Study on the interaction mechanism between deep displacement of soil and internal force of anchor cable under pile-anchor support system of ultra-deep foundation pit

J H Han¹, J P Wang² and C Y Gu³, *

¹,²,³ Civil engineering, University of Jinan, Jinan, Shandong, China, 250022

Corresponding author’s e-mail: cea_gucy@ujn.edu.cn

Abstract. Based on a concrete engineering example, the change law of soil deep displacement and internal force of anchor cable in the excavation process of foundation pit under pile and anchor support system is simulated by numerical analysis method, and compared with the measured results, and the synergistic action law of soil deep displacement and internal force of anchor cable is discussed. The comparison between the results of finite element numerical analysis and the field measurement shows that the two-dimensional finite element numerical analysis can reflect the variation law of the deep displacement of soil and the internal force of anchor cable in the field to some extent.

1. Introduction
Pile and anchor support is a common form of foundation pit support. Pile and anchor support technology is mainly applied in the design of pile row.[1] In actual construction, it can control the construction site with high groundwater level and reduce the influence of groundwater flow on foundation pit support[1-5]. Piles form a curtain underground to stop the flow of groundwater. This technology can not only reduce the shadow noise of groundwater flow on the foundation pit support engineering, but also protect the surrounding soil condition, and avoid the phenomenon of the surrounding mud soil collapse and landslide at the construction site[6-10] It has been widely used in China and has achieved high economic and social benefits. It has been widely used in China and has achieved high economic and social benefits. But now the displacement of deep foundation pit under the pile anchor support system and the change of the internal force of the prestressed anchor cable interaction mechanism research is still less, of the pile anchor foundation pit supporting engineering examples, this paper applied finite element numerical simulation method, analysis of deep foundation pit displacement and internal force variation law of prestressed anchor cable and the mutual relationship between both, and the results are compared with measured results.

2. Working condition
The first layer of soil is plain filled soil, with an average thickness of 4m, brown yellow, plastic, partial hard plastic, mainly composed of clay soil, containing a small amount of brick debris and ash residue; The second layer of soil is miscellaneous filling soil with an average thickness of 6.6m. It is various-colored, loose and slightly wet, and its main composition is steel slag. The third layer is silty clay with an average thickness of 2.7m, slightly brownish red, hard plastic-hard, containing a small amount of iron and manganese oxides, occasionally ginger stone. The cut surface is shiny, without shaking reaction, and the toughness and dry strength are moderate. The fourth layer of soil is cemented

¹HCEA 2021 Journal of Physics: Conference Series 1904 (2021) 012019 doi:10.1088/1742-6596/1904/1/012019
gravel, with an average thickness of 4.7m, cayish grey and argillaceous cement. The original rock structure is moderately weathered limestone, showing sub-angular shape and a little elliptical shape, with a general particle size of 1-3cm. The fifth layer of soil is moderately weathered limestone, with an average thickness of 3m, bluish gray, cryptocrystalline structure and layered structure. The main mineral composition is calcite, and the joints and fissures are relatively developed. The core is short columnar and a little massive, and the joint length is generally 10-20cm, and the maximum is 50cm. The sixth layer of soil is fully weathered gabbro, with an average thickness of 1.1m, grayish yellow and severely weathered. The original rock structure has been completely weathered and destroyed. The core is columnar and sandy, and the hand twisting is fragile. The seventh layer of soil is strongly weathered gabbro with an average thickness of 1.6m and is grayish yellow. The original rock structure has been weathered and destroyed. The core is mostly fragmented and a few short columnar, with a general particle size of 3-8cm.

The safety level of the foundation pit supporting structure is the first level. The elevation of the top of the foundation pit slope is 76.45-76.50m, the elevation of the bottom pit is 57.00m, and the excavation depth is 19.45-19.5m. The calculation value of the additional load on the top of the foundation pit slope is considered according to the strip load of 20kPa.

The foundation pit is supported by piles and anchors, with row piles and 5 prestressed anchor cables in the vertical direction. The row piles are completed before the excavation of the foundation pit. The foundation pit is excavated in six steps. The first step is excavated to 3.7m and the first prestressed anchor cable is constructed. The locking value is 100kN. The second step is to excavate to 6.7m and construct the second prestressed anchor cable with a locking value of 300kN. The third step is excavated to 9.7m and the third prestressed anchor cable is constructed with a locking value of 300kN. The fourth step is excavated to 12.7m and the fourth prestressed anchor cable is constructed with a locking value of 300kN. The fifth step is excavated to 15.7m and the fifth prestressed anchor cable is constructed with a locking value of 200kN. The sixth step is completed. The concrete strength of row pile body is C30, pile diameter is 800mm, and pile spacing is 1.5m. Figure 1 shows the section diagram of the excavation area, and Table 1 shows the mechanical properties of the soil.
### Table 1 Soil parameter information

| Name                        | Thickness (m) | Density (KN/m³) | Coagulative power (KPa) | Internal friction angle (°) | Young modulus (MPa) | Poisson's ratio |
|-----------------------------|---------------|-----------------|-------------------------|----------------------------|---------------------|-----------------|
| Grain filling               | 4             | 1.85            | 15                      | 15                         | 10                  | 0.25            |
| Miscellaneous fill          | 6.6           | 1.6             | 12                      | 14                         | 15                  | 0.32            |
| Silty clay                  | 2.7           | 1.86            | 41                      | 20.8                       | 30                  | 0.26            |
| Gravel cemented             | 4.7           | 2               | 50                      | 35                         | 35                  | 0.35            |
| Moderately weathered limestone | 3           | 2.7             | 100                     | 40                         | 100                 | 0.25            |
| Fully weathered gabbro      | 1.1           | 1.87            | 22                      | 40                         | 130                 | 0.2             |
| Highly weathered gabbro     | 1.6           | 1.9             | 45                      | 25                         | 150                 | 0.2             |

### 3. Analysis method

#### 3.1. The range and boundary conditions are analyzed

Numerical simulation method was used to analyze the excavation process of the foundation pit. The finite element calculation model is shown in Figure 2.

![Figure 2 Finite element calculation model](image)

According to previous engineering experience and finite element calculation results\cite{11-13}, the influence width of foundation pit excavation is about 3 ~ 4 times of the excavation depth, and the influence depth is about 2 ~ 4 times of the excavation depth. Considering the symmetry between the foundation pit and the calculation domain, the half section of the calculation domain is taken for analysis, and the range selected in the analysis is 60m × 30m. The boundary conditions of the calculation model are as follows: the left and right boundary displacements in X direction are zero, the lower boundary displacements in X and Y direction are zero, and the other displacement boundaries are free.

#### 3.2. Constitutive model and calculation parameters

Soil was simulated using the Molar-Coulomb model. The calculation parameters of soil layer were shown in Table 1. Row piles were considered as beam elements, Poisson's ratio $\gamma=0.2$, and elastic modulus $=3 \times 10^7$ kPa. The anchor cable is considered as line element, the transverse spacing is 1.5m, the vertical spacing is calculated according to the excavation depth of the cross section, and the outer diameter D is 0.0178m.
3.3. Simulation of excavation process
After the model is built, the gravity load and uniform load are applied to calculate the initial stress field and displacement field of the soil. In this case, the soil elements are considered as elastic. Use the self-supporting height of the upper soil layer to excavate to a depth of 3.7m below the surface for the first time, eliminate the excavated soil in the model, activate the first row of anchor cables and activate the row of piles; The second excavation was carried out to 6.7m below the surface to eliminate the excavated soil in the model and activate the second row of anchor cables; Carry out the next step of excavation in turn. Every time the excavation reaches the design depth, the excavated soil will be immediately eliminated in the model, and the next row of anchor cable will be activated in the corresponding part until the excavation reaches the depth of 19.5m.

4. Results analysis

4.1. The deep displacement is compared with the measured results and analyzed
Figure 3 and Figure 4 show the simulated and measured values of the lateral deformation of the vertical section through the apex of the foundation pit at each excavation stage. In the first excavation, the self-supporting height of the top soil layer is used to excavate 2m deep, and the first anchor cable is set up at this time. With the increase of the excavation depth, the lateral displacement gradually increases, which is manifested as the rapid change of the displacement in the middle and upper part, the gentle change of the displacement in the lower part, oblique bending, support bulging and protruding into the foundation pit. The maximum horizontal displacement occurs in the upper part of the foundation pit. During the whole excavation process, the maximum horizontal displacement is 9.79mm, which is close to the measured value of 10.31mm. It can be seen that the finite element calculation can well simulate the change of horizontal displacement, and the finite element numerical analysis can basically reflect the deep horizontal displacement of foundation pit excavation.
According to the two figures, the horizontal displacement of deep foundation pit is larger at the top and smaller at the bottom. And from the top to the bottom of the site of the decline in order\textsuperscript{14}. The variation of horizontal displacement of deep foundation pit is related to the corresponding working conditions. When the foundation pit is excavated, the horizontal displacement of deep foundation pit will increase correspondingly, and it will decrease correspondingly after the construction of each prestressed anchor cable\textsuperscript{15}. The results of parameter analysis show that the second layer has a great influence on the calculation results, because the layer is thick and the soil quality is poor, so the deformation of the foundation pit is great when the cohesion and internal friction Angle change. Therefore, in the geological survey, special attention should be paid to this kind of soil layer. In case of instability, appropriate reinforcement measures should be taken.

Figure 5 and Figure 6 show the comparison between the final excavation simulated by the finite element method and the horizontal displacement measured in the deep layer. The displacement trend of the final displacement simulated by the excavation is basically the same as that of the measured data, which shows that the displacement of the middle and upper part changes rapidly, while the displacement of the lower part changes gently and protrudes into the foundation pit. The maximum horizontal displacement occurs in the upper part of the foundation pit. The maximum horizontal displacement is 9.785 mm, which is close to the measured value of 10.72 mm.
4.2. Analysis of internal force change of prestressed anchor cable

Figure 7 shows the development and change of internal forces during the excavation of each row of prestressed anchor cables. It can be seen from the Figure that the internal force of the anchor cable increases with the excavation and decreases with the completion of the construction of the lower anchor cable. Each step of excavation will lead to the increase of the internal force of the anchor cable. The internal force of the upper layer of the anchor cable immediately adjacent to the excavation site will increase the most, and the internal force of the other upper anchor cable will also increase.
correspondingly, but the increase range gradually decreases with the increase of the distance from the excavation site. At the same time, the internal force of the corresponding anchor cable decreases due to the completion of each step of the construction of the prestressed anchor cable. The internal force of the upper layer of the anchor cable immediately adjacent to the excavation site decreases the most, and the internal force of the other upper anchor cable also decreases correspondingly, but the reduction range gradually decreases with the increase of the distance from the excavation site. The internal force of each anchor cable will appear peak value in the next step of excavation after the completion of construction, which can be understood from the construction and stress process of anchor cable. When the first layer of anchor cable is constructed after the first excavation, the lateral movement of soil has been completed at this time, and the internal force of anchor cable begins to increase gradually, constraining the horizontal displacement of soil. The anchor cables in the following layers are subjected to similar forces. Therefore, the stress of the prestressed anchor cable increases gradually in the process of excavation and restricts the horizontal displacement of soil.

![Anchor cable internal force change curve](image)

Figure 7 Anchor cable internal force change curve

4.3. Interaction mechanism analysis of deep displacement and prestressed anchor cable internal force changes

As can be seen from the Figure, with the excavation of the first step of the foundation pit, the horizontal displacement of the deep foundation pit increases, and with the completion of the construction of the first prestressed anchor cable, the horizontal displacement of the deep foundation pit decreases correspondingly. Therefore, it can be seen that the internal force of the anchor cable can effectively restrain the horizontal displacement of the deep foundation pit. With the second step excavation of foundation pit, the horizontal displacement of deep foundation pit gradually increases, and the internal force of anchor cable also increases correspondingly. This is because the horizontal displacement of deep foundation pit increases due to the second step excavation, which further leads to the internal force of anchor cable to restrain the horizontal displacement of deep foundation pit. Each excavation step and the next step of prestressed anchor cable construction are the same phenomenon. It can be seen that the horizontal displacement of deep layer leads to the increase of internal force of anchor cable. The increase of anchor cable internal force restricts the further increase of horizontal displacement in deep foundation pit.

5. Conclusion

The comparison between the results of finite element numerical analysis and the field measured data shows that the two-dimensional finite element numerical analysis can reflect the deformation and
internal force distribution of the excavation site to a certain extent. In the simulation process, the steel mesh shotcrete hanging on the surface of the foundation pit and the waist beam set in the middle of the foundation pit are not considered, which will affect the accuracy of the simulation results.

The results show that the horizontal displacement of deep foundation pit has a great correlation with its position. The horizontal displacement near the top of foundation pit has a great change, and the horizontal displacement at the bottom of deep pit has a little change. As the foundation pit is gradually excavated, the stress of prestressed anchor cable will gradually increase. With the completion of the construction of the next prestressed anchor cable, the internal force of the upper anchor cable decreases correspondingly. The internal force of each layer of anchor cable is caused when the next layer of soil is excavated, and with the excavation, the internal force of anchor cable increases gradually. The horizontal displacement of deep layer leads to the increase of internal force of anchor cable. The increase of anchor cable internal force restricts the further increase of horizontal displacement in deep foundation pit. The stiffness of row pile and the prestress of anchor cable have great influence on the horizontal displacement of deep foundation pit.

In engineering practice, economic benefits and deformation control requirements should be considered comprehensively, and each parameter of pile row and prestressed anchor cable should be controlled in a reasonable way to achieve a balance between economic benefits and deformation control as far as possible.

References
[1] He, F., Mu, R., Liu, Y.H. (2021) Numerical analysis of stress of pile-anchor retaining structure in deep foundation pit construction. J. Journal of Henan Polytechnic University, v.40;No.198(01):151-159.
[2] Zhang, E.C. (2020) Problems and Countermeasures in the Design and Construction of Deep Foundation Pit Support in Geotechnical Engineering [J]. Engineering Technology Research, 5(12):207-208.
[3] Guo, X., Li, C., Zeng, L., et al. (2019) Discussion on the internal force and deformation calculation method of pile in the pile-anchor supporting system[J]. Building Structure.
[4] Zhang, Y.J. (2016) Study on application and control of the pile-anchor supporting technology in deep foundation. J. 042(013): 79-80.
[5] Xiong, J. (2020) Design and Numerical Simulation of Pile and Anchor Support for a Deep Foundation Pit in Handan. D. Hebei University of Engineering.
[6] Chen, X.J. (2014) Research on the design of foundation pit supporting engineering. J. Times Report: Academic Edition, (9): 297-297.
[7] Liu, L., Wu, R., Sarat, S., et al. (2021) Design optimization of the soil nail wall-retaining pile-anchor cable supporting system in a large-scale deep foundation pit. J. Acta Geotechnica.
[8] Xi, J.M., Xiong, Y.L., Zhang, C., Wuli, H.L., Pan, Z.X.(2021) Influence of deep foundation pit excavation in soft soil on surrounding environment in complex environment. J. Journal of henan university of science and technology, v.42;No.188(01): 8-9+78-85.
[9] Jia, T., Hao, S., Xing, J. (2019) Monitoring and Analysis of Pile-anchor Support of a Deep Foundation Pit in Zhengzhou. J. Journal of Water Resources Architectural Engineering,
[10] Zhang, C.J. (2020) Research and engineering application of composite pile bracing retaining structure for foundation pit excavation with layer increase in soft soil. D.Zhejiang university.
[11] Wang, J.P., Du, Y., Yan, P.(2007) Finite element analysis of double row pile composite soil nailing in soft soil foundation pit. J. Building science,(11): 17-19.
[12] Du, Y., Wang, J.P., Yan, P.(2009) Study on application of double row bamboo pile composite soil nailing. J. Cryogenic building technology, (09): 99-100.
[13] Du, Y., Wang, J.P., Yan, P. (2010) Analysis of engineering case of double row pile composite soil nailing supporting foundation pit. J. Engineering Investigation, (01): 33-36.

[14] Lou, C.H., Xia, T.D., Liu, N.W. (2019) Analysis of spatial effect of foundation pit on surrounding environment in soft soil area. J. Chinese Journal of Geotechnical Engineering, (S1).

[15] Cai, L.Z., Zhao, L.J., Zheng, P.F., et al. (2020) Study on the influence of anchor cable preloading on the deformation of foundation pit and internal force of structure. J. The subgrade engineering, 000(002): 109-113.