Application and Deformation Control of Pile-anchor Support for Deep Foundation Pit in Soft Soil Area

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Abstract. Based on the engineering practice of deep foundation pit project in a coastal area, design plan and conceptual method for control the deformation of pile-anchor support system for foundation pit were introduced. The methods for insurance of the stability and decreasing the influence to the surrounding structures during excavation of the foundation pit were as below: increasing the excavation area with considering the position of seepage cutoff wall and construction road to reduce the earth pressure; evaluating the deformation of the stratum and support structure during excavation of pit by 3-D numerical simulation; using site test to provide guideline for construction of the jet grouting anchor; employing dynamic monitoring to provide the early warning. The application of the design can provide reference for similar projects.

1. Introduction

With the rapid development of society and economy of China, the utilization rate of underground space is constantly improving, and the foundation pit is developing towards a deeper and larger scale. Especially in coastal area, support for the foundation pit was more difficult because of poor engineering geological and hydrogeological condition and thickness soft soil stratum, and the deformation of the support structure should be strictly controlled once there were operating structures nearby. The support structure for the foundation pit should not only consider stability, but also be combined with the surrounding environment conditions.

Because of the complex geological conditions and environments in soft soil area, researches on support technique for support of foundation pit were generally based on engineering practice of specific projects. Theoretical method, numerical simulation and in situ monitoring analysis were employed to analysis the process of deformation of the stratum and earth force on support structures\textsuperscript{[1-8]}. Though internal support system was generally used for support of foundation pit in soft soil area as the great earth pressure and difficulty to control the deformation of the structure, pile-anchor support system could also be used with the advantage of opening construction, easy to construct, saving cost and time if the surrounding environment was allowable.

Thus, based on the deep foundation pit project of the siphon well number 3 of a nuclear power project in the coastal area of southeast of China, the design method of pile-anchor support for foundation pit in soft soil area with high ground water level was introduced, and the conceptual for
controlling the deformation of the stratum and support structures was elaborated. The application of the design can provide reference for similar projects.

2. Project profile

2.1. Site profile
Sanmen nuclear power project was located in Sanmen county, Zhejiang province. The surface elevation of the project site was about +11.7m, which was backfilled 12m crushed stone on the initial beach. The water elevation of the project was about +2.5m because of near the sea. The siphon well number 3 was in the south of the conventional land number 3, with the south and west sides near the constructed underground drainage culvert and the operating area of conventional land number 2, respectively. The only advantage of the project is that the east side was wide and not have any existing structures.

The siphon well number 3 was 45m length and 24m width, and the bottom elevation was about -12m, so, the project was a support of super-deep foundation pit with maximum excavation of 23.7m.

2.2. Geological conditions
As shown in Figure 1, the project site of the foundation pit of siphon well number 3 was with thickness soft soil stratum. Generally, the depth of the rock was about from -10m at the northeast to -35m at the southwest. The stratum from site surface to rock surface were crushed stone, with depth from +11.7m to -1m, mucky clay with depth from -1m to -10m, and soft silty clay with depth from -10m to -35m.

![Figure 1. General layout plan of foundation pit of siphon well number 3](image)

2.3. Difficulties of the project
The difficulties of the support system for foundation pit of siphon well number 3 were generally at the west and east side, because the north side was already excavated for the pipe culvert of the conventional land number 3, and the south side was already strengthen by embedded underground drainage culvert. Firstly, great deformation and broken of the structures should be avoided by great earth pressure; secondly, allowable utilize land at the west side was limited and the excavation of the foundation pit should not influence the operating of the conventional land number 2; thirdly, ground water level could not be reduced during the excavation as the sea nearby.
3. Design description
Designed cross sections of support system for west and east side of the foundation pit were shown in figure 2. For the west side, the maximum distance between boundary of the siphon well number 3 and the operating area of conventional land number 2 was about 35m, this area was fully used by slope excavation in the crushed stone stratum; for the east side, as there had enough land, the construction road was designed nearby, and the exaction width could also be increased. These methods could reduce the earth pressure on the pile-anchor support system.

As the ground water elevation was about +2.5m, the top elevation of the seepage cutoff wall was designed at +3m. Thus, the first step of cut slope of the crushed stone stratum was from +11.7m to +3m, considering the anti-sliding effective of the seepage cutoff wall, a 1:1 slope was cut from +3m to -2m inside of the wall. Though the toe of the slope was about 1m in the mucky clay, the slope could be stable by the limits of the seepage cutoff wall and compaction of the mucky clay at the toe of the slope by crushed stone.

Pile-anchor support system was employed for the foundation pit from -2m to -12m. From top to bottom, 3 layers of pre-stressed anchors were designed, which were at -2.5m, -6m and -9.5m elevation respectively. The significant difference between the support system for west and east sides of the foundation pit was that, for the west side, as the rock surface was very deep, anchorage area of the anchors were in silty clay stratum, the pre-stressed jet grouting anchors were used to increase the diameter of anchorage area.

Because the bottom of the foundation pit was still in soft soil stratum, jet grouting pile foundation stabilization were used to increase the bearing capacity of the foundation, and this could also limit the deformation of the pile-anchor support system. The work was designed to be done after the foundation pit was excavated to -9.5m.

![Figure 2. Pile-anchor support system for foundation pit siphon well number 3](a: west side) (b: east side)

4. Numerical simulation
4.1. Mesh generation and calculation parameters
As shown in figure 3, a 3-D numerical simulation model was created by using software MIDAS-GTS. The excavation process was modelled to evaluate the stability, deformation and inner force of the support structure, and the reference warning data was provided.

The model area was 251m*233m*55m (length * width * depth), which was 2 times of the excavation depth of each side, and below the rock surface. The number of the tetrahedral element of the model was 168316. Fixed and normal constraints were used at the bottom and side boundary of the model, respectively. The calculation parameters were shown in table 1.
Figure 3. Calculation model and mesh generation

Table 1. Calculation parameters

| Stratum and structure | Unit weight (kN/m³) | Deformation /elastic model (MPa) | Poisson’s ratio | Coherence (kPa) | Angle of friction (°) | Constitutive model |
|-----------------------|---------------------|---------------------------------|----------------|----------------|----------------------|-------------------|
| Crushed stone backfill| 20                  | 25                              | 0.2            | 1              | 35                   | Drucker-Prager     |
| Mucky clay            | 17                  | 4                               | 0.4            | 22.5           | 6.5                  | Drucker-Prager     |
| Silty clay            | 19                  | 6                               | 0.33           | 20.4           | 14.2                 | Drucker-Prager     |
| rock                  | 26                  | 10000                           | 0.23           | 7000           | 50                   | Drucker-Prager     |
| Jet grouting foundation| 19                 | 400                             | 0.25           | 110            | 30                   | Drucker-Prager     |
| Seepage cutoff wall   | 25                  | 25500                           | 0.17           | /              | /                    | Elastic            |
| Pile wall             | 25                  | 28800                           | 0.17           | /              | /                    | Elastic            |

4.2. Deformation of seepage cutoff wall

The horizontal displacement of the seepage cutoff wall after excavation to -2m was shown in figure 4. The results reveal that, the maximum horizontal displacement of the top and bottom of the seepage cutoff wall were 33.1mm and 105.7mm, and the operating area of conventional island number 2 could not be influenced during the cut slope. Greater displacement at the bottom of the wall was because of the poor parameters of the mucky clay stratum, and the seepage cutoff wall was sliding together with the soft stratum, but generally, water leakage could not occur because there was not had locally offset and tension crack.

Finally, for sufficiently using the advantage of sliding limitation by seepage cutoff wall, the bottom elevation was increased 4m, from -7m to -11m, and the toe of the slope was compacted by crushed stone in mucky clay area.
4.3. Deformation and force analysis of pile-anchor support system

Maximum horizontal displacement of the support pile and the maximum axial force of the jet grouting anchor were shown in table 2, and the final horizontal displacement of the support pile was shown in figure 5.

The results reveal that, the maximum horizontal displacement and bending moment of the pile wall and the anchor force were increasing with the excavation of the foundation pit, and the positions of the maximum data were below the excavation elevation, and finally occurred at the bottom of the foundation pit after the jet grouting pile foundation stabilization was constructed. This was because that the soft soil stratum could not provide enough passive soil pressure and limit the deformation of the pile-anchor support system before it was strengthen by jet grouting pile.

The maximum horizontal displacement, bending moment of the pile and axial force of the pre-stressed jet grouting anchors were 33.6mm, 953.5kN*m and 484.5kN, respectively, and the east side was a bit lower than the west side. Based on the calculation result, the excavation of the foundation pit of siphon well number 3 would not influence the operating area of conventional island number 2, and the warning data of the horizontal displacement of the pile could be given as 35mm, and during the excavation process, if the maximum monitoring data was greater than the warning data, development process and reasons for leading deformation should be analyzed, and the needed measurements to control the deformation such as stop excavation, backfill stone to support the support pile and construct the jet grouting pile inside of the foundation pit immediately could be used.

Table 2. Maximum deformation and bending moment support pile and axial force of anchor

| Excavate elevation | Horizontal displacement /(position) | Bending moment /position) | Axial force of jet grouting anchor /anchor elevation) |
|--------------------|-----------------------------------|---------------------------|-----------------------------------------------------|
| -6m                | 30.7mm/(-8m)                      | 490.3kN*m/(-7.5m)         | 230.9kN/(-2.5m)                                     |
| -9.5m              | 31.8mm/(-13m)                     | 854.2kN*m/(-10.5m)        | 431.5kN/(-6.0m)                                     |
| -12m               | 33.6mm/(-12m)                     | 953.5kN*m/(-11.5m)        | 484.5kN/(-9.5m)                                     |

5. Quality control method of pre-stressed jet grouting anchor

The pull out strength of the pre-stressed anchors was the key factor of controlling deformation and keeping stability of the pile-anchor support system. Usually, it is not a problem for anchors in rock, but for this project, as the rock surface at the west side was deep, and bottom of anchor was not possible to be placed into rock, jet grouting anchor was used in the pile-anchor support system, the anchorage body was with larger diameter to provide enough pull out strength of the anchor. Thus, diameter of the anchorage body should be strictly ensured to satisfy the design requirement.
To ensure the quality and decrease the disqualification numbers of the jet grouting anchors, based on theoretical analysis, a convenient method for evaluate the anchorage diameter was proposed as below \[6\]:

\[
D_1 = \sqrt[3]{\frac{\varepsilon \phi \rho_0 \sqrt{2P_g \rho_g}}{\nu \left[ \left( \rho_s - \rho_g \right) / \left( \rho_1 - \rho_s \right) - (1 - n) - S_r n \right]}} + D_0^2
\]  

(1)

Where, \(D_1\) and \(D_0\) were diameters of anchorage body and drill rod; \(\varepsilon\) was the coefficient of contraction, which was about 0.946 for the nozzle with cone angle of 13.5°; \(\phi\) was the flow coefficient, which was about 0.97 to 0.98; \(d_0\) was the diameter of the nozzle; \(P_g\) was the jet pressure; \(\rho_1, \rho_g\) and \(\rho_s\) where density of mud discharged from the borehole, jet flow and soil particles; \(\nu\) was the drilling speed of the drill rod; \(n\) and \(S_r\) were porosity and saturation of the soil.

The in situ test result of the anchorage body was shown in figure 6. Based on the result, the construction process of the jet grouting anchor was generally as one time reaming by water, one time reaming by cement slurry, and compensation grouting after install the anchor. Based on the geological investigation report, the suggested diameter of the nozzle was 2.5mm or 2.7mm, jet grouting pressure was 30 to 35MPa, drilling speed of the drill rod was 8cm/min to 10 cm/min, rotating speed was 12r/min to 15r/min. what is more, during the reaming by water, the average specific gravity of the mud discharged from the borehole should not be less than 1.2, or two times reaming by water should be done.

6. Dynamic monitoring results

Dynamic monitoring was important for deep soft soil foundation pit as the geological condition was complex, and lots of unevaluable factors, and reasonable measurements should be determined based on understanding the process of deformation and inner force of the pile-anchor support system.

During the excavation and using stages of the siphon well of number 3, horizontal displacement of the stratum and pile, axial force of the jet grouting anchor were monitored. For this project, the maximum monitored horizontal displacement of the support pile was about 28mm, which was smaller than the warning data (35mm), and the maximum axial force of the jet grouting anchor was smaller than the range of the design limit, so the support system of the foundation pit was on safe side.

7. Conclusion

(1) For support of deep foundation pit in soft soil area, geological and construction conditions should be considered together, and reducing the earth pressure on the support structure by excavation unloading method was useful to control the deformation of the structure;
(2) 3-D numerical simulation method was able to evaluate the process of the deformation and force of the pile-anchor support system, and the results could be used as reference warning data;

(3) Jet grouting anchor was the key factor to ensure the stability of the pile anchor support system. Theoretical analysis and field test are the basics to select reasonable construction parameters of jet grouting anchor;

(4) Through dynamic monitoring, we can know the actual deformation process and stress situation of support structure, and can provide early warning before danger.

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