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Three-dimensional finite element analyses of monopiles in cohesive soil for offshore wind turbines

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Abstract. In the vast majority of offshore wind farms, monopile-type foundations are the most used in the construction of wind turbines, however, there are limited guidelines available for analysis and design of foundation/support structures. Although it is a simple structure, its behavior under loads of wind, waves and currents is very complex. As there is no design standard for offshore monopiles, offshore wind turbines are designed based on the API standard, which has only been designed for small diameter monopiles; but, for the wind industry, diameters greater than 4 m are used. Consequently, monopiles are commonly designed for an extreme load scenario. For this reason, in this article a three-dimensional finite element analysis of the mechanical behavior of offshore monopiles under vertical, horizontal and moment loads placed in cohesive soils is carried out, since these soils, by presenting high plasticity, decrease their load capacity and increase their properties. A Modified Drucker-Prager/Cap model (MDPC) and Mohr-Coulomb model (MC) is used to study the soil and its response to complex loads. The results of the numerical simulations are presented and compared with the results of the vertical bearing capacities predicted by the American Petroleum Institute (API) code method and the lateral displacement at the pile top with the p–y curve method and the LAP GEOCALCS software. The analysis indicates that the MDPC model has a better prediction of the load-displacement response than the MC model. The prediction of the stress in the monopile in both models are very similar. The API method underestimated the lateral displacements of the monopile at large forces and the LAP software predicts a flexible behavior of the monopile.

Keywords: API, finite element analysis, monopile foundations, *p-y*, offshore wind turbine.

1 Introduction

Currently, wind farms power are land (onshore) and marine (offshore). The ideal areas for construction of onshore wind farms are coastal areas due to high wind currents; however, the growth in population density has affected these construction projects [1]. Offshores have greater advantages in terms of abundance of resources, higher wind speeds, a large space and less environmental impact [2]. According to the magazine Wind Europe [3], in Europe, the size, type of turbine and power of a wind turbine depend on each country, for example, in the United Kingdom the installed power of offshore wind turbines reached an average of 9.3 MW, while the average installed power of offshore wind turbines on the European continent is 8.5 MW.

The large offshore wind farms are located 10 km from the coast at a depth of 10 m and their wind turbines must be located above the highest wave crest level recorded in the area and according to the design of the wind turbine, foundations of gravity, monopile, floating, among others [4]. Gravity foundations use reinforced concrete to support service loads, which is why they are expensive and are only recommended for depths less than 10 m. Monopile structures are made up of a steel tube pile that is coupled by means of a transition piece to the wind turbine and are used in depths between 10-25 m [5].

Studying the behavior of offshore monopile is important, due to the fact that, in the vast majority of offshore wind farms, monopile-type foundations are used in the construction of wind turbines, since the monopile, by supporting the weight of the tower and the wind turbine, supports vertical loads that are transferred from the pile to the ground and the lateral loads that are transferred to the foundation through bending [6]. Therefore, some research has focused on protecting the integrity of the monopile; reinforcing its foundation with the incorporation of additional structures of natural or artificial barricades, other research to reduce erosion at the base with the increase in the diameter and depth of the foundations [7].

As there is no design standard for offshore monopiles, offshore wind turbines are designed based on the API standard, which has only been designed for small diameter monopiles; however, for the wind industry, diameters greater than 4 m are used, this leads to oversizing that can harm the mechanical behavior of the offshore monopile. For this reason, in this article a three-dimensional finite element analysis of the mechanical behavior of offshore monopiles under vertical, horizontal and moment loads placed in cohesive soils is carried out, since these soils, by presenting high plasticity, decrease their load capacity and increase their properties. A Modified Drucker-Prager/Cap model (MDPC) and Mohr-Coulomb model (MC) is used to study the soil and its response to complex loads. The results of the numerical simulations are presented and compared with the results of the vertical bearing capacities predicted by the American Petroleum Institute (API) code method and the lateral displacement at the pile top with the p–y curve method and the LAP GEOCALCS software.

2 API code

The API code [8] is a series of recommendations established by the organization in order to develop national standards for the United States. In its offshore foundation design standard, the axial load capacity of the pile, axial performance, reaction of soil for axially and laterally loaded piles, etc. In this article, the soil reaction for laterally loaded piles will be used by means of the *p-y* curve of a saturated clay soil, since, in this curve, the non-linear relationship between the lateral resistance of the soil and the deflection of the pile is considered, since the lateral resistance of the soil is discretized in uncoupled springs and the deflection of the pile is determined according to the depth of analysis, in this way better results are presented in the behavior of laterally loaded deep foundations.

2.1 Lateral bearing capacity for soft clay

Static lateral loads influence the ultimate unit lateral bearing capacity, so the capacity of P_u soft clay can vary between 8c and 12c, except at shallow depths, given the minimum overburden pressure. In the absence of definitive criteria, the API standard (2000) suggests the following, for P_u values between 3c and 9c, see Eq. (1) and P_u limit see Eq. (2).

$$P_u = 3c + yX + J\frac{cX}{D} \tag{1}$$

$$Pu\ lim = 9c \tag{2}$$

2.2 Load-deflection curves for soft clay

With the values obtained for ultimate strength at the depth of the analyzed soil, it is possible to obtain *p-y* curves for the case of short-term static load, since the soil strength-deflection relationships for piles in soft clay soils are nonlinear.

Table 1. Relationships between ultimate strength - deflection [8].

p/p_u	y/y_c
0	0
0.50	1
0.72	3
1.00	8
1.00	∞

where: *p* is the actual lateral resistance (kPa), *y* is the actual lateral deflection (mm), y_c= 2.5ε*cD* (mm), ε is strain which occurs at one-half the maximum stress on laboratory undrained compression test undisturbed soil samples.

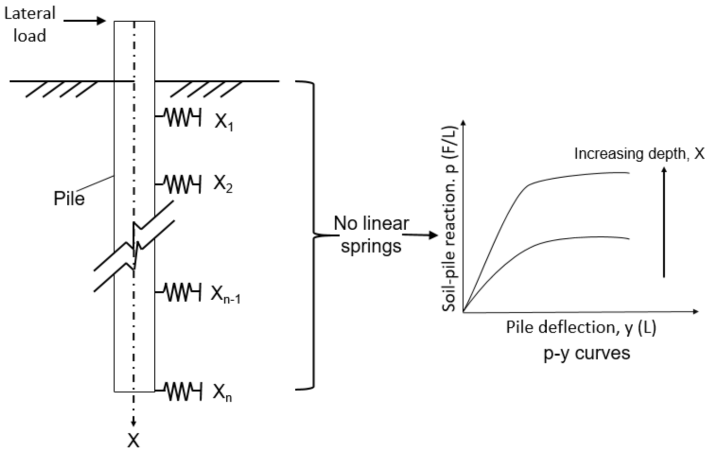
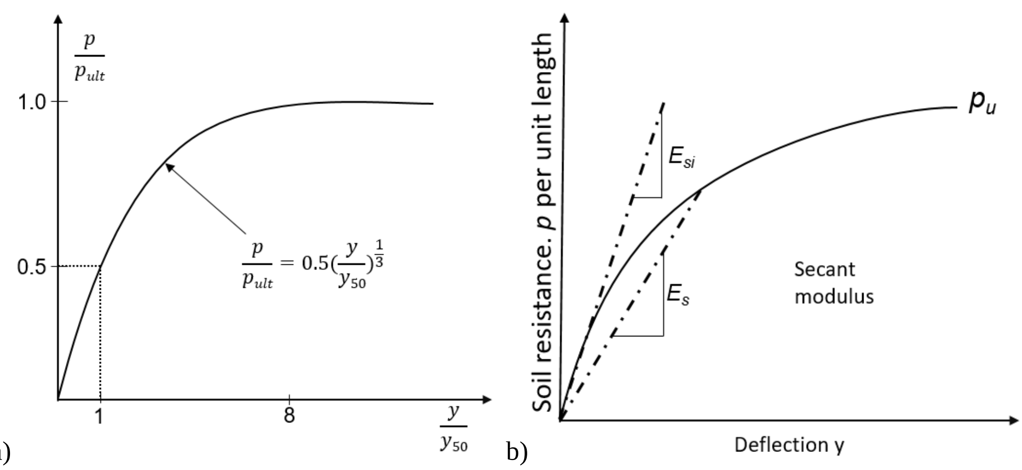


Figure 1. Idealization of the problem and *p-y* curve for clays [9].

2.3 Correlations for design of laterally loaded piles soft clay (Matlock)

With the lateral deflection values "*y*" obtained by the API method, the data is processed by means of the Matlock method for the depth of the analyzed soil substratum [10].



a) b)

Figure 2. a) *p-y* curve for clays [10] and b) ballast coefficient [11].

With the p-y curve, the ballast coefficient in the analyzed stratum is determined. The soil stiffness is obtained by multiplying this coefficient by the depth of the stratum. This soil stiffness calculation procedure is carried out in all the analyzed strata. With the stiffnesses obtained, the data is used in the SAP 2000 program to calculate the deflection of the pile. Finally, the results will be compared with the LAP GEOCALCS software [12].

3 Numerical modeling

A 3D model was created to study the behavior of the monopile in the Abaqus software [13]. Monopile has a diameter of D = 5 m and a length of L = 36 m, of which 35 m is buried. The API recommended a formula that was followed to calculate the thickness, a value of t = 57 mm was obtained. The dimensions of the soil were calculated according to Figure 3.

The monopile was modeled with 2304 elements type C3D8R. An elastic material with a steel elasticity modulus E_s = 210 GPa and a Poisson's ratio of 0.3 was used. Restricted model movement at the base in all directions and lateral movement at the sides. Likewise, the geostatic stresses in the entire soil and the void ratios of each substratum were calculated and assigned. The interaction between the pile and the soil was modeled in the normal with the “hard” contact type and in the tangential direction with the “penalty” type and a value of u = 0.24. Vertical, lateral and moment loads were applied to the monopile top with an eccentricity of 1 m, these have values of 9104 kN, 10234 kN and 374805 kN.m respectively. These loads were obtained from Haiderali [14].

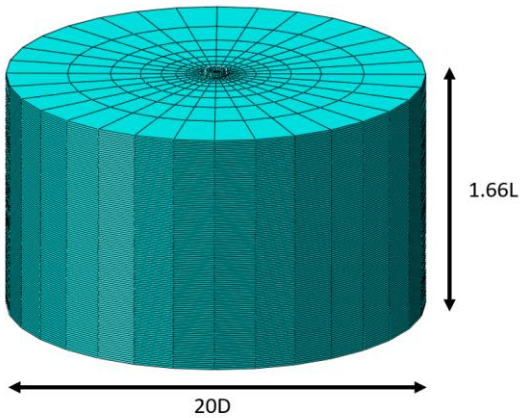


Figure 3. Geometry of the 3D model.

The analysis was carried out in 4 steps: Initial, geostatic, vertical and lateral. In the initial step, the boundary conditions and the geostatic stresses of the soil were generated. In the geostatic step, the weight of the ground was applied and an equilibrium was reached. Then, in the vertical step, the vertical loads due to the weight of the monopile and wind turbine were applied. Finally, in the lateral step, the lateral force and moment loads due to wind, current and wave loads were applied. All the analysis was carried out taking into account non-linear displacement, this parameter is NLGEOM in Abaqus [13].

The yield surface of the soil is usually given by a shear failure function based on the frictional character of the soils, for example, by adopting the Mohr-Coulomb or Drucker-Prager models. However, these models cannot take into account the appearance of plastic deformations due to the application of hydrostatic loads. In this way, "Cap models" emerged that combined the capabilities of the critical state and friction models by adopting two yield surfaces [15]. An elastoplastic behavior was considered using two constitutive models, Mohr-Coulomb model and Modified Drucker-Prager/Cap model. The constitutive relationships of the model MDPC and the input parameters to represent the elasto-plastic behavior of the soil are described in different works [15]. Due to the fact that the loads that the wind turbine receives horizontally are of short duration, parameters of the undrained soil were taken. To obtain the MDPC parameters an equivalence was made between the MC and MDPC models. To define the cap hardening of the MDPC model, the soil was divided into 58 substrates of 1 meter each. The parameters of each model are shown in Table 2.

Figure 4 shows the mesh of the finite element model, on the monopile and on the nearby ground a denser mesh was used and it becomes looser as it moves away from it, while in the vertical direction a constant separation was maintained. To model the soil, 57152 elements of the C3D8 type were used.

Table 2. Parameters for the MC and MDPC model adopted.

Parameter		Units	Value
Effective unit weight	γ'	kN/m^3	8
Young's modulus	E	kPa	19150
Poisson's ratio	ν	(-)	0.3
Logarithmic bulk modulus	κ	(-)	0.009
Angle of internal friction	ϕ	°	1
Dilatancy angle	ψ	°	0
Cohesion	c	kPa	50
Angle of friction	β	°	2
Cohesion	d	kPa	100.6
Critical state ratio	M	(-)	0.04
Cap eccentricity	R	(-)	0.1
Transition surface radio	α	(-)	0.05
Flow Stress Ratio	K	(-)	0.778

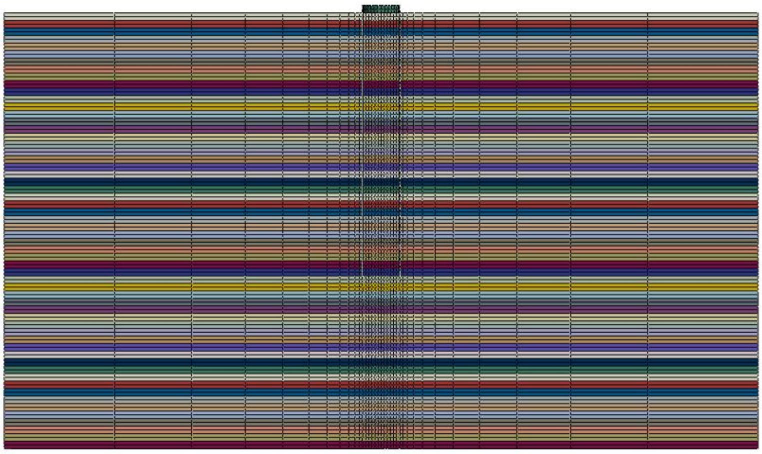


Figure 4. Lateral view and mesh of the numerical model.

4 Results

Figure 5 shows the lateral displacement along the pile. Maximum lateral displacements of 0.28, 0.33, 0.69 and 0.64 m are obtained with the p-y method, LAP software, MC model and MDPC model, respectively. It is observed that the MC model obtains the greatest lateral displacement, while the p-y method is the one with the least displacement. It can be noticed that the monopile presents a rigid behavior, having a negative displacement at the tip, but, it is observed that the LAP software shows a more flexible behavior, having almost a zero displacement at the tip. Also, the point of zero displacement or the point of rotation is located around 24 m of the buried length of the monopole in all analyses. It is evident that the p-y method predicts less lateral displacement than the numerical models.

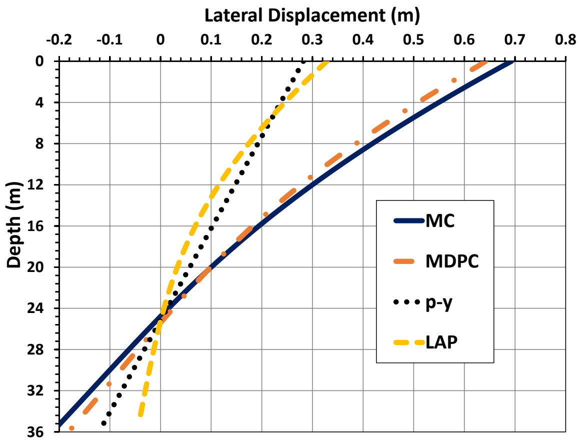


Figure 5. Lateral displacement vs depth.

In Figure 6 the relations force-displacement are shown. The API method calculates less lateral displacement for large forces, however, at forces under 6000 kN the method overestimates the displacements, this could lead to a bad design of the monopile. The LAP software has a good agreement with the numerical model at lower forces, but also predicts a lower displacement at large forces. The MC model shows a large displacement in comparison with the MDPC model, but they have a good agreement at lower values. It is observed that the MDPC model can simulate the load-displacement response better than the MC model. A new analytical method called PISA, developed by the PISA project, enhances the p-y method by considering further soil reaction and approaching the monopile behavior as a Timoshenko beam [9]. It would be great to compare this method in future research.

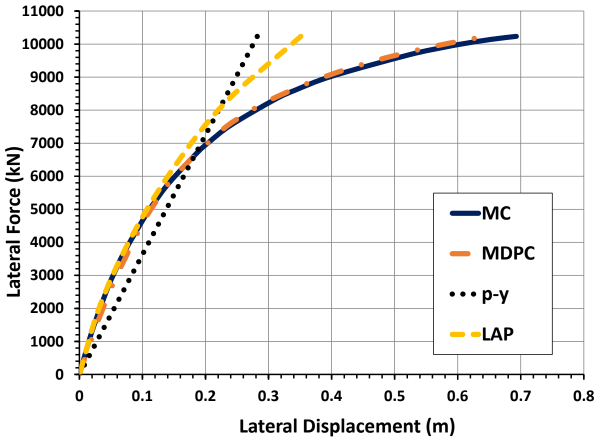


Figure 6. Lateral force vs Lateral displacement.

Figure 7 shows the stresses in the monopile in the numerical models. It is observed that the stress distribution in both models are very similar. The MC model predicts a lower value of stress than the MDPC model, however, they are very similar. The stress the monopole supports is under the limit of the elastic range for a steel A65, if the stress would have been above the elastic limit, it would be needed to consider the plastic behavior in the Abaqus model.

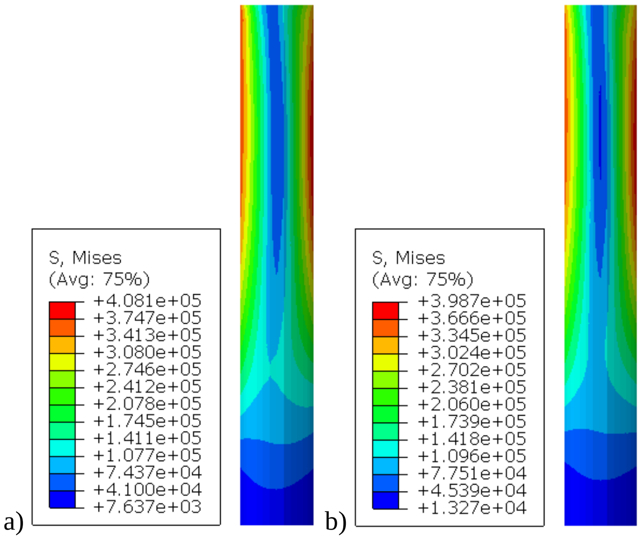


Figure 7. Stresses (kPa) in the monopile: a) MDPC and b) MC.

5 Conclusions

Numerical analysis can give an insightful view into the monopile and ground behavior. The maximum lateral displacement of the monopile by the p-y method was 0.28 m, 0.33 m for LAP, by MC it was 0.69 m and by MDPC was 0.64 m, respectively.

The API method underestimated the lateral displacements of the monopile at large forces, but overestimated them at lower forces. The LAP software predicts a flexible behavior of the monopile.

MDPC and MC models have a good agreement in the prediction of lateral displacement at a low value force, however, the MC model presents a large displacement when the force increments. The MDPC model has a better prediction of the load-displacement response than the MC model. The prediction of the stress in the monopile in both models are very similar.

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