Research on optimize design of pile foundations in collapsible loess areas

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Abstract: Collapsible loess has the poor characteristics of obvious strength reduction after being soaked by water. The construction of towering structure in western China is threatened by the unfavourable geological conditions of collapsible loess. This paper analyses the foundation treatment, pile foundation optimization design of the towering structure in collapsible loess areas, provide technical support for the construction of towering structure in collapsible loess areas.

1. Introduction
Collapsible loess undergoes significant additional deformation and obvious strength reduction after being soaked by water [1]. In the case of engineering construction on collapsible loess sites, the possible damage to the project caused by additional settlement of the foundation must be considered. In new energy-rich area in Northwest China, the proposed new energy power plants, which have many towering structures, are mostly located in collapsible loess areas [2]. The foundation of towering structure has the characteristics of bearing 360-degree repeated load and large eccentric force, so it has higher requirements on foundation bearing capacity and uneven settlement. If the foundation design is unreasonable or the foundation treatment is improper, it will directly affect the safety of the towering structure, resulting in incalculable losses. The commonly used treatment methods of collapsible loess foundation are pile foundation method, lime soil compaction pile method and soil replacement cushion method [3]. However, there is no explicit specification for the foundation treatment of towering structures in collapsible loess areas.

In this paper, the foundation design of towering structure in collapsible loess area is studied, to find the appropriate design and optimize scheme, so as to provide technical support for the construction of towering structure in collapsible loess areas.

2. Project Case and foundation treatment
The proposed new energy power plant is located in Northwest China, the site soil is Quaternary, the first layer is plain fill, mainly loess like silt, the second layer is loess like silt, which is mainly yellowish brown, with large pores and developed vertical joints, and this layer can be divided into two sub-layers. The underground water depth of the site is more than 50m. The physical and mechanical parameters of soil layer are shown in Table 1.
Table 1. Physical and mechanical parameters of soil

| Soil types                   | soil depth (m) | bulk density (kN/m³) | compression modulus (Mpa) | poisson’s ratio | internal friction angle(°) | cohesion (kPa) |
|------------------------------|----------------|----------------------|---------------------------|-----------------|-----------------------------|----------------|
| plain fill                   | 1              | 15                   | 6.3                       | 0.34            | 22.0                        | 20.0           |
| self-weight collapsible loess| 15             | 16.5                 | 8.3                       | 0.33            | 22.6                        | 20.6           |
| non collapsible loess        | 30             | 17                   | 11.7                      | 0.32            | 25.0                        | 23.4           |

The pile foundation construction technology is mature and the pile quality is easy to control [4]. Therefore, it is reasonable to use pile foundation in this case, and considering precast concrete pile is prone to fracture in collapsible loess site [5], so it is more suitable for adopt bored pile in this case.

3. Design and optimization of pile foundation

The design of pile foundation consists of two parts: pile and cushion cap. The pile is the main load-bearing structure, while the cushion cap connects the pile as a whole. The main calculation contents include calculation of vertical bearing capacity, shear resistance of bearing platform, bending resistance calculation, etc. The main formula is as follow:

\[
N_i = \frac{k_o \times F_z + G_1 + G_2}{n} \pm \frac{k_o (M_x + F_x \times h_y) y_j + k_o (M_y + F_y \times h_x) x_i}{\sum y_j \cdot \sum x_j}
\]  

(1)

where \(N_i\)—vertical bearing capacity of the No.i pile, \(F_z\)—vertical load of the towering structure, \(F_x\), \(F_y\)—horizontal load of the towering structure, \(M_x\), \(M_y\)—moment of flanges on foundation Ring, \(G_1\)—weight of cushion cap, \(G_2\)—weight of overlying soil, \(x_i\), \(x_j\), \(y_i\), \(y_j\)—pile spacing, \(n\)—number of piles, \(h_y\)—the height from the top of the foundation ring to the bottom of the cushion cap.

The design and optimization scheme are as follows:

(1) Calculate the size of the cushion cap. (2) For end-bearing bored pile, calculate the pile length and basal area of the pile, the self-weight collapsible loess with a thickness of 15 m was taken as the representative thickness to determine the negative friction resistance [6]. (3) Optimize the design by changing the number of piles, the corresponding minimum number of piles with different pile diameters is finally obtained. (4) For friction bored pile, the design scheme is directly determined by the pile length. the optimized scheme of pile foundation in collapsible loess area is finally determined by the aspects of economy and construction.

Finite element software ANSYS is used to further analyze the three-dimensional stress state of the selected pile foundation scheme. The width and depth of the subgrade soil is 3 times that of the foundation structure, and the Mohr-Coulomb constitutive model is chosen. The elasticity modulus of the pile foundation is 30 GPa, the poisson's ratio is 0.2, and the bulk density is 25 kN/m³. The boundary conditions are taken as displacement constraints, the upper and lower portions are vertical displacement constraint, and the left and right are horizontal displacement constraint.

The negative friction resistance is equivalent to the tensile force around the pile, which is applied to the pile foundation in self-weight collapsible loess stratum.

4. Results and Discussion

The bottom of the cap is 14 m in diameter and 2.5 m in height. The length of end bearing pile is 19 m, and the expanded bottom area is 3 times of the cross-sectional area of pile body.

Table 2 lists the optimization design results, the proposed pile diameter changes between 750 mm and 1200 mm, and the scheme with the least number of piles were labelled. The concrete amount and the least number of piles with different pile diameter is shown in Figure 1. It can be seen that with the increase of pile diameter, the number of piles decreases, while the total amount of concrete fluctuates. This is because the change of the number of piles and pile diameter are related to the arrangement of
piles, furthermore, the calculation of the contra bending moment of the pile section is nonlinear. The scheme 16 piles with a diameter of 900mm has the least amount of concrete (223.8 m³), which is economical.

| Number of piles | Maximum vertical load of single pile (kN) | Vertical bearing capacity of single pile (mm, kN) |
|-----------------|------------------------------------------|-----------------------------------------------|
| 10              | 2884                                     | 2644.22887.53144.4                             |
| 11              | 2576                                     | 2409.12644.22887.5                             |
| 12              | 2458.3                                   | 2409.12644.22887.5                             |
| 13              | 2229.9                                   | 2187.42409.12644.2                             |
| 14              | 2040.9                                   | 19742187.42409.1                              |
| 15              | 1881.8                                   | 1773.819742187.4                              |
| 16              | 1746.1                                   | 1582.21773.81974                              |
| 17              | 1689.9                                   | 1582.21773.81974                              |
| 18              | 1579.3                                   | 1403.51582.21773.8                            |
| 19              | 1482.4                                   | 1403.51582.21773.8                            |
| 20              | 1442                                     | 1403.51582.21773.8                            |
| 21              | 1360.6                                   | 1233.71403.51582.2                            |

Table 3 is the comparison table of end bearing bored pile and friction bored pile schemes. From the perspective of investment, end bearing bored pile is better. In the case of similar construction conditions, the investment plays a controlling role, so the end-bearing bored pile scheme is recommended for foundation design of collapsible loess area.

The numerical model is shown in Figure 2. Figure 3 and Figure 4 show the vertical and horizontal deformation of the end-bearing pile foundation. It can be seen that under the self-weight and vertical load of towering structure, the pile foundation shows a sinking trend, with the maximum settlement of 20.8 mm. The long-term large eccentric bending moment makes the foundation incline, and the inclining rate is 0.00056. The horizontal deformation is small, no more than 1.3 mm, all of which meet the specification requirements.
Figure 2. numerical model of the pile foundation

Figure 3. vertical deformation of the pile foundation

Figure 4. horizontal deformation of the pile foundation

Figure 5. maximum principal stress of the pile foundation

Figure 5 shows the major principal stress distribution of pile foundation, the gray area is the area where the maximum principal stress exceeds the tensile strength of concrete (1.43 MPa), however, the role of steel reinforcement is not taken into account in the calculation, so it is still considered that the pile foundation as a whole is safe. It is suggested to make a good connection between the pile cap and the foundation pile.

5. Conclusions and suggestions
In collapsible loess areas, bored pile foundation is more suitable in eliminating collapsibility of foundation soil, end-bearing bored pile foundation can effectively reduce the pile length, for the design bearing capacity of pile foundation can be improved by making full use of the tip resistance of pile in non-collapsible soil. In general, the amount of concrete used for pile foundation varies nonlinearly. The combination of pile number distribution and pile diameter should be optimized to choose a reasonable design scheme.
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