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Hybrid monopile: a new foundation concept for 20+ MW wind turbine generators

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ABSTRACT: The current demands and projections of offshore wind energy field outputs, together with increasing wind turbine generator capacities and increasing water depths, continue to push the limits of the design, construction and installation of the foundations for bottom-fixed wind energy developments. Although currently being the main foundation concept for bottom-fixed wind energy, increasing monopile weights and dimensions are resulting in installation challenges such as stringent noise regulations, vessel availability and lifting capacity, and hammer availability and capacity and mission equipment. In parallel, jacket foundations remain complex and resource-intensive to construct and transport. The Hybrid Monopile concept tackles these challenges by using multiple pin piles, replacing the deeply embedded monopile, thereby reducing pile driving peak noise levels. A section of the tower, from sea water level till seabed, is pre-welded to an interface piece and connected to the pin piles on site. The concept combines the smaller pin piles of the jacket below the mudline with the simplicity of the monopile above the mudline. To design and implement a Hybrid Monopile foundation for a 20 MW offshore wind turbine in typical North Sea dense sands, geotechnical topics such as axial and lateral pile capacities, group effects, driveability and installation noise emissions need to be considered and will be discussed in this paper.

Keywords: Hybrid Monopile; axial capacity; lateral capacity; group effects

1 HISTORY

The current market trends demand increasingly larger wind turbine generators with consequently larger structures and foundations. Similar to Moore's law, stating that processing power doubles every few years, WTG sizes are doubling as well every 5-10 years on average.

Turbines with a capacity of 15 MW are currently installed, but the use of 20 to 25 MW turbines is projected and are being designed for 2030-2035 offshore wind farm (OWF) projects. New challenges are emerging because installation boundaries exceed current market capabilities. The supply of impact hammers and increasingly demanding noise regulations are key bottlenecks.

An alternative foundation, the hybrid monopile (HMP) is proposed to generate a wider range of possible foundation solutions and aim for easier deployment. The HMP concept, depicted in Figure 1, consists of a monopile (MP), pin piles foundation (PP), and an interface piece (IP) which connects the pin piles to the MP.

The pin piles are pre-installed, after which the monopile with interface piece is lifted onto the pin piles. The monopile has a limited embedded length to provide additional horizontal stiffness.

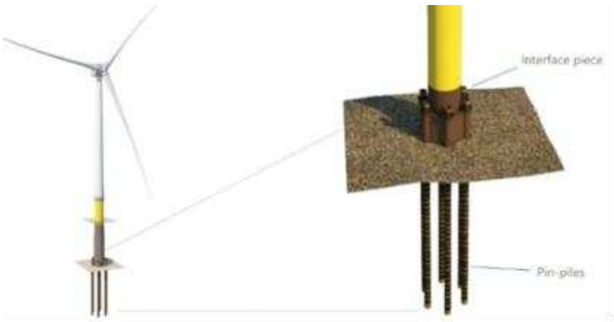

Figure 1: HMP3D concept sketch.

After installation, the PP-IP connection is grouted. Since the monopile tower is not subjected to pile driving, a Transition Piece, TP-less connection could be used, reducing installation cycle times.

The pin piles' diameters are predefined, based on exploratory analysis, to have diameters ranging from 3 to 4 m. Compared to monopiles, the reduced pile size increases the number of capable installation vessels and pile (impact/vibratory) driving assets. With respect to jackets, the HMP has a reduced footprint (transportation benefit) and potentially a less complex production process.

As presented by Cerfontaine et al. (2021) and Davidson et al. (2024), both foundation types, jacket and monopiles, can use silent piling for pin pile installation, eliminating noise limitations. Although silent piling is a powerful solution, it will not be assessed in this paper.

This paper aims to provide a methodology for estimating the geotechnical capabilities of this foundation type in order to assess the project feasibility. The geotechnical behaviour of these foundations tackles topics such as axial and lateral capacity as well as group effects since the pin piles interact with each other.

2 STUDY CASE

The study case presented highlights an anonymised feasibility study performed to assess the potential benefits and shortcomings of the HMP solution for an Offshore Wind Farm located in the North Sea. The soil is comprised of typical North Sea dense sands, and the foundation design is for 20 MW wind turbines with a 35-year design life.

The feasibility study complies with DNV and API offshore standards. Determination of the environmental and structural loads on the foundation has been done with SACS, a finite element method (FEM) software package, enhanced with axial and lateral soil springs. The presented design is the integration of all these iterations. A final PLAXIS 3D analysis of the complete foundation has been performed to verify the geotechnical calculations made by the structural model in SACS, in which the soil behaviour is simplified by nonlinear springs.

2.1 Soil Investigation

The considered soil profile consists of a top layer of loose to medium-density sand of varying thickness on top of softer deposits of silt, clay, and peat. Below these softer layers, a dense to very-dense sand is present, which is interrupted by a silty clay layer. The adopted soil parameters are presented in Table 1.

Table 1: Static soil characteristics - study case site

Soil type	Top level [m below SBL]	Undr. Shear strength [kPa]	Eff. Frictio n angle [◦]	Cone resist. [MPa]
Sand	0.0	-	30	5.0
Silt	7.0	-	28	2.0
Clay	11.0	30	-	-
Peat/Clay	15.0	45	-	-
Sand	16.0	-	35	45
Silty clay	20.0	45	-	-
Sand	22.0	-	42	55
Sand/Silt	50	-	33	40

The scour protection has been assumed for an area around the foundations. It is expected that the piles can be driven through the filter layer and/or armour layer.

2.2 Load scenarios

The environmental load scenarios account for the full design of the Wind Turbine. The loading conditions include wave, current, and wind loading on the MP, along with wind loading on the turbine (thrust). Wind wave and current loading on the MP are generated by SACS.

The loads under consideration are provided in Table 2. ULS limit states were considered for bearing capacities and SLS for deflections (rotation).

Table 2: Maximum Load Case scenarios Study case

Action	Units	SLS scenario
Lateral	Fx [MN]	14
Axial	Fz [MN]	45
Moment	My [MN.m]	904

3 GEOTECHNICAL DESIGN

The geotechnical design for the hybrid monopile is focused on the pin pile-soil interface reaction. The pin piles are assumed to be rigidly connected via the interface plate. The model only accounts for the axial and lateral resistance of the pin piles. Axial and lateral group effects are included in the behaviour of the pin piles, c-t-c referring to centre to centre pin pile distance.

Table 3:Final HMP design

Parameter	Units	Value
Number of Pin Piles	[-]	6
Pin pile Outer Diameter	[m]	3
Pin Pile embedded length	[m]	42
Pin Pile length	[m]	50
Pin Pile c-t-c min distance	[m]	9
Interface Plate Diameter	[m]	22

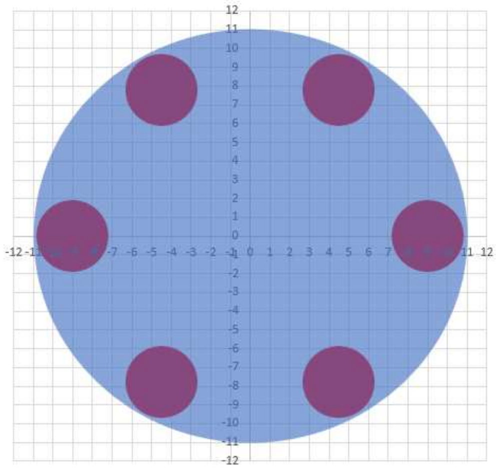

Figure 2: Pin Pile locations in the x and y directions, in meters

The design is based on the API and DNV standards and relevant literature. Based on the presented soil investigation, the Best Estimate soil scenario is used to generate the soil springs. These soil springs are integrated into SACS software to simulate the complete load cases required for the WTG, which will be presented later. The Upper Bound soil scenario will later be used for driveability and noise assessments.

The structural design, evaluated in SACS and Abaqus, was driven by fatigue damage due to wave loading on the MP and wind loading on the turbine. Associated peak stresses in the interface piece determined the design of the interface piece.

3.1 Lateral behaviour

Offshore industry standards, such as DNV and API, calculate lateral pile resistance and deflection via p-y curves. These curves are an approximation of the lateral behaviour of a pile, and have been implemented in SACS for a first design concept. Since the piles of the HMP are considered to behave in a slender manner and to reduce modelling complexity, the p-y methodology has been followed in the current assessment and the base shear has been neglected.

3.1.1 p-y curve models

The p-y curve models selected for this site are cohesionless static for Sand (Reese, 1984) and cohesive static without running water for Clay (Welch and Reese, 1972). Peat/Clay and Silty clay layers have been assumed as clay layers, since it represents the dominant soil type. Static lateral loading has been considered at this early design stage but for later phases of the Hybrid Monopile design it is strongly recommended to check dynamic or cyclic lateral loading.

The resulting p-y curves have been computed and integrated into SACS for a complete structural and geotechnical verification, integrating wind, waves and current loads. Spacing between soil springs has been defined every metre of pile penetration in average, with the corresponding surrounding soil characteristics.

3.1.2 Limitations

The p-y procedures have fine-tuned parameters based on field tests on laterally loaded slender piles of outer diameters starting from 0.31 m up to 2.5 m except for Cuxhaven test project, 4.2 m, for sandy and clayey soils, as noted by Buckley et al. (2017) Keynote lecture.

The considered outer diameters for the HMP pin piles range between 2.5 and 3.5 m, having an L/D ratio around 13 to 19. Despite the considered pile diameter range falls outside the majority of the tested range, it remains in the proximity of these test cases. For this paper the resulting p-y curves will be considered representative, with some conservatism.

Additionally, for pile outer diameters exceeding 2.5 m, DNV-RP-C212 recommends a verification of the p-y curve results with a finite element software, such as PLAXIS, which is presented afterwards.

3.2 Axial behaviour

Several t-z models are available from the literature, describing the load-displacement behaviour in axial direction. API standardised the first model in the 1980s, but it was based on limited small-scale axial tests. Nowadays, extended models are available, the most recommended ones, by API and DNV, are CPT based. Models such as UWA-05, Fugro, NGI, ICP, and the unified CPT integrate much larger databases of axial pile tests. Among these CPT-based t-z models, the ICP method was selected because it was calibrated for North Sea dense sands, which are representative of the analysed site. The database integrates large-diameter monopiles as well, thus avoiding larger monopiles' diameters axial uncertainty.

3.2.1 t-z curve models

The ICP t-z model selected for sands and clays is integrated into the SACS software calculation. Similar to p-y models, t-z models follow a predefined generic curve.

Following ICP recommendations, for axial shaft compression, due to the dense sands present at pile toe level a coring condition is implemented. For axial shaft tension, a plugged condition is used, where the inner soil weight contribution is added to the external unit shaft springs.

3.2.2 Q-z curve models

The end-bearing resistance is directly correlated to the CPT cone resistance. This tip resistance is averaged 1.5 pile diameters above and below tip level. The development of these curves in relation to soil deformation z is outside the scope of this design. Only Q_{max} is considered based on annulus cross section area and cone resistance.

3.3 Group effects

Pile group effects are complex to define. The group effect considers that a pile influences a nearby pile through soil-structure interaction, both axially and laterally. Therefore the group effect limits soil resistance due to that interaction. See Figure 3 below for axial and lateral stress interferences.

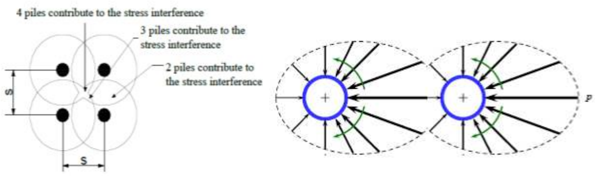

Figure 3: Stress interference for axially loaded piles (left) and laterally loaded piles (right)

Although the concept is clear, standards such as DNV and API do not offer comprehensive methodologies to properly account for that effect. Based on available literature, different simplified direct formulas have been analysed to estimate quantify this effect. More comprehensive solutions such as Cesaro et al. (2024) were not computed to maintain model flexibility and to allow quik iterations between different designs.

3.3.1 Lateral group effects

Lateral group effect has been tested more extensively than axial pile group effects, e.g., Lieng (1988) and Prakash (1962). Based on their empirical results, an efficiency formulation has been derived and implements. Three different types of lateral group interactions are distinguished: leading, trailing and side-by-side, and skewed piles which is a combination of the previous three, as can be seen in Figure 4.

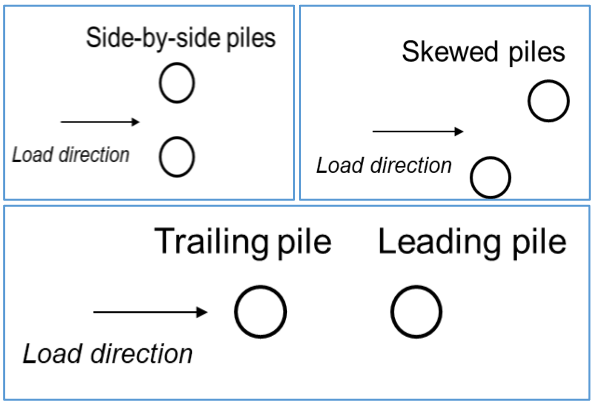

Figure 4: Schematic top view showing leading, trailing and side-by-side lateral pile group interactions

Based on the results of various experimental studies, e.g., Lieng (1988) and Prakash (1962), the leading and trailing effects are computed for each pin pile relative to the other piles, as well as side-by-side effects. The angle between those components and the loading direction is computed to determine the skewness of the piles. By combining the effects of all other piles to the subjected pile, the group effect factor for the subjected pile is computed.

After calculating the lateral group factor for each pile in the pile group, an overall average lateral pile group effect of 0.86 is considered for the analysed pile group of the HMP. This factor has been applied afterwards as an increase to the rotations found in the overall service limit state results obtained from the SACS model. Future iterations will integrate lateral group effect on the maximum yield of the computed p-y springs to incorporate the group effect in the model rather than superpositioning of the effect.

Additionally, another formulation from Zao and Stolarski (1999) was reviewed for reliability purposes. This study generated lateral group efficiency factors based on empirical results with a much simpler approach. From this research, and an s/D ratio of 3, a factor 0.85 is directly extracted, consistent with the current analysis.

Table 4: Lateral Pile Group effects

Zhao	Calculated in this study	Selected final value
0.85	0.86	0.86

3.3.2 Axial group effects

The Converse-Labarre formula from (1980) proposes to quantify axial pile group effects by an empirical formulation. When applying pin pile diameters of 3 m and a pin pile separation centre to a centre of 9 m, an overall group effect of 0.99 results.

For reliability purposes, an additional angle to look at the pile group effect is the more restrictive ISO standard for static pile load testing. As can be seen from the picture below, the requirement to ensure no soil stress interference is a minimum spacing between pile edges.

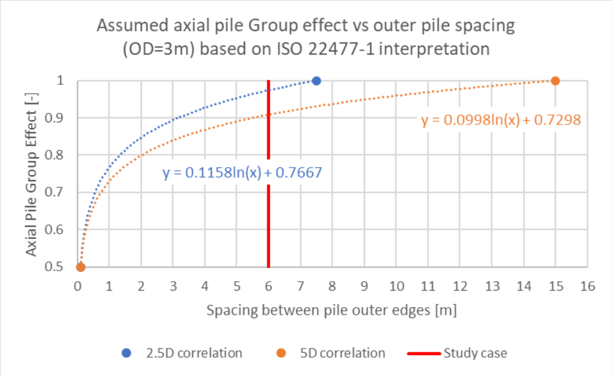

Figure 5: Axial pile group effect interpretation of the ISO 22477-1 spacing requirements for static load tests

For this estimation it has been assumed that a spacing of 0 m between piles allows for 50% of the axial resistance of each pile to develop and 100% if the requirement is met. Based on those assumptions and a logarithmic regression, we can interpret the corresponding axial pile group effect, as the average between 2.5D and 5D $\eta_{av,2.5D/5D} = 0.94$ for the assessed case. The finally selected value averages both approaches as a first estimate. The axial group effect factor has been applied as a reduction to the ultimate axial capacity resulting from the SACS model.

Table 5: Axial Pile Group effects

Converse Labarre formula	**Static Load test standards interpretation**	**Selected value**
1.0	0.94	0.97

3.3.3 PLAXIS verification

The previously defined modelling using soil springs has been verified with PLAXIS 3D. The PLAXIS model was defined in line with the properties given in Table 1, Table 2 and Table 3. The constitutive soil models used were HSS for sands and NGI-ADP for clays. *Figure 6* gives an overview of the generated PLAXIS model. Although the central monopile is considered to penetrate into the soil to a limited extent, the beneficial effect of the central monopile has not been included in the current models.

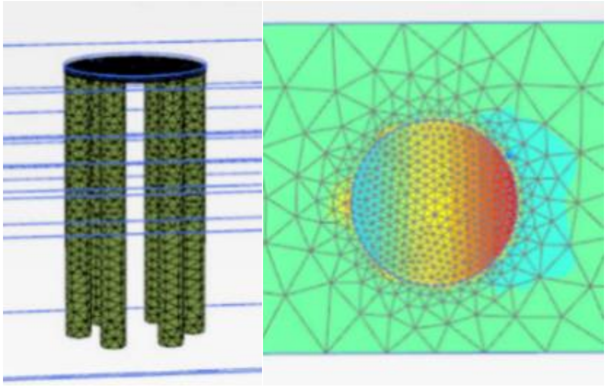

Figure 6: PLAXIS simulation of the full HMP; model (left) and vertical displacements of the IP (right).

The final results in terms of rotation of the interface piece are comparable to the previously shown methods, considering the maximum SLS load case. Although the PLAXIS model results are considered the most realistic, the soil spring approach in SACS is computationally more efficient, allowing quick calculations for all load cases and subsequent design iterations. A model calibration and final check with PLAXIS will be needed to verify the assumptions in the presented methodology. Nonetheless, for the current case the results of the soil spring simplified approach are representative.

The critical parameter to assess in this case was the overall rotation of the foundation when subjected to service loads. While accounting for the lateral group effect, the rotation obtained with the SACS model was 0.17 degrees, whereas the PLAXIS calculation resulted in 0.40 degrees of rotation. Application of the lateral group effect after calculation of the SACS model could lead to smaller displacements due to the nonlinear nature of the p-y springs, and the application of different soil models (p-y model and constitutive soil models) could lead to differences as well. Although these could be causes for changes in the results of both models, the overall results are comparable. As stated previously, subsequent design iterations will implicitly include the lateral group effect factor within the p-y spring definition.

A bigger dataset of soil profiles and monitored pile group behaviour would allow further fine-tunning group effects, but this paper constitutes a first attempt to approximate a holistic solution with overall good results.

3.4 Installation assessment

This section summarises the main results of the driveability and noise implication assessment for the HMP concept for the analysed site, assuming impact-driven installation. Although other installation methods (e.g. silent piling) are not addressed in this paper, these could bypass the noise limitations to certain extents.

3.4.1 Driveability

For comparison purposes an equivalent monopile has been predesigned to roughly compare the HMP potential. Jacket pin piles are expected to have similar dimensions to the HMP pin piles. The considered monopile has an OD of 9 m and embedded length of 30 m.

Figure 7Figure 7 shows the hammer energy required as a function of the penetration depth for the HMP in black and MP in blue, using a 3500 kJ hammer for reference (although a larger hammer would better suit the reference MP).

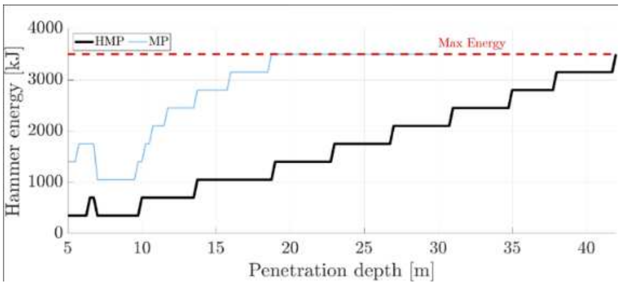

Figure 7: Hammer energy vs penetration depth comparison between the HMP (OD = 3 m) and the MP (OD = 9 m) concepts for the analysed site

3.4.2 Underwater noise

The sound exposure level (SEL) for unmitigated pile driving is estimated using the method proposed by Von Pein et al. (2022) with the expected hammer energy resulting from the drivability assessment as input, see section 3.4.1. This method is based on scaling laws calibrated using data from various OWFs where noise levels were monitored during pile driving. Since the method proposed by Von Pein et al. (2022) considers similar soil conditions as the current study, the application of the same reflection coefficient was deemed reasonable. Von Pein provides nonlinear regression scaling laws that have been applied, after which the average of the reference projects was taken.

As the impact energy applied by the hammer varies during the driving process, the corresponding SEL is dynamically computed using the impact energy per penetration depth. Additionally, adjustments are made to account for changes in the unembedded pile length, with the formula:

$$\mathrm{SEL}_{i,\mathrm{corr}} = \mathrm{SEL}_i + C_{\mathrm{pile}} \log_{10}\left(\frac{W}{h_i}\right) \tag{1}$$

Where, $C_{\mathrm{pile}} = 8.3$ is a correction coefficient considering the changing pile length during driving, W is the wetted pile length (i.e. wet stickup), and h_i is the maximum water depth, which is 42 m for the analysed site.

Figure 8Figure 8 illustrates the SEL as a function of penetration depth for both the HMP and MP concepts along with the maximum SEL requirement according to German standards (160 dB, indicated by the thick red dashed line). In addition, the required noise mitigation strategies for compliance are shown also in red, with single (SBBC), and double (DBBC) big bubble curtains. Compliance with German noise standards is achieved for the HMP concept only with a DBBC, while the MP concept necessitates both a noise mitigation system (NMS) and a DBBC. PULSE and MNRU noise mitigation system are not included in this study. This case represents a conservative approach with some room for noise mitigation.

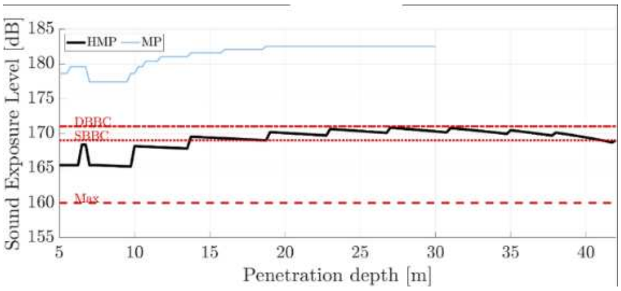

Figure 8: Sound exposure level (SEL) vs penetration depth comparison between the HMP (OD = 3 m) and the MP (OD = 9 m) concepts for the analysed site

4 CONCLUSIONS

This paper outlined a methodology to assess the HMP's geotechnical capabilities, while integrating structural requirements for 20+ MW wind turbines in its design. The methodology is not yet finalised, but represents a first step from the concept design phase. Pile group effects should be further assessed as the mode of failure of the foundation follows compression/tension (push/pull) behaviour of a jacket. This type of assessment should be performed in conjunction with a structural analysis to validate all requirements of the complete wind turbine. Lateral cyclic loading is another topic that has not been analysed at this stage. Once the design methodology and modelling becomes more matured, additional optimisation loops are needed to achieve an economical design. Finally, a comparison with an equivalent monopile should be assessed. In the current study, an equivalent monopile comparison was not pursued, since a preliminary installation analysis of an equivalent monopile of 12 m in diameter showed that installation by impact hammer would not be feasible with the largest hammers available on the market.

AUTHOR CONTRIBUTION STATEMENT

N. Moscoso: Data curation, Formal Analysis, Writing- Original draft. **T. van der Linden**: Conceptualization, Methodology, Supervision. **T. Balder**: Supervision, Writing- Reviewing and Editing. **T. Kamphuis**: Supervision, Writing- Reviewing and Editing.

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