NEW HYBRID FOUNDATION SOLUTIONS

FOR OFFSHORE WIND TURBINES

Solid and more stable support structures are needed for new OWTs; however, an innovative 'hybrid' foundation is a new type of support proposed to reduce the length of a standard monopile, increase its lateral stiffness, and ease construction in offshore conditions.

By **KRZYSZTOF TROJNAR**

This article reviews the latest developments of substructures for offshore wind turbines focusing on investigations and applications of hybrid foundations. Model tests and numerical analyses were used to simulate the loading of hybrid piles in sand. The results of pile-soil interaction were investigated to confirm the changes in soil stiffness around the hybrid monopile head. The mechanism and factors affecting the change in lateral stiffness of the hybrid foundation were explained by analyzing p–y curves for M+H loading conditions in sand. Based on this research, a new shape of p–y curves for hybrid monopiles was established and a method for determining key parameters was proposed. The effectiveness of new p–y curves was verified by comparing back-calculated results with those from numerical simulations. The conducted tests confirmed that the hybrid monopile displacement is 30 to 50 percent smaller when compared to a standard monopile with similar dimensions. The gained experiences can be useful for designers and researchers to enhance the design of foundations for offshore wind turbines.

1 INTRODUCTION

Development of wind energy has a major impact on a sustainable, long-term energy balance and on an increasing technological potential. It can be achieved, in short term, through faster development of offshore wind energy. Currently, offshore wind contributes to 45 percent of the total wind capacity installed in Europe. In 2019, 3.6 GW of new capacity was connected to the grid, which is a 1.3-fold increase in capacity comparing to 2018 [1].

Notably, energy obtained from offshore wind shows promise due to higher wind speed and lower disturbance to human lives. Comparing to onshore counterparts, offshore wind has 1.2 to 2 times higher wind speed. In open sea areas, electrical output is expected to be 1.7 times for the same wind turbine, and the energy field tends to be more efficient by going farther from coastlines. Figure 1 shows an evolution of offshore wind turbine sizes. Increasing diameters of rotors transfer increasingly higher loads to turbine foundations.

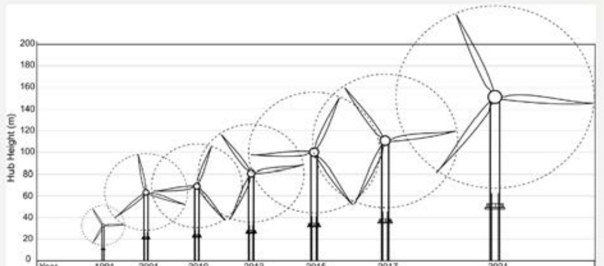
Additionally, a distance to land for newly installed offshore wind turbines (OWTs) could increase from 30 kilometers to 60 kilometers. Therefore, solid and more stable support structures for new OWTs are needed. There are ambitious plans to increase the share of renewable energy sources by almost 30 percent in the total energy balance all over Europe.

As a result, up to several hundred new OWTs are planned to be built in Poland between 2027 and 2035 in the southern Baltic Sea. Today, an important challenge for offshore wind energy is to design efficient and reliable offshore wind turbines. The cost of offshore wind support structures (design, construction, and installation) accounts for as much as 35 percent of the investment cost. The installation cost of tower support structures is 60 percent of the total cost for installing a whole wind turbine [2, 3]. Meanwhile, foundation parts have a great role in reductions of the total cost, with the potential of being 6 percent less by introducing innovative monopile techniques. Therefore, reliable and efficient foundations are preferable for the offshore wind industry, and a uniform design of new foundations with the potential of mass production is necessary.

2 FOUNDATION FOR OFFSHORE WIND TURBINES

2.1 Types of foundations

The offshore wind turbine foundations can be divided into main categories depending on the depth of the seabed. Gravity foundations are the right solution for shallow waters (10 to 30 meters). Tripod and jacket foundations are recommended in intermediate waters (30 to 40 meters). Meanwhile, monopile foundations can be installed in waters 40 to 50 meters deep. The concept of floating foundations is best for deep waters (50 to 200 meters). Floating foundations are not often used for commercial OWTs. Currently, the most widely used support structures for OWTs are monopile foundations. They have the largest market share of OWTs in Europe at more than 80 percent. It is anticipated that by 2030, the standard location of wind farms in the sea will be at a depth of 60 meters and 60 kilometers from the mainland. It should be noted that while most operating turbines are supported by monopile foundations, future deployment farther offshore in deeper waters may require more stable structures. Gravity foundations now account for only 5 percent of the market share in Europe. The gravity base provides resistance by its self-weight, and it is fabricated by reinforced concrete with ballasts. Although these materials and construction are less expensive than monopile foundations, the installation cost is a significant concern.



Year	1991	2001	2010	2013	2015	2017	2021
OWT	Vindeby	Middelgrunden	Horns Rev 2	Anholt	Westermost Rough	Burbo Bank Extension	Haliade-X
Power, MW	0.45	2.0	2.3	3.6	6.0	8.0	12.0
Height, m	35	64	68	82	102	113	150
Diameter, m	35	76	95	120	154	164	220

Figure 1: Evolution of offshore wind turbine sizes.

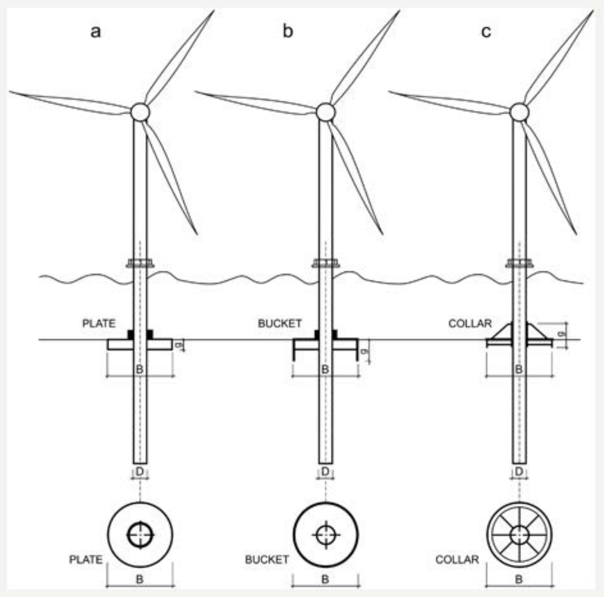


Figure 2: Various ways to shape hybrid foundations for offshore wind turbines.

Suction buckets are another popular solution of shallow foundations. They are inserted into the seabed using self-weight and suction, which significantly accelerates the installation process, saving time and cost. However, the application of gravity-base foundations is significantly limited by the water depth and soil conditions. Tripod foundations are structures with a wider base and anchor piles driven to the seabed to hold the foundation firm. Jacket foundations are designed with a lattice truss supported with three or four tubular steel legs. These foundations have high resistance of dynamic responses.

They are used in relatively deeper water; however, their high construction and installation cost is the main limitation for wider practical applications. Monopile foundations are made of large-diameter pipe piles. Limited lateral stiffness and installation cost are disadvantages of this type of foundation. All the presented foundations for offshore wind turbines have their advantages and limitations. Taking this

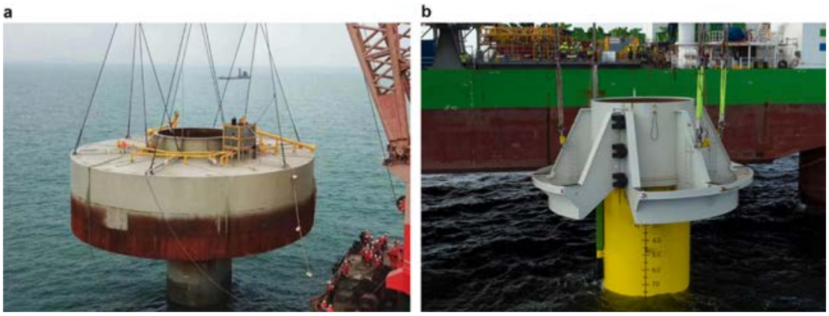


Figure 3: First applications of hybrid foundations in the world: a) monopile-bucket hybrid foundation [Source: www.offshore-energy.biz], b) hybrid collared monopile [Source: www.rwe.com].

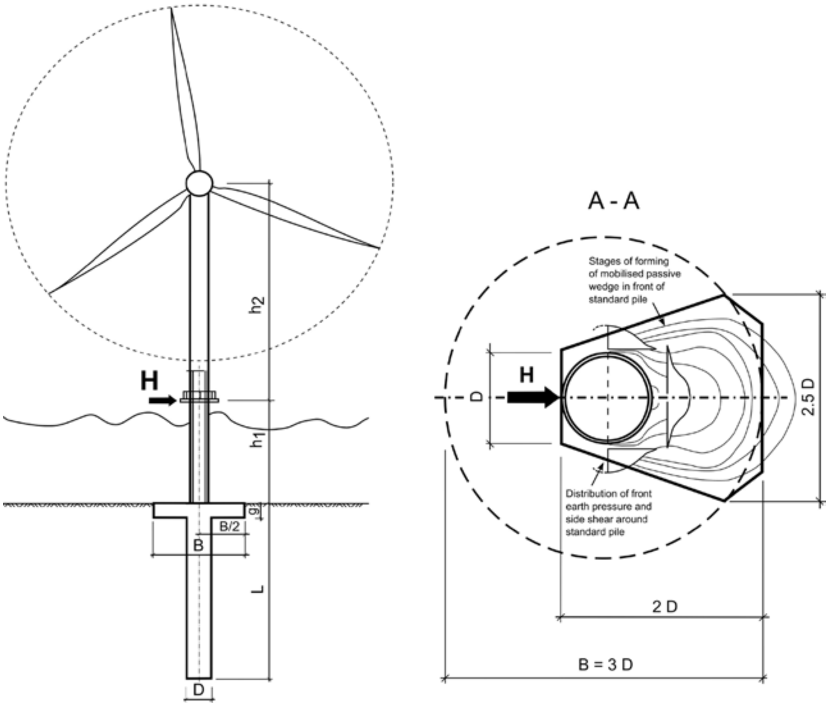


Figure 4: Load scheme and geometry of hybrid foundation for OWTs.

into account, new innovative types of foundations with better technical parameters and wider adaptability have been investigated [4-5].

2.2 Hybrid foundation concept

The novel substructure, “hybrid monopole,” is a new type of foundation proposed to reduce the length of a pile, increase its lateral stiffness, and ease construction in marine conditions [6–9]. Figure 2 presents various ways to shape hybrid foundations.

The main objective of this concept is a reduction in the cost of obtaining wind energy; as turbine sizes get larger, standard monopiles become uneconomical, and thus, there is a need for an alternative new solution. Hybrid monopiles are reliable up to a depth of 45 meters. The support structure consists of a vertical pile and a horizontal plate, which provides extra stiffness against lateral load resistance. The horizontal bearing plate is a circular rigid collar or an element showing the appearance of a bucket. The main benefits of this solution are a shorter pile length and greater lateral stiffness of the foundation.

The horizontal plate provides an additional restoring moment in the pile shaft, and friction under the plate can reduce the lateral movement of the pile foundation. The vertical pressure of the plate acting on the soil in front of the pile provides extra lateral pile resistance. Additionally, the relative scour depth around the pile is reduced, since the plate enlarges the contact area between the foundation and the seabed soil. It helps to minimize the scour failure [10–14]. After the wind turbine’s service life, the plate and pile can easily be removed and decommissioned. There are no codes of practice for design methodology of hybrid monopile foundations. In 2020, the first novel hybrid foundation had been successfully used for supporting an offshore wind turbine at the Putian Pinghai Phase II site on the southeast coast in the Fujian province in China, as shown in Figure 3a.

The hybrid foundation consisted of a large diameter monopile and a wide shallow bucket. For installation, the monopile was first embedded into the seabed and become a guideline for locating a bucket. The bucket was then installed through the center of the monopile by pumping out the water inside the bucket. High-strength grouting materials were then filled in the gap between the monopile and the bucket to connect these two components. The bucket had a diameter of 14 meters and a height of 6.4 meters. The pile was cylindrical and open-ended. Its geometric dimensions were: diameter 6 meters, wall thickness 0.05 meters, and embedding depth 60 meters. Although the hybrid monopile-bucket foundation has been used in practice, the existing studies on the lateral bearing capacity of these solutions are extremely limited [15, 16]. Wang [17] performed a series of numerical analyses on hybrid monopile-bucket foundations to investigate its lateral static and dynamic responses. The results of the analysis showed the addition of the bucket to the pile foundation effectively restrained the rotation and lateral displacement. In 2022, a steel hybrid monopile technology premiered at the Kaskasi offshore wind farm on the North Sea in Germany, as shown in Figure 3b. For the first time ever in the renewable energy industry, special collars were installed around the monopiles at the seabed level around three wind turbines [18]. Each wind turbine has a capacity of up to 9 MW. The innovative foundation collars were successfully embedded into the seabed, each 7 meters high, weighting 170 tons. The installation was carried out up to a depth of 25 meters. The space between the collar and the monopile foundation was filled with grout material, firmly connecting these construction elements. The new technology provided additional support for the pile lateral loading, increased the bearing capacity, and improved the structural integrity of this OWT foundation.

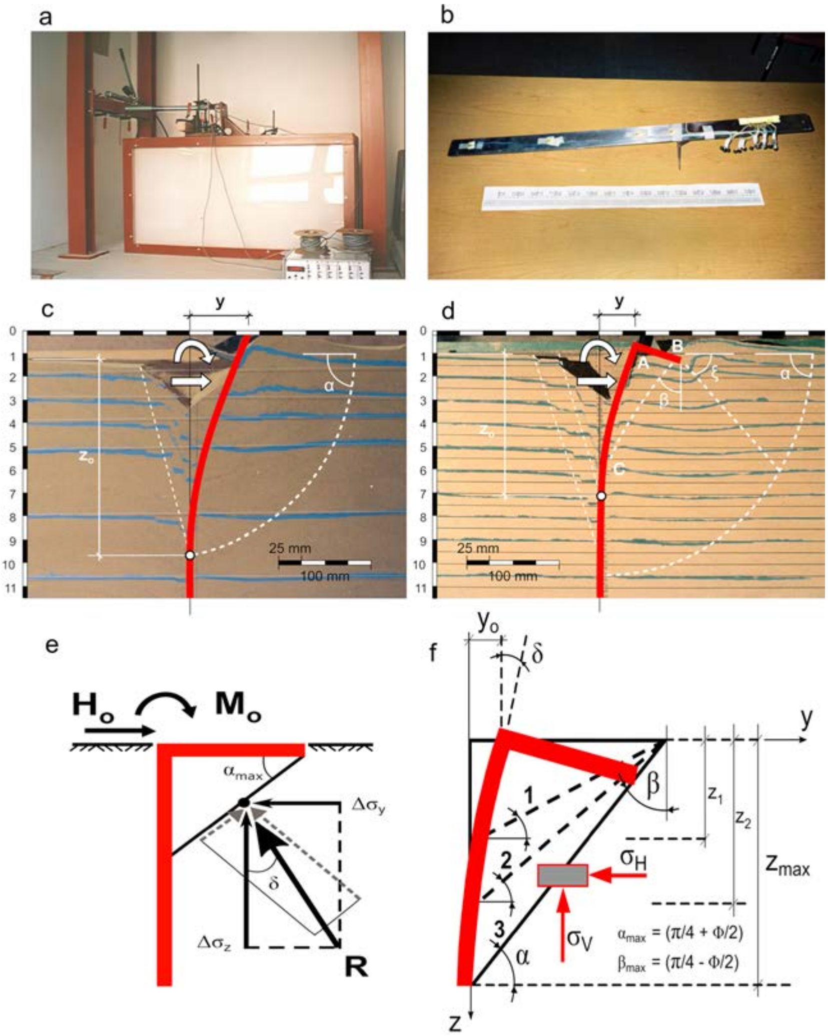


Figure 5: Model tests of piles under lateral load M/H = 4: a), b) test stand and hybrid pile model; c), d) deformation zones near tested pile models; e), f) assumptions of the calculation method for hybrid pile.

3 RESEARCH ON HYBRID FOUNDATIONS

3.1 Scope and purpose

The lateral load bearing capacity of hybrid pile foundations depends mainly on soil stiffness. The requirements for designing OWTs foundations are now more SLS- than ULS-oriented [19- 20]. The serviceability of OWTs may get lost due to excessive tilting or horizontal displacement of the tower at the mudline level. Considering strict operational requirements of turbines, a maximum rotating angle of 0.5 degrees and horizontal displacement of the pile head are often limited. Based on the author's studies and analyses, a practical method of calculating hybrid monopiles for OWTs was developed. The proposed solution was improved with regards to the pile-soil interaction in the initial phase of increasing displacements. By using the proposed method, calculations for the hybrid monopile allows the impact of a horizontal plate on the monopile to be initially assessed, which generally improves the pile lateral stiffness by 30 to 50 percent. The geometry and the lateral load scheme for hybrid foundations are shown in Figure 4.

Fine sand parameters	Unit	Value
Unit weight, γ	[g/cm^3]	1.60
Internal friction angle, Φ	[°]	30
Soil moisture content, w	[%]	12
Effective particle size, D_{10}	[mm]	0.15
Effective particle size, D_{50}	[mm]	0.30

Table 1: Soil characteristics in model tests.

3.2 Methodology

In this study, the self-developed monotonic load test loading system was adopted to carry out a series of model tests for a monopile foundation. The theoretical calculation results of lateral load were adopted for the pile-soil interaction analyses and were analyzed in accordance with the model test results. The laboratory model tests were treated as a qualitative assessment of the research problem. The small-scale experiments were conducted at the Rzeszow University of Technology, Poland. Fine silica sand was used for testing. A general view of the test stand and the hybrid pile model are shown in Figure 5a,b.

Depth		P–y function
Normalized	m	
0.50 D	0.6	$p = 7 \cdot 10^7 y^5 - 3 \cdot 10^7 y^4 + 4 \cdot 10^6 y^3 - 31611 y^2 + 13828 y$
1.00 D	1.0	$p = 5 \cdot 10^8 y^5 - 2 \cdot 10^8 y^4 + 2 \cdot 10^7 y^3 - 10^6 y^2 + 37962 y$
1.25 D	1.5	$p = 7 \cdot 10^8 y^5 - 2 \cdot 10^8 y^4 + 2 \cdot 10^7 y^3 - 10^6 y^2 + 46555 y$
1.67 D	2.0	$p = 10^9 y^5 - 3 \cdot 10^8 y^4 + 3 \cdot 10^7 y^3 - 10^6 y^2 + 47374 y$

Table 2: P–y functions for a hybrid pile in sand.

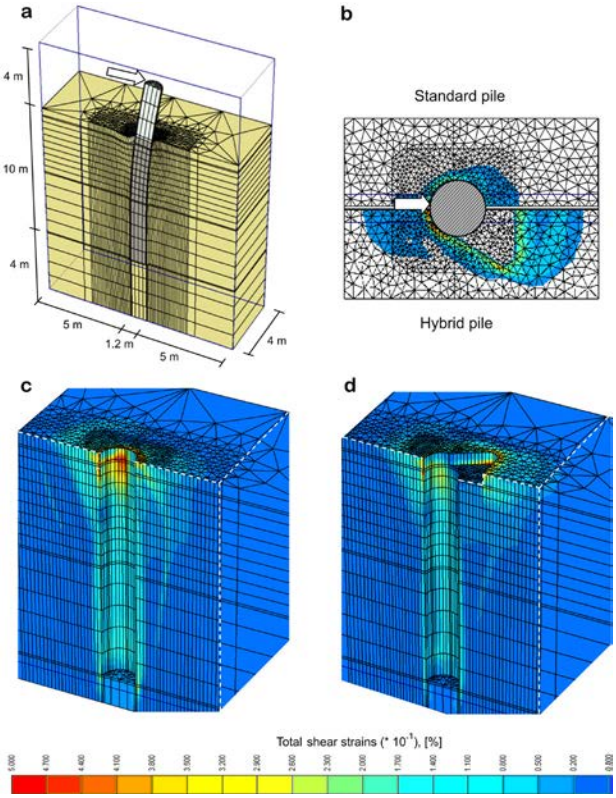


Figure 6: Results of the 3D FE analysis: a) numerical model; b) soil wedge range as stress difference for hybrid and standard piles; c), d) impact zones around two types of piles for the same pile head displacement of 20 mm.

The box was filled with sand using the curtain method, with the container moving at a constant height to provide uniform compaction conditions. The layers of the sand placed in the box were of different colors for better observation of both models of foundations and soil through the transparent box wall. The soil parameters are summarized in Table 1.

The aim of these tests was to qualitatively assess the behavior of the soil under the plate in front of the hybrid pile laterally loaded. The lateral load scheme was adopted for M/H ratio = 4. The foundation model was subjected to a horizontal force on a reduced scale 1/N2 = 100. The model tests confirmed that standard piles interact with the soil in a different way than hybrid piles. Significant differences in shapes of the active soil zones in the vicinity of two pile models are shown in Figure 5c (standard pile) and Figure 5d (hybrid pile). It was observed that sand movement starts at the beginning of the pile load and continues throughout the load duration. A resistance zone appeared under the plate, which divided the soil area into a convective zone and a wedge zone (ABC). The wedge area is shown in Figure 5e.

When the standard pile was loaded, the entire active area in front of the pile was significantly smaller compared to the hybrid pile with the same displacement. The pivot point zo of the hybrid pile model was found to be in sand approximately 1/3 above that of the standard pile model. Based on the model tests, it was determined the active soil area formed under the bearing plate in front of the hybrid pile is always wedge-shaped. It was assumed on the basis of other studies [21, 22]. The depth of the wedge increases with the hybrid pile loading, as shown in Figure 5f. Based on the previous analyses of hybrid piles, it was found the change of depth of the wedge under the bearing plate occurs only in a limited range of the pile displacement [5, 6]. In this case, the lateral pressure of the pile on the soil is due to the stress wedge. It was assumed that the reaction force R in front of the hybrid pile resulting from stresses in the wedge impact zone depends on the vertical plate pressure and changes with the pile rotation.

3.3 Results

The numerical FE analysis was used to quantify the soil behavior around the hybrid pile with a flexible shaft and to develop a method for calculating its wide displacement range. Numerical modeling was carried out using the FE method and Plaxis 3D software, as shown in Figure 6. The non-linear elastic-plastic Mohr-Coulomb type soil model was used.

The analysis was carried out using homogeneous sand with parameters: angle of internal friction 30 degrees, Young's modulus 80 MPa increased 1.5z with depth (z), cohesion 1 kPa, Poisson's ratio 0.3, and dilatation angle 5 degrees. The numerical model was validated for the behavior of the standard pile and the experimental data of the field test for a 10 meter-long, 1.2 meter-diameter pile. The presented results of 3D FE calculations are applicable for loads causing the same pile head displacement of 20 mm. In this case, the horizontal force was 400 kN and 1,000 kN for the standard and hybrid piles, respectively. Figure 7 shows the stress-displacement curves of the hybrid and standard piles calculated for different depths.

It can be seen that in the displacement range (y) 10–50 mm, the stress (p) increases significantly for the hybrid pile compared to the standard pile. At depths greater than 2 meters, the curves in both diagrams have a similar shape. The changes of stresses in the soil zone in front of the pile are observable only up to the depth of 2 meters, and their values depend on the displacement of the pile at a given depth. The FE analysis shows the type of *p–y* curves for depths up to 2 meters is crucial for calculating the hybrid pile. The forms of *p–y* functions for different depths in the active zone of the soil in front of the hybrid pile can be written by fifth-degree polynomials, as shown in Table 2.

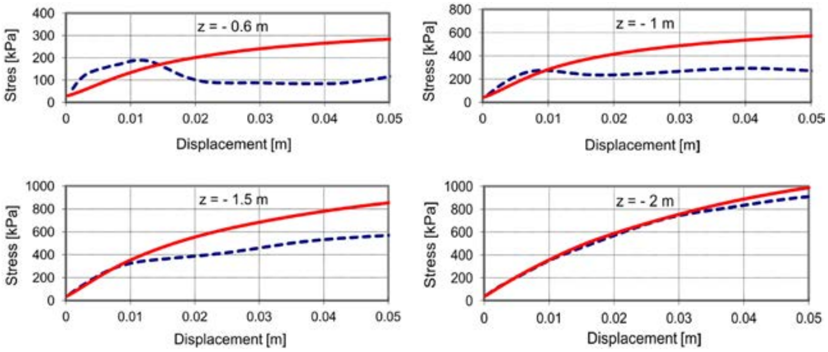


Figure 7: P–y curves for the 10 m-long pile based on FE analysis: red line – hybrid, blue line – standard.

4 DISCUSSION

In engineering practices, special attention should be paid to the actual lateral response of bending hybrid piles in the soil in the zone below the seabed level. For this purpose, a modification of the *p–y* curves with 2 meters of depth below the plate has been proposed. The new shape of *p–y* curves is particularly important in the initial range of pile displacements up to 50 mm. Figure 8 shows control calculations for the analyzed standard and hybrid piles.

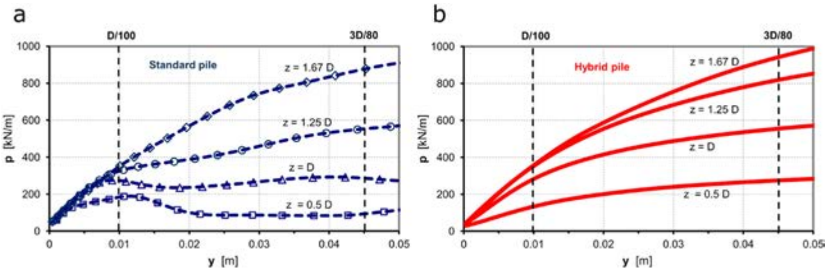


Figure 8: P–y curves for piles D = 1.2 m, L = 10 m; a) standard, b) hybrid.

The assumptions on the shape of new *p–y* curves for hybrid piles were based on two main considerations: First, numerical analyses show that, for the standard piles, soil failure occurs at a displacement of 10 mm; in the *p–y* diagram, this corresponds to the value of D/100. Thus, this value can be taken as the upper limit of the range in which the pile is still elastic in the soil. Second, the shape of *p–y* curves for the hybrid pile is different from that of the standard pile. The main difference is that, above the displacement D/100, the hybrid pile is still stable, unlike the standard pile whose behavior in the ground is clearly non-linear.

The modification consists in providing new p-stress values for the curves in the range of normalized displacements y in the range from 10 mm (D/100) to 50 mm (3D/80). The *p–y* curves for the standard and hybrid piles were used in control calculations. According to Figure 9 and Figure 10, the displacement and bending moments of the hybrid pile are smaller than the standard pile.

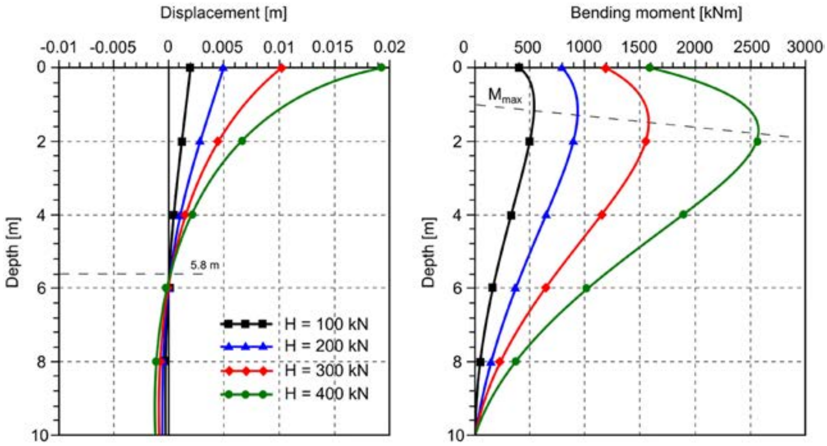


Figure 9: Calculation results of the standard pile: a) displacement; b) bending moment.

In both cases, pile displacements and soil response distributions were in a satisfactory agreement with previous FE simulations. Calculations with the modified *p–y* curves for the hybrid pile allowed for accurate determination of the plate effect Ep. The Ep value described as a ratio of the standard pile displacement to the hybrid pile displacement under the same lateral load was assumed as a measure of the plate effect. The Ep values obtained are consistent with the results of other tests in sand [4, 5]. With an increase in the lateral load of the hybrid pile, the distribution of the maximum bending moment and soil reaction occurs at the same depth. A comparison of the parametric results in Figure 11 shows the lateral stiffness of the analyzed hybrid pile increases with deflection.

When the pile is loaded with a force of 400 kN and a bending moment of 1,600 kN•m, in control calculations, the value of the plate influence coefficient Ep is 1.45. The use of the proposed modified *p–y* curves affects the horizontal stress distribution in the soil in front of the hybrid pile. As a result of the calculations, lower deflections of the hybrid pile were

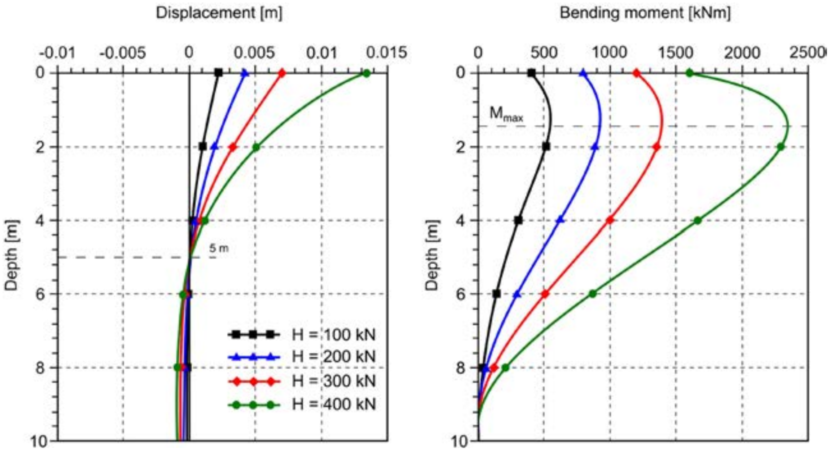


Figure 10: Calculation results of the hybrid pile: a) displacement; b) bending moment.

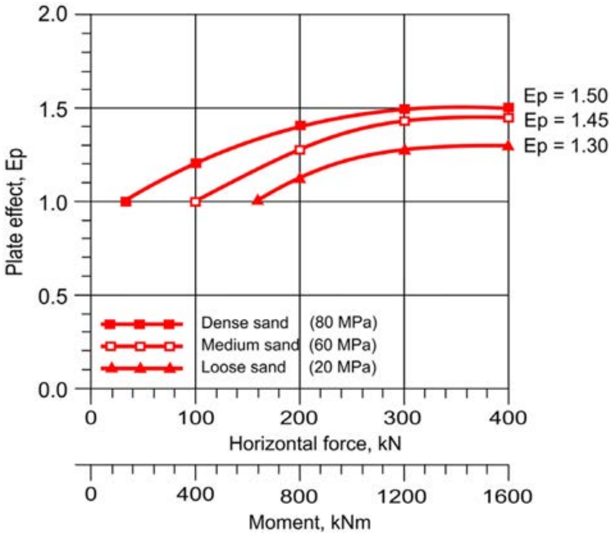


Figure 11: Comparison of lateral stiffness calculation results of hybrid monopiles in sand.

obtained, which is consistent with the results of the field tests. No significant changes were found in the bending moment distribution in the pile. Calculations also showed a smaller depth of the pivot point of the hybrid pile in the soil. Analyzing the changes in the lateral pressure of the pile on the ground, it can be seen that at a rotation of 0.002 rd, there is no failure of the soil under the plate. This proves the beneficial effect of the plate on the stability of the hybrid pile. The hybrid pile can carry a higher lateral load at the same displacement as the standard pile. The proposed method for calculating hybrid piles is a simplified solution. Nevertheless, the calculated displacement values are generally consistent with the results of accurate numerical calculations. Increasing the accuracy of the proposed method is still possible, but it requires further correction of *p–y* curves by taking into account, to a greater extent, the contribution of lateral zones around the piles. A similar problem was analyzed in the proposal for calculating hybrid piles with rigid and flexible shafts. Details are available in previous studies [7, 23].

5 CONCLUSIONS

Currently, solid and more stable support structures are needed for new OWTs. An innovative "hybrid" foundation is a new type of support proposed to reduce the length of a standard monopile, increase its lateral stiffness, and ease construction in offshore conditions. The hybrid monopiles have been analyzed by means of model tests and numerical calculations. The following conclusions are drawn from this study:

◤ **1:** The stiffness of the hybrid monopile increases with its deflection under lateral loading.

◤ **2:** The analysis showed that the pile-soil interaction for depths up to 2 meters is crucial for the hybrid monopile.

◤ **3.:** Modified forms of *p–y* functions for the hybrid monopile can be proposed for the range of displacements up to 50 mm.

◤ **4:** The conducted studies confirmed that displacements of hybrid monopiles are 30 to 50 percent smaller compared to displacement of standard monopiles with similar dimensions.

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