels in respect to the load-displacement response at the P4 position are presented in Figure 3.

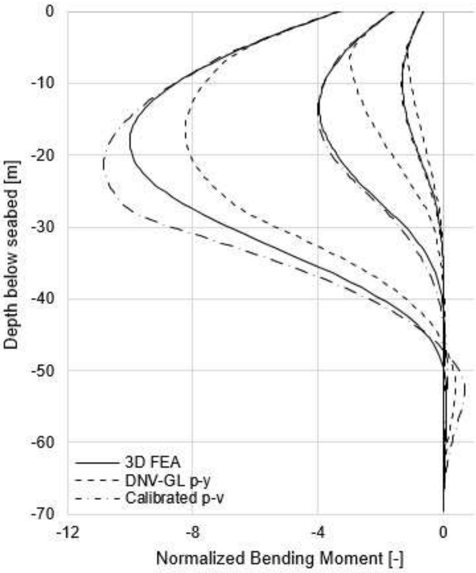

Figure 4. Comparison of the bending moment along pile using the *DNV-GL p-y* and *Calibrated p-v* SRCs against the 3D FEA results from position P4.

From Figure 4, it can be seen that the *Calibrated p-v* predictions provide a better or conservative match to *3D FEA* predictions than the *DNV-GL p-y* predictions for all load levels. The *Calibrated p-v* predictions tend to overestimate compared to the *3D FEA* predictions for larger load levels, whereas the *DNV-GL p-y* predictions consistently underestimate the bending moments for all presented load levels. At the largest presented load level, the *DNV-GL p-y* predictions underestimate the maximum bending moment by approximately 15 % whereas the *Calibrated p-v* predictions overestimate the maximum bending moment by approximately 10 %.

4 CONCLUSIONS

The assessment of lateral pile response for jacket foundations has traditionally been performed by employing the standard *p-y* methods proposed by design standards (DNV-GL, 2019 and API, 2014) which are specifically applicable to long slender pile geometries with high *L/D* ratios. At the selected site, large diameter piles were required and therefore a site-specific calibration of SRC's for the top two geotechnical soil units governing the lateral pile response was performed. The PISA framework was considered appropriate for the derivation of site-specific SRC calibrations despite the framework originally having been developed for large-diameter monopiles.

The lateral response of the piles using site-specific SRC calibrations, used in conjunction with an in-house 1D beam model, is benchmarked against the responses from 3D FEA and industry standard recommendations. This is shown for both the pile head load-displacement response and the distribution of bending moments along the pile. The results indicate that the calibrated SRC formulations can capture the site-specific load-displacement response very well and can also accurately capture the bending moment along the pile, especially for low to medium load levels. Moreover, the predictions obtained from using the industry standard *p-y* formulations (DNV-GL, 2019) indicate that the use of these formulations could lead to non-conservative predictions of the load-displacement response and assessment of the maximum bending moment.

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