Simulation And Analysis Of Interaction In Soft Clay Pile Foundation

Li bin 1, 2, 3, 4, 5, 6,*

1 Tianjin Port Engineering Institute Co., Ltd. of CCCC First Harbor Engineering Co., Ltd., Tianjin 300222, China
2 Key Laboratory of Port Geotechnical Engineering, Ministry of Communications, PRC, Tianjin 300222, China
3 Key Laboratory of Tianjin Port Geotechnical Engineering, Tianjin 300222, China
4 CCCC First Harbor Engineering Company Ltd., Tianjin, 300461 China
5 China Key Laboratory of failure mechanism and safety control techniques of earth-rock dam of the Ministry of Water Resources, Nanjing 210029;
6 Guangxi Key Laboratory of Geomechanics and Geotechnical Engineering Guilin University of Technology, Guilin 541000, China

* Corresponding author: lee_binbin@163.com.

Abstract. The single pile foundation is the most common forms of offshore wind turbine, but it is different from offshore oil platforms because of the load and the overturning moment. The elastic-plastic element of ABAQUS has been used to simulate failure modes of the single pile foundation in soft clay. The results shown that the single pile foundation has no plastic strain region under vertical load and has plastic strain under horizontal load; in front of the pile, the single pile foundation has plastic strain region under bending moment load condition.

1. Introduction
Offshore wind power generation technology has become a hot point in recent years, as our country is rich of wind energy resources in offshore area. China's offshore wind energy resources are expected to reach 75000000 kilowatts, which is three times than onshore wind energy resources, and offshore wind power will become the focus of energy development. At present, there are three types of offshore wind power foundation, such as gravity type, the single pile type, the triangle type, the jacket type and the floating type. Single pile foundation is used widely in offshore wind farms, but the load and overturning moment are different from the offshore oil platform, so the bearing characteristics and failure mode are different too. In particular, the diameter (4~7m) of the single pile foundation is larger than offshore oil platform (1~2m). Bearing mechanism of offshore wind power generation is the most important point to this paper.

The elastic-plastic element of the ABAQUS is used to simulate to simulate failure modes of offshore pile foundation in soft clay.
2. Model parameters

The finite element software ABAQUS is used to establish the single pile foundation finite element model of different pile diameters. The range of foundation has been taken larger to eliminate the effect of boundary. Mohr-Coulomb models have been chosen in order to better simulate the interaction between piles and soil. Specific parameters are shown in Table 1. In this paper, the failure mode of large diameter piles in the soft clay foundation is studied by theoretical analysis, numerical simulation, and model experiment.

Six groups of different pile diameters are selected to simulate failure modes of a single pile foundation. The effect of soil arch effect on the single pile foundation has been considered.

Table 1  Parameters of soil

| Foundation | H  | γ   | E  | c   | f  |
|------------|----|-----|----|-----|----|
| Soft clay  | 100| 18.0| 7.0| 20.0| 12 |

The elastic-plastic model is used to simulate soil of foundation, and the parameters are shown in Table 2.

Table 2  Parameters of pile material

|         | γ   | E   | $E_a$ |
|---------|-----|-----|-------|
| Steel   | 68.5| 0.3 | $2.1 \times 10^5$ |
| Concrete| 24.5| 0.2 | $3.0 \times 10^4$ |

Tangential and normal are respectively friction contact and hard contact between the pile and the soil.

Steel type of single pile foundation is Q345, which use elastic-plastic model to simulate; parameters are shown in Table 2, stress and strain of steel are shown in figure 1.

![Relationship of stress and strain stress](image)

Fig. 1 Q345 Relationship of stress and strain stress

3. Foundation failure mode

The failure mode and bearing characteristics of single pile foundation are analyzed based on the finite element software ABAQUS. The finite element model is shown in Figure 2.
3.1 Foundation failure mode under vertical load

The different diameter of pile equivalent plastic strain chart and the distribution of plastic region in soil are respectively shown as in Figure 3, Figure 4 when the pile under the ultimate vertical load in soft clay.

From Figure 3, it is known that the equivalent plastic strain of piles in different diameters is 0, which has no plastic strain. Therefore, the failure mode of single pile foundation under vertical load is the bearing failure in the soil.
Fig. 4 is shown with the change larger of the pile diameter, the plastic zone distribution in the soil gradually increases, the fracture surface is not extended to the surface of the foundation soil; the failure mode of the foundation is manifesting shear failure. With the pile diameter becomes larger, the distribution of plastic zone in the soil is gradually increased, but the shape of plastic zone is basically the same. The plastic point of the soil is first appeared below soil mass at the bottom of the pile foundation, then gradually extends to the soil of pile bottom and both sides of the pile, the slip surface is formed at the bottom of the pile in the end, the plastic zone in the soft clay is different from sand soil, not only the plastic zone of the pile tip, but also plastic zone.

3.2 Foundation failure mode under horizontal load
The plastic strain region is shown in Figure 5, Figure 6 and Figure 7, when the different diameters single pile foundation under horizontal load.

From Figure 5, plastic strain of piles appeared in different diameter piles under ultimate horizontal load. When the diameter is smaller, the range of the plastic zone is distributed in the upper part of the pile; when the diameter is increased, the plastic zone is distributed in the middle part of the pile. Compared with the foundation in sand, the foundation in soft clay has less resistance, and position of pile body has changed along the load direction when the pile is bearing the horizontal load, and the plastic zone gradually moves down.

Compared with the finite element simulation results, the maximum surface settlement at 10m from the edge of the foundation pit is about 62mm, and the finite element simulation results are about 3% smaller.
As shown in Fig 6, when the pile diameter is smaller, the lower part of the pile is embedded in the soil, plastic zone are mainly distributed in the surface of the soil mass which in front of the pile body; when the pile diameter increased, the shape of plastic zone is always same, the range is gradually increased, the foundation in soft clay has less resistance under horizontal load, the large diameter piles (the rigid pile) are reverse, and the bottom of the pile is also plastic zone.
As shown in Figure 7, when the pile diameter is smaller, lower pile is blocking in the soil, the upper part of the pile body moves along the horizontal loads direction, displacement of pile top is the biggest, the front side soil is uplifting and the back side soil moves to the pile body direction. When the pile diameter increases and the pile body rotation, the upper part of the pile body moves along to the horizontal loads direction, displacement of top pile is the biggest, soil produces spherical rotation failure surface at the end position of pile body, the soil in front of pile body, and back side moves to the direction of pile body.

3.3 Foundation failure mode under the bending moment.

In soft clay foundation, when the pile body bears bending moment load, the pile equivalent plastic strain and plastic region of different diameters in soil and the displacement of the pile foundation are shown in figure 8, Figure 9 and figure 10. From figure 8, the plastic train of piles appears in different diameters of piles under the ultimate bending moment load, the plastic zone is distributed in the top area of the pile, and the plastic strain of the foundation is the same as sand soil foundation, different from the clay foundation under the horizontal load.
From Fig. 9, it is known that the plastic zone of the soil is upper part of the pile body when the pile body bear bending moment load, plastic zone is relatively smaller than horizontal load condition. The plastic zone in front of pile body is increased when the diameter increased; the plastic zone is almost unchanged compared with the sand foundation.
Fig. 9 distribution of plastic zone in soil under the bending moment

From Figure 10, the lower pile embedded in soft clay when pile body bear the moment load, the upper pile has rotated, the soil in front of pile body is heaved. When pile diameter is smaller, a smaller range in uplift soil, the surface of soil in the back side moved towards pile body direction, the situation of the foundation under bending moment condition is similar to the sand soil.
Fig. 10 displacement vector diagram of pile and soil under the bending moment

4. Conclusions

In this paper, the bearing characteristics and failure modes of the single pile foundation in soft clay are analyzed by using the large finite element software ABAQUS.

1) Single pile foundation in soft clay under the ultimate vertical load, no plastic strain in the elastic working stage, single pile foundation under the vertical load appears failure is the destruction of the soil. The distribution of plastic zone in the soil is closely related to the single pile foundation in soil layer.

2) Single pile foundation in soft clay under the horizontal load, the pile body has plastic strain which part has slight change compare with sand foundation. Single pile foundation bearing layer is clay, surface of soil mass in front of pile side and the pile tip appears plastic zone.

3) The position of the plastic strain of the pile foundation in soft clay is always the top of the pile and the same position when single pile foundation in soil layers under the bending moment load. The plastic zone is mainly distributed in front of pile side; plastic zone is smaller comparing with the horizontal load condition.

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