Analysis of Deep Foundation Pit Pile-Anchor Supporting System Based on FLAC3D

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Relying on a deep foundation pit project in Beijing, using FLAC3D three-dimensional finite-difference software simulation combined with displacement monitoring data verification method, the deep foundation pit excavation and three-pile and two-anchor rod support system in anhydrous sand pebble stratum are systematically analyzed, and summed up the variation law of formation stress, internal force of soil nail, axial force of bolt, stress and displacement of pile in the process of excavation and support of deep foundation pit. The results show that during the excavation of the foundation pit, the maximum horizontal displacement of the sidewall is not at the top of the pile and the top of the slope but at a certain distance below the top of the pile. The axial force of the anchor rod is unevenly distributed along the length direction, the axial force of the free section is equal, the axial force of the anchoring section decreases in turn, and the prestress of the anchor rod spreads to the anchoring section after tensioning and locking. The soil-nailed wall is a passive force-bearing system, the force is small during the excavation and support process, and the axial force distribution along the length direction is large in the middle and small at the two ends. By analyzing the variation law of stress and deformation, the timeliness of the data in the construction process is improved, and an effective and reasonable case reference is provided for the informatization construction of simulated relevant working conditions.

1. Introduction

Deep foundation pit engineering is a very complex engineering problem involving many factors such as engineering geological conditions, climatic conditions, surrounding construction environment, technical level, and management level; therefore, it has the characteristics of comprehensiveness and high risk. The current regulations require that large-scale deep foundation pit projects should adopt informationized construction management technology to ensure the safe and smooth implementation of deep foundation pit projects. However, few urban foundation pit projects can successfully implement information-based construction. Therefore, geotechnical engineering software should be used for numerical simulation aided analysis in the construction process, and quantitative and qualitative research on the main control items such as anchor rod axial force and pile body displacement increase the timeliness and reliability of information-based construction.

With the continuous development and utilization of urban space and the large-scale construction of high-rise buildings in recent years, there are more and more deep foundation pit engineering problems. Whether the design of a deep foundation pit supporting system is reasonable and safe is the key to the success of foundation pit engineering. Many researchers have carried out a series of studies on the foundation pit supporting structure system. Chen et al. [1–13] studied the synergy and deformation law of deep foundation pit supporting structures under different working conditions by combining numerical simulation and field monitoring. Kang et al. [14–19] established a simulation model considering the coupling of the stress field and seepage field and put forward the effect of confined water level change on the stability of the foundation pit support.
structure. Er-Chao et al. [20, 21] established the numerical model relationship between the axial force, deformation law of pile anchor support, and the change of traffic dynamic load from the perspective of an external load of the foundation pit. Cao et al. [22] used uniform test, numerical simulation, and ACE nonparametric regression technology to optimize the excavation parameters of the foundation pit and construct the optimal excavation scheme for the foundation pit. Ziyong et al. [23–29] analyzed and compared the optimal design of the foundation pit by using the method of experiment combined with numerical simulation analysis and verified the feasibility and superiority of the optimal design combined with the field monitoring results. Based on FLAC3D software, Zhibin et al. [30] quantitatively analyzed the coupling effect of seepage and creep during the excavation of a soft soil foundation pit. Zhang et al. [31] carried out a numerical simulation on the whole process of groundwater extraction in a deep foundation pit and studied a new groundwater mining method for the sandy cobble stratum. Wang et al. [32] established a three-dimensional foundation pit frost heaving model by using a numerical simulation method and discussed the functional relationship between soil frost heaving deformation and low temperature.

At present, the research on supporting structure systems has made some achievements for reference. The pile anchor support has the advantages of simple construction conditions, wide adaptability, and low cost, which is widely used in deep foundation pit engineering construction. The main contents of the design of the pile anchor support system are the strength and stiffness of the support pile, the depth of the pile body, the position of the anchor, the prestress of the anchor, and the tensile force. Barley and Barley Anthony and Windsor [33, 34] studied the relationship between the anchorage length of the anchor and its bearing capacity, creep rate, load distribution, and the bond stress distribution of the anchor through model tests. Fattah et al. [35–37] studied the change of bearing capacity and displacement of single pile and pile group foundation under load through indoor model test. Gang et al. [38] used the method of deleting the free segment of the anchor to simulate the failure of the anchor and further studied the internal force change and deformation of the foundation pit supporting structure after the failure of the local anchor. Kim [39] carried out full-scale model tests on low-pressure grouting anchors in weathered soil, such as pull-out resistance and stress relaxation, and obtained research results on the transmission mechanism of the anchor’s axial force. Ding et al. [40–47] used FLAC3D software to establish the numerical model of pile-anchor supporting structure of foundation pit and analyzed the influence of foundation pit excavation on adjacent buildings. Zhang et al. [48] used FLAC3D software to analyze the pile-anchor support of the deep foundation pit and obtained the stress deformation characteristics of the support structure and the deformation form of the surrounding soil. Based on Plaxis3D software, Wang et al. [49] simulated and compared the differences between different forms of pile support mode and the traditional cantilever pile model in the deformation law of support pile and the settlement outside the pit.

Based on a deep foundation pit project in Beijing, this paper summarizes the change law of internal force and displacement of the support structure in the process of deep foundation pit support through construction process management and numerical simulation analysis, to ensure the smooth progress of the project. The correctness of the model is verified by comparing the simulation results and monitoring results, and then the internal force, deformation, and stratum deformation of the supporting structure in each process of deep foundation pit excavation are analyzed from the perspective of numerical simulation.

2. Project Overview

The project is located on Nanlishi Road, Xicheng District, Beijing. The building has three underground floors (partially four underground floors) and 13 floors above ground. With a frame-shear wall structure, the foundation depth is 16.67 m–20.47 m, and the outer wall of the foundation is 84.30 m long and 75.40 m wide. The importance level of the foundation pit is level 1. This paper focuses on the west side of foundation pit engineering.

2.1. Engineering Geology and Hydrogeology. The project site is located in the middle and upper part of the alluvial-prolulvial fan of the Yongding River, and the terrain of the site is relatively flat. The strata revealed by the exploration holes are all Quaternary clay silt, fine sand, and pebble layers except for the upper 2.70–5.40 meters of miscellaneous fill. The detailed ground conditions are as follows:

(a) Miscellaneous fill, with a layer thickness of 2.70–5.40 meters
(b) Clay silt with a layer thickness of 0.80–3.60 meters
(c) Fine sand, the layer thickness is 0.80–3.60 meters
(d) The pebble is sandwiched with round gravel, and the layer thickness is 7.00–10.80 meters
(e) Pebble sandwich fine sand lens body, the maximum thickness is 12.00 meters

Drilling revealed that the groundwater level was initially 18.30 meters above sea level, and the still water level was 18.41 meters above sea level. The groundwater isdiving, and the water level changes with the seasons, with an annual variation of about 1.00 meters. The average groundwater level in the past five years is 20.00 meters. The groundwater in the site is weakly corrosive to the concrete structure and the steel reinforcements in the reinforced concrete structure in the alternating dry and wet state.

2.2. Stratum Parameters. According to the geotechnical engineering investigation report, the site strata can be divided into five layers, and the physical and mechanical parameters of each layer are shown in Table 1.
2.3. Design of Foundation Pit Support Scheme. The importance level of this foundation pit is first grade. The supporting form of soil nailing wall combined with pile anchor is adopted to avoid the influence of unfavorable factors such as small available space, complex surrounding building environment, and large excavation depth on construction safety. According to the different surrounding environment and depth of foundation pit, the whole foundation pit support design is divided into four sections. This paper takes the design parameters of the west slope with the excavation depth of 17 m as an example to introduce the support scheme design.

Since the original foundation in the site can only be constructed after the slope protection pile is broken, considering the construction period and economic factors, the top beam is specially designed at 4.00 meters below the surface, and the first-floor anchor rod is set on the top beam. A retaining wall with a height of 4.00 meters and a thickness of 370 mm is built with concrete structural columns on the east side and south side of the site foundation pit above the pile top, and the back of the wall is filled with graded sand and gravel. There are two rows of soil nails behind the retaining wall. The length of the first row of soil nails is 5.00 meters, the length of the second row of soil nails is 4.00 meters, the vertical spacing is 1.50 meters, the horizontal spacing is 1.60 meters, and it is connected with the retaining wall structural column to form a reinforced retaining wall. The west and north sides of the foundation pit are supported by soil nailing walls.

Since the stratum of the site is mainly sand and pebble stratum, the pebble particle size is large and the stratum’s self-stabilizing ability is poor, so artificial digging and lining digging and pouring piles are used. Since the stratum is mostly miscellaneous fill and sand and pebble stratum, the anchor construction adopts the casing follow-up method to form holes. The concentrated load of the buildings around the foundation pit is considered as 20 kPa per floor. Since there is no groundwater, the additional load of groundwater is not considered. The specific design parameters of foundation pit support are shown in Tables 2–4.

### Table 1: Stratum physical and mechanical parameters.

| Level number | Soil layer         | Thickness/m | γ/kN·m⁻³ | C/KPa | Φ/°  | Modulus of compression/MPa | Poisson ratio |
|--------------|--------------------|-------------|----------|-------|------|---------------------------|--------------|
| 1            | Miscellaneous fill | 0.70        | 19.0     | 10.00 | 18.00| 9.0                       | 0.41         |
| 2            | Powdery soil       | 1.50        | 19.6     | 20.00 | 27.00| 15.0                      | 0.35         |
| 3            | Fine sand          | 2.80        | 20.0     | 3.00  | 32.00| 31.0                      | 0.32         |
| 4            | Pebbles            | 9.00        | 20.5     | 0.00  | 45.00| 40.0                      | 0.23         |
| 5            | Pebbles            | 10.00       | 21.0     | 3.00  | 50.00| 50.0                      | 0.19         |

### Table 2: Design parameters of soil nails and prestressed anchors.

| Serial number | Type of anchor | Horizontal spacing/m | Vertical spacing/m | Angle of incidence/° | Overall length/m | Rod diameter/mm | Anchorage section/m | Prestress/kN |
|---------------|----------------|----------------------|--------------------|----------------------|-----------------|-----------------|--------------------|-------------|
| 1             | Soil nailingØ16| 1.60                 | 1.50               | 10                   | 5.5             | 130             |                    |             |
| 2             | Soil nailingØ16| 1.60                 | 1.50               | 10                   | 4.5             | 130             |                    |             |
| 3             | Strand3*7Ø5    | 1.60                 | 4.30               | 15                   | 21              | 150             | 14                 | 360         |
| 4             | Strand3*7Ø5    | 1.60                 | 6.00               | 15                   | 13              | 150             | 7                  | 330         |

### Table 3: Design parameters of slope protection piles.

| Pile type          | Pile length/m | Pile spacing/m | Pile diameter/m | Embedded depth/m | Concrete strength | Main reinforcement | Hooped reinforcement | Prestressed strands rounding the opening |
|--------------------|---------------|----------------|-----------------|------------------|-------------------|--------------------|---------------------|----------------------------------------|
| Manual excavation pile | 16.4          | 1.60           | 0.8             | 3.5              | C25               | 12Ø20              | Ø14@2000                 | φ6.5@200                              |

### Table 4: Design parameters of the crown beam and waist beam.

| Serial number | Position     | Sectional dimension/mm | Main reinforcement | Prestressed strands rounding the opening | Concrete strength |
|---------------|--------------|------------------------|--------------------|-----------------------------------------|-------------------|
| 1             | Top beam     | 900*500                | 8Ø20               | φ6.5@200                                 | C35               |
| 2             | Middle beam  | 25Btwin-i girder       |                    |                                         |                   |
3. Numerical Simulation Analysis

The construction of the foundation pit has an obvious space-time effect. The stress and displacement of supporting structures are closely related to the physical and mechanical parameters of rock and soil, excavation, and supporting technology. In this paper, the three-dimensional geotechnical finite difference software FLAC3D is used for numerical simulation analysis of the western section of the foundation pit. By comparing the numerical simulation results with the monitoring results, the scientificity of the numerical simulation results is verified. At the same time, qualitative and quantitative analysis of FLAC3D simulation of formation stress, internal force of soil nail, the axial force of anchor, and forced displacement of pile body in the process of partial excavation and support of deep foundation pit, etc. guide the process control of key construction procedures and processes and improve the reliability and systematicness of information construction.

3.1. Constitutive Model. FLAC3D includes three elastic models, eight plastic models, and one empty model. The Mohr-Coulomb plastic model is suitable for yielding under shear stress, but the shear stress only depends on the maximum and minimum principal stresses. The material that the second principal stress does not affect the yield is the most widely used geotechnical constitutive model.

The failure envelope of the Mohr-Coulomb model is divided into two parts: the shear failure envelope and the tensile failure envelope (see Figure 1). The Mohr-Coulomb model adopts the Mohr-Coulomb criterion and the maximum tensile stress strength criterion. Its yield the criterion expression which is as follows:

\[
(\sigma_1 - \sigma_3) - (\sigma_1 + \sigma_3) \sin \phi - 2C \cos \phi = 0, \tag{1}
\]

where: \(\sigma_1, \sigma_3\) are the maximum and minimum principal stress, respectively, and \(\phi\) is the cohesion and internal friction angle.

Since both shear failure and tensile failure are considered in the FLAC3D failure criterion, it can be seen from Figure 2 that \(\sigma_1, \sigma_3\) face \(f(\sigma_1, \sigma_3) = 0\). Segments A to B are shear failures, defined by the Mohr-Coulomb criterion, namely,

\[
f_s = \sigma_1 - \sigma_3 \left(\frac{1 + \sin \phi}{1 - \sin \phi}\right) + 2c \sqrt{\frac{1 + \sin \phi}{1 - \sin \phi}} \tag{2}
\]

in the formula \(\varphi\)-internal friction angle cohesion.
failure criterion, namely, where $\sigma$ is the tensile strength.

Therefore, the tensile strength of the material cannot exceed the $\sigma_3$ value corresponding to the intersection of the two lines $f_s = 0$ and $\sigma_3 = \sigma_1$; that is, the maximum tensile strength is

$$f_s = \sigma_3 - \sigma_1, \quad (3)$$

where $f_s$ is the tensile strength.

Table 5: Parameters of anchor and soil nailing elements.

| Type                              | Elastic modulus/Pa | Tensile strength/Pa | Binding force/N·m$^{-1}$ | Angle of friction/$^\circ$ | Rigidity/Pa | Sectional area/m$^2$ | Outer circumference/m |
|----------------------------------|--------------------|---------------------|---------------------------|---------------------------|------------|----------------------|-----------------------|
| Soil nailing                     | $2.1\times10^3$    | $3.1\times10^6$    | $5.2\times10^5$          | 25                        | $1.67\times10^5$ | $1.33\times10^{-2}$ | $0.4082$             |
| Prestressed ground anchor bar    | $1.95\times10^3$   | $1.86\times10^6$   | $5.46\times10^5$         | 25                        | $4\times10^5$   | $4.12\times10^{-4}$ | $0.471$              |

Note: soil nail adhesion, friction angle, stiffness, and outer perimeter are all parameters of cement slurry.

Table 6: Element parameters of slope protection piles.

| Density/kg·m$^{-3}$ | Shear rigidity/Pa | Shear cohesive force/N·m$^{-1}$ | Shearing friction angle/$^\circ$ | Sectional area/m$^2$ | Perimeter/m | Iy/m$^4$ |
|---------------------|-------------------|--------------------------------|-------------------------------|----------------------|-------------|----------|
| 2500                | $2\times10^6$     | $1\times10^7$                | 20                            | 0.5                  | 2.513       | 0.02     |
| Concrete strength grade | Normal stiffness/Pa | Normal cohesion/N·m$^{-1}$ | Normal friction angle/$^\circ$ | Poisson ratio | Elastic modulus/Pa | ly/m$^4$ |
| C25                 | $5\times10^6$     | $1\times10^7$                | 20                            | 0.3                  | 2.8$\times10^6$ | 0.02     |

Sections B to C are tensile failure, defined by the tensile failure criterion, namely,

$$f_s = \sigma_3 - \sigma_1, \quad (3)$$

where $f_s$ is the tensile strength.

The plane of the deep foundation pit described in this paper is rectangular. Therefore, according to the principle of symmetry, a 4.8-meter-wide support section in the middle of the west side of the foundation pit is selected to simulate the three-pile and two-anchor rod support with the same form as the actual support. The model is 60 m long, 30 m high, and 4.8 m wide. It is divided into 5400 units, including 7564 nodes, and the excavation depth is 16 meters. The deep foundation pit excavation model is shown in Figure 3.

Table 7: Surface element parameters.

| Density/kg·m$^{-3}$ | Elastic modulus/Pa | Poisson ratio | Thickness/m |
|---------------------|--------------------|--------------|-------------|
| 2500                | $10\times10^9$     | 0.2          | 0.1         |

3.2. Numerical Model. In this paper, the Pile unit is used to simulate manual digging and pouring piles, the Cable element simulates soil nails and prestressed anchors, the Beam element simulates the top beam and waist beam of slope protection piles, and the Shell element simulates soil-nailed walls and soil anchoring between piles. The actual physical and mechanical properties of rock and soil are not completely consistent with the numerical simulation constitutive model. The following assumptions are made before the analysis and simulation in this paper:

(i) The stratum soil is a uniform and isotropic elastoplastic element, which obeys the Mohr-Coulomb strength criterion

(ii) Before excavation, the soil was fully consolidated under the action of its weight

(iii) The physical and mechanical properties of soil are not affected by the construction process and remain unchanged. There are no groundwater seepage and vibration load effects

(iv) Soil nails and anchors have no transverse shear resistance and shear resistance, and the anchoring force is generated by the soil displacement and changes with the soil displacement

The model includes a total of 5 soil nails, 3 piles, 4 anchors, two top beams and waist beams, and several soil nail surface layers and soil anchoring structures between the piles. The specific parameters are shown in Tables 5–8.

The bottom surface of the model $(Z = 0)$ adopts a fixed constraint; the front and rear surfaces $(y = 0$ and $y = 4.8$) are constrained in the $y$-direction; the left and right sides $(x = 0$ and $x = 60$) are constrained in the $x$-direction; the top face is set as a free face without constraints.

3.3. Excavation Steps of Foundation Pit. There is a foundation pit project before October 25 for soil nailing wall and manual hole digging pile construction process. October 25 to November 24 is the main excavation monitoring construction period, followed by the cushion and foundation construction period. Due to the large horizontal area of the foundation pit, the excavation and support of each layer are alternately designed. The detailed excavation progress of the west side of the foundation pit is shown in Figure 4.
During excavation, use the NULL command to define the soil layers in the corresponding depth range as an empty model to simulate excavation. The excavation follows the principle of step-by-step excavation and subbracing. First, excavate the upper 4 meters of soil in steps and apply two rows of soil nails arranged in a plum-shaped arrangement. Then, set up the piles, crown beams, and prestressed anchor structures and connect the piles, crown beams, and prestressed anchor structures through nodes to transfer forces and moments to each other. Finally, continue the step-by-step excavation calculation, set the second row of prestressed anchor rods until the excavation reaches the bottom of the pit, and the simulation ends.

4. Results and Discussion

4.1. Convergence Criteria and Maximum Unbalanced Force. The convergence criterion is the judgment condition for the termination of the calculation and solution, which directly controls the speed and accuracy of the calculation and solution. The maximum unbalanced force is the maximum value of the difference between the external and internal forces at all nodes in each calculation time step. The external load is the external cause of the unbalanced force of the model system, and the calculated truncation error is the internal cause of the unbalanced force of the model system. Since the numerical calculation itself is a kind of
**FLAC3D 3.00**
Step 12083 model perspective
22:54:26 Sat Apr 28 2012

Center: Rotation:
X: 3.073e+001 X: 30.000
Y: 3.586e+000 Y: 0.000
Z: 1.500e+001 Z: 40.000
Dist: 1.683e+002 Mag.: 1.2
Increments: Ang.: 22.500
Move: 6.695e+000
Rot.: 10.000

Cable axial force
Magfac = 1.000e+000
Tension
Compression
Maximum = 7.960e+004

Contour of X-displacement
Magfac = 1.000e+000
-6.724e-004 to -4.0000e-004
-4.0000e-004 to -2.0000e-004
-2.0000e-004 to 0.0000e+000
2.0000e-004 to 4.0000e-004
4.0000e-004 to 6.0000e-004
6.0000e-004 to 6.4690e-004
Interval = 2.0e-004

Sketch
Itasca consulting group, Inc.
Minneapolis, MN USA

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**FLAC3D 3.00**
Step 14974 model perspective
22:53:42 Sat Apr 28 2012

Center: Rotation:
X: 3.073e+001 X: 30.000
Y: 3.586e+000 Y: 0.000
Z: 1.500e+001 Z: 40.000
Dist: 1.683e+002 Mag.: 1.2
Increments: Ang.: 22.500
Move: 6.695e+000
Rot.: 10.000

Cable axial force
Magfac = 1.000e+000
Tension
Compression
Maximum = 1.011e+005

Contour of X-displacement
Magfac = 1.000e+000
-6.3941e-004 to -6.0000e-004
-6.0000e-004 to -4.0000e-004
-4.0000e-004 to -2.0000e-004
-2.0000e-004 to 0.0000e+000
2.0000e-004 to 4.0000e-004
4.0000e-004 to 6.0000e-004
6.0000e-004 to 7.5813e-004
Interval = 2.0e-004

Sketch
Itasca consulting group, Inc.
Minneapolis, MN USA

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*Figure 6: Continued.*
**Figure 6: Continued.**
Figure 6: Continued.
| FLAC3D 3.00 | FLAC3D 3.00 |
|-------------|-------------|
| Step 34575 model perspective | Step 40608 model perspective |
| 22:47:49 Sat Apr 28 2012 | 23:10:31 Sat Apr 28 2012 |
| Center: Rotation: X: 3.073e+001 X: 30.000 | Center: Rotation: X: 3.073e+001 X: 30.000 |
| Y: 3.586e+000 Y: 0.000 | Y: 3.586e+000 Y: 0.000 |
| Z: 1.500e+001 Z: 40.000 | Z: 1.500e+001 Z: 40.000 |
| Dist: 1.683e+002 Mag: 1.2 | Dist: 1.683e+002 Mag: 1.2 |
| Increments: Ang. 22.500 | Increments: Ang. 22.500 |
| Move: 6.695e+000 | Move: 6.695e+000 |
| Rot: 10.000 | Rot: 10.000 |

Cable axial force

| Tension | Compression |
|---------|-------------|
| Maximum = 3.548e+005 |

Contour of X-displacement

| Magfac = 1.000e+000 |
|--------------------|
| -3.6456e-003 to -3.5000e-003 |
| -3.5000e-003 to -3.0000e-003 |
| -3.0000e-003 to -2.5000e-003 |
| -2.5000e-003 to -2.0000e-003 |
| -2.0000e-003 to -1.5000e-003 |
| -1.5000e-003 to -1.0000e-003 |
| -1.0000e-003 to -5.0000e-004 |
| -5.0000e-004 to 0.0000e+000 |
| 0.0000e+000 to 0.0000e+000 |

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Figure 6: Continued.
difference approximation, there is an inevitable truncation error; so, the maximum unbalanced force cannot reach zero. The variation curve of the maximum unbalanced force with step in this paper is shown in Figure 5.

Analysis of the results in Figure 5 shows that the maximum unbalanced force of the excavation system decreases with the increase of the calculation time step in each calculation step until the calculation converges and the system reaches a state of force equilibrium.

The first three steps in Figure 5 are the initial in situ stress generation and the excavation of the soil nail wall. Due to the shallow excavation depth of the foundation pit, the lateral earth pressure of the stratum is small, and the peak value of the maximum unbalanced force of the system is small. It can be seen that it is more reasonable to set 4 meters of soil nail wall support on the upper part of the foundation pit. However, with the deepening of the subexcavation depth, the formation stress is gradually released, the...
lateral earth pressure of the pit wall gradually increases, and the peak value of the maximum unbalanced force of the model system increases. The fourth and eighth steps have the largest peak unbalance force, mainly because the two simulation processes of excavation and support are mainly the application process of prestressed anchors. The larger prestress causes a significant increase in the internal nodal force of the model. As the prestress gradually expands to the anchoring section, the unbalanced force of the system gradually weakens until the entire model system is mechanically stable.

4.2. Foundation Pit Displacement Analysis. Figure 6 shows the simulated contour of the horizontal displacement of the soil in the foundation pit. It can be seen from Figure 6 that the maximum horizontal displacement of the foundation pit soil is about 5 meters below the top of the slope protection pile, and the maximum displacement is 4.66 mm. Within the length of 21 m behind the pit, the horizontal displacement of the soil is greater than 1 mm, and it can be seen that the influence of excavation is large.

According to the monitoring scheme and the change of weather, construction technology, and surrounding environmental load in the actual construction site, the horizontal displacement of the pile body is regularly measured, and the horizontal displacement curve of the supporting pile body on the west side of the foundation pit is obtained as shown in Figure 7(a). Since this project mainly monitors the changing trend of the horizontal displacement of the supporting pile body, the horizontal displacement of each node of the pile body is extracted and drawn into the curve in Figure 7(b), which is compared with the measured curves. It can be seen from Figure 7 that after the prestressed anchor is applied, the upper part of the pile has a negative displacement when the foundation pit is excavated from 5 meters to 7 meters, indicating that the prestressed anchor has an active supporting effect. It can effectively limit the lateral displacement of the pile and soil during the excavation of the foundation pit. As the horizontal displacement increases during

![Figure 7](image-url)  
(a) Horizontal displacement of piles monitored on the west side of foundation pit. (b) Horizontal displacement of simulated body of foundation pit.  

![Figure 8](image-url)  
Figure 8: Simulation curve of horizontal displacement of supporting pile top.
the excavation, the displacement of the pile top is relatively large at the initial stage of the excavation, and the position of the maximum horizontal displacement at the end of the excavation gradually moves down to a position of about 4 meters below the pile top. Comparing Figure 7(a): horizontal displacement of the west side of pit foundation with Figure 7(b): horizontal displacement of the simulated body of foundation, it can be seen that the variation trends of the measured curve value, the simulated curve, and the design curve of the deep horizontal displacement of the pile are consistent, and the maximum horizontal displacement is located in the middle of the pile. As the horizontal displacement increases during the excavation, the displacement of the pile top is relatively large at the initial stage of excavation; at the end of the excavation, the maximum horizontal displacement position gradually moves down to about 4 meters below the pile top. A comparison of horizontal displacement monitoring and simulation results shows that the numerical model meets the verification requirements.

From the simulation curve of the horizontal displacement of the pile top (Figure 8), it can be seen that the horizontal displacement of the pile top is affected by the prestressed anchor, and the outside of the foundation pit moves and increases with the deepening of the excavation depth. During the excavation simulation stage from 10 m to 12 m, the horizontal displacement of the pile top is affected by the tension of the second row of anchors, and the growth slows down.

4.3. Vertical Displacement of Foundation Pit. The simulated contour of vertical displacement of foundation pit soil is shown in Figure 9. The stratum settlement mainly occurs in the depth range of the upper soil nail wall, and the maximum vertical displacement occurs in a certain area of the soil behind the soil nail wall of the pit wall. Since the soil nail wall is supported by a gravity-like reinforced soil retaining wall, the soil nailing reinforcement is not prestressed; so, it can only passively bear the soil pressure of the stratum, and the ability to resist horizontal displacement and settlement is relatively weak, resulting in a large amount of settlement at the top of the foundation pit. The pile-anchor support system is used for the excavation depth of the foundation pit below 4 meters, which has a significant limiting effect on the settlement of the soil mass on the sidewall of the foundation pit. The manual digging and pouring pile can not only resist the lateral earth pressure of the soil body but also reduce the settlement caused by the horizontal displacement of the soil body; at the same time, it can also work together with the soil between the piles to limit the settlement of the soil through frictional resistance. The prestressed anchors, top beams, and waist beams provide the main power for the support system, balance the lateral earth pressure of the formation, and reduce the horizontal displacement and settlement of the sidewall of the foundation pit.

The simulation curve of horizontal displacement of pit roof after excavation is shown in Figure 10.

4.4. Mechanical Analysis of Piles and Anchors. The mechanical analysis of pile and anchor is of great significance in the information construction of foundation pit, and the mechanical stability of pile and anchor directly affects the result of foundation pit support. Therefore, many scholars obtained the mechanical characteristics of the anchor and the factors affecting the stability of the foundation pit.
through the analysis of the axial force of the soil nail and the anchor and used various theoretical foundations to predict the possible slip surface when the foundation pit was damaged; at the same time, through the analysis of the shear force and bending moment of the supporting pile, the characteristics of the force change of the pile during the excavation process are studied, determine the most dangerous point of pile body stress, and strengthen on-site monitoring and control of key parts to improve the safety factor and stability of foundation pit excavation and support.

This paper mainly analyzes and verifies the mechanical characteristics of soil nails and pile anchors through numerical simulation, and it provides some reference for the future three-pile two-anchor support system. It can be seen from Figures 11(a) and 11(b) that the axial force on the soil-nailed reinforcement is small, the axial force along the length of the reinforcement is roughly larger in the middle, the two ends have a small "jujube stone" shape, and the axial force of the soil nail increases with the deepening of the excavation depth of the foundation pit.
It can be seen from Figures 12(a) and 12(b) that although the design locking values of the anchor prestress are 360 kN in the first row and 330 kN in the second row, in the FLAC3D calculation process, the anchor prestress gradually spreads from the free section to the anchoring section, and the anchoring force gradually plays a role, which eventually leads to a large loss of prestress in the free section of the anchor, while the axial force in the anchoring section increases, and the distribution is linear. In this stage, the prestress loss of the free end is mainly related to the elastic modulus, stiffness, cohesion, and formation deformation of the anchor rod. With the increase of foundation pit excavation depth, the lateral earth pressure of the stratum increases, and the axial force of the anchor increases accordingly due to the balance of greater lateral earth pressure until it reaches the equilibrium state.

It can be seen from Figure 13 that the axial force of the anchor rod varies with the excavation depth. As the excavation depth of the foundation pit deepens, the prestress of the free end of the anchor rod gradually increases, and the application of the second row of anchor rods has a certain influence on the prestress of the first row of anchor rods. When the foundation pit was excavated to 12 meters, the second row of anchors was prestressed, resulting in a significant decrease in the slope of the rising curve of the axial force of the first row of anchors, and it can be seen that the application of the second row of anchor rods significantly shares the effect of the first row of anchor rods to balance the earth pressure on the sidewall of the foundation pit and cooperates with the first row of anchor rods to balance the formation pressure through coupling beams and piles.

From the shear force and bending moment curves of the supporting piles in Figures 15(a) and 15(b), it can be seen that the shear force and bending moment of the supporting piles are the results of the mutual balance between the axial force of the anchor and the lateral earth pressure of the stratum, the maximum shear force is the bending moment zero point, and the shear force zero point is the bending moment maximum point. Since the top of the pile is affected by the load of the upper soil nailing wall, the shear force on the pile body after the excavation is large, which is 156.3 kN-m. The shear force applied to the second row of anchors 7 meters below the pile top is 72.67 kN-m. It can be seen from the distribution curve of pile shear force and bending moment that
the application of a prestressed anchor is not only beneficial to limiting the displacement of the pile body but also can make the shear force on the pile body relatively evenly distributed along the length direction of the pile body and improve the mechanical stability of the pile.

5. Conclusions

Based on the excavation and support examples of deep foundation pit engineering, this paper systematically analyzes the excavation of a deep foundation pit and the three-pile two-anchor support system in anhydrous sandy cobble stratum with the aid of FLAC3D three-dimensional finite element simulation analysis results and draws the following conclusions:

(i) By summing up the current academic research results, the theory and construction status of deep foundation pit support are studied. The necessity of application of informatization construction in excavation and support of long pile foundation pit is analyzed.

Figure 14: Numerical simulation results of shear force and a bending moment of supporting pile. (a) Simulation results of the shear force of the supporting pile. (b) Simulation results of the bending moment of the supporting pile.
(ii) By comparing and analyzing the monitoring results of horizontal displacement of foundation pit and FLAC3D numerical simulation results, the feasibility of FLAC3D three-dimensional numerical simulation software is verified, and its advantages in foundation pit excavation and information construction are further analyzed.

(iii) Use the FLAC3D three-dimensional numerical simulation software to simulate the excavation and support process of the foundation pit, the stress and deformation law of the surrounding stratum during the excavation of the foundation pit, and the deformation law, and mechanical characteristics, and supporting effect of the three-pile and two-anchor support system are analyzed and summarized. In the process of foundation pit excavation, when the foundation pit is excavated from 5 m to 7 m, there is a negative displacement on the upper part of the pile, indicating that the prestressed anchor has an active support effect, which can effectively limit the lateral displacement of the pile and soil in the process of foundation pit excavation. The soil nailing wall is a passive force system, and the force is small in the excavation and support process. The axial force distribution is large in the middle and small in the two ends along the length direction. Because the top of the pile is affected by the load of the upper soil nailing wall, the shear force of the pile is large after the excavation, which is 156.3 kN-m. The shear force of the second row of anchor anchors 7 m below the pile top is 72.67 kN-m; The axial force of the prestressed anchor is unevenly distributed along the length direction, the axial force of the free section is equal, and the axial force of the anchored section decreases in turn. The prestress of the anchor rod spreads to the anchoring section after tensioning and locking.

(iv) At the initial stage of the anchor locking, the prestress is lost due to the deformation of the stratum and its elastic deformation, and then the axial force of the anchor increases gradually with the excavation of the foundation pit until the end of the excavation of the foundation pit and tends to be stable. The application of the second row of anchor rods has a certain influence on the axial force of the upper anchor rod and changes the form of shear force on the pile body. The two rows of anchor rods cooperate with the supporting pile body, crown beam, and waist beam to stabilize the lateral earth pressure of the stratum.

(v) Use FLAC3D numerical simulation software to simulate the excavation process and quantitative and qualitative analysis of the main control items such as anchor axial force, horizontal displacement, and other changes, predict the internal force and deformation characteristics of the slope in each construction process, and establish a reasonable early warning value. At the same time, high-precision monitoring technology is used to collect and organize information promptly, scientifically analyze the data, and take measures in advance for the parts with serious safety hazards, to avoid engineering accidents in time.

(vi) In this paper, an accurate and effective model is established in the simulation process. By analyzing the variation law of stress and deformation, the timeliness and reliability of the construction process...
Data Availability

The (data type) data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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