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Construction Monitoring and Numerical Simulation of the Foundation Pit in the Upper Subway Tunnel

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Abstract: With the rapid development of China's urbanization construction, the demand for land has gradually increased. In order to save land, people have begun to develop and utilize underground space, so that the foundation pit project has ushered in a new era of development. More and more common. However, in the deep foundation pit engineering of subway stations, the surrounding environment of the foundation pit has become more and more complicated, and the excavation depth of the foundation pit is also getting larger and larger, which makes the construction and design more difficult, The issue of stability is becoming increasingly prominent. Based on the above background, in order to ensure the safe construction operation and the stability of the foundation pit, the research content of this paper is to monitor the foundation pit in real-time on-site, and carry out experimental simulation on the construction site of the upper foundation pit of a Shenzhen subway tunnel. Under various working conditions of foundation pit excavation, the monitoring of the supporting structure can timely detect the deformation and stress of the supporting structure and surrounding buildings to predict the development trend of deformation, so that the deformation and displacement of the supporting structure are controlled within the allowable deformation Within the scope, to ensure the safety and stability of the foundation pit.Nowadays, the numerical simulation technology is well used in foundation pit engineering. Through numerical simulation, we can understand the deformation mode of foundation pit excavation more intuitively, and analyze the displacement and force changes of the supporting structure. The experimental results show that the foundation pit supporting structure composed of cast-in-place piles is more conducive to the stability of the foundation pit than the graded grading excavation; the maximum cumulative horizontal displacement of the two is -36.3mm and -42.4mm, respectively; as the foundation pit is opened During the excavation, the axial force of the steel support will increase first and then decrease. When the excavation approaches the bottom, the support axial force will stabilize; the deep horizontal displacement of the cast-in-situ pile support structure gradually increases with the excavation of the foundation pit. By comparing and analyzing the laws of simulation and monitoring values, the feasibility of the numerical simulation method is verified, which provides a basis for the design of foundation pit support schemes, the selection of construction methods, and the deployment of monitoring points.

1. Introduction

With the development of the subway's economic construction in Chinese cities, a lot of subway and building structures have crossed. [1]. Foundation pit engineering is the basis of all these constructions, and its safety often affects the safety of the entire project. To ensure the safe construction of cross foundation pit engineering, construction monitoring of the foundation pit project is required [2-3]. Foundation pit engineering is a comprehensive geotechnical engineering problem, which involves many issues such as the strength, stability and deformation of soil mechanics, and the coordinated work of soil retaining structures [4-5]. In the process of foundation pit support, with the deepening of the excavation, the unloading of the soil after the support structure will greatly change the internal force and deformation of the structure. Therefore, attention should be paid to this aspect to ensure the safe progress of the construction [6].

The foundation pit project is different from other projects and can be copied and copied. It has its special features [7-8]. The same excavation size and regional differences lead to different stratum conditions. Second, the surrounding environment of the construction site is very different. The support method adopted may be there are many differences [9-10]. Therefore, the design and optimization of the supporting structure of the foundation pit in the upper part of the subway tunnel is carried out, and a reasonable supporting structure is adopted [11]. By simulating and analyzing the construction conditions of the foundation pit, the construction process is optimized, and the construction monitoring is strengthened [12-13]. The construction technology is of great significance to ensure the safety of the foundation pit construction of the subway tunnel [14-15].

Finite element analysis has been used in many deep foundation pit excavation projects to improve construction efficiency and safety. Its reliability depends on the accuracy of model parameters and the applicability of boundary conditions. Tan proposed an inverse analysis model of soil parameters based on artificial neural network and its application in excavation of deep foundation pits. When developing this model, they determined the structure of the neutral network based on the size and number of parameters of the monitoring data and used a genetic algorithm to start the neutral network. They then developed a neutral network training set through finite element calculations. After completing all the training, they entered the monitoring data into the network and started back-calculating the soil parameters. The verification results show that the back analysis model proposed by Tan is effective and accurate in soil calculation [16].In large and medium cities, the rapid development of municipal engineering construction has led to more and more deep foundation pit projects. Due to the lack of construction land, there must be existing buildings or structures around the deep foundation pit. Combined with the rare situation of high-speed railway bridge pile foundations surrounding deep foundation pits, Jun analyzed the influence of deep foundation pit excavation on the supporting structure and pile foundation through finite element numerical simulation, and then verified the numerical results with field monitoring data. The results show that the excavation of the deep foundation pit causes unloading, which destroys the balance between the surrounding rock and the soil, and then causes the redistribution of stress. The excavation of the deep foundation pit causes the turbulence of the foundation pit, and the retaining structure moves forward into the pit; The change of the stress field causes the change of the displacement field, which leads to the displacement of the rock and soil due to the movement of the pile foundation and other structures in the rock and soil. The direction of the pile foundation is basically toward the tunnel, the upper displacement is larger, and the lower displacement is smaller; the simulation data and the test data match, indicating that the final displacements are within the safe range; and it proves that the engineering support structure design proposed by Jun is safe for the deep foundation pit. Effectively, its support structure design and pile foundation displacement mode can be used in similar projects in the future [17]. Deformation of the operating tunnel and soil settlement caused by deep foundation pit excavation are of great significance in the safety management and risk assessment of urban rail transit construction. Zhang analyzed the laws and characteristics of ground settlement around the foundation pit, deformation of the partition wall, horizontal convergence, and vertical displacement based on the monitoring data of the Shanghai Symphony Orchestra's foundation pit project and the operating tunnel and its surrounding structures. The actual measurement results show that the general trend of ground subsidence is a trend of subsidence, which is usually distributed in a parabola; the lateral deformation of the soil and the partition wall shows basically the same change and moves towards the inside of the foundation pit. The influence of the beam is not a simple linear relationship; the lateral additional convergence is expressed by outward extension, and the convergence increases with the excavation of the foundation pit; SMW reinforcement on both sides of the diaphragm wall can effectively control the tunnel, the outer surface of the foundation pit and the diaphragm wall. Deformation [18]. In order to study the effect of changes in soil parameters on the deformation of pile-anchor supporting structures, Liu used a finite element software Midas GTS to analyze and numerically analyze the deformation characteristics of the supporting structures in combination with a foundation pit project in Liaoning. Comparing the results with the measured results shows that with the increase of the excavation depth, the horizontal displacement of the pile-anchoring structure gradually increases, and the deformation curve of the horizontal displacement is arched. The position of the maximum horizontal displacement is not at the top of the pile, but at a position where the top of the pile is at a certain distance from the pile. It gradually decreases with the increase of the excavation depth, and finally stabilizes at about 7/10 of the excavation depth. The dehydration of the foundation pit will cause changes in soil parameters. The cohesive force is large and the horizontal displacement of the supporting structure is small. The internal friction angle is large and the horizontal displacement of the supporting structure is small [19].In Newtonian fluid-modified thick alluvial clay Nishihara model, the upward displacement of the pile and the bottom plate destroys the balance of the support system in the foundation pit excavation. This model can well describe the creep deformation behavior during the excavation of the foundation pit, You can track the behavior of the foundation pit. The ratio of the depth of the inserted pile to the excavation depth, the side length and spacing of the supporting piles, and the law of the bottom plate's upward displacement when the column piles with different depths rebound. Dan analyzed the soil, location and type of the pile through field data, improved Nishihara model and secondary development of FLAC3D. Dan took the deep foundation pit of Jinan Cultural Center as the engineering background. The research found that the sensitivity of the upper displacement of the foundation pit affects different factors: the distance of adjacent support piles, the depth of the insertion and the ratio of the excavation depth of the support piles; The susceptibility of piles to rebound follows the order of pile depth in the pile-like soil position. Dan's results can provide guidance for reducing the impact of excavation on the upward displacement of the pile foundation and floor [20].

In this paper, a foundation pit project on a subway tunnel in Shenzhen is taken as an example. The horizontal displacement of the supporting structure of the foundation pit and the axial force of the steel support are monitored on site. The results show that the deformation of the supporting structure on the east and west sides is The digging progressed gradually, the maximum deformation calculated value was 12.72mm, and the maximum monitored value was 12.5mm. Comparing the monitoring data, in the vertical direction, the deformation of the supporting structure is small at the two ends and large in the middle, which is in line with one of the four failure deformation modes of the retaining structure. Looking at the transverse direction, the calculated value of the central deformation of the supporting structure is the largest. In the monitoring of the foundation pit, the deep horizontal displacement measuring tube is set at WX07. Comparing the early warning value of the deep horizontal displacement in the design plan of 25mm, it can be known that the support structure of the cast-in-situ piles on the north and south sides are in a safe and controllable state during the excavation of the foundation pit. It is conservative and can be appropriately optimized in the future support design.

2. Proposed Method

2.1. Foundation Pit Engineering

(1) Engineering characteristics of foundation pits

Soil is the closest and most direct object to the foundation pit engineering. Like the rock, the soil is a product of natural history. There are many types of soils with complex characteristics. They have three states of existence: solid, liquid and gas, and their properties will change as the environment changes. The diversity and complexity of the soil body makes the foundation pit project have the following characteristics:

1) The foundation pit project has a strong particularity. In the design, construction and earth excavation of foundation pit engineering, not only site conditions, engineering geological conditions, and hydrological conditions should be considered, but also the location of buildings, structures, underground pipelines adjacent to the foundation pit, and Their importance and ability to resist deformation. The particularity of the factors affecting the foundation pit engineering determines the particularity of the foundation pit engineering.

2) The foundation pit project is highly comprehensive. In theory, it involves not only geotechnical engineering theory, but also structural engineering theory. Technically, foundation pit engineering requires the coordination and cooperation of engineering management technology, construction technology, measurement technology, computer technology and rotary machinery.

3) Foundation pit engineering has strong regional characteristics. There are many factors that affect the difference of foundation pit engineering. Different regions have different characteristics, and even there may be differences in different regions of the same place. Therefore, the design and construction of the supporting structure of the foundation pit must be carried out according to the actual situation. The experience of similar projects can be used for reference, but it must not be simply copied or copied, otherwise it will cause engineering accidents due to the geographical adaptability of experience.

4) Foundation pit engineering is system engineering. It mainly includes earth excavation and support structure design. Whether the earthwork excavation construction is reasonable has an important effect on the success of the foundation pit support. Unreasonable earth excavation methods may cause excessive deformation of the supporting structure, displacement of the pile foundation, and even cause instability and damage of the supporting structure.

5) As a temporary structure, the foundation pit support has the characteristics of high risk and unstable safety performance. The monitoring work should be strengthened during the construction of the foundation pit to provide guarantee for safe construction.

6) The space-time effect of foundation pit engineering is relatively strong. Soils have a certain creep property, and the earth pressure on the supporting structure will change with time. Creep will also reduce the strength of the soil and reduce the stability of the slope. Therefore, the time effect of foundation pit engineering should be fully considered. At the same time, the construction of the foundation pit is a dynamic process. The shape and depth of the foundation pit will change with the construction progress. These two factors have a great impact on the deformation and stability of the foundation pit support system. Also pay attention to the space effect when designing the foundation pit support system.

(2) Classification of foundation pits

Different types of foundation pits should be classified according to their excavation depth and surrounding environment. The main classification methods are as follows:

1) Divided by geological complexity: foundation pits with very complicated geological conditions are first-level foundation pits; foundation pits with moderately complicated geological conditions are second-level foundation pits; foundation pits with simple geological conditions are third-level foundation pits.

2) Divided according to the surrounding environment level: the foundation pit with important buildings, important underground facilities, communication or living pipe network within the range of 1 ~ 2 times the depth of the foundation pit is a first-level foundation pit; the depth of the foundation pit is 1 Foundation pits with important buildings and important underground pipe network branch lines within twice the range are secondary foundation pits; foundation pits without important buildings or pipelines within the range of twice the depth of the foundation pit are tertiary foundation pits.

The method used to grade foundation pits will vary from place to place. Generally, we will comprehensively consider the three classification methods. If foundation pits that meet two or more conditions are generally upgraded by one level, the ultimate purpose of pit classification is to ensure safety.

2.2. Numerical Calculation of Foundation Pit Excavation

The foundation pit engineering calculation is based on the principle of the finite difference method. In the finite difference method, the basic equations and boundary conditions (generally differential equations) are approximately represented by the difference equation (algebraic equation), which is replaced by an algebraic formula of the field variables (stress, displacement) at the discrete points in space. These variables are non-deterministic in the unit, so the problem of solving differential equations is replaced by the problem of solving algebraic equations. In contrast, the finite element method requires that the field variables (stress, displacement) be changed within each element according to special equations controlled by certain parameters. In the formula, adjust these parameters to reduce the error and energy terms. The finite difference method regenerates the finite difference equations in each calculation relatively efficiently. Usually, the "explicit", time-stepping method is used to solve the algebraic equations. The finite difference numerical calculation uses two sets of parallels with equal intervals h-cut parallel to the coordinate axis The grid is divided by lines. Let f = (x, y) be a continuous function in the elastic body, which may be a certain stress component or displacement component, or it may be a stress function, temperature, or seepage.

The stress state at any given point in a solid medium can be described by the stress tensor σ_{ij}. An external force acting on the surface with a unit normal vector n can be given by the Cauchy formula:

$$t_i = \sigma_{ij} n_j \tag{1}$$

Let the velocity of the point of the medium be v. Within an infinitely small time dt, the medium has experienced an infinitely small strain $v_t dt$. Each component corresponding to the strain rate tensor can be written as:

$$\zeta_{ij} = \frac{(v_{i.j} + v_{j.i})}{2} \tag{2}$$

In the formula, the partial derivative is performed according to the current position vector x. In addition, the unit body also experiences instantaneous rigid body displacement, which can be determined by the translation speed v. Angular velocity rotation is

$$\Omega = -\frac{e_{ijk}\omega_{jk}}{2} \tag{3}$$

In the formula, e_{ijk} is the cycle symbol, and ω is the spin tensor rate, and its component is determined by the following formula:

$$\omega_{ij} = \frac{(v_{i.j} - v_{j.i})}{2} \tag{4}$$

From the continuous form of the law of momentum, the Cauchy equation of motion can be obtained:

$$\sigma_{ij.j} + \rho b_i = \rho \frac{dv_i}{dt} \tag{5}$$

In the formula, ρ is the mass per unit volume of the medium, b is the volume force per unit mass, and $\frac{dv_i}{dt}$ is the material derivative of velocity. In mathematical models, these laws control the motion of the media unit body after it is stressed.

The constitutive equation of solid medium can be expressed by the following formula:

$$[\breve{\sigma}]_{ij} = H_{ij}(\sigma_{ij}, \zeta_{ij}, \kappa) \tag{6}$$

Where $[\breve{\sigma}]_{ij}$ is the co-stress rate spin tensor, H is the given control function, and κ is a parameter that depends on the load history. The co-stress rate spin tensor $[\breve{\sigma}]_{ij}$ is defined by:

$$[\breve{\sigma}]_{ij} = \frac{d\sigma_{ij}}{dt} - \omega_{ik}\sigma_{kj} + \sigma_{ik}\omega_{kj} \tag{7}$$

Where $d[\sigma]/dt$ is the time derivative of material stress σ and ω is the rate of rotation tensor.

For three-dimensional problems, the specific calculation object is first divided into finite difference meshes with hexahedral elements. Each discretized cube element can be further divided into several constant strain triangular pyramid sub-elements.

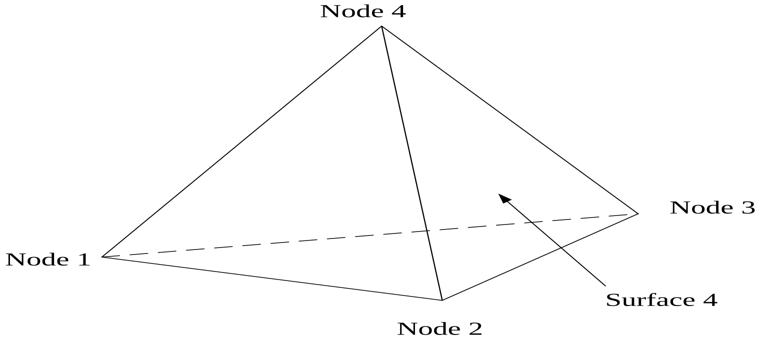

Figure 1. Triangular pyramid element

As shown in Figure 1. Applying the Gaussian divergence theorem to triangular pyramid elements, we can derive:

$$\int_V v_{i,j} dV = \int_S v_i n_j dS \tag{8}$$

In the formula, $\int_V v_{i,j} dV$ and $\int_S v_i n_j dS$ respectively integrate the volume and area of the pyramid, and n is the outer normal vector of the pyramid surface.

For a constant strain rate pyramid, the velocity field is linear and n is constant on the same surface. Therefore, by integrating equation (8), we get

$$V v_{i,j} = \sum_{f=1}^{4} \bar{v}_i^{(f)} n_j^{(f)} S^{(f)} \tag{9}$$

In the formula, the superscript f represents the corresponding variable on the surface f, and $\bar{v}_i$ is the average value of the velocity component v_i. For linear velocity changes, there are

$$v^{-(f)} = \frac{1}{3} \sum_{l=1, j \neq f}^{4} v_i^l \tag{10}$$

Substituting equation (10) into (9), the contribution of the node to the entire unit body is obtained:

$$V v_{i,j} = \frac{1}{3} \sum_{l=1}^{4} v_i^l \sum_{l=1, j \neq f}^{4} n_j^{(f)} S^{(f)} \tag{11}$$

If we replace v_i in equation (8). with 1, and apply the law of divergence, we can get

$$\sum_{l=1, j \neq f}^{4} n_j^{(f)} S^{(f)} = 0 \tag{12}$$

Using equation (12) and dividing V by equation (11), we get

$$v_{i,j} = \frac{1}{3V} \sum_{l=1}^{4} v_i^l n_j^{(l)} S^{(l)} \tag{13}$$

Similarly, the component of the strain rate tensor can be expressed as

$$\zeta_{i,j} = -\frac{1}{6V} \sum_{l=1}^{4} (v_i^l n_j^{(l)} + v_j^l n_i^{(l)}) S^{(l)} \tag{14}$$

2.3. Monitoring Scheme and Data Simulation

The monitoring plan shall determine the monitoring purpose, monitoring items, monitoring instruments, monitoring frequency and alarm value of the foundation pit according to relevant technical standards and technical regulations. The formulation of the monitoring plan should comprehensively consider a variety of influencing factors in accordance with the characteristics of the foundation pit project to be excavated, never move the hard sleeve, and make timely adjustments based on the actual excavation of the foundation pit. The purpose of testing is mainly in the following aspects: (1) Enabling relevant persons involved in the monitoring of the construction site and key indicators of the construction site of the construction pit, the construction party, the supervisor and the independent third party to ensure that the construction site Safety during pit excavation and support. (2) Arrange and analyze on-site monitoring data in time, give early warning of potential safety hazards, and take corresponding remedial measures to ensure the safety of the foundation pit itself and the surrounding building environment.(3) By sorting and analyzing the monitoring data at the excavation site of the foundation pit, the calculation results of the foundation pit design and the selection of the calculation parameters can be checked. When necessary, the design and construction can be adjusted in time based on the monitoring data to obtain good engineering results. (4) The monitoring data of foundation pits provides first-hand information for design and construction and researchers. The accumulation of experience can help improve the level of design and construction of foundation pit projects, and can provide reference for design and construction of similar projects. Building foundation pit support technology and foundation pit monitoring projects should be selected based on factors such as the complexity of the address conditions, the type of support structure, the method of groundwater control, and the importance of the surrounding environment of the foundation pit. The selected monitoring items and the location of monitoring points should be able to reflect the safety status of the envelope structure and the degree of influence on the surrounding buildings (structures) and underground pipelines.

As a simple and effective calculation method, the numerical analysis method is widely used in various types of foundation pit excavation simulation analysis. At present, numerical analysis software commonly used at home and abroad includes ABAQUS, ANSYS, FLAC3D, MIDAS, etc., and has been widely used in practical engineering due to its different characteristics. Excavation of foundation pits in cities is likely to have a great impact on the surrounding environment, so it is necessary to use finite element software to simulate the construction process. For the change of horizontal displacement of deep soil, it can be passed through the underground diaphragm wall. Reflect the change of the horizontal displacement of the wall. The foundation pit excavation research mainly considers the safety of the foundation pit itself and the impact of the surrounding environment, so the support structure of the foundation pit needs to be studied. The impact of the foundation pit excavation on the surrounding environment is mainly reflected by ground settlement.

Among them, it is necessary to pay attention to the following points in the level and total station construction: the selection of the base point position should not be affected by the construction and be easy to measure; the base point should be fixed and reliable; the first observation should be made twice in a row, and the difference between the two measurements is less than ±2mm.It is considered effective at 2mm, and the average value of the two observations is finally taken as the initial value. The difference between the readings of each measurement point during the observation should not exceed 0.2mml. The settlement value of each monitoring point can be calculated by the following formula:

$$\Delta H = H_n - H_0 \tag{15}$$

In the formula, ΔH: Settling point of the measuring point, mm: Hn Actual height of the measuring point, mm: H0: Initial height of the measuring point, mm.

The horizontal and vertical displacements of the monitoring points can be calculated by the following formula:

$$\Delta X = X_n - X_0 \tag{16}$$

$$\Delta Y = Y_n - Y_0 \tag{17}$$

$$\sum \Delta X_i = \Delta X_i + \sum \Delta X_{i-1} \tag{18}$$

$$\sum \Delta Y_i = \Delta Y_i + \sum \Delta Y_{i-1} \tag{19}$$

Where ΔX : change in horizontal displacement, mm; ΔY : change in vertical displacement, mm; $\sum \Delta X$: cumulative change in horizontal displacement, mm; $\sum \Delta Y$: cumulative change in horizontal displacement, mm.

The reference point is set, and the reference point for the observation of the deformation of the retaining pile is generally set at the bottom of the inclined pipe. When the measured pile body deforms, the deflection axis of the incline pipe produces deflection, and the inclination angle of each section of the incline pipe axis is determined by the inclinometer, and the horizontal displacement of the pile can be calculated. Let the reference point be O point and the coordinates be (X_0,Y_0), then the plane coordinates of each measuring point of the inclined pipe axis are determined by the following two formulas:

$$X_j = X_0 + \sum_{i=1}^{j} L \sin \alpha_{xi} = X_0 + L \cdot f \cdot \sum_{i=1}^{j} \Delta \varepsilon_{xi} \tag{20}$$

$$Y_j = Y_0 + \sum_{i=1}^{j} L \sin \alpha_{yi} = Y_0 + L \cdot f \cdot \sum_{i=1}^{j} \Delta \varepsilon_{yi} \tag{21}$$

Where i is the serial number of the measuring point, i = 1,2,..., j; L: the standard distance of the inclinometer or the distance between the measuring points, m; f: the constant of the inclinometer; $\Delta \varepsilon_{xi}$: the i-th paragraph Half of the difference between the positive and negative measured strain readings; $\Delta \varepsilon_{xi}$: Half of the difference between the positive and negative measured strain readings in the i-th segment of the Y direction. In order to eliminate the error caused by the zero drift of the measurement device, the inclination angles in both directions of each measurement segment should be measured in both positive and negative directions, that is,

$$\Delta \varepsilon_{xi} = \frac{(\varepsilon_x^{+})_i - (\varepsilon_x^{-})_i}{2} \tag{22}$$

$$\Delta \varepsilon_{yi} = \frac{(\varepsilon_y^{+})_i - (\varepsilon_y^{-})_i}{2} \tag{23}$$

When $\Delta \varepsilon_{xi}$ or $\Delta \varepsilon_{yi}$ > 0, it means positive tilt to the X or Y axis, and when $\Delta \varepsilon_{xi}$ or $\Delta \varepsilon_{yi}$ <0, it means negative tilt to the X or Y axis. Point the horizontal position, and compare the horizontal coordinates of each measurement point in different measurements to know the horizontal displacement of the pile.

Water level elevation calculation:

$$H_w = H_g - h \tag{24}$$

Where Hw: water level elevation, unit: m; Hg: nozzle elevation, unit: m; h: distance from the water surface in the pipe to the nozzle, unit: m. The difference between the water level elevations in the two pipes is the current change in the water level of the water level hole, and the difference between the current water level elevation and the initial water level elevation is the cumulative change.

Axial force meter works:When the axial force meter receives the axial force, it causes the tension of the elastic steel string to change, which changes the vibration frequency of the steel string. The frequency of the steel string can be measured by the frequency meter to measure the magnitude of the force. The general calculation formula is as follows:

$$P = K_i (f^2 - f_0^2) \tag{25}$$

Where P: monitoring support axial force, kN; Ki: calibration constant of the axial force meter, kN/HZ2; f: monitoring natural frequency of the axial force meter, Hz; f0: initial natural frequency of the axial force meter, Hz.

3. Experiments

3.1. Experimental Environment and Data

This article mainly uses a foundation pit project in the upper part of the Shenzhen subway tunnel as the background, analyzes the force and deformation of the foundation pit by using on-site monitoring and numerical simulation methods, and uses the Tianbao level to monitor the surface settlement. The accuracy of the instrument is 0.2mm; TS09Plus the total station monitors the horizontal displacement and vertical displacement of the top of the supporting pile, the accuracy of the instrument is 2 ". 2mm + 1ppm; the CX-06B inclinometer performs the horizontal displacement of the supporting pile and the horizontal displacement of the deep soil outside the pit. Monitoring, instrument accuracy ± 5mm / 20m; SWJ-8090 steel ruler water level meter for monitoring groundwater level outside the foundation pit, instrument accuracy 3mm. XP02 frequency reading instrument for internal force monitoring of support structure (three steel supports), instrument accuracy 0.2kN.Comprehensively consider the key research objects, design requirements, and foundation pit monitoring levels of this paper to determine the specific monitoring content.

Table 1. Summary table of monitoring contents and number of measuring points in foundation pits

Measurement item	Using the instrument	Performance	Number of measuring points
Ground subsidence	Trimble spirit level	0.2mm	150
Vertical displacement of the top of the supporting pile	TS09Plus total station	2”.2mm+1ppm	50
Horizontal displacement of top of supporting pile	TS09Plus total station	2”.2mm+1ppm	50
Horizontal displacement of supporting piles	CX-06B Inclinometer	±5mm/20m	50
Horizontal displacement of deep soil outside the pit	CX-06B Inclinometer	±5mm/20m	/
Axial force of steel support	Steel string frequency axial force meter	±0.02/FS	60
Groundwater level	SWJ-809 Water level gauge	Error ±1mm	25

3.2. Experimental Steps

Perform on-site monitoring of the foundation pit in the upper part of the subway tunnel, select a representative monitoring section of the foundation pit, analyze the actual monitoring data, and focus on the analysis of foundation pit excavation on the ground surface outside the foundation pit, groundwater level, internal force of the support structure, and bored The horizontal displacement of the pile and the horizontal and vertical displacement of the top of the bored cast-in-situ pile are compared with the specifications and design requirements, and the law of deformation of a certain foundation pit in the upper part of the Shenzhen subway tunnel is obtained. The large-scale finite element software ⅦDAS GTSNX is used to build a three-dimensional finite element model of the deep excavation of the subway station and the surrounding rock and soil layer, and to simulate the precipitation of the deep excavation. Excavation. The supporting process focuses on the deformation and stress of the soil outside the pit, the retaining structure and the supporting system under various excavation conditions. Finally, the numerical simulation results are compared with the on-site foundation pit monitoring data to verify the validity of the three-dimensional numerical model. The rationality and reliability further reveal the deformation law of a foundation pit in the upper part of the Shenzhen subway tunnel.

4. Discussion

4.1. Horizontal Displacement of Supporting Structure (Slope)

The horizontal displacement monitoring object is a total of 10 foundation pits from GM01 to GM10, and the monitoring data of representative pit GM07 is taken for analysis. Its horizontal displacement point arrangement is shown in Figure 2.

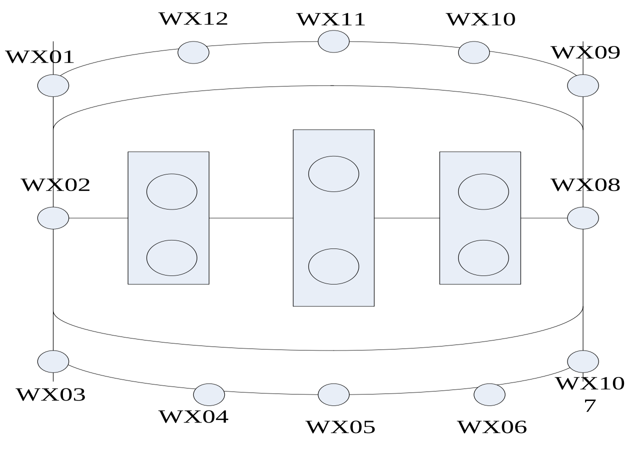

Figure 2. Horizontal displacement monitoring point layout

According to Figures 3 and 4, it can be seen that with the excavation of the foundation pit, the cumulative horizontal displacement of the retaining wall and slope of the foundation pit gradually increases. The excavation construction changed the depth of the foundation pit, and the change in depth caused the change in the size and distribution of the displacement. The change in horizontal displacement eventually caused the change in earth pressure. GM07 cumulative maximum horizontal displacement on the east and west sides is -30mm (WY03 monitoring point), the average cumulative horizontal displacement is -24.84mm; cumulative maximum horizontal displacement on the north and south sides is -39mm (WX02 monitoring point), the average cumulative horizontal displacement is -36.3mm. With the progress of the foundation pit project, the cumulative displacement of the east-west and north-south sides gradually increased, but the change of displacement state on the east-west side was gentler than that on the north-south side. The support structure of slope excavation has high strength and rigidity, which is more conducive to maintaining the stability of the soil around the foundation pit.

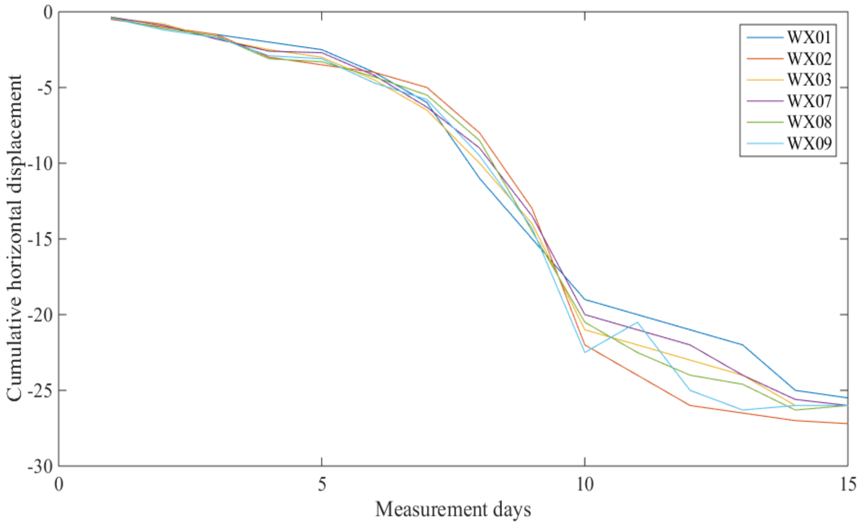

Figure 3. Monitoring points on the east and west side retaining walls

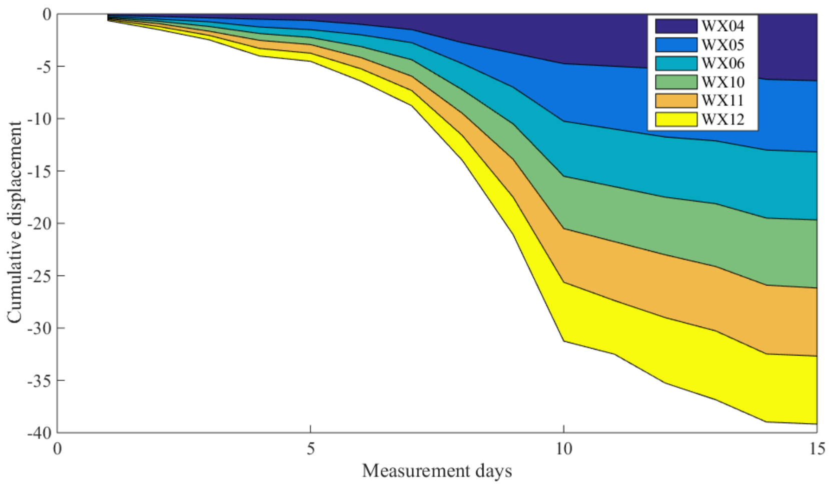

Figure 4. Monitoring points on the slope of the north-south side retaining pit

4.2. Supporting Axial Force

During the construction of the foundation pit, the surrounding soil will give a squeezing force to the supporting structure, and the supporting structure will transmit this force to the supporting structure through the enclosure, and this force will be reflected as the supporting axial force. Based on the analysis of the supporting axial force monitoring data at the measuring points of the foundation pit and the corresponding working conditions, it is found that during the excavation process of the foundation pit, the supporting axial force values of each channel mostly increase or decrease regularly. A total of 50 foundation pits were installed during the axial force monitoring of GM01 ~ GM10, and the monitoring time was from the beginning of the steel support installation to the removal of the steel support before the backfill of the foundation pit. In the analysis of this paper, the monitoring data of the same axial force meter monitoring point (GM07-ZL04) of representative pit GM07 was taken. Its measured values are shown in Table 2.

Table 2. GM07-ZL04 monitoring point axial force frequency value and corresponding axial force value

Monitoring days	Frequency	Axial force/kN	Monitoring days	Frequency	Axial force/kN
1	1843.4	25.8	8	1825	184,5
2	1816,3	238.3	9	1821.3	174,8
3	1848,3	15.0	10	1828,5	128,4
4	1835,2	117,4	11	1817,5	201.8
5	1823.7	175.6	12	1827.8	168.4
6	1801.3	308.9	13	1825.2	127.4
7	1801.3	308.3	14	1820.4	137.8

It can be known from Table 2 that the excavation from the surface of the foundation pit to the lowest level, with the foundation pit excavation, the value of the supporting axial force gradually increased, the maximum value was 308.9kN. The value gradually decreases, and the minimum value is 127.4kN.

4.3. Deep Horizontal Displacement

The displacement of the pile body completely reflects the deformation of the surrounding pile body, and is also an important indicator for maintaining the safety status of the structure. Figure 5 shows the inclination data of the main time nodes of the GM07 foundation pit during the monitoring period.

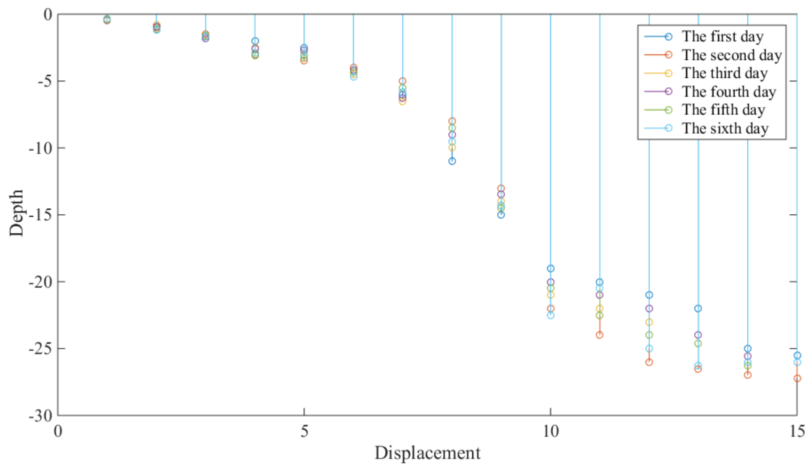

Figure 5. Inclination data chart at various time points during the M07 monitoring period

It can be seen from Figure 5 that with the progress of the excavation, the deep horizontal displacement of the east-west cast-in-situ pile gradually increases, and the maximum displacement area is concentrated in the middle and upper part of the cast-in-place pile. Compared with the design plan, the deep horizontal early-warning value of 25mm is known. During the excavation of the pit, the support structure of the cast-in-situ piles on the north and south sides is in a safe and controllable state. The maximum deep horizontal displacement value is 41% of the early warning value, which indicates that the design of this support is conservative and can be appropriately optimized in the future support design.

Based on the numerical simulation results, the design is optimized and information-based construction methods are used to implement dynamic monitoring of the weak points of the foundation pit project and the surrounding environment under different working conditions, and the various monitoring data are analyzed and predicted to verify the safety and reliability of the support scheme Only in this way can better guide the implementation of various construction measures and protection measures. The comparison between the monitored maximum value of the horizontal displacement of the supporting structure (slope) and the deep horizontal displacement and the maximum value calculated by simulation are shown in Figure 6 and Figure 7.

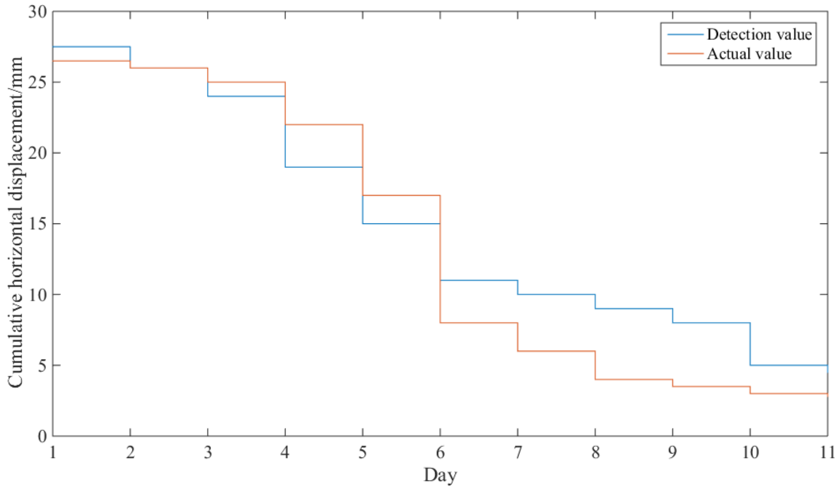

Figure 6. WX10 monitoring point

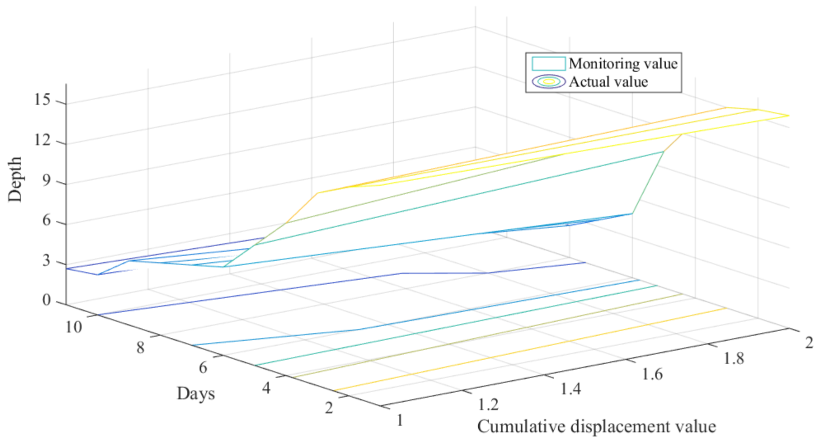

Figure 7. Maximum deep horizontal displacement

From Figure 6, it can be seen that the maximum deformation of the foundation pit support structure in the simulated calculation and monitoring values is 31.5mm (the middle of the north-south slope) and 41mm (the WX10 monitoring point), which meets the design requirements of not more than 75mm. The pit is in a safe state. From the simulated deformation cloud diagram, it can be seen that from the initial excavation of the foundation pit to the design elevation, the deformation at the bottom of the foundation pit gradually increases, and the main manifestation is the uplift, which is consistent with the monitoring data performance of the actual project. Compared with several supporting structures of foundation pits, the deformation of the soil around the supporting piles on the east and west sides of the foundation pit with cast-in piles is less than the deformation on the north and south sides of the foundation pit with graded slope excavation. Compared with the graded grading support, the protection has a better limit on the displacement of the soil.

It can be known from Figure 7 that the simulation calculation values show that the deformation of the support structure on the east and west sides gradually increases with the progress of the excavation. The maximum deformation calculation value is 12.72mm and the maximum monitoring value is 12.5mm. Comparing the monitoring data, in the vertical direction, the deformation of the supporting structure is small at the two ends and large in the middle, which is in line with one of the four failure deformation modes of the retaining structure. Looking at the transverse direction, the calculated value of the central deformation of the supporting structure is the largest. In the monitoring of the foundation pit, the deep horizontal displacement measuring tube is set at WX07.

This paper analyzes the deformation trend of subway tunnels and guides the actual construction by combining on-site monitoring and numerical models. The maximum deformation in the X, Y, and Z directions of the subway tunnel in the numerical simulation calculations is -2.72mm, 1.47mm, and 11.87mm, respectively. The vertical displacement (Z direction) and horizontal displacement (X, Y direction) affect the subway tunnel segments. The structural impact meets the requirements of the safety control index, but the vertical displacement does not meet the control index requirement of the tunnel floating up to 3mm under the completed track laying condition of the section tunnel. Therefore, according to the current foundation pit excavation scheme, it is recommended that the foundation pit project should be in the subway tunnel was completed before the track was laid.

5. Conclusion

In this paper, the support structure (slope), steel support axial force, and deep horizontal displacement of the support structure were monitored for the construction of the upper foundation pit of a Shenzhen subway tunnel. The monitoring data and numerical simulation values were analyzed by comparison. The support structure of cast-in-situ piles in the support system is more conducive to maintaining the stability during the excavation of the foundation pit than the grading support structure. When the excavation is carried out, the axial force value of the steel support will increase first and then decrease. When the foundation pit is excavated to the bottom, the axial force reaches the maximum value; the deep horizontal displacement of the cast-in-situ pile support structure will increase with Progressive increase.

This paper uses the midas / gts finite element analysis software to carry out numerical simulation of the excavation of the foundation pit. By comparing and analyzing the change law of the simulated value and the monitored value, it is proved that the numerical simulation analysis can predict the deformation trend of the excavation process, which can provide a basis for the design of foundation pit support scheme, the selection of construction methods and the layout of monitoring points. And it was found that through the safety monitoring of the foundation pit project, not only the hidden dangers of the project can be found in time, it is a warning for the safe construction, and it is of great significance to inspect the construction quality of the supporting structure.

This paper uses field monitoring data and numerical simulation methods to analyze the deformation of the surrounding structure and surrounding environment during the deep foundation pit excavation of Lanzhou subway station. However, due to the current limited knowledge and level, there are still many places that need to be improved and studied in the future. For example, Wen only selected the foundation pit of a subway station in Shenzhen to analyze the monitoring results on site. In order to analyze the reliability of the results and the uniformity of the rules, multiple deep foundation pit monitoring data in Shenzhen subway station can be selected for comparative analysis.

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Data Availability

Data sharing is not applicable to this article as no new data were created or analysed in this study.

Conflict of Interest

The author states that this article has no conflict of interest.

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