Forest Chemicals Review
www.forestchemicalsreview.com
ISSN: 1520-0191
March-April 2022 Page No. 356-363
Article History: Received: 08 February 2022, Revised: 10 March 2022, Accepted: 02 April 2022, Publication: 30 April 2022

An Analysis of Envelope of Pile-Soil Interaction of OWT in Layered Soils

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Abstract:

In recent years, with the increase of energy demand and the need of environmental protection, offshore wind turbines (OWTs) are gradually used in offshore and deep water and single pile foundation is the most common foundation form. But with the increase of the depth, combined with complex load combination such as wind, wave and flow, and with the increase of buried depth, the soil property around pile foundation becomes more complex and changeable. Therefore, the research on the bearing capacity of OWT with super-large diameter foundation has become an important issue. In this paper, FEM is adopted with ABAQUS, and the model of pile and layered soil is set to analysis the ultimate bearing capacity in single load, and the envelope for horizontal and vertical load. In addition, the strength of soil is considered as an affecting factor to analysis the related response.

Keywords: *ABAQUS, soil-pile interaction, envelope of soil, ultimate bearing capacity.*

I. INTRODUCTION

Monopile is widely used at offshore and deep waters engineering facilities, with the simplicity of installation, security and comprehensive research. Monopile for OWTs is a pile, with commonly 22 – 40 m in length, 3 – 6 m in diameter [1]. As a component, it usually applied with concrete to support upper structure by penetrating into certain depth of soil. In marine environment, monopole is frequently affected by wind and wave loads, Therefore, it is vital to study the mechanism of soil-pile interaction and the failure process under different combination of loads.

Karasev [2]first found that preloading on the top of the pile will increase the horizontal bearing capacity by experiment. However, some studies proposed that the vertical load will create adverse effects when lateral load is applied. Trochanis [3] found there is positive correlation between vertical bearing capacity of pile and the lateral load by FEM. Chatterjee[4] suggested that the compactness should be considered while in analysis, he found that the compactness is an critical factor in sand layers: in soft sand layers ,the vertical load will weaken the bearing capacity on horizontal load. Hazzar [5] adopted FEM in ABAQUS, found the horizontal bearing capacity will reduce in clay after applying vertical load.

In view of this, FEM is adopted in ABAQUS to carry out relevant research.

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II. EM MODEL

In this paper, ABAQUS is used to build a model to perform a simulation. As the model presented in Figure 1, the pile is modeled as a solid cylindrical pile with an equivalent stiffness calculated by Equ(1), and the Young's modulus of pile is set as 210 GPa, as well as Poisson's ratio ν of 0.3. The diameter is 9m, and the length buried in soil is 45 m. In order to simplify the research, upper structure is omitted. The diameter of soil domain is 189m (21 D totally) and 90 m depth to ignore boundary effects. The parameters used are shown in Table I-III [6-7].

Both soil and pile are modeled with C3D8R elements, and the interaction between the pile and the sand layer is M-C interaction. The friction coefficient μ=0.3 is used in this study. The interaction between clay layers and pile is set as tied. And a thin layer is set between and pile and clay layers to simulate the destroyed clay. Different strength is applied to simulate the different coefficient of friction. The strength of the thin layer is applied by Equ(2). The model is shown in figure 1.

$$E_p = E_I \frac{\pi}{64}\left(D^4 - d^4\right) \tag{1}$$

$$\tau = \alpha \cdot S_u \tag{2}$$

Table I. Parameters of pile used in FEM.

Pile:	
Length	45 m
Diameter	9 m
E	19.79 GPa
ν	0.3

Table II. Parameters of sand used in FEM.

Sand layer:	
Depth	0-3m
E	24MPa
φ	34.25°

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ψ	4.25°
c	0
ν	0.2

Table III. Parameters of clay used in FEM.

Clay layers:	Dimension	Properties
Clay1	Depth:3-9 m	G=37.56 MPa
		su =20 kPa
Clay2	Depth:9-18m	G=70.4 MPa
		su =60 kPa
Clay3	Depth:18-36m	G=99.6 MPa
		su =120 kPa
Clay4	Depth:36-72m	G=140.8 MPa
		su=240 kPa
Clay5	Depth:72-90m	G=215.6 MPa
		su =480 kPa

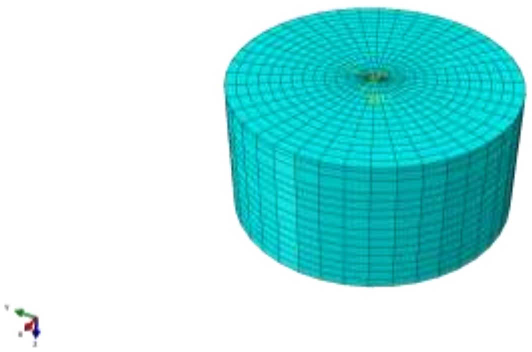

Figure 1: FEM model

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III. MATERIALS AND METHODS

To ensure the accuracy of the result, mesh refinement is made around the pile. Three types of meshing are shown in Figure 2. 10 MN force is applied on the top of the pile, and table IV shows the deflections on the top and calculation time of three methods of meshing. In view of the accuracy of results and the time consumed, type B is applied.

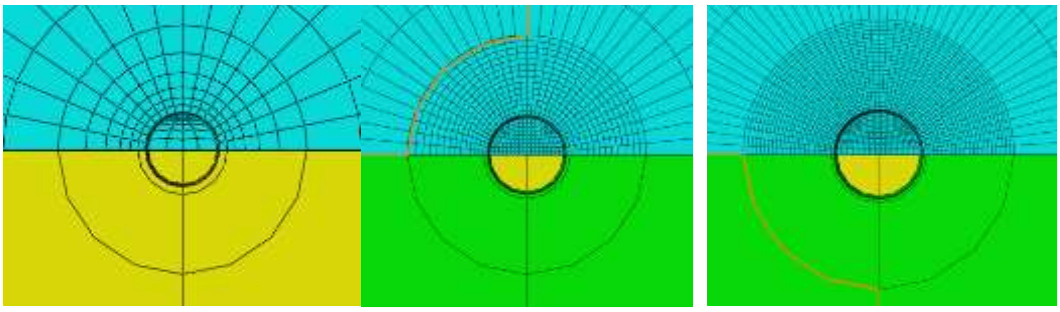

Figure 2: 3 Refinement methods

Table IV. Refinement methods

Types	Thickness of the thin layer	External area	deflection	time
A	D/10	D/10 - D/3	4.483mm	10min
B	D/20	D/20 - D/10	4.512mm	14min
C	D/30	D/30 - D/20	4.519mm	35min

Then verify the model on this basis. To test the validation of the model, p-s curve is extracted to compare with the experimental data. Figure 3 shows that the p-s curve matches well with the data.

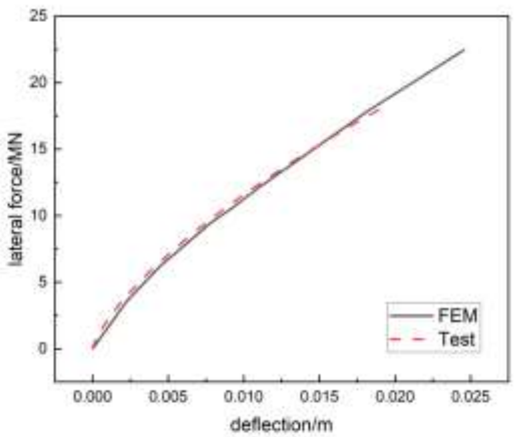

Figure 3: Validation of FEM model

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Ⅳ.Results and Discussions

Based on the above model, some responses were got from the model. The p-s curves for lateral and vertical load were shown in figure 4 and 5. It shows that the ultimate load for horizontal and vertical load reaches 192 MN and 364 MN respectively. Figure 6 shows the soil deformation affected by vertical ultimate load. It shows that the soil beneath the end of the pile bear the most vertical load, and the soil around the pile hardly bear the load. Figure 7 and 8 shows the soil deformation affected by horizontal load. It shows that the pile rotate around the corner at the depth of 36m, and deformation occurs on both sides of the soil because of the the ultimate load for horizontal and vertical load reaches 192 MN and 364 MN respectively.

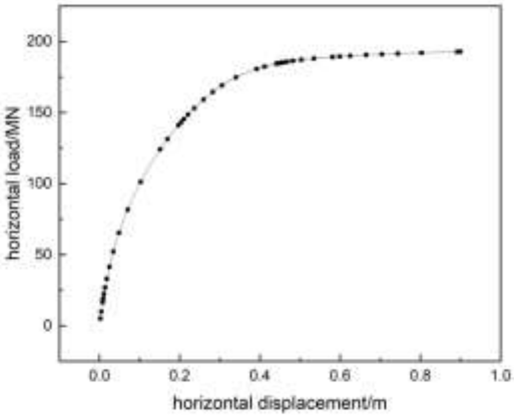

Figure 4: Curve of lateral reaction and displacement

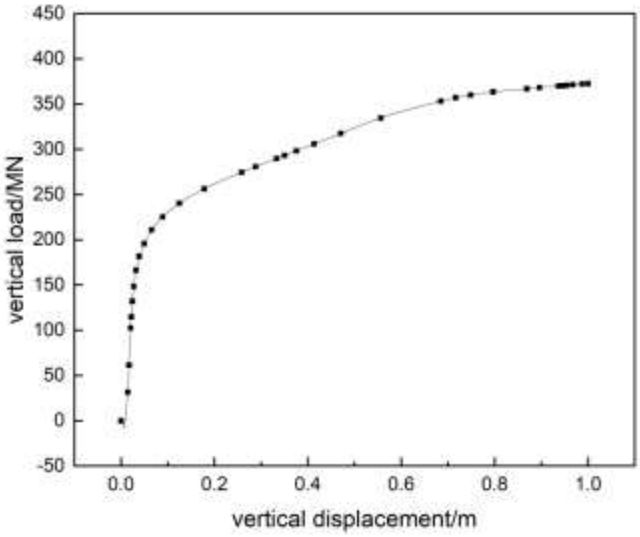

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Figure 5: Curve of vertical reaction and displacement

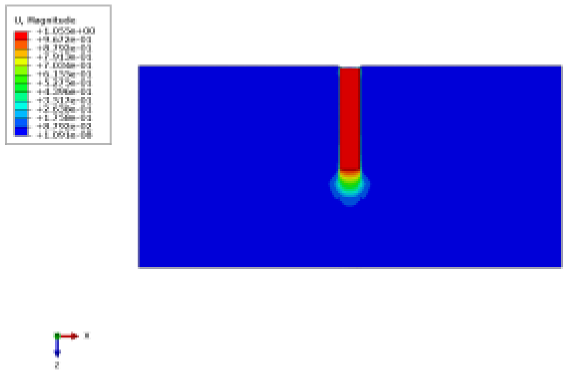

Figure 6: Displacement nephogram under vertical load

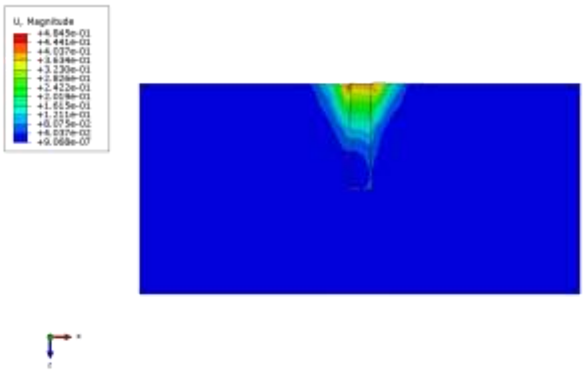

Figure 7: Displacement nephogram under lateral load (1)

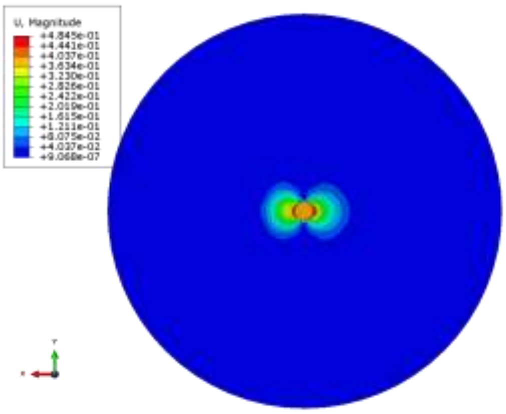

Figure 8: Displacement nephogram under vertical load (2)

On this basis, failure envelope of the soil was shown in figure 9. Two loading methods were applied to contrast differences. It shows that soil has a smaller bearing capacity under combined load. The envelope is similar to an elliptical line, and basically conform to Equ(3). Usually the α and β is set as 2[8-10],

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however some studies recommended the α and β as 3, and the result of contrast is shown in figure 10. Figure 10 shows that the result is within two lines.

$$\left(\frac{H}{H\mathrm{ult}}\right)^{\alpha}+\left(\frac{V}{\mathrm{Vult}}\right)^{\beta}=1 \tag{3}$$

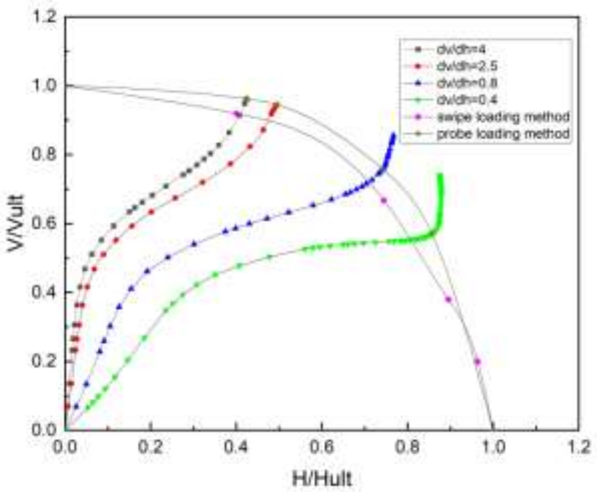

Figure 9: Envelopes of V-H joint action

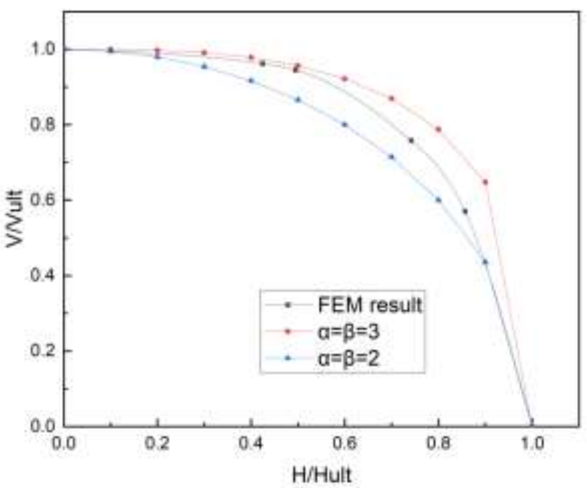

Figure 10: Comparison of envelopes

Ⅴ. CONCLUSION

In this study, FEM analyses results are presented. Responses under horizontal and vertical load were shown in this study. And the envelope for combined load was studied and contrast. In view of this study, the conclusions of this paper are as follows:

(1) The ultimate load for horizontal and vertical load reaches 192 MN and 364 MN respectively in this model.

(2) The soil at the end of the pile bears the most vertical load; and for horizontal load, the viscosity of clay layers makes the pile rotate instead of bending.

(3) The envelope shows that the bearing capacity of the soil for combined load is weaker than under any single load, and the envelope was contrasted with two common theories. The envelope for this model is within two common envelopes for horizontal-vertical combined effect.

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