Three-dimensional Numerical Analysis of Stress and Deformation of Soft Soil-pile group-pile Cap System under Coal Pile Load

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Abstract. In order to study the stress and deformation characteristics of adjacent pile cap system under the action of coal pile load in soft soil site, taking a large coal storage field in Malaysia as the specific engineering background, based on the large finite element numerical computing platform ABAQUS, the three-dimensional nonlinear numerical model of pile foundation and soft soil site under the action of pile coal load is established to consider the spatial stiffness effect, the stress deformation analysis and safety evaluation of pile group foundation pile foundation for a given site are carried out. It can provide guidance and reference for the design and practice of related engineering.

Introduction

Coal storage field, as the main storage site of coal, often appears and even overloading. The pile foundation of coal storage site may have large lateral deformation under the long-term load of coal, thus making the pile has a larger additional bending moment, which has a negative impact on the bearing capacity and stability of the pile foundation. The effect of loading on the pile foundation is more significant in the soft soil site. Therefore, the research on the bearing capacity and deformation characteristics of pile foundation under mid long term coal loading is very important for guiding the design and practice of related geotechnical engineering.

At present, many scholars have studied the stress and deformation of pile foundation under pile loading. Rowe and Poulos[1] (1979) consider the relative slip between the anti-slide pile and the soil and the elastoplasticity of the soil, and analyze the stress and deformation of the pile. Wei Ru-long[2] (1992) and Wang Nian-xiang[3] (2000) have established a two-dimensional and three-dimensional finite element model of the pile soil interaction system of high pile wharf, analysing the influence of height of slope, thickness of fill, spacing of pile, connection condition of pile top and stiffness of pile on the bearing behavior of pile foundation of wharf. Pan et al.[4] (2002) adopted Von Mises constitutive relation to simulate the nonlinearity of soil. The three-dimensional finite element model of soft soil site pile foundation interaction system was established, and the stress and deformation characteristics of single pile under horizontal displacement of soil were analyzed. Hu Jian-rong et al.[5] (2011) derives the elastoplastic difference scheme of passive pile considering the relative displacement of pile and soil. Based on the theory of single pile analysis, considering the constraint effect of the bent on the pile top and considering the group pile effect, the elastoplastic difference calculation formula with row bent piles is deduced.

Due to the limitations of previous computational theory and hardware conditions, most of the research results at home and abroad have adopted two dimensional plane strain model or simplified calculation method for soft soil foundation group pile system. The three-dimensional space effect and the nonlinear deformation of the soft soil foundation system can not be truly reflected. This article is based on the characteristics of the existing research results at home and abroad, taking a large coal storage field in Malaysia as the specific engineering background, based on the large finite element numerical computing platform ABAQUS, the three-dimensional nonlinear numerical
model of pile foundation and soft soil site under the action of pile coal load is established to consider the spatial stiffness effect, the stress deformation analysis and safety evaluation of pile group foundation pile foundation for a given site are carried out.

**Engineering General Situation and Numerical Calculation Model**

The maximum heap height of the closed strip coal storage field is 12.0m, the closed coal field span is 160m, the longitudinal length is 176m, and the double cylinder net frame structure of bolt ball joints is adopted. The height of the column reinforced concrete (rack bearing elevation) 1.2m. The section of a closed coal field is shown in Figure 1. The arrangement of pile foundation in coal storage field is shown in Figure 2. According to the stratigraphic distribution, stratigraphic lithology, depth and physical and mechanical properties of various soil layers and in situ test results, the fourth strong weathered mudstone is identified as the pile end bearing stratum.

![Figure 1. The profile of closed coal field.](image1)

![Figure 2. The layout map of pile foundation.](image2)

In order to take the effect of space stiffness into consideration, a three-dimensional numerical calculation model of soft soil group pile cap interaction system is established in this paper, as shown in Figure 3. Specifically, according to the site survey data, the most unfavorable section of the silt soil layer is selected as the most disadvantageous section, and the number of pile body is shown in Figure 4.

![Figure 3. Three dimensional finite element model.](image3)

![Figure 4. The layout of piled bearing platform.](image4)
The pile body, the pile cap and the foundation short column material are C30 concrete, and the linear elastic constitutive model is adopted without considering its cracking and plasticity. The modulus of elasticity of concrete is 32.5 GPa, Poisson's ratio is 0.2, and the density is 2500 kg/m$^3$.

Site formation by Quaternary Holocene artificial soil (Q$_4^s$), Quaternary Holocene marsh sediments (Q$_4^h$), Quaternary Holocene alluvium (Q$_4^{al+pl}$) and the three Departments of the Pliocene (N). The main lithology is filled, silt, clay, silt, sand, weathered mudstone, strong weathering powder the sandstone and coal rock composition. The M-C constitutive model is used in the soil around the pile, and the soil parameters are listed in Table 1.

| No. | Layer       | $E_s$ (MPa) | $c$ (kPa) | $\phi$ (°) | $\nu$ | $f_{ph}$ (kPa) |
|-----|-------------|-------------|-----------|------------|------|----------------|
| 1   | Plain fill  | 3.0         | 18.0      | 25         | 0.3  | 80             |
| 2   | Silt        | 1.5         | 11.5      | 0          | 0.3  | 40             |
| 3   | Clay        | 10          | 30        | 5          | 0.3  | 150            |
| 4   | Mudstone    | 20          | 60        | 15         | 0.3  | 350            |

The contact between the pile and the soil around the pile is set up by the penalty function method, and the friction coefficient is 0.3. The soil (more flexible surface) is from the Slave Surface, the pile (the more rigid surface) is the Master surface. The calculated load includes the superstructure load and the coal pile load. The initial stress balance of the site is first carried out before the external load is applied. The load transmitted by the superstructure (the short column 810 kN on the side cap, the lateral load 520 kN, the short column 1200 kN on the cap), is applied to the short column on the basis of the uniformly distributed load. The pile coal load is simplified as trapezoid load according to the actual pile coal curve, and applied to the surface of the soil.

**Calculation Results and Analysis**

Under the load of pile coal, the lateral displacement of the pile foundation under the left side of the bearing platform varies with the depth of the pile as shown in Figure 5. It is shown in Figure 5 that the soft soil layer is greatly deformed under the load of the pile coal. The extrusion effect of the pile foundation is obvious, and the pile body has significant lateral displacement. The lateral displacement of P4 and P5 piles near the heap side is maximum, and the maximum value is up to 51.5 mm.

![Figure 5. Variation of horizontal displacement of piles under border bearing platforms with depth.](image-url)
From Figure 6, we can see that the lower pile body of the middle cap is also affected by the coal loading on both sides of the central line of the storage yard. However, due to the thicker soft soil on the left side, the P6 and P7 piles under the middle cap will have a larger positive horizontal displacement, and the maximum amplitude level is about 10mm.

Under the action of pile coal load, the shear strength of the pile under the left side of the bearing platform varies with the depth of the pile, as shown in Figure 7. As can be seen in Figure 7, the pile foundation of pile and coal load increase the increase of shear force, and the increase of shear strength of the left side bearing platform is more significant than that of the middle cap. Specifically, the maximum shear force increment of pile P4 and P5 on the side of the pile cap on the left side is 478kN, and the maximum shear force increment of piles in the middle pile cap side P6 and P7 piles is 341kN.

Under the load of pile coal, the bending moment of the pile body under the left side of the bearing platform varies with the depth of the pile, as shown in Figure 8. As can be seen in Figure 8, the pile foundation of pile and coal can increase the increase of bending moment, and the increase of shear strength of the bearing platform on the left side is more significant than that of the middle cap. Concretely, the maximum value of moment increase of pile P4 and P5 piles on the side side of the left side pile cap is 652kN.m, and the maximum increase of pile moment of P6 pile and P7 pile in the middle pile cap is 277kN.m.

From Figure 9, we can see that the maximum tensile stress of the pile below the left side cap and middle cap is 8.66MPa and 4.73MPa respectively, and the extreme value of tensile stress is located at the middle part and bottom of the pile body P4 and P5 piles on the left side of the pile cap, as well as the connection between the P6 pile top and the cap of the middle pile cap side. Obviously, the maximum tensile stress values of all the above piles all exceed the standard value of C30 concrete tensile strength 2.01MPa. Therefore, for the established pile foundation design scheme,
corresponding soft soil foundation treatment measures should be taken to meet the requirements of pile foundation bearing capacity and stability.

![Figure 8](image1.png)  
**Figure 8.** Variation of bending moment of piles under bearing platforms with depth.

![Figure 9](image2.png)  
**Figure 9.** Contour of the maximum principal stress of piled bearing platform.

**Conclusion**

This paper takes a large Malaysia coal storage yard for specific engineering background, using the ABAQUS general-purpose numerical platform, through the establishment of soft soil-pile cap system three-dimensional elastoplastic numerical calculation model of deformation analysis and safety evaluation of the established site pile foundation scheme, the calculation and analysis results show that:

1. Due to the large deformation of the soft soil layer, the pile body has a significant lateral displacement under the load of the pile, and the lateral displacement near the pile side pile is maximum.
2. For coal loading, the increase of shear force and moment on the left side cap is more significant than that in the middle, and there is a sudden change in the internal force variation of pile in the depth of weak interlayer.
3. For the weak intercalated field of coal storage yard, there is a tensile stress concentration area at the middle part and bottom of the pile cap and the connection between the pile cap and the cap of the middle bearing platform, so we should attach importance to the relevant design.

**References**

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