Laterally Loaded Monopile for Large Scale Offshore Wind Turbines

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ABSTRACT

Offshore wind energy provides tremendous potential for clean energy growth around the world. Offshore wind turbines often have a monopile base installed. Action of large-sized monopiles against horizontal load is studied using a finite element model in three dimensions by Plaxis software in order to determine lateral load capacity of the monopile. The correlation between horizontal ultimate load and lateral displacement has been studied and the lateral monopile capacity can be enhanced by adding jointed plates or winged plates as discussed here. Monopile failure shape has been studied in all the cases in order to identify how monopile act at failure.

Keywords: **Monopile, Plaxis, Horizontal Displacement, Offshore Wind Turbines, Jointed Plates, Winged Plates, Failure Shape.**
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INTRODUCTION

Energy sources are the basis of today's economic development. The quality of the energy sector will be changed and the standards of human life enhanced by the use of clean renewable energy are one of the highlights. The wind power is generated by the wind, which in this case is considered a natural resource. In comparison, wind power is the greatest renewable and regenerated energy in the world (Guy et al., 2005).

Coal and oil resources are needed to generate electricity, but they produce large amounts of carbon emissions and pollution (Byron et al., 2003). Offshore wind turbines are a source of generated energy with the production of wind power. The offshore wind turbines offer several advantages including hyper wind speed, low turbulence flow, and high performance, in addition to saving large precious inland areas for development.

As one of the typical formulas, one steel pipe pile with a diameter ranging from 2.0 m to 7.0 m simply makes offshore wind turbine monopile and is mounted beneath the sea bed by embedded length ranging between 18 and 25 m, as presented in Figure 1.Many large-scale offshore wind turbines use monopiles., examples of existing wind farms include: Horns Rev, Samso constructed in Denmark, Utgrunden in Sweden and Arklow in Ireland (Nils et al., 2005).

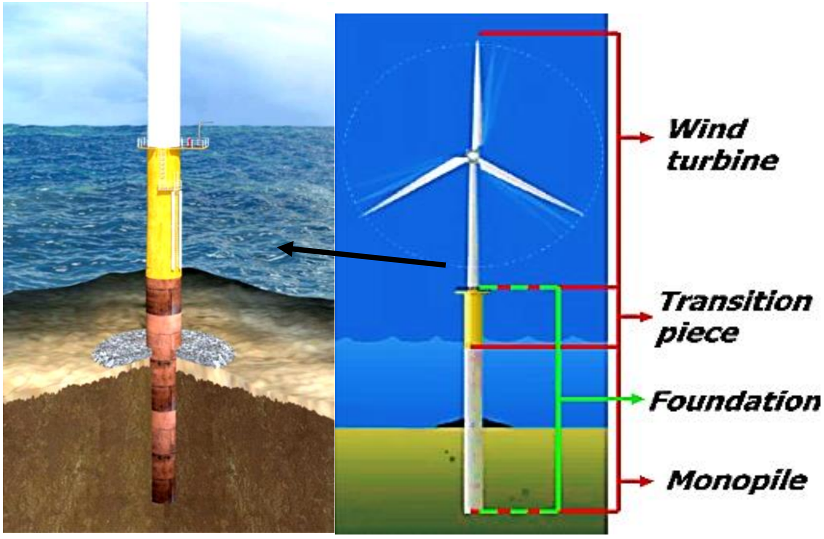


Figure 1 Monopile installed for Wind Turbine.

The turbine and machinery weights subject the monopile to a vertical (V) load, as well as the lateral force (H) and bending variable moment (M) caused by the wind, current and wave. Stability and the failure mode of the monopile under horizontal loads are evaluated as one of the main issues of design and construction of offshore wind turbines. Numerical analysis with finite elements software Plaxis, is used in this paper will offer resources that can be used as a reference for analysis the monopile foundation.

Numerical Model

The Finite Element Analysis (FEA) general purpose software (Plaxis [V20]) is used in the computational implementation of a finite element model in three dimensions for the wind turbine foundations. According to the symmetric loading assumption, only one half of the sub-soil and monopile is taken into account in the study. The discretized model's overall dimensions are 80 metres long and 60 metres wide. The model's bottom line is set at 10 metres below the monopile's tip. The estimated pile behaviour is unaffected by the side or lower boundaries when using these model dimensions. Moreover, mesh size convergence analysis is also performed to assure that the finite element size and boundaries are not affecting the results.

The monopile is mainly two parts protruded above the sea floor and driven under it, along with all the surrounding soils are all simulated using 10-noded finite elements, as shown by Figure 2.

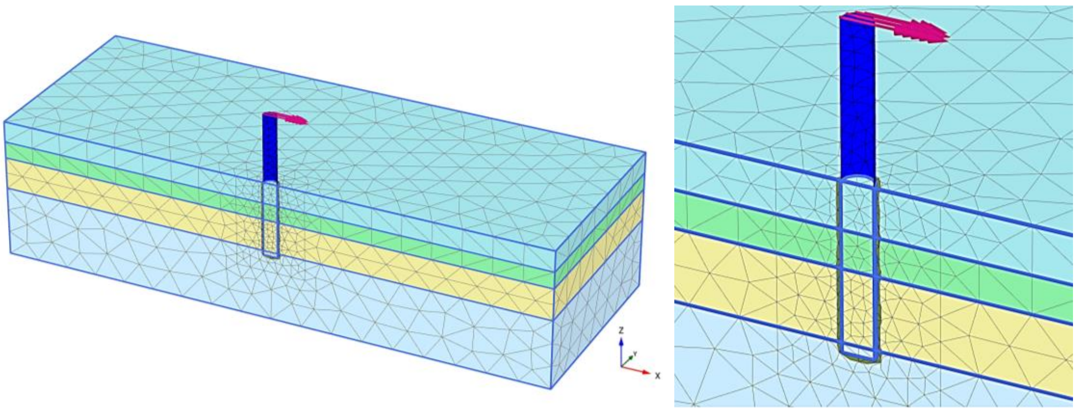


Figure 2 Plaxis Model Used in Analyses of the Monopile.

Verification of the Numerical Model

Step-by-step finite element analysis is used. The first step is to create an initial stress state (geostatic pressure) for the whole model domain. The monopile is then put in place by swapping out the soil components at the pile's location with steel ones and activating the conditions that allow contact between the monopile and the soil.

Finally horizontal force is gradually applied incrementally. The monopile components are stretched above the sea floor surface in order to take in account different load arrangements (horizontal loads and moments). The main objective of the finite element analysis is to model the monopile load-transfer behavior into the surrounding soil domain. Upon model calibration and verification with the field data, the numerical model is extended to model different soil and monopile properties, along with other factors.

This verification is depends on the soil characteristics at Dunkirk location that is employed during the PISA project for laterally loaded monopile tests in dense sand (McAdam et al., 2020). All Plaxis 3D calibration calculations, termed herein, are carried out with (HS) model (Benz, 2007) as shown in Table 1.For the soil profile $E_{50,ref}$ = 60 MPa , $E_{oed,ref}$ = 60 MPa and P_{ref} = 100 kPa.

Results obtained during monopile testing are used to verify the numerical model which is performed using the finite element software Plaxis with different properties, as shown in Table 2 and Figure 3. The monopile itself is a steel tube and modeled as a linear elastic material because of the large differences between the soil and steel stiffnesses. Summary of the input parameters are presented in Table 3.

Table 1 Hardening Soil Model with Small Strain Stiffness Properties (Minga, 2019).

Layer	Depth	RD^{real} (%)	Ko	γ_{sat} (kN/m^3)	c'_{ref} (kPa)	ϕ' (°)	ψ (°)	ϕ'_{int} (°)	$G_{0,ref}$ (kPa)	$E_{ur,ref}$ (kPa)	$\gamma_{0.70}$	R_f
1	0-3	100	0.40	17.10	5	44	15	29	196852	460633	0.0001	0.875
2	3-5.40	75	0.40	17.10	10	40	10	29	169675	397040	0.000125	0.906
3	5.40-10	75	0.40	19.90	0.10	40	10	29	165878	388155	0.000125	0.906
4	10-20	75	0.40	19.90	0.10	40	10	29	156998	367376	0.000125	0.906

Table 2 Steel Monopile Dimensions.

D (m)	L (m)	t (m)	h (m)
2.00	10.61	0.038	9.90

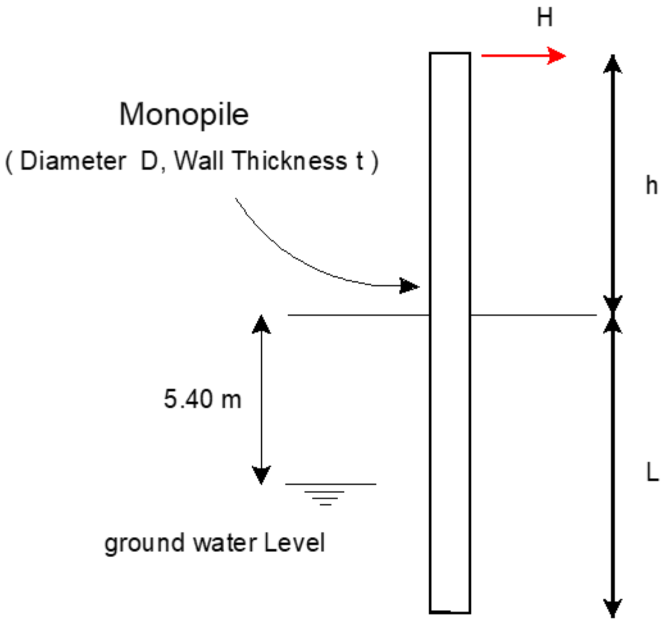
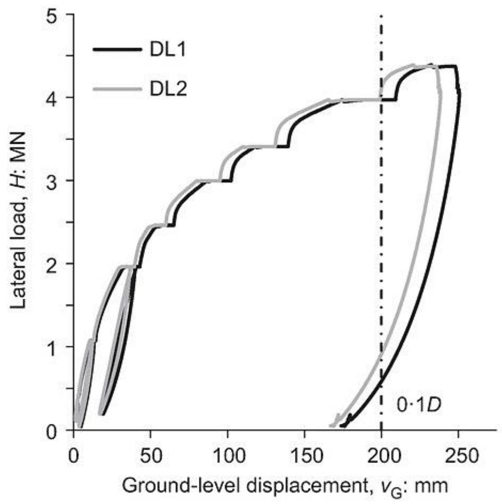


Figure 3 Monopile Dimensions and Properties.

Table 3 Pile Model Parameters.

Parameter	**MonoPile, Elastic (Isotropic Model)**
Modulus of Elasticity, E (GPa)	200.0
Unit Weight, γ (kN/m^3)	78.50
Poisson's ratio, ν	0.30

Figure 4a depicts the relation between lateral load H and the pile's horizontal displacement at ground level, VG. The hold durations specified during the field testing are shown by the constant load stages in the field data. On the other hand, in Figure 4a, you can see the unload-reload loops performed shortly after the start of the test and the unloading response at the end of the test. Figure 4b illustrates the 3D plaxis analysis response that is in good accordance with the field data. Field test data and associated finite element comparisons are of similar quality., at ground displacement (10% D) = 0.20 m at which the field load is equal to 4100 kN and the numerical load for half model equal to 2048 kN, for full model it will be 4096 kN, so the numerical results are consistent with the experimental ones.



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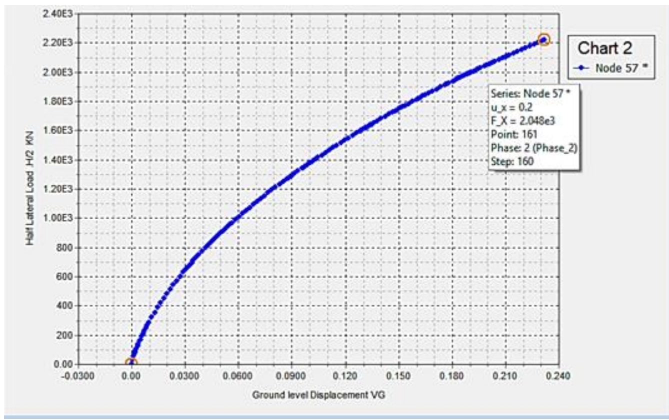

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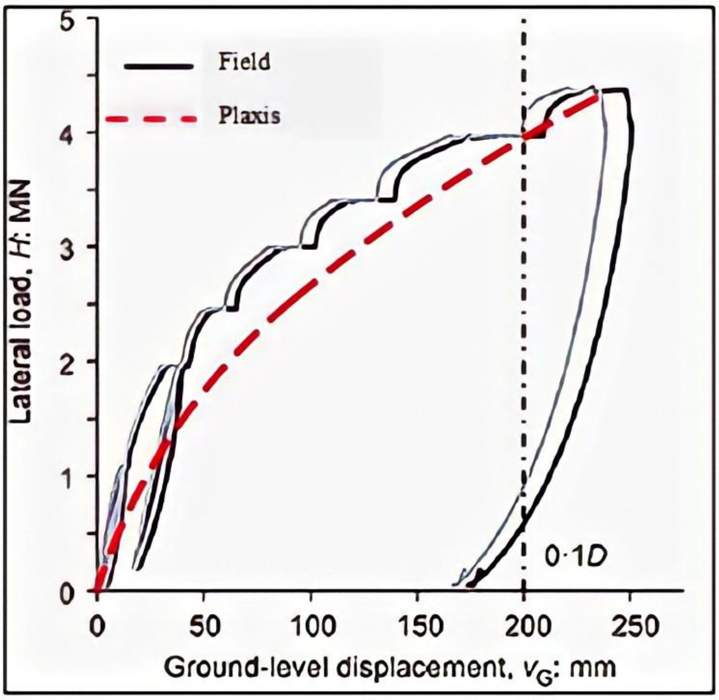

Figure 4 Comparisons between Field and 3D Plaxis Model Outcomes for Monopile Tested at Dunkirk; Horizontal Load, H, vs. Ground displacement, V_G, Response.

Parametric Study

A numerical parametric study is carried out to have a better understanding and shed more light into the behavior of monopiles taking into account various actual pile configurations and applied bending moments. Three cases are studied in the paper to explore the performance of the horizontal resistance of the monopile of large offshore wind turbine, which has different h/L values employing the same soil properties presented in Table 1. Pile properties used in this study is listed in Table 4.

Table 4 Different Configurations for Monopile.

h/L	D (m)	L (m)	t (m)	h (m)
0.20	2.00	10.61	0.038	2.122
0.60	2.00	10.61	0.038	6.366
1.00	2.00	10.61	0.038	10.610

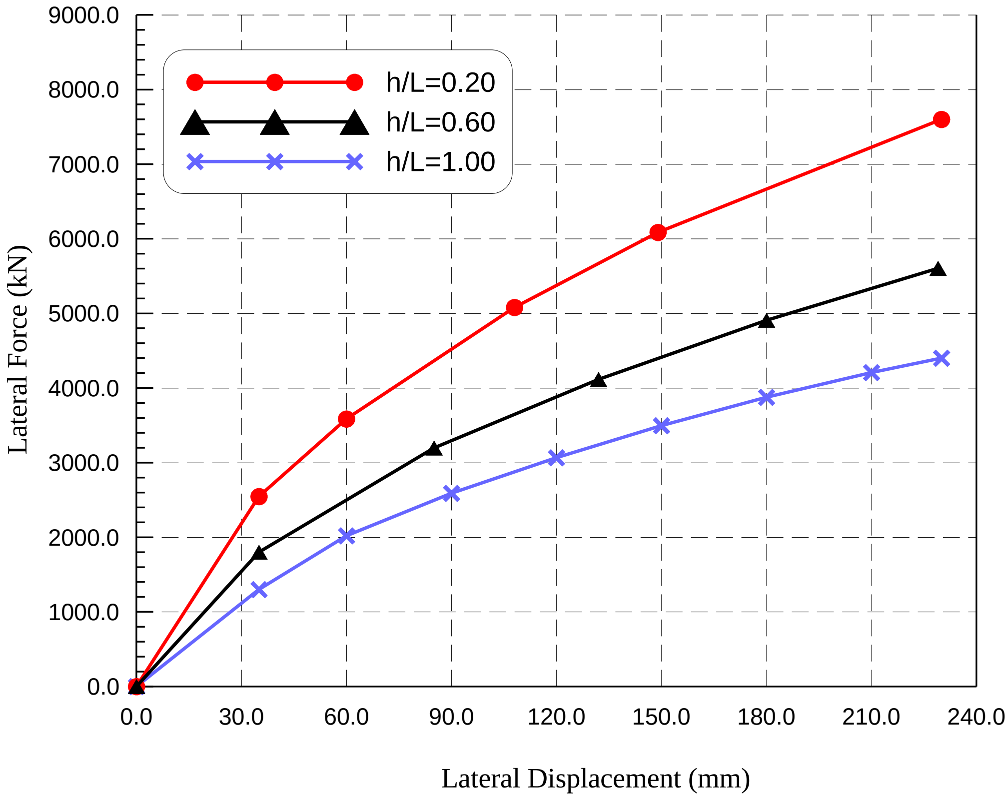

Figure 5 Lateral Load Displacement Curve for h/L= (0.20, 0.60, and 1.00).

Figure 5 shows the relation between lateral force and lateral displacement for different heights (h) above the mud line to embedded length(L) namely; (h/L) = 0.20, (h/L) = 0.60, (h/L) = 1.00. Variable Lateral loads H acting at different heights, is also explored above sea floor line. Various lateral forces H and moments M = H x h are generated by changing the load application height h. with three different load eccentricities (h/L). At failure displacement, 200 mm in this case, the lateral force for h/L = 0.20 is 7200 kN, for h/L

= 0.60 is equal to 5400 kN and for h/L = 1.00 the lateral force is equal 4200 kN, as the monopile is going to be longer the stiffness become lower.

Failure Mechanism

Figure 6 shows the deformed mesh shape at failure, the pile body is deformed and rotated, and plastic areas occurred in the passive zone in front of the pile. Within a specific range of depths, the soil has inclined downward displacement in the direction of the monopile, and away from this range, the calculated displacements are negligible.

The soil in the passive area is extruding up to a certain height range, and the soil is inclined upward away from the pile. Outside the mentioned zones, the soil has inclined downward displacement away from the pile. The soil around the bottom of the pile body moved slightly away from the pile body direction, and the displacement is continuously decreasing with depth.

This deformed shape can be created only by employing an interface, in which node pairs are formed at the interface between monopile and soil. One node in a node pair belongs to monopile, while the other node belongs to the surrounding soil. One elastic-perfectly plastic spring to represent the gap displacement and another elastic-perfectly plastic spring to represent the slip deformation.

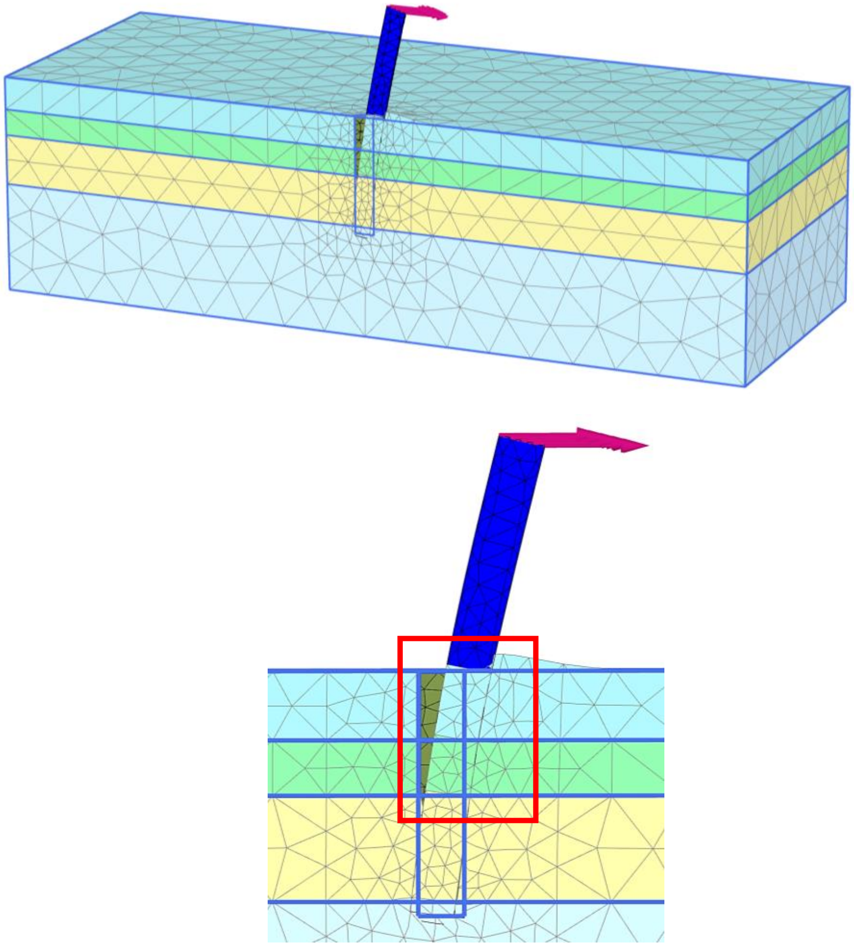

Figure 6 Deformed Mesh Shape.

Enhancing the Behavior of Existing Monopiles

Improving the vertical and lateral capacities of monopiles has a lot of benefits regarding two aspects, first improving the vertical and lateral loads of existing monopiles. Secondly, improving the vertical and lateral capacities of new monopiles to be driven with the below mentioned enhancements.

Using Bearing Plates to Improve Monopile Vertical and Horizontal Capacities

The analysis considered two different approaches, pile with no bearing plate, and another one having 4-m-diameter extra (extended) bearing plate located at the mud-line, as shown in Figure 7.

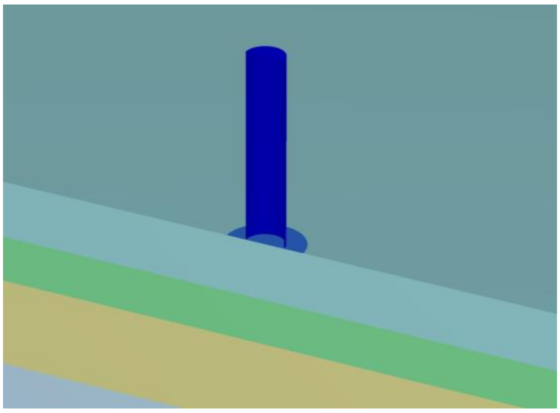

Figure 7 Monopile with 4m Extended Diameter External Bearing Plate at the Mud Line.

Lateral Load

Comparing the load versus deflection response of the 3D FE results presented in Figure 6 shows a consistent increase in the measured displacements when increasing the applied loads till failure by excessive lateral deformations.

The tested soil is sand and the failure took place with no plate at about 4096 kN, as defined in the failure criteria which is 10% pile diameter,which is equal to 200 mm for such pile diameter. In case of adding the bearing plate, numerical analysis shows the same trend with higher computed lateral resistance force reaching up to 4936 kN. The increase in the lateral capacity at failure between the two cases is about 20.50% which is considered an effective enhancement to existing and new monopiles.

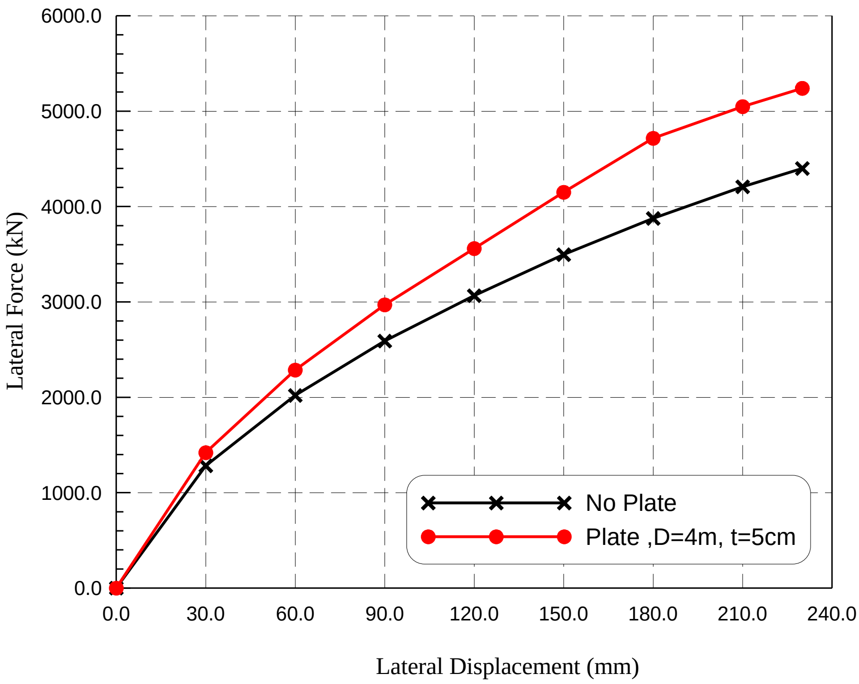

Figure 8 Lateral Load Displacement Curves for a Pile with and without Bearing Plate at Mud Line.

Vertical Load

The vertical load only (H ≈ 0) is considered under theoretical calm sea conditions, this is because the offshore wind structure's vertical loads apply to the installation of load turbines first .The wind turbine is then subjected to lateral loading as a result of wind and wave action while being in operation.

. This theoretical case is applied herein to quantify the effect of adding the plate on the vertical response of the monopile.

It is clear that the vertical response significantly enhances when a monopile is having an additional extended 4 m bearing plate as the failure vertical load without plate is equal to 28,000 kN, and when adding the plate the load became 52,500 kN with total increase in the vertical load capacity of 87.50%, as presented in Figure 7. It is found that the vertical loads tend to continuously increase due to the compression and densification of the upper sand under the added plate. Therefore, the load resistance at a displacement of 0.1 d (d is the diameter of pile) is taken as the vertical loading capacity to quantitatively assess the performance of the hybrid foundation (monopile with plate).

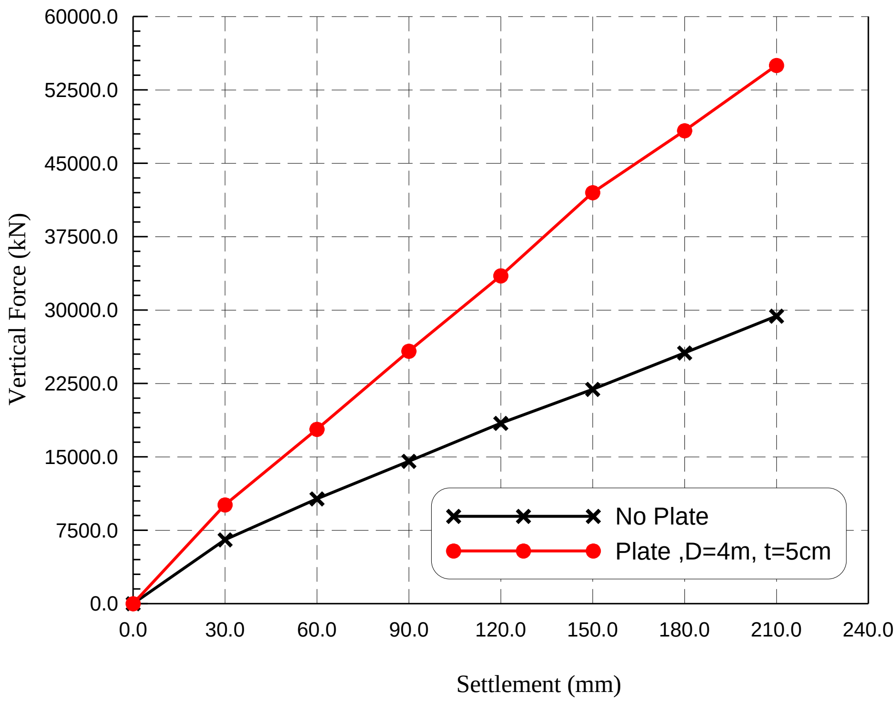

Figure 9 Vertical Load Settlement Curve for a Pile with and without 4 m Steel Plate.

Winged Monopiles,or Monopiles with Fins

Top Winged Monopile and Lateral Capacity of Monopile

Another suggested method for increasing the monopile passive lateral resistance is employing the "winged-monopile" concept, firstly suggested by Grabe et al. (2005). Plate members are connected to the outside section of the pile shaft in the winged pile to mobilize extra strength in the soil close the mud line, which improves the lateral performance of the monopile foundation. Given the comparatively high cost of the offshore structure in the total project budget, there will be such an enhancement in performance would be highly useful in increasing the competitiveness of offshore wind energy over traditional energy sources. This study investigates the potential usage of monopiles in deeper seas via the advancement of a winged monopile structure. Another case in which the top winged system can be employed is increasing the existing monopile capacity when geotechnical assessment for such pile is showing safety concerns.

Grabe et al. (2005) suggested that expanding the cross-sectional area of the piles at mud level, the lateral load capacity of monopile foundations could be increased. The installation of steel wings (or fins) to the pile body near the mud line is one technique of increasing the pile area, as presented in Figure 10. Four steel wings are attached to the monopile body, with wing length = 2.65 m, breadth = 1.00m, and thickness of 5.0 cm respectively at each side of the pile.

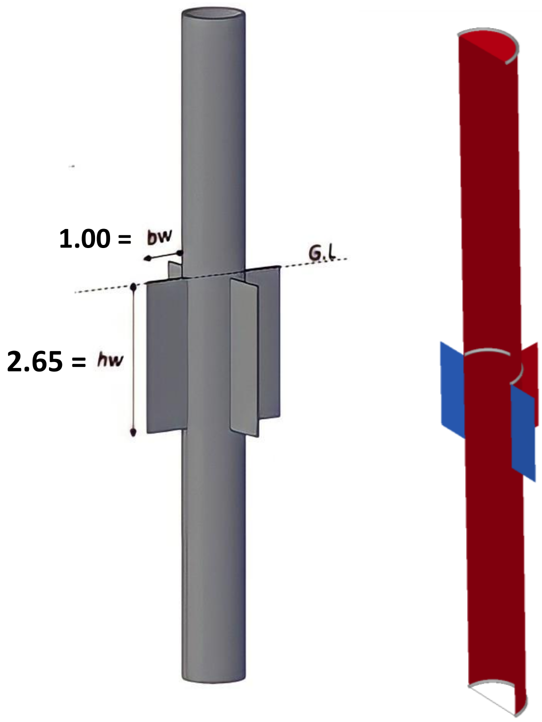

Figure 10 Top Winged Monopile, with Wings Located at Mud Line.

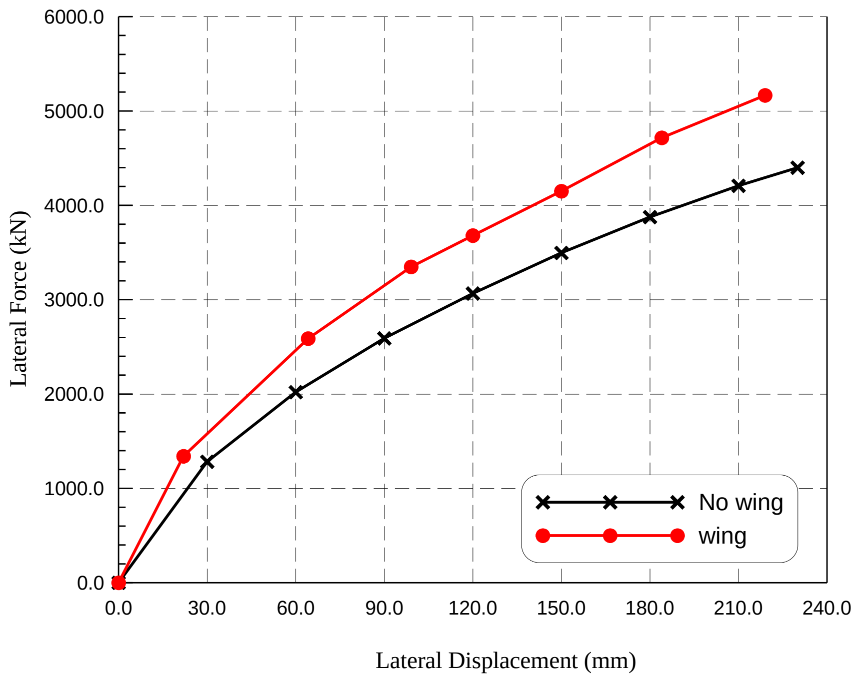

Figure 11 Lateral Load Displacement Curve for Top Winged and Non-Winged Piles.

The load-displacement response of both the winged and non-winged piles is shown Figure 11. The installation of wings considerably increased the lateral load capacity and rigidity of the piles, according to the results. The ultimate bearing capacity increases by 904 kN (22%) at 10% of monopile diameter (200 mm), relative to the reference pile with no wings.

Bottom Winged Monopile

Although less effective, but the bottom winged monopile case is presented herein for the sake of completeness. This technique of enhancing the pile performance against lateral loads can be carried out before pile driving. The bottom part of the pile can be formed with two wings which give the monopile larger lower diameter. The pile has two sections, the first section is the lower part of the pile and is called lower section in which the pile diameter is enlarged with b_w = 1.0 m to a certain depth h_w = 2.65m having a thickness of 5.0cm. The second section is the rest of the pile body and is called upper section.

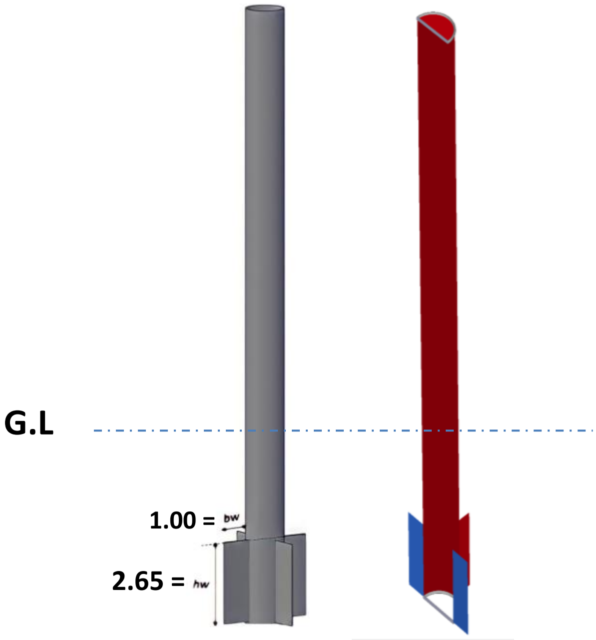

Figure 12 Bottom Winged Monopile.

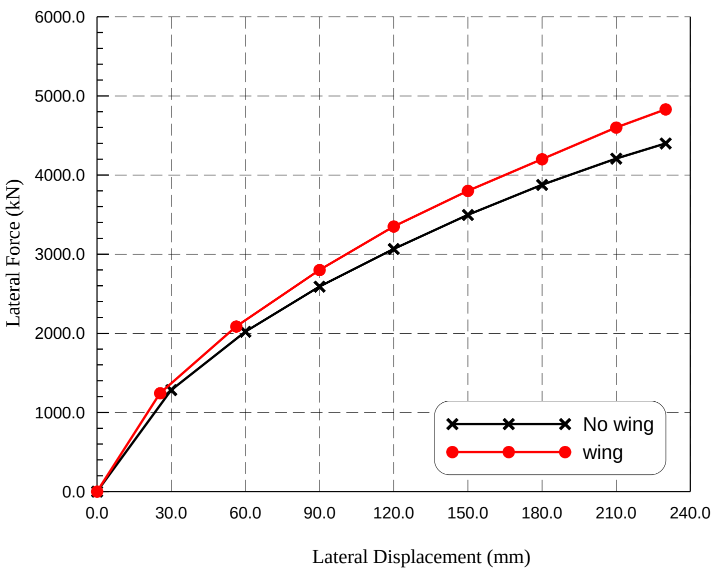

Figure 13 Lateral Load Displacement Curve for Pile with and without Bottom Wings.

The load-displacement relationship for bottom winged and reference case is presented in Figure 13. This figure indicates that a relatively low increase of lateral load capacity took place when adding the lower wings to the pile section. The figure shows that the enlargement of pile diameter has a low to moderate effect in the lateral displacement of pile head, as shown in Figure 13. The ultimate bearing capacity increased by approximately 374 kN (9.13%) at 10% of monopile diameter , which is considerably lower than the case of top winged piles reaching 22.00%.

Optimized Case Study by Using the Most Efficient Enhancement Proposal

The case study presented here is based on information from the offshore wind energy park, Horns Rev I, which is built off the coast of the North Sea in Denmark. The farm was put into operation in December of 2002. This park has an area of 20 km2 and 80 turbines; the distance from the coastline is around 14-20 km, and the sea depth is between 6-14 m., as shown in Table 5, Leite, (2015). The installed capacity is 160 MW, and the yearly production is projected to be 600 GWh/year.

The most significant considerations in the design of offshore wind turbine projects are efficiency and economics. Thus, in this paper the aim is to get the most optimized monopile dimensions according to the applied loads and existing soil properties. The data are presented in Table 6, after Augustesen, (2009).

Table 5 Horns Rev I data.

Operational	Cut-in Wind Speed:	4 m/s
	Rated Wind Speed:	16 m/s
	Cut-out Wind Speed:	25 m/s
Rotor & Hub:	Rotor Type:	3-bladed, 86-horizontal axis
	Rotor Diameter:	80 m
	Rotor Weight (incl. hub):	20 t
	Hub Height (above MSL):	70 m
Blades	Blade Tip Height (above MSL):	110 m
	Blade Length:	39 m
	Blade Max Chord (max width):	3.5 m
	Weight pr. Blade:	6.5 t
Nacelle	Nacelle Weight:	79 t
Tower	Structure Type:	Tubular Steel Tower
	Height:	61 m
	Weight:	160 t
Substructure	Transition Piece:	Grouted; Diameter: 4.2 m; Length: 18 m
	Support Structure Description:	Diameter: 4 m; Thickness: 5 cm
	Foundation:	The monopiles are pushed 25 meters below the seafloor.

Table 6 Soil Profile Including Average Values of the Strength and Stiffness Parameters for Each Soil Layer.

Soil Layer	Type	Depth (m)	E_s (MPa)	γ/γ' (kN/m^3)	ϕ (°)	ψ (°)	ν (-)
1	Sand	0-4.5	130	20/10	45.4	15.4	0.28
2	Sand	4.5-6.5	114.3	20/10	40.7	10.7	0.28
3	Sand to silty sand	6.5-11.9	100	20/10	38.0	8.0	0.28
4	Sand to silty sand	11.9-14.0	104.5	20/10	36.6	6.6	0.28

5	Sand/silt/organic	14.0-18.20	4.50	17/7	27.0	0.0	0.28
6	Sand	18.20 ⟶	168.80	20/10	38.7	8.7	0.28

The monopile is exposed to the static maximum horizontal load = 4.6 MN applying at the height h = 20.65 m above mud level and the water level is 13.50 m above sea bed level. By applying this loads the calculated horizontal displacement = 41.74 mm, as shown in Figure 14.

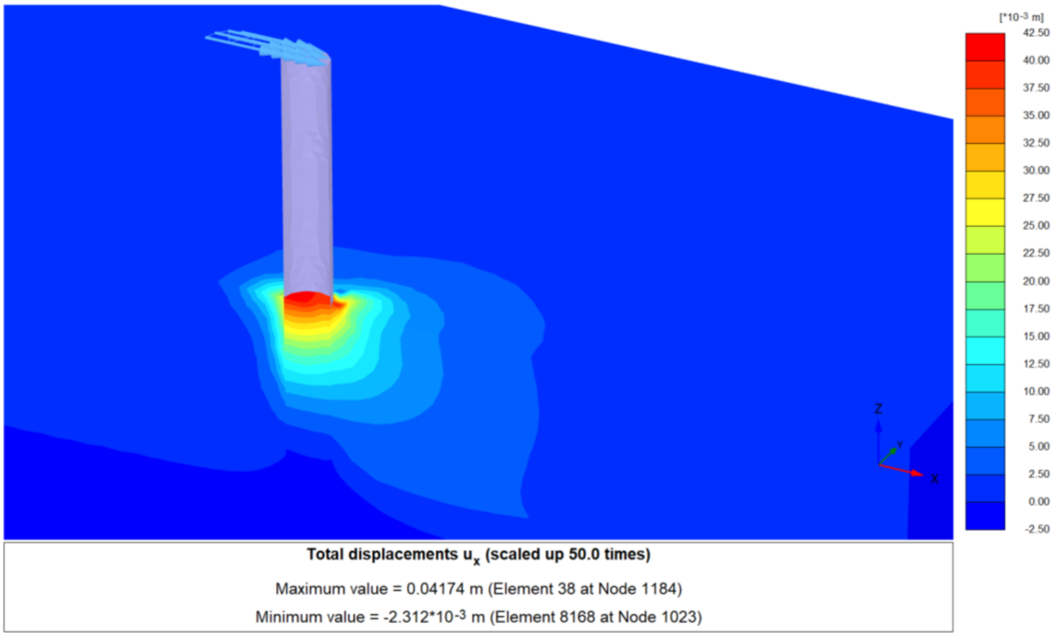

Figure 14 Lateral Deformation at Sea Bed Level in Horns Rev.

To get the same deformation with optimized pile shaft dimensions, a parametric study is performed by adding top wings with different configurations as presented in Table 7.

Table 7 Different Configurations for Top Winged Monopiles.

Pile	**Diameter m**	**b_w m**		**h_w m**		**U_x mm**
1	2.20	0.50 D =	1.10	1.00 D =	2.20	110
2		1.00 D =	2.20	2.00 D =	4.40	82
3	2.80	0.50 D =	1.40	1.00 D =	2.80	60
4		1.00 D =	2.80	2.00 D =	5.60	38

The optimized monopile has a diameter of 2.80 m and has four wings with of 2.80 m width and 5.60 m height. The total differences in weights between the two cases before and after optimization are presented in Table 8.

Table 8 Actual and Optimized Total Weights of Monopiles.

Actual Horns Rev Monopile Weight (Ton)	Optimized Horns Rev Monopile Weight (Ton)
=3.14×4×45.65×0.05×7.85 = 225.045	=3.14×2.80×45.65×0.05×7.85 +4×2.80×5.60×0.05×7.85 = 182.149

The total weight difference = 225.045 - 182.149 = 42.896 t

The foundation expenses for offshore wind turbines account for roughly 25% of the overall cost (Feld 2001). The proposed pile modifications save about 19% of total direct cost of foundation materials and about 5% of total direct cost of one turbine. For this wind farm which contains 80 wind turbines, it will give the chance to add more 4 turbines to reach 84 not only 80 at the same cost.

Application of Offshore Wind Turbines Farm in Zafarana, Egypt

Egypt with its Integrated Sustainable Energy Strategy 2035, aims to meet more than 25% of its burgeoning energy demand from renewable resources. Studying offshore wind turbines in Egypt has a great importance due to the existence of required wind speed to produce the target power using clean resources.

The Egyptian government aims to increase its electricity capacity from renewable energy sources such as solar, wind, and hydro to 20 percent of total electrical power. The remaining 20% will be allocated to renewable energy sources in the following proportions: 12% to wind power, 6% to hydropower, and 2% to solar energy. As a result, the Egyptian government is putting a lot of effort into increasing its power output through wind energy.Zafarana is located 120 km south of Suez on the Red Sea, lies in the highest wind speed zones all over the world. The wind speed required to create wind turbine farms is more than 6 m/s in order for the turbine blades to move and generate energy. As a result, the Gulf of Suez in Egypt has a high wind speed, with an annual average wind speed of 10.50 m/s, while Zafarana has an average annual wind speed of 9 m/s.

Proposed Offshore Wind Turbine

The proposed offshore wind turbine configuration and monopile dimensions are presented in Table 5. Soil profile and average values of the strength and stiffness parameters in Zafarana are listed in Table 9. The monopile is exposed to a static maximum horizontal load H = 4.6 MN operating at a height of h = 20.65 m above seabed level and a water level of 13.50 m above seabed level. As this load is applied, the measured horizontal displacement = 94.76 mm as shown in Figure 15.

Table 9 Soil Profile Including Average Values of the Strength and Stiffness Parameters Hs Model in Zafarana, (Saudi, 2020).

Layer	Depth	C (kPa)	ϕ (°)	ψ (°)	E (MPa)	ν
1	0-10	0	37	7	40.00	0.35
2	10.00-18.80	100	0	0	30.00	0.45
3	18.80-30.0	250	0	0	90.00	0.23

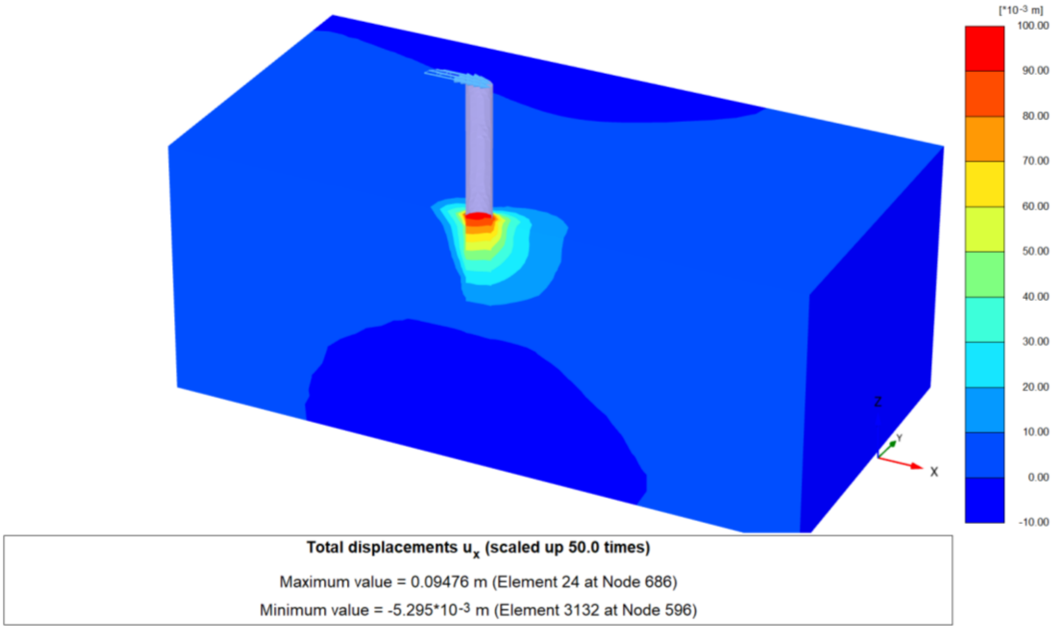

Figure 15 Lateral Deformation at Sea Bed Level in Zafarana.

Proposed Offshore Wind Turbine with Bearing Plate

To get the same deformation with the optimized pile shaft dimensions, a parametric study is performed by adding bearing plate with different configurations presented in Table (10).

Table 10 Different Configurations for Bearing Plate Monopiles.

Pile	Diameter m	D_{plate} m		U_x (at sea bed level) mm
1	2.20	1.50 D =	3.30	261
2		2.00 D =	4.40	224
3	2.80	1.50 D =	4.20	193
4		2.00 D =	5.60	165
5		2.20 D =	6.16	130
6	3.00	1.50 D =	4.50	128
7		2.00 D =	6.00	120
8	3.20	2.25 D =	7.20	104
9		2.50 D =	7.50	94

The optimized monopile has bearing plate diameter of 7.50 m. The total differences in weights between the two cases before and after optimization are presented in Table 11.

Table 11 Actual and Optimized Total Weights of Monopiles.

Zafarana Typical Monopile Weight (Ton)	Zafarana Monopile with Bearing Plate Weight (Ton)
=3.14×4×45.65×0.05×7.85 = 225.045	=3.14×3.20×45.65×0.05×7.85 +3.14×$(3.75)^2$×0.05×7.85 = 197.367

The total steel weight difference = 225.045 - 197.367 = 27.678 t

Proposed Offshore Wind Turbine with Top Wings

Table 12 Different Configurations for Top Winged Monopiles**.**

Pile	**Diameter** m	b_w m		h_w m		U_x (at sea bed level) mm
1	2.20	1.00 D =	2.20	2.00 D =	4.40	250
2	2.80	0.50 D =	1.40	1.00 D =	2.80	128
3		1.00 D =	2.80	2.00 D =	5.60	93

Table 13 Actual and Optimized Total Weights of Monopiles.

Zafarana Typical Monopile Weight (Ton)	**Zafarana Monopile with Top Winged Weight (Ton)**
=3.14×4×45.65×0.05×7.85=225.045	=3.14×2.80×45.65×0.05×7.85 +4×2.80×5.60×0.05×7.85=182.149

The total weight difference = 225.045-182.149=42.896 t

Conclusions

A comprehensive numerical investigation is conducted to assess the lateral performance of offshore wind turbine monopiles. The Numerical results are verified and their results are in complete accord with the full scale load test results. A numerical parametric study is then performed to account for the effect of many factors. Two lateral load enhancement of existing and new offshore monopiles are presented herein. These enhancements included using steel plate at the mud-line and upper and lower wings (fins). Economic assessment for both cases is also presented. Based on the numerical results, the following conclusions are drawn:

(1) Monopile ultimate horizontal capacity can be enhanced using joined plate and increased up by 20.50 %, has a in addition to having good contribution in vertical capacity by 87.50 %, for the studied cases.

(2) Using tTop winged monopile has more efficiency in enhancing the lateral capacity of monopiles by about 22 %, while bottom winged pile has only 9.13% only.

(3) A practical application of top winged monopile technique for Horns Rev I wind farm it would saves about 19% of total direct cost of foundations.

(4) Using top winged monopile or bearing plate as enhancing techniques depend on the soil layer properties at which it is applied, as the layer has a good properties make the enhancement very effective .

(5) At the failure the monopile is deformed and rotated and soil in the passive area is extruding up to a certain height range.

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