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Multi-Stage and Multi-Parameter Influence Analysis of Deep Foundation Pit Excavation on Surrounding Environment

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Abstract: As urbanization accelerates, deep excavation projects have become increasingly vital in the construction of high-rise buildings and underground facilities. However, the potential risks to the surrounding environment and the inherent complexities involved necessitate thorough research to ensure the safety of those engineering projects with deep foundation pit excavation and to minimize their impact on adjacent structures. This study introduces a multi-stage and multi-parameter numerical simulation method to scrutinize the construction process of deep foundation pits. This approach not only investigates the influence of excavation activities on nearby buildings and roads but also enhances the fidelity of simulation models by establishing a three-dimensional finite element model integrated with on-site investigated geological information. Therefore, the proposed method can provide a more holistic and accurate analysis of the overall impacts of the pit excavation process. To examine the feasibility and effectiveness of the proposed method, this study adopts the multi-stage and multi-parameter influence analysis approach for a real practical engineering case to explore the impact of excavation on the foundation pit support structure, nearby buildings, and surrounding roads. The foundation pit support's maximum displacement was 8.64 mm, well under the 25 mm standard limit. Anchor rod forces were about 10% below the standard limit. Building and road settlements were also minimal, at 10.33 mm and 16.44 mm, respectively, far below their respective limits of 200 mm and 300 mm. This study not only validates the feasibility of design and construction stability of deep foundation pits but also contributes theoretical and practical insights, serving as a valuable reference for future engineering projects of a similar scope.

Keywords: deep foundation pit excavation; multi-stage and multi-parameter analysis; surrounding environmental influence; 3D finite element modeling

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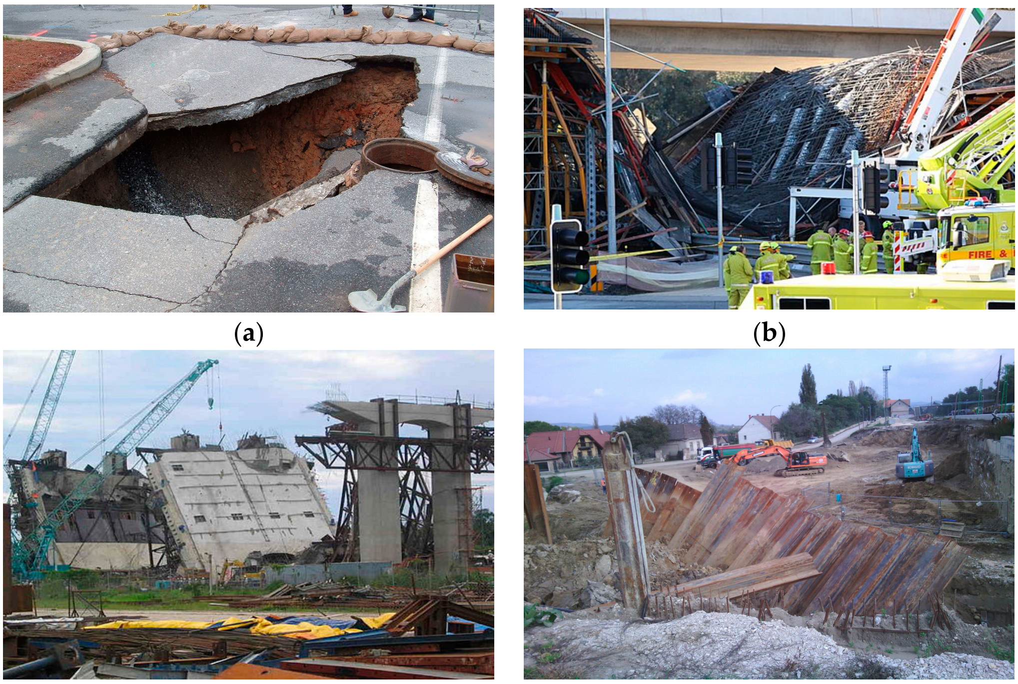
1. Introduction

An increasing number of skyscrapers have been built, and the development and utilization of above-ground space has become saturated for a lot of economically developed cities all over the world. People have begun to explore the development of underground space, and releasing ground pressure through underground space has gradually become an important way to solve contradictions of urban land [1–3]. The construction of underground space plays a significant role in the large-scale urban development process. While improving the ground environment, it also provides a broad space for urban development [4–6]. With the continuous development and utilization of underground space in cities and the gradual improvement in deep excavation technology and equipment [7–9] to comprehensively utilize underground space resources, underground space development will gradually develop to the deep level. The subterranean levels of skyscrapers, including underground corridors and subway lines, necessitate the implementation of deep foundation pit engineering. However, the intricate nature of such engineering has historically led practitioners to depend predominantly on empirical knowledge for both design and construction. This reliance on experiential methods has hindered a precise understanding of the effects that foundation pit engineering may exert on the adjacent environment [10].

Deep foundation pit engineering is a complicated engineering issue involving engineering geological conditions, climate conditions, surrounding construction environment, technical level, management level, and many other factors, so it has the characteristics of comprehensive and high risk [11–13]. During the construction of deep foundation pits in high-rise buildings and other projects, the supporting structure interacts with the soil to adjust their stress and deformation stably so that the soil inside and outside the foundation pit is stable or unstable. This is a physical process with complex mechanisms [14–20]. The higher the degree of urbanization, the more complex the adjacent buildings in cities, such as adjacent high-rise buildings, viaducts, subway stations, underground pipe networks, etc. During the construction of foundation pits, the groundwater level and stress field will be redistributed [21]. The most direct consequence of excavation unloading is to destroy the initial equilibrium state of the soil mass. The disturbance leads to the redistribution of the soil stress around the foundation pit, subsequently causing the movement and deformation of the surrounding rock mass. As a result, there is a ground settlement and uneven settlement, with soil deformation extending into the interior of the foundation pit, which adversely impacts the surrounding environment. The development of deep foundation pit excavation projects in urban areas is especially associated with high risks and complexities, which frequently harbor the potential for precipitating accidents or catastrophic events (see Figure 1). Inadequate control of groundwater can result in uneven soil settlement and alterations in soil pressure. These changes pose significant risks, including the potential collapse of the foundation pit and the destabilization of adjacent ground. Furthermore, surrounding structures are at risk of experiencing cracks and severe structural failure due to the uneven settlement. Additionally, encountering unmarked underground obstacles during deep excavation adds to the construction's uncertainty and potential hazards. These challenges significantly increase in urban environments for deep foundation pit excavation, especially in areas where commercial and infrastructure construction necessitates frequent development of both the urban surface and underground spaces, such as super high-rise buildings, subway lines, underground pipelines, bridges, shopping malls, etc. Firstly, the large scale and depth of the deep foundation pits bring about a range of complexities. This includes the complexity of groundwater control, where the increased depth intensifies the uncertainty and pressure variations of groundwater flow, necessitating highly accurate hydrogeological assessments and continuous monitoring. Moreover, deep excavation can impact the stability of the surrounding soil, especially in heterogeneous strata, heightening the risk of soil structural changes and potential collapse. Additionally, the spatial constraints in urban settings add extra complexity to deep foundation pit construction. The proximity of dense buildings and underground facilities, such as subway lines and pipelines, imposes higher demands on construction planning and the design of pit-wall support structures. The construction process must carefully consider the safety and stability of these neighboring structures, as well as the potential impact of ground settlement or vibrations on them. Currently, many engineering accidents resulting from deep foundation pit excavation have been reported. Prominent incidents, like the 2008 collapse at Xianghu Station's North 2 foundation pit in Hangzhou Metro, resulted in 21 fatalities, 24 injuries, and direct economic losses of 49.61 million RMB. More recently, the 2018 Foshan Metro Line 2 construction accident led to 11 deaths, 1 missing individual, and 8 injuries, with an economic loss of approximately 53.238 million RMB. A lot of similar accidents have highlighted the challenges of deep foundation excavation. Therefore, it is necessary to consider not only the impact of adjacent facilities on the safety of the foundation pit but also the influence of foundation pit construction on the safe use of surrounding sites [22,23].



(a) (b) (c) (d)

Figure 1. Accidents caused by deep excavation development: (**a**) ground collapse accident; (**b**) infrastructure collapse accident; (**c**) bridge collapse accident; (**d**) support structure collapse accident.

After decades of development, the high-end Settings of computing science have provided us with smarter, simpler, and faster algorithms for our work, and more powerful hardware configurations have made it possible to conduct finite element simulation analysis of actual engineering in multiple physical fields and complex environments [18]. The numerical simulation and analysis of foundation pit excavation are of great significance to improve the design theory and construction level of deep foundation pits. At present, many scholars have published relevant papers on foundation pit excavation [24–28], but some numerical simulations on foundation pit excavation mainly analyze the influence of foundation pit supporting structure, such as stress and strain of underground diaphragm wall and stress and strain of anchor rod and lack relevant research on the influence of foundation pit excavation on the surrounding environment [11,29–32]. At the same time, some numerical simulation models of foundation pit excavation use two-dimensional models instead of three-dimensional models, which cannot analyze the overall situation of foundation pit excavation comprehensively and accurately [33,34]. In deep foundation pit excavation, geotechnical parameters are usually obtained via on-site testing (such as standard penetration test and cone penetration test), indoor testing (such as direct shear test and triaxial compression test), geological exploration (including borehole sampling and core testing), and geophysical exploration (such as seismic wave and resistivity measurement). In addition, remote sensing technology offers an alternative, enabling the real-time extraction and inference of surface-level rock and soil properties [35,36]. This approach facilitates the gathering of crucial geotechnical data even in challenging or inaccessible environments.

In actual deep foundation pit excavation engineering cases, it is often necessary to consider issues such as support structure cracking, road collapse, and uneven settlement and cracking of buildings during the construction process. These issues reflect the potential negative impacts of deep foundation pit excavation in engineering applications, especially the risks associated with inadequate numerical simulation study before construction. Some insights or lessons were derived from practical engineering cases. Firstly, the design of the foundation pit needs to consider the complex underground environment, especially in densely populated urban areas. Secondly, the stress changes and limits of the supporting anchor rods need to be considered to ensure the safety of deep foundation pits and prevent collapse. Finally, accurate prediction of groundwater level and soil characteristics is crucial for preventing road collapse and protecting surrounding buildings. By considering the existing lessons for numerical simulation of deep excavation, the ability to predict and control risks of deep foundation pit excavation can be improved in practical engineering cases. For example, detailed consideration of the interaction between the support structure, surrounding soil, and hydrological conditions can not only optimize the design of the support structure but also reduce the risk of uneven settlement during excavation. Meanwhile, simulation of groundwater dynamics and soil conditions can help prevent road collapse and damage to buildings. Therefore, incorporating the experience and lessons learned from practical cases into numerical simulations not only enhances the practicality of the model but also significantly improves the safety and reliability of deep excavation engineering.

In this paper, the multi-stage and multi-parameter numerical simulation method is utilized to simulate the construction process of a deep foundation pit and analyze the influence of each stage of excavation on the surrounding environment, such as buildings and roads. Moreover, the proposed method has been used for a real engineering example to demonstrate its effectiveness and feasibility. Using the numerical simulation of the results of each construction stage, the rationality of foundation pit design and the stability of construction are evaluated. This study lies in the application of a multi-stage, multi-parameter numerical simulation approach to model the construction process of deep foundation pits, which fills a gap in existing research that often overlooks the environmental impacts of such excavations. This research provides a comprehensive analysis of the effects of excavation stages on surrounding structures, offering both theoretical and practical insights for similar future engineering projects. Moreover, it moves beyond the limitations of two-dimensional models, employing a three-dimensional approach to more accurately reflect the overall situation of foundation pit excavations. The main parts of this paper are organized as follows. Section 2 provides the multi-stage and multi-parameter analysis of the foundation pit excavation method. Section 3 presents a real engineering case study, including its project overview and the finite element model. Section 4 describes the study of multi-stage and multi-parameter analysis of foundation pit excavation containing displacement analysis of foundation pit supporting structure and analysis of the influence of foundation pit excavation on surrounding buildings and roads. It is followed by Section 5 with further discussion. The conclusions are drawn in Section 6.

2. Multi-Stage and Multi-Parameter Analysis Scheme for Foundation Pit Excavation

Foundation pit construction has an obvious space-time effect. The stress and displacement of support structures are closely related to the physical and mechanical parameters of rock and soil, excavation, and support technology. For the numerical simulation of deep foundation pit excavation, it is very important to select a reasonable constitutive model and numerical simulation method. In this paper, the Mohr-Coulomb constitutive model will be selected as the constitutive model. The numerical simulation method will adopt the multi-stage and multi-parameter method and combine it with a 3D finite element model to accurately restore the complex three-dimensional construction environment and excavation process of deep foundation pit engineering.

2.1. Numerical Model and Assumptions

In traditional deep excavation engineering, the primary simulation approaches encompass empirical methods, simplified calculation models, and standard design techniques. Empirical methods depend on historical data and prior experiences, while simplified computational models utilize one or two-dimensional frameworks to compute essential parameters. These models often overlook complex aspects but simplify the calculation process. The standard design approach adheres to construction guidelines, typically applying conservative safety margins, making it apt for routine projects. While these conventional strategies are effective in straightforward situations, they may fall short under intricate geotechnical conditions or specific project demands, necessitating more sophisticated numerical simulations for enhanced predictive accuracy and safety.

To more accurately simulate the impact of deep excavation on the surrounding environment, this paper establishes a three-dimensional geotechnical finite element model integrated with on-site or lab test investigated geotechnical parameters (such as bearing capacity characteristic value, natural weight, cohesion, angle of internal friction, compression modulus, and deformation modulus) for numerical simulation analysis of specific deep foundation pit excavation projects. This method uses three-dimensional (3D) models to simulate the effects of excavation, such as settlement and the load on structures, at different stages of the project. Compared to one-dimensional (1D) and two-dimensional (2D) models, 3D models have significant advantages in deep foundation pit simulations. They offer a more detailed and accurate representation of underground conditions and soil behavior, including the varied nature of soil layers and the analysis of stress and displacement in different directions. This comprehensive approach improves the accuracy of simulations, especially in reflecting real-life scenarios, predicting the impact of excavation on the surrounding area, and evaluating support structures. 3D models are also better at handling complex, nonlinear problems and various interactions during excavation, providing more reliable information for engineering decision-making. The rationality and accuracy of the foundation pit design are verified by comparing the numerical simulation results with the relevant standards. At the same time, the numerical simulation is used for qualitative and quantitative analysis of formation stress, bolt axial force, and support displacement during local excavation and support of deep foundation pit, which is helpful to guide the process control of key construction procedures and technologies and improve the reliability and systematization of information construction.

To ensure the fidelity and consistency of the staged excavating process, this study adopts a multi-stage excavation simulation scheme, which provides more detailed risk assessment and engineering control compared to traditional methods. Compared to traditional methods, this advanced simulation provides a more dynamic and thorough examination, capably foreseeing and addressing a range of issues in deep foundation pit projects, thereby markedly enhancing the project's safety and dependability. Furthermore, using multi-stage in deep excavation simulation provides more accurate risk assessment and engineering control. Using this method, engineers can gradually analyze the soil's mechanical behavior and structural response at each stage to better predict and adjust the design of support structures. This staged simulation allows for a more detailed examination of groundwater flow, soil pressure changes, and interactions with adjacent structures, thereby reducing uncertainty during excavation. In addition, it also helps to optimize construction plans and ensure timely identification and response to potential problems during excavation.

To more accurately reflect and predict the underground environment and behavior during deep excavation, this study adopted a multi-parameters influence analysis approach to enhance the comprehensive safety assessment. Multiple parameters (such as displacement of foundation pit, displacement of surrounding buildings or roads, the stress of foundation pit, and maximum anchor axial force) regarding the safety of excavation are observed in different excavation stages, which can offer an in-depth insight into the influence on the surrounding environment. Such an extensive assessment enables the simulation to reflect more realistically the complexities of actual geotechnical scenarios, encompassing variations in soil stratification, stress distribution, and groundwater movement. Additionally, the consideration of diverse parameters aids in pinpointing areas of potential risk, like unstable soil layers, thereby facilitating the development of more effective strategies during the phases of planning, design, and construction.

Moreover, a soil-structure interaction is considered in the following numerical simulation study. The numerical simulation helps engineers perform each step of the analysis of excavation, structural placement, loads, and other factors that will directly affect design and construction. The program supports various conditions (soil characteristics, water levels, etc.) and analytical methods to simulate real phenomena. Nonlinear analysis methods and various coupling analysis methods can be used to simulate the setting of various field conditions.

Frankly speaking, the actual physical and mechanical properties of rock and soil are not completely consistent with the numerical simulation constitutive model. This paper will conduct numerical simulation and simulation for deep foundation pit excavation based on the following assumptions: (1) Formation soil is a uniform, isotropic elastoplastic unit that follows Mohr-Coulomb strength criteria. (2) Before excavation, the soil mass has been completely consolidated under the action of its weight. (3) The physical and mechanical properties of soil are not affected by the construction process and remain unchanged; There is no influence of groundwater seepage and vibration load. (4) Soil nails and bolts do not have transverse shear resistance and shear resistance, and the anchorage force is generated by the soil displacement and changes with the soil displacement.

Note that there is much software that integrate a series of powerful functions to support engineers in accurate design planning and risk assessment in deep foundation pit engineering projects. The application of finite element method (FEM) software is not limited to dealing with complex nonlinear problems, such as large deformations and complex material behaviors, but also includes simulation of complex geological conditions and structural responses, especially when considering soil mechanics and structural interaction problems. This makes FEM an ideal choice for simulating soil structure interactions and supporting structure design in deep excavations. Additionally, discrete element method (DEM) software provides a deep understanding of soil discontinuous behavior, especially in the analysis of particle level dynamic response, by simulating the flow and interaction of soil particles. Generally, DEM has significant advantages in simulating complex soil behaviors, such as particle fragmentation, changes in fluidity, and interactions between particles and structures during construction. When it is necessary to accurately simulate the interaction between large-scale soil and support structures, evaluate structural stability, and predict ground settlement, FEM can provide a more suitable solution. Therefore, FEM is used for deep excavation simulation analysis in this paper.

2.2. Constitutive Model for Numerical Simulation

Because of the complex composition of soil, different types of soil have different complex mechanical behaviors. Under the action of external force, the soil will not only undergo elastic deformation but also irreversible plastic deformation [14]. The numerical simulation of this article adopts the Mohr-Coulomb constitutive model commonly used in foundation pit excavation simulation, which is an ideal elastic-plastic model. By considering the modification of the Mohr-Coulomb model, the calculation problems in the numerical simulation process can be well reflected, and the basic characteristics of soil are more consistent [37]. Meanwhile, the Mohr-Coulomb model, which combines Hooke's law and Coulomb failure criterion, is widely used to simulate most geotechnical materials. Shear failure is considered the most fundamental cause of soil failure in the Mohr-Coulomb strength criterion [23]. The shear strength everywhere in the soil is only associated with normal stress. σ_n on the plane as follows

$$\tau_{\mathrm{f}} = f(\sigma_n) \tag{1}$$

This function is a curve called the Mohr-intensity line, containing the $\tau_{\mathrm{f}} - \sigma_n$ coordinates. The Mohr envelope, also known as the Coulomb equation, can be approximated as a linear relationship, as shown below.

$$\tau_{\mathrm{f}} = c + \sigma_n \tan \phi \tag{2}$$

In Equation (2), τ_{f} represents the shear strength at any point in the soil, c represents the cohesive stress of the soil, σ_n represents the normal stress on the calculated plane, and ϕ represents the internal friction angle of the soil. Equation (3) shown as follows is the stress state of any point in the soil under the limit equilibrium state (the pressure and compression are positive). This equation is called the Mohr-Coulomb strength criterion. The radius of the stress Mohr circle is shown below.

$$R = \left(\frac{c}{\tan\phi} + \frac{\sigma_1 + \sigma_2}{2}\right)\sin\phi = c\cos\phi + \frac{\sigma_1 + \sigma_2}{2}\sin\phi \quad (3)$$

where, σ_1 and σ_2 are the maximum and minimum principal stresses of plane soil under shear failure, respectively.

Shear failure occurs when the Mohr envelope is tangent to the most stressed molar circle in the material. This means that the size of σ_2 does not affect the strength of the shear. The irregular hexagonal cone in the principal stress space represents the Mohr-Coulomb strength criterion. The projection of a hexagonal cone on the π plane is an irregular hexagon. Because of its accurate reflection on the non-uniform tensile and compressive properties of rock and soil materials, the Mohr-Coulomb criterion is widely used. However, due to the angular discontinuity of hexagonal cones, the numerical calculation of this model is prone to non-convergence. The numerical simulation analysis in this paper will avoid this problem to the greatest extent.

2.3. The Process of Multi-Stage and Multi-Parameter Analysis

According to the design scheme of deep foundation pit excavation, a multi-stage and multi-parameter strategy is proposed for the influence analysis on the supporting structure and anchor rods as well as surrounding buildings and roads. The innovation of this paper is mainly reflected in three aspects: Firstly, a three-dimensional finite element model is adopted for multi-stage modeling of deep foundation pit excavation; Secondly, the finite element model combines in-site investigated geological parameters to enhance the accuracy of the analysis; Finally, the multi-stage modeling implements a multi-parameter influence of deep foundation pit excavation on the surrounding environment. The detailed implementation procedure of the proposed multi-stage and multi-parameter influence analysis of deep foundation pit excavation on the surrounding environment is depicted in Figure 2 and described as follows:

Step 1: Investigate geological information on the deep foundation pit using in-site and laboratory testing.

Step 2: Establish a three-dimensional finite element model based on the design of deep foundation pit construction plans for conducting multi-stage modeling, which includes initial seepage analysis and stress field calculation, as well as subsequent precipitation, slope excavation, foundation pit excavation, and anchor rod construction. Moreover, the proposed method conducts a multi-parameter influence analysis at each stage, which includes displacement of the foundation pit, displacement of surrounding buildings and roads, excavation stress, and anchor cable axial force.

Step 3: If excavation is not completed, proceed to the next stage and update the finite element model. If excavation is completed, start analyzing the results of each stage and the overall situation.

Step 4: Analyze the results of the foundation pit excavation, including the impact on the foundation pit support structure, anchor rods, surrounding buildings, and roads. Compare analysis results with the safety standards, ensuring that the maximum stress and displacement of the surrounding environment and support structure can meet the prescribed design standard of foundation pit excavation.

Step 5: If all the results of the analysis meet the safety standards, the process ends to ensure the robustness and reliability of the design. If not, revise the scheme of foundation pit excavation and repeat Steps 2 to 4.

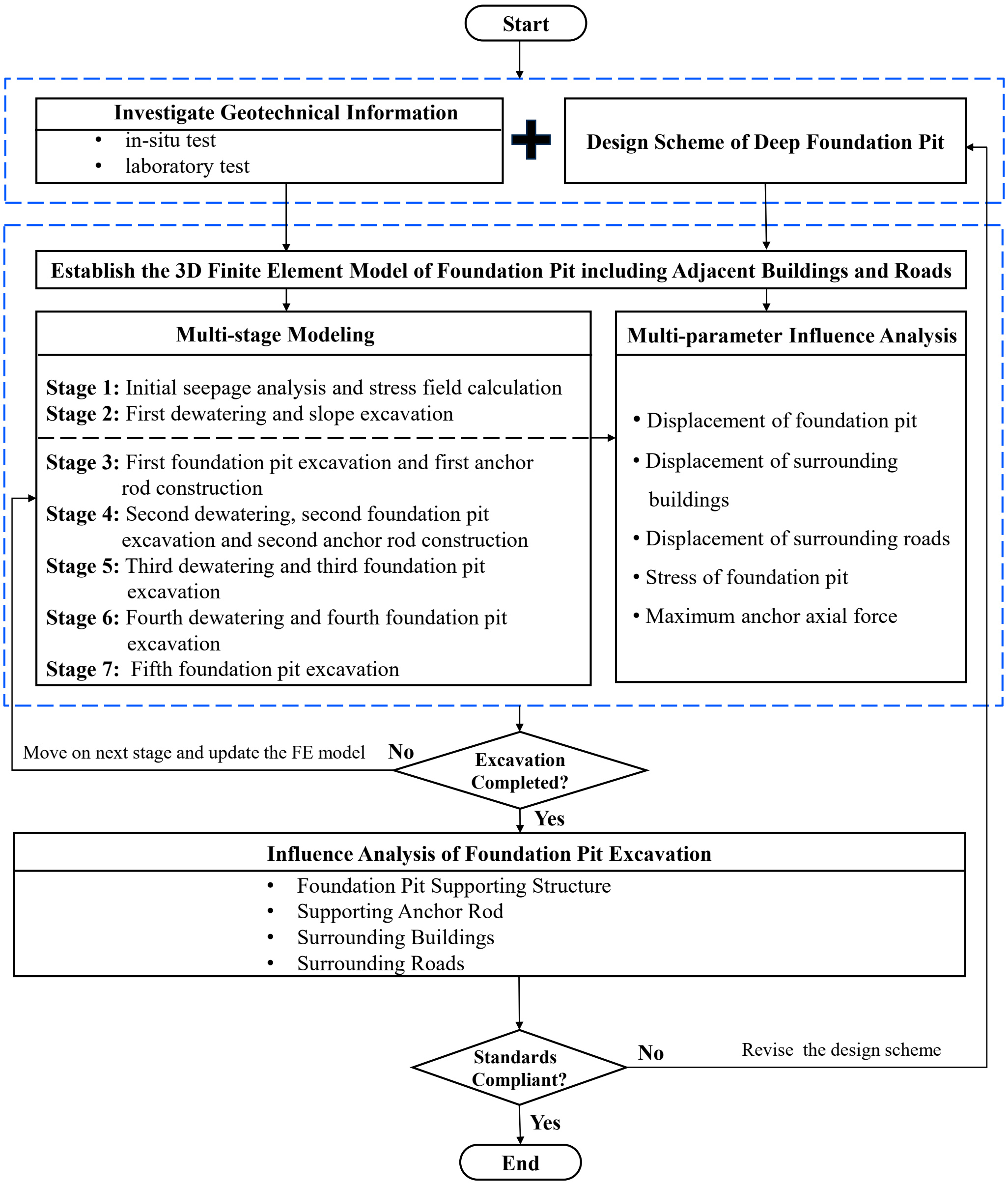


Figure 2. Flowchart of the proposed multi-stage and multi-parameter influence analysis of deep foundation pit excavation.

3. Project Description and Model Establishment

3.1. Project Description

To analyze the multi-stage and multi-parameter influence of deep foundation pit excavation on the surrounding environment, a practical project is selected for numerical simulation. This real engineering project is in Shenzhen, adjacent to Langxin Road and Zhikang Road, and it is used for a case study in this paper. The flowchart of the case study using the multi-stage and multi-parameter influence analysis of foundation pit excavation is shown in Figure 3. The general plan of the project is shown in Figure 3. The excavation depth of the foundation pit of this project is 6.05–12.55 m, the excavation circumference is about 561 m (the bottom line of the foundation pit), and the excavation area is about 19,031 m^2 (the bottom line of the foundation pit). The north side of the project: the boundary blue line of the basement is 3.0 m away from the control red line of the land, the open space outside the red line, and the distance of the red line from the north Zhikang Road is about 25.3–28.5 m; East side of the project: the basement boundary line is about 9.1–26.8 m away from the red line of the land, and some parts of the red line on the east side are close to the building; On the south side of the project, the basement boundary line is about 5.9–2.6 m away from the red line of the land, which is close to Langxin Road, and about 22.3–28.8 m away from the building on the south side. West of the project: the basement boundary line is about 17.3–19.7 m away from the red line of the land, which is close to Feixia Electromechanical Industrial Park, and there are simple board houses in the industrial park close to the red line of the land.

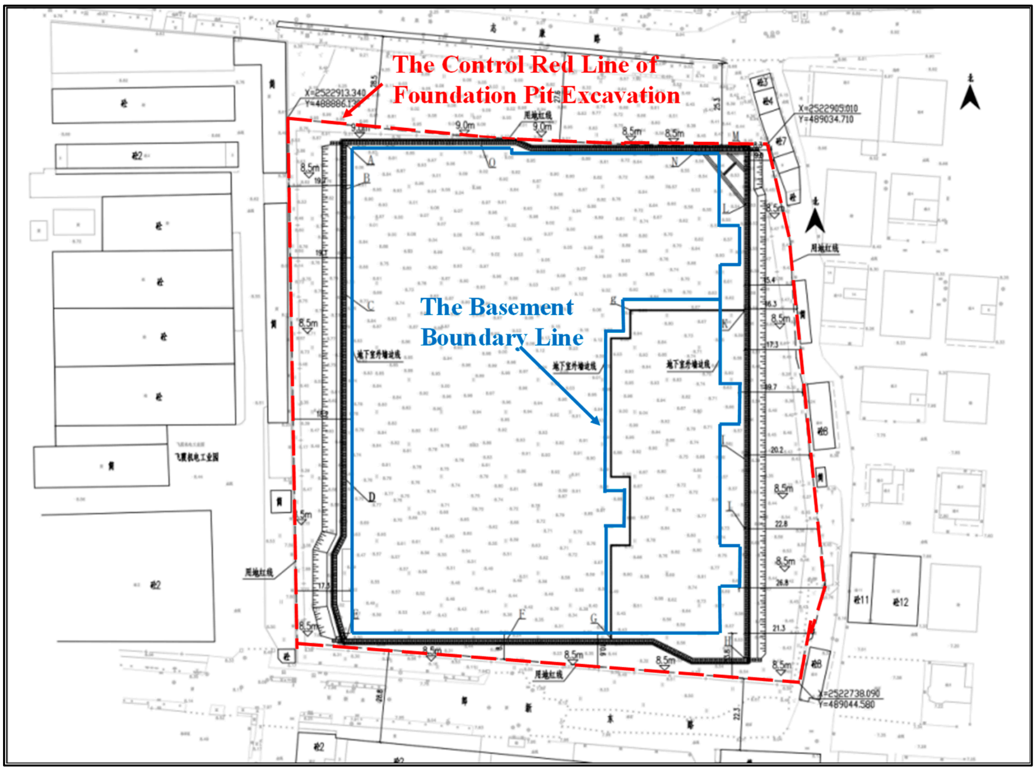


Figure 3. Project general plan for deep foundation pit excavation.

Since the project is mainly surrounded by industrial plants with a long history of self-built houses with low construction standards, considering the possible impact of foundation pit excavation on the surrounding environment and ensuring the safety of foundation pit excavation on the basis of adopting relatively safe measures in foundation pit design, numerical simulation analysis model is also needed to study the stress and strain characteristics of soil mass during foundation pit construction. It is necessary and significant to analyze the influence of foundation pit excavation on the surrounding environment and evaluate the safety of the foundation pit structure.

3.2. Stratum Parameters

Based on the statistics and comprehensive analysis of the results of the on-site geological survey and observation, In situ test, and laboratory test, the suggested values of ground parameters of the ground layer in the site are determined according to the relevant regulations and the regional engineering experience. To more accurately simulate the impact of deep excavation on the surrounding environment, this paper establishes a three-dimensional geotechnical finite element model integrated with on-site or lab test investigated geotechnical parameters as shown in Table 1 (such as bearing capacity characteristic value, natural weight, cohesion, angle of internal friction, compression modulus, and deformation modulus) for numerical simulation analysis of specific deep foundation pit excavation projects.

Table 1. Suggested values of geotechnical parameters.

No.	Name	Bearing Capacity Characteristic Value (kPa)	Natural Weight (kN/m^3)	Cohesion (kPa)	Angle of Internal Friction (°)	Compression Modulus (MPa)	Deformation Modulus (MPa)
#1	Plain fill	75	18.5	15	12	3.0	5.0
#1-2	Miscellaneous fill	90	19.5	-	20	-	15
#2-1	Fine sand	120	19.0	1	25	-	20
#2-2	Silty soil	60	16.5	10	4	2.0	4.0
#2-3	Clay	130	18.8	20	9	4.0	10.0
#2-4	Fine sand	130	19.0	1	30	-	24
#2-5	Coarse sand	220	19.5	-	35	-	30
#2-6	Clay	130	18.8	22	9	4.0	10.0
#3	Cohesive soil	200	19.1	28	20	6.0	26
#4-1	Fully weathered rock	280	19.5	30	25	10.0	40.0
#4-2	Heavily weathered rock (Massive)	450	20.5	33	26	-	100
#4-3	Heavily weathered rock	600	21.5	38	32	-	120
#4-4	Moderately weathered rock	1500	23.0	-	-	-	-
#4-5	Breezite	5000	24.5	-	-	-	-

3.3. Engineering Hydrogeology

According to the survey results, all boreholes in the site have exposed groundwater, the underground water level buried depth is 0.50–1.60 m, and the elevation is 7.01–8.41 m. The variation range of groundwater level is generally 1.00~2.00 m. The highest water level in 3 to 5 years of history was not achieved. The upper part of the proposed site contains pore water in the quaternary soil layer and fracture water in the bedrock. Each borehole meets groundwater. The depth of the water table is generally shallow. Pore diving mainly occurs in the quaternary artificial-filled soil and sand layers, and the water is abundant. The fractured water of bedrock is a kind of micro-confined water that exists in weathering fractures such as bedrock, and its distribution is very uneven. Its permeability and water richness are closely related to the degree of development of joint fractures of the rock mass. The main permeable layers in the excavation depth range are (#1-1) plain fill, (#1-2) miscellaneous fill, (#2-2) silty soil, (#2-4) fine sand, (#2-3) and (#2-6) clay, (#3) viscous soil, etc.

3.4. Design of Foundation Pit Support Scheme

The foundation pit support design needs to comply with the following design rules: (1) The engineering geological conditions, groundwater conditions, geotechnical characteristics and the surrounding environment (roads, pipelines, buildings) of the foundation pit design are the primary contents that need to be understood and analyzed in detail; (2) The design scheme must ensure the safety of the supporting structure, ensure the safety of the roads around the foundation pit and the underground pipelines and municipal roads that have been constructed and used; (3) The support scheme under the premise of safety, economy, reasonable, to meet the relevant laws and regulations of national construction engineering requirements; (4) The supporting structure can ensure the excavation of foundation pit and the smooth construction of underground structure; (5) The design must consider the construction period through the rainy season and typhoon season, its adverse impact on the stability of the foundation pit; (6) The design scheme must be feasible in the construction of the existing construction site.

To meet the design needs of the basement floor, cap, and gutter, the foundation pit support is designed to retreat no less than 1.5 m from the basement sideline as the bottom line of the foundation pit excavation slope. Foundation pit support design according to the surrounding environment and strata, adopt the "upper slope + lower pile anchor", "pile anchor", and "pile support" support. The water sealing measure of the foundation pit adopts the way of mixing piles. As the foundation pit support is a temporary structure, its safety and normal service life is 1.5 years, according to the standard.

In deep foundation pit engineering, the pile-anchor support structure is an ideal support system that is economical, safe, and reliable. The bolt-jet support structure is adopted in this project. Considering the influence of foundation pit excavation on the surrounding buildings, the final distance between the building and the foundation pit, the load and size of the house, and the design of the foundation pit supporting structure are shown in Table 2.

Table 2. The main component parameters of the foundation pit.

Structure Name	Sectional Dimension	Elastic Modulus (kN/m^2)	Unit Weight (kN/m^3)	Constitutive Relation	Remark
Diaphragm wall	1000 mm	3.0×10^7	20.1	elastic	Plate element
Top beam	800 mm × 1200 mm	3.0×10^7	20.1	elastic	Beam element
Middle beam	1000 mm × 1000 mm	3.0×10^7	20.1	elastic	Beam element
Inner support1	1000 mm × 1000 mm	3.0×10^7	20.1	elastic	Beam element
Inner support2	600 m × 600 mm	3.0×10^7	20.1	elastic	Beam element
Anchor bolt	25 mm	2.0×10^8	76.98	elastic	Truss element
Shotcrete	100 mm	3.0×10^7	20.1	elastic	Plate element
Basement wall	500 mm	3.0×10^7	20.1	elastic	Plate element

3.5. The Establishment of Finite Element Model of Foundation Pit

Incorporating data from field geotechnical surveys into a three-dimensional finite element model enhances the representation of subterranean features, encompassing attributes like soil density, compressibility, and shear strength. This integration of authentic data into the model ensures a more accurate reflection of the actual geotechnical conditions, leading to better predictions of geotechnical subsidence in terms of displacement and stress variations. Additionally, this approach is effective in pinpointing potential problematic zones within the model, such as areas prone to lower stress resistance or seepage, thus aiding in the improvement in risk assessment and mitigation measures. Therefore, the amalgamation of field-sourced geotechnical information into a three-dimensional finite element model is instrumental in elevating both the fidelity and precision of the simulation models.

The selection of a constitutive model in the numerical analysis should avoid not only the simple model, which cannot reflect the main characteristics of the problem but also the complicated model, which needs to determine many obscure parameters. Since the classical yield criterion ignores the frictional component of the shear strength of the soil, this criterion can only be used for the undrained analysis of saturated soil, e.g., $\phi = 0$. The Mohr-coulomb criterion goes beyond the classical criterion and also considers the friction component of soil, so it is more suitable for most scientific research and engineering practice and has been widely used in numerical simulation. This project will be based on the Mohr-Coulomb constitutive model for numerical simulation analysis.

According to the relevant national norms, the selection of the range of the calculation model fully considers the boundary effect. The influence of foundation pit excavation on the surrounding environment has obvious regional characteristics. It is generally believed that the main influence range of ground settlement caused by foundation pit excavation is twice the depth of foundation pit excavation. The range of the excavation depth expanded beyond the horizontal range is controlled by 1~2 times, and the depth of the excavation in the vertical direction is controlled by two times. The east–west length of the calculation model is 340 m, the north–south length is 340 m, and the calculated depth of the soil layer is 40 m. It can be considered that the boundary effect does not affect the calculation result of the evaluation object, and the accuracy of the model meets the requirements. At the same time, due to the different elevations of the foundation pit, according to the possible influence range of the standard foundation pit, the appropriate surrounding structures are selected for modeling, which ensures the accuracy and efficiency of the calculation. The boundary conditions of the 3D global model are as follows: the bottom of the model constrains the displacement in the Z-direction, the front and back of the model constrain the displacement in the Y-direction, and the left and right sides of the model constrain the displacement in the X-direction.

The excavation described in this project includes supporting structures such as cast-in-place piles and anchor rods. In numerical simulation, it is necessary to simplify the foundation pit excavation and support model to ensure computational power and accuracy. Because it is difficult to simulate a cast-in-place pile, the supporting mode of a cast-in-place pile is simulated by an equivalent diaphragm wall. The bottom end of the underground diaphragm wall is buried about 2.0 m below the foundation pit, and the thickness is 1.0 m combined with the calculation. The results show that it can reflect the real situation well. The rest of the supporting structure is input in accordance with the design size of the foundation pit design drawing. To ensure the applicability of the calculation, it is also necessary to simplify the construction steps. The structure construction of the retaining wall of the underground continuous wall is carried out before the excavation of the foundation pit, and then the excavation of the foundation pit is carried out by layers. The excavation method selects a single layer of flat excavation, and the corresponding supporting structure is constructed after the completion of each layer of excavation. The process continues until all the structural steps are completed.

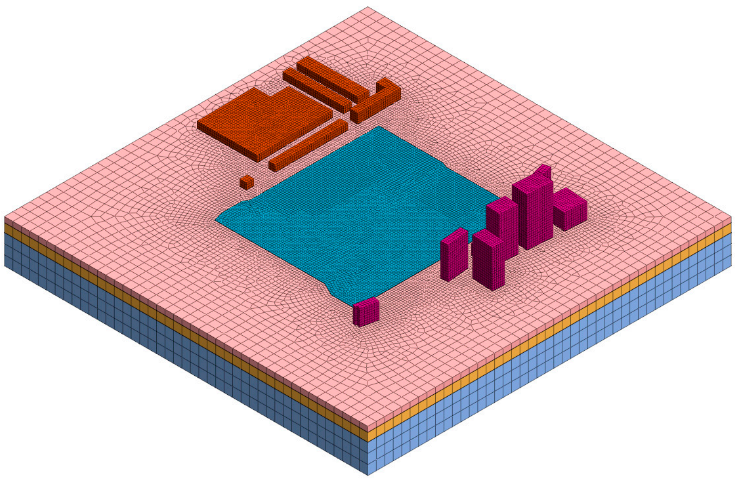
The analysis of the interaction between soil structure is significant to geotechnical engineering for the numerical simulation based on the finite element model. This paper mainly studies the impact of foundation pit excavation on the surrounding environment, which includes buildings, roads, and other entities. Therefore, in the process of numerical simulation, interaction between soil and structure will be involved. Finite element analysis is a general analytical method that can easily analyze complex problems such as soil-structure interaction, nonlinear behavior of soil, and various loads under appropriate boundary conditions. For the building entities in numerical simulation, this paper mainly considers the coupling of supporting structure building piles and stratum. In the numerical simulation process of this paper, when two kinds of materials with different properties appear at the same time due to their different stiffness and strength properties, to match the calculated stiffness, a reasonable interface element is set for different situations, and the interface element is used to simulate the interaction between the soil mass and the underground diaphragm wall, so that the adjacent entities can share the surface, so as to ensure the node coupling between the adjacent entities in the subsequent grid division.

The excavation of the foundation pit involves the change of total soil stress caused by excavation and the change of pore water pressure caused by dewatering, drainage, and other measures. These two physical and mechanical processes have a great influence on the deformation and stability of the foundation pit, and their functions are coupled with each other and should not be considered separately. Therefore, it is necessary to simulate the real mechanical process of foundation pit excavation and the influence of groundwater on soil strength and deformation. In the analysis of rock and soil structure, the change of groundwater level often causes the stress change of the structure and then causes the deformation. In the numerical simulation of this paper, the influence of groundwater level will be considered. The numerical model will simulate the whole process of foundation pit excavation step by step. For each stage of excavation, the foundation pit dewatering is equal to the foundation pit bottom; that is, the pore water pressure at the foundation pit bottom is 0. The detailed stages are shown in Table 3. Through the simulation of foundation pit dewatering, the results of numerical simulation can be closer to the actual situation, which has important reference value for practical projects.

Table 3. Main calculation stage for foundation pit excavation.

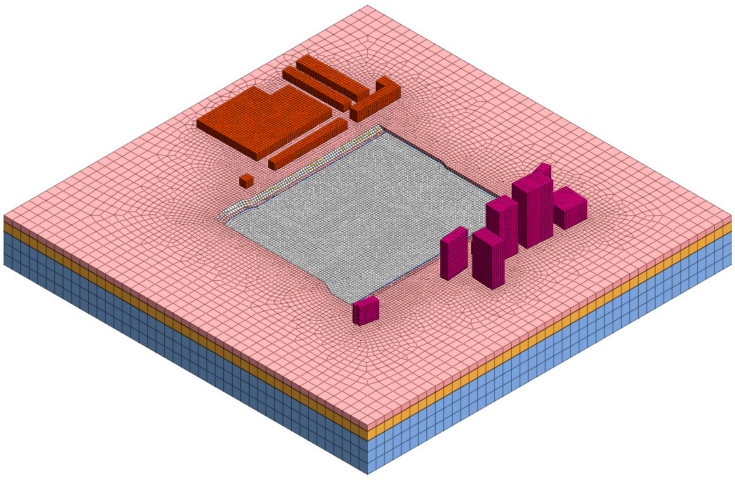
Calculation Stage	Specific Content
1	Initial seepage analysis, calculation of initial stress field in the unexcavated state of foundation pit
2	First dewatering, slope excavation
3	Foundation pit excavation 1, construction of the first prestressed anchor cable of the foundation pit
4	Secondary dewatering, foundation pit excavation 2, construction of the second prestressed anchor cable of the foundation pit
5	Third dewatering, foundation pit excavation 3
6	Fourth dewatering, foundation pit excavation 4
7	Foundation pit excavation 5

The model has a total of 128,260 units and 189,944 nodes. To simplify the modeling difficulty and ensure the accuracy of calculation, the soil layer where the foundation pit is located is divided into three layers due to the complex geological conditions in the actual project. The first layer in the model was a plain fill layer with a thickness of 5 m; the second layer was a cohesive soil layer with a thickness of 8 m; the third layer was a fully weathered rock layer with a thickness of 27 m. According to the numerical simulation process of foundation pit excavation proposed in the previous part of the article, combined with the actual situation of the project, the numerical simulation analysis for the specific project is carried out. The principal computational phases of foundation pit excavation are delineated in Table 3. Correspondingly, the numerical simulation schematic for each respective stage is depicted and demonstrated in Figure 4.



(**a**)

Figure 4. *Cont*.



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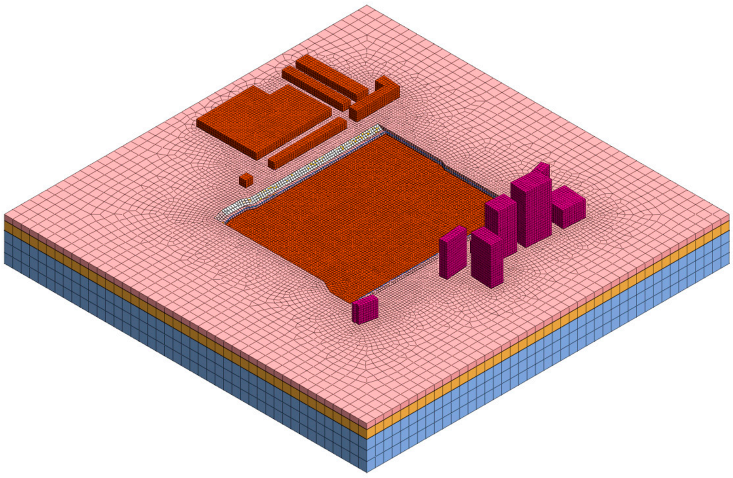

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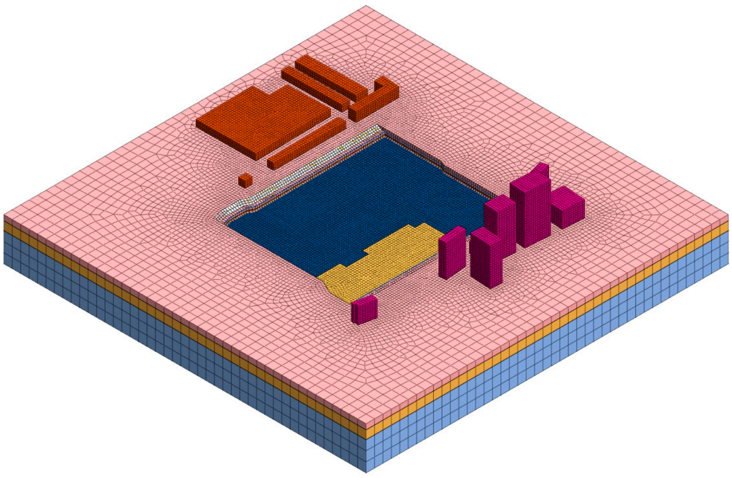

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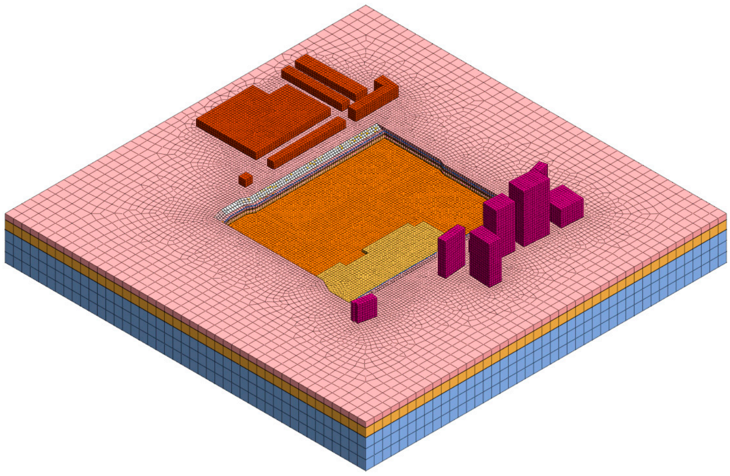
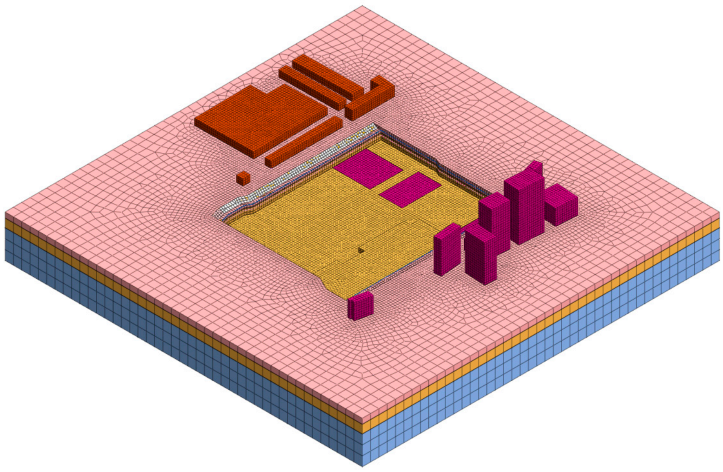
Figure 4. *Cont*.



(e)



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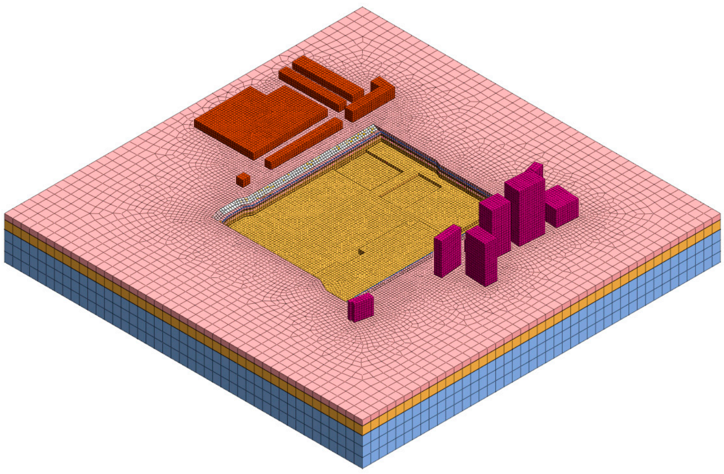


(g)

Figure 4. Sequential computational phases for foundation pit excavation: a numerical simulation schematic for each stage: (**a**) Stage 1; (**b**) Stage 2; (**c**) Stage 3; (**d**) Stage 4; (**e**) Stage 5; (**f**) Stage 6; (**g**) Stage 7.

4. Study of Multi-Stage and Multi-Parameter Analysis of Foundation Pit Excavation

Due to the excavation of the foundation pit, the inherent balance of the soil is destroyed, and due to the lateral unloading of the soil, the supporting wall moves towards the foundation pit, and the soil behind the wall moves, resulting in the surface settlement. Therefore, the deformation of foundation pit excavation mainly includes wall deformation and surface settlement behind the wall. According to the main calculation steps of foundation pit excavation described in the previous section, numerical simulation is conducted to simulate the excavation process of specific projects. This paper will compare and analyze the numerical simulation results of this project from the perspective of multiple parameters such as displacement, stress, and strain in combination with the multi-stage simulation construction method, focusing on the impact of foundation pit excavation on the foundation pit-supporting structure, surrounding buildings, and surrounding roads.

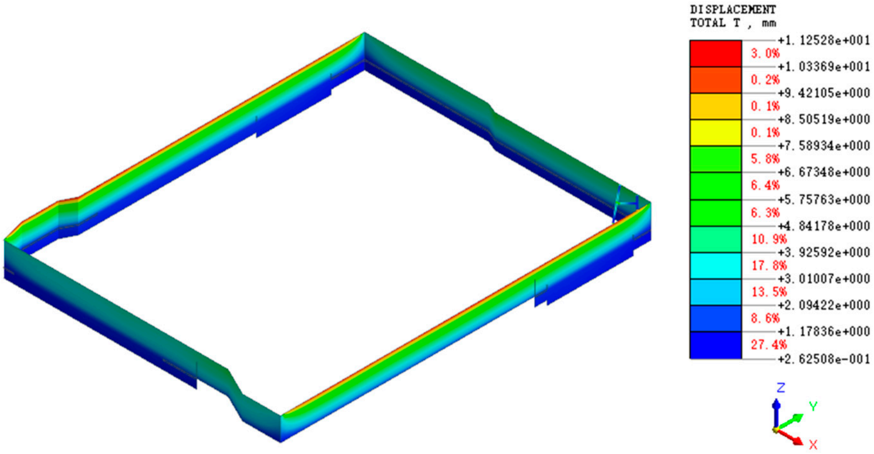
To better quantify and evaluate the impact of excavation on the foundation pit supporting structure, surrounding buildings, and surrounding roads, the proposed multi-stage and multi-parameter analysis approach will compare the numerically computed results of multiple parameters in terms of displacement, stress, and axial force with their corresponding limitation values from current relevant design codes in China during the multi-stage excavation process. The relevant technical codes include the code for building foundation excavation (DBJT 15-20-2016), the code for the design of building foundation (GB 50007-2011), and the code for design of highway subgrades (JTGD30-2004), and the limitation values from the prescribed codes for four analyzed parameters of foundation pit excavation are listed in Table 4.

Table 4. Limitation value for four parameters of foundation pit excavation.

Key Parameter	Limitation Value			
	Horizontal Displacement of Supporting Structure	**Settlement Value of the Surrounding Buildings**	**Settlement Value of the Surrounding Roads**	**The Tension Value of the Anchor Bolts**
Allowable value of displacement	≤30 mm, and also ≤0.002H (H is the excavation depth of the foundation pit)	≤200 mm	≤0.3 m	-
Allowable value of bolt tension	-	-	-	Less than 1.1 times the maximum design tension value

4.1. Analysis of the Foundation Pit Supporting Structure

For the results of each step of foundation pit excavation, the foundation pit support displacement nephogram of each step is generated. By checking the displacement results of foundation pit support after each excavation step, it can be found that the maximum value of total displacement of foundation pit support after each excavation step is within the allowable value range, and the numerical changes are consistent with relevant engineering experience, indicating that the 3D numerical simulation can reflect the actual excavation situation well (as shown in Figure 5). According to the nephogram of the foundation pit supporting displacement shown in Figure 6, the midpoints of each part around the foundation pit are selected to calculate the displacement changes of each point during excavation, and the specific contents are shown in Figure 7.



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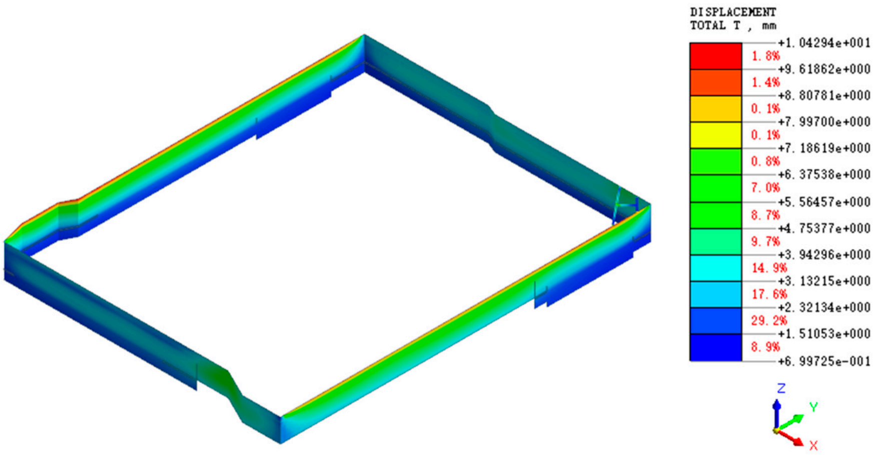

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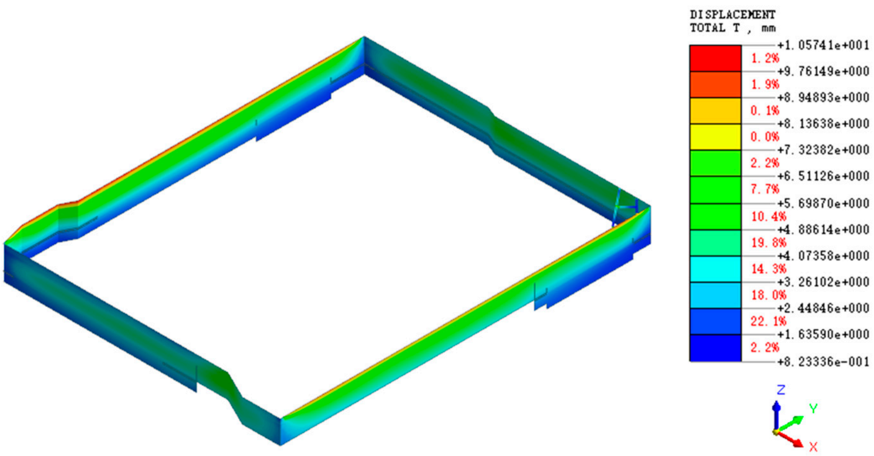

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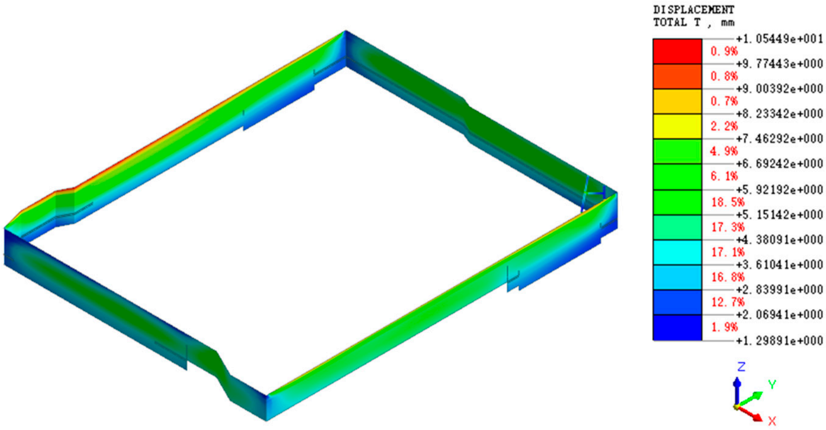
Figure 5. *Cont*.



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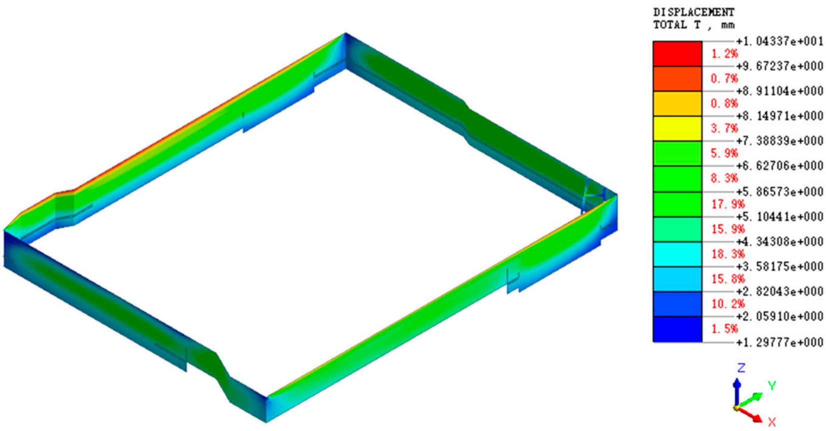


(**e**)

Figure 5. Displacement nephogram of maximum total displacement values for foundation pit support at each stage for pit support structures: (**a**) Stage 3; (**b**) Stage 4; (**c**) Stage 5; (**d**) Stage 6; (**e**) Stage 7.

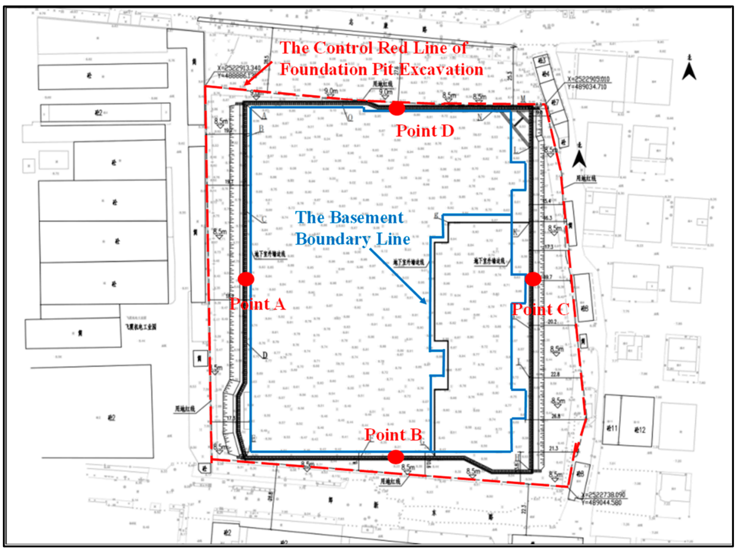
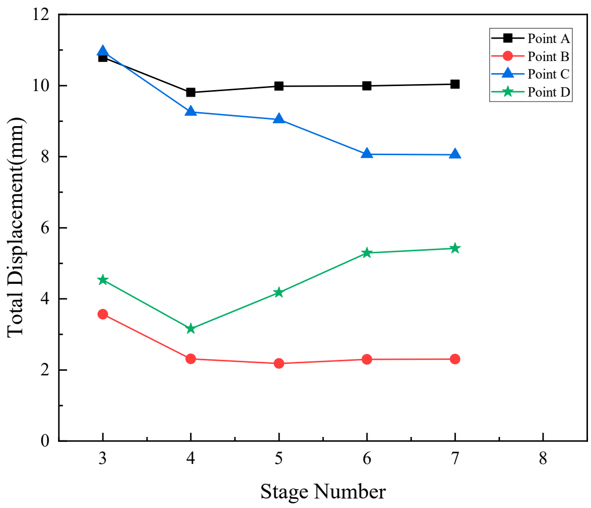


Figure 6. Feature points of numerical simulation.

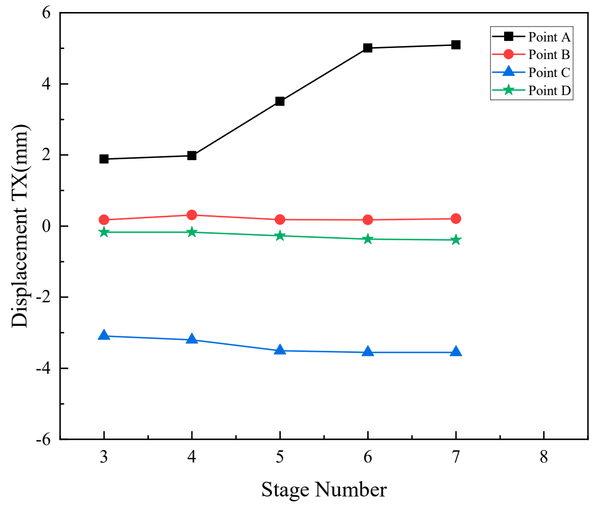
As shown in Figure 6, the foundation pit can be regarded as an approximately rectangular arrangement. According to engineering experience, the weak point of the foundation pit is usually in the middle, and the large displacement value usually appears in the middle of the foundation pit. The displacement and stress values of critical points in the middle edges of the foundation pit are used for the multi-stage and multi-parameter influence analysis based on the 3D finite element model of the foundation pit in this paper. Therefore, to better understand the displacement and stress changes related to foundation pit support, four points, A, B, C, and D, are selected as critical positions, where A and C are located in the middle of the long side and B and D are located in the middle of the short side. Subsequently, the changes in displacements and stresses of these four points at different stages will be observed and compared. The displacement of each feature point around the foundation pit at each stage is shown in Figure 7, including the total displacement, X-direction displacement, Y-direction displacement, and Z-direction displacement. In the total displacement diagram, the total displacement of the four sides is regularly distributed, where the displacement of points A and C is larger than that of points B and D, which accords with relevant engineering experience. From the first excavation to the last excavation, the total displacement of the four points is within the limit of the specification. The total displacement of point A in the five stages, respectively. is 10.79 mm, 9.81 mm, 9.98 mm, 9.99 mm, and 10.04 mm, showing a trend of first decreasing and then increasing. The total displacement of point B in the five stages, respectively. is 3.56 mm, 2.31 mm, 2.18 mm, 2.29 mm, and 2.30 mm, showing the tendency of lower leveled off after the first. The total displacement of C in the five stages, 10.95 mm, 9.25 mm, 9.05 mm, 8.06 mm, and 8.05 mm, respectively, shows a decreasing trend. The total displacement of point D in the five stages, respectively. is 4.53 mm, 3.16 mm, 4.18 mm, 5.29 mm, and 5.42 mm, showing a trend of first decreasing and then increasing. In the displacement diagram in the X-direction, the displacement around the foundation pit presents a regular distribution, in which the displacement at point B and point D is symmetrically distributed, and the absolute values are close to each other, while the displacement at point A and point C is roughly symmetrical. The X-direction displacement of point A in five stages, respectively, is 1.89 mm, 1.98 mm, 3.50 mm, 5.01 mm, and 5.10 mm, showing a trend of gradual increase. The X-direction displacement of point B in five stages, respectively, is 0.17 mm, 0.31 mm, 0.18 mm, 0.18 mm, and 0.20 mm, showing a trend of first increasing, then decreasing, and then stabilizing. The X-direction displacement of C in five stages, respectively, is −3.09 mm, −3.20 mm, −3.51 mm, −3.56 mm, and −3.55 mm, showing a gradual decreasing trend. The X-direction displacement of point D in the five stages, respectively, is −0.17 mm, −0.17 mm, −0.27 mm, −0.37 mm, and −0.39 mm, shows a trend of increasing gradually. Considering that there are mainly single-story industrial plants around point A and multi-story frame structure self-built houses around point C, the surrounding environment has different influences on the support of the foundation pit. The X-direction displacement at point A is larger than that at point C. In the Y-direction displacement diagram, the displacement around the foundation pit presents a regular distribution, in which the displacement at point A and point C is symmetrically distributed, and the absolute values of the values are close to each other, while the displacement at point B and point D is roughly symmetrically distributed. The Y-direction displacement of point A in five stages, respectively, is −0.04 mm, −0.10 mm, −0.13 mm, −0.17 mm, and −0.17 mm, showing a trend of increasing gradually. The Y-direction displacement of point B in five stages, respectively, is 1.12 mm, −0.58 mm, 0.89 mm, 1.88 mm, and 1.94 mm, showing a trend of first decreasing, then increasing gradually. The Y-direction displacement of C in the five stages, respectively, is −0.12 mm, −0.28 mm, −0.17 mm, −0.25 mm, and −0.23 mm, showing a trend of first increasing and then decreasing and finally slight fluctuation. The Y-direction displacement of point D in the five stages, respectively, is −0.17 mm, −0.17 mm, −0.27 mm, −0.37 mm, and −0.39 mm, showing a trend of increasing gradually. Considering the different site environments around point B and point D, the absolute values at point D are relatively larger than those at point B. In the Z displacement diagram, the displacement around the foundation pit presents a regular distribution. The Z-direction displacement of point A in the five stages, respectively, is 10.63 mm, 9.60 mm, 9.34 mm, 8.64 mm, and 8.64 mm, showing a trend of gradual decrease. The Z-direction displacement of point B in five stages, respectively, is 3.38 mm, 2.21 mm, 1.99 mm, 1.30 mm, and 1.22 mm, showing a trend of first decreasing gradually. The Z-direction displacement of C in the five stages, respectively, is 10.51 mm, 8.68 mm, 8.34 mm, 7.23 mm, and 7.23 mm, showing a trend of gradual decrease. The Z-direction displacement of point D in the five stages, respectively, is 3.54 mm, 2.50 mm, 2.11 mm, 1.32 mm, and 1.05 mm, showing a trend of gradual decrease. Due to the influence of the weight of the buildings around the foundation pit, the soil layer around the foundation pit is lifted, resulting in positive displacement at the four points A, B, C, and D. With the deepening of excavation, the displacement of the foundation pit supporting gradually decreases and tends to be stable, in which the displacement values of point C and point A are close, and the displacement values of point B and point D are close, which generally conforms to the empirical rules related to foundation pit excavation.

To better verify the reliability of the design scheme of the foundation pit, the stress values of the previous four critical points, A, B, C, and D, are further observed simultaneously. Since the stress values of the four selected points are all smaller than the design strength, their changing trends are mainly observed and compared. Figure 8 shows the stress variation of the main points of foundation pit support in X-, Y- and XY-directions with the deepening of excavation. In the X-direction foundation pit support diagram, the stress at each point increases gradually with the depth of excavation, and the changing trend at the A, C, and D points is the same, while the change at the B point is small. In the supporting diagram of the Y-direction foundation pit, the stress at point D almost does not change, except for point D; the stress at other points increases gradually with the depth of excavation. In the second excavation, the stress changes at A, B, and C points, which are larger than those at the first excavation and then change less with the deepening of the excavation. In the XY-direction foundation pit support stress diagram, the stress change of point A increases with the depth of excavation, and the second excavation increases more than the first excavation. The changes at points C and D are more gradual, while the changes at point B are almost unchanged. It can be seen from the figure that the change in stress and displacement has a certain regularity and correlation, but the change in stress has a certain lag compared with the change in displacement. At the same time, due to the different locations and environments of different points, such as soil quality, anchor bolt quantity, anchor bolt strength, and surrounding environment, the stress change and displacement change may be inconsistent.



(a)

Figure 7. *Cont.*



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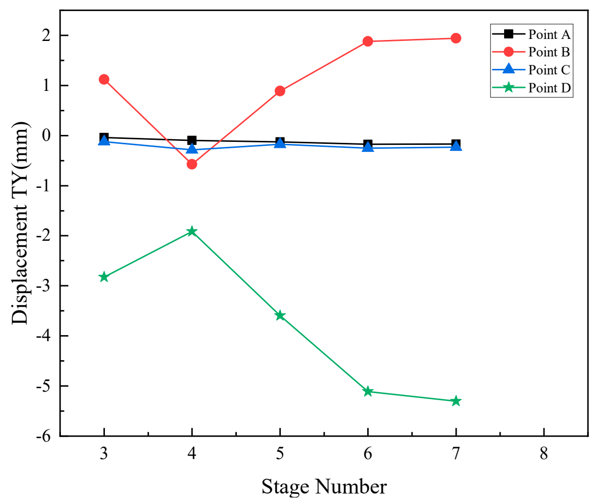

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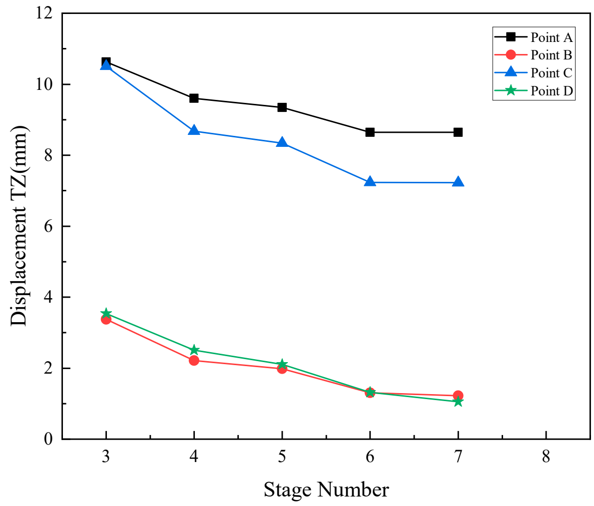


(**d**)

Figure 7. Pit support displacement cartogram: (**a**) Total displacement; (**b**) Displacement TX; (**c**) Displacement TY; (**d**) Displacement TZ.

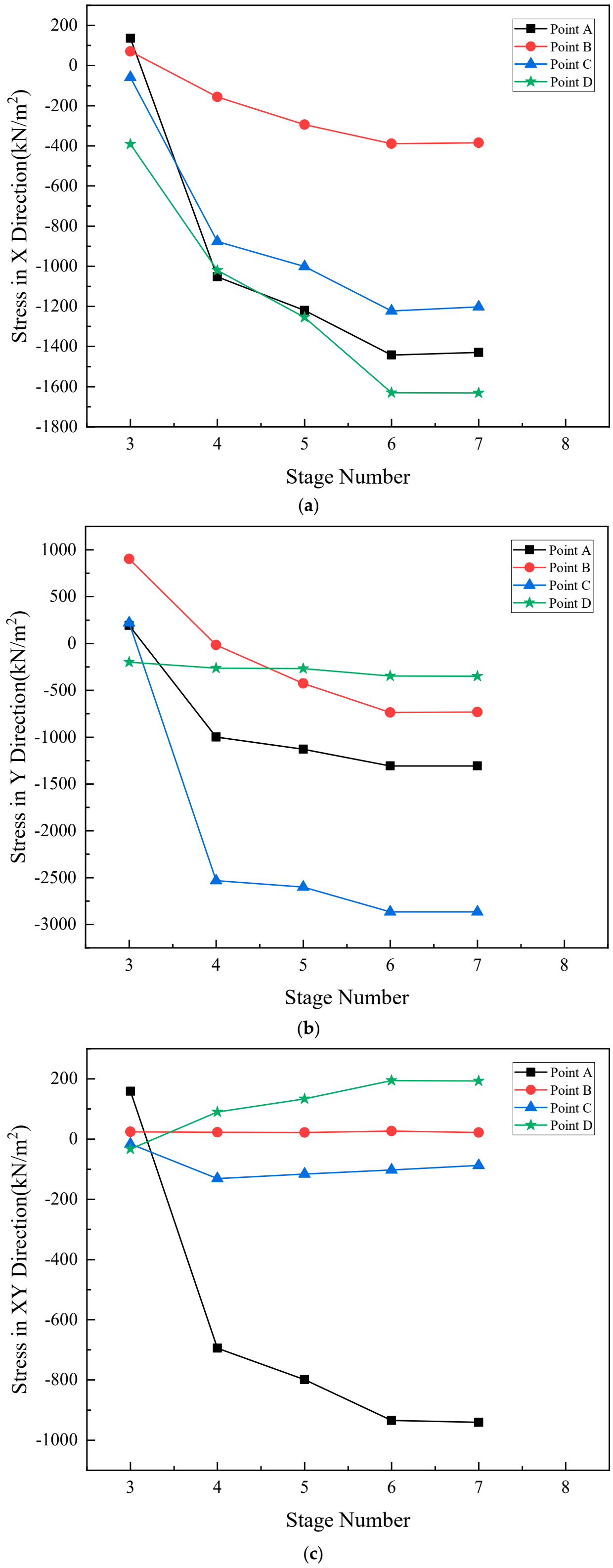
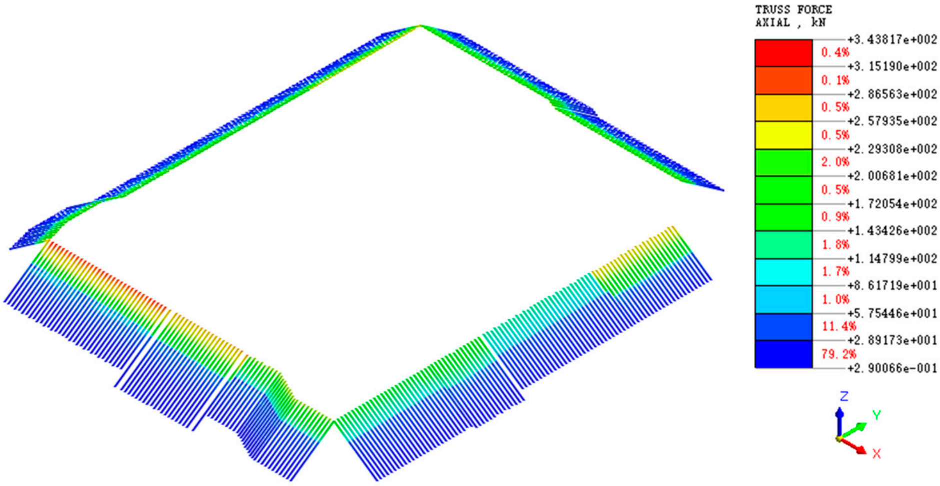


Figure 8. Pit support stress cartogram: (**a**) X-direction; (**b**) Y-direction; (**c**) XY-direction.

4.2. Analysis of the Supporting Anchor Rods

Figure 9 presents a nephogram illustrating the peak axial force of the two-layer bolt encountered by the anchor bolt. To better understand the changing trend of the internal force of the supporting anchor rod with the excavation of the foundation pit, the maximum point of the internal force of the supporting anchor rod is selected in this paper, and the internal force of the supporting anchor rod in each stage of excavation is calculated. When the foundation pit is excavated to the bottom, the internal force of the anchor bolt is the largest, so this study focuses on the maximum internal force value of the anchor bolt after the completion of excavation. Specifically, Figure 10 shows the maximum pulling force value of the maximum internal force point of the anchor bolt at different excavation stages. The pulling force value increases with the deepening of excavation, but it is still less than the standard limit: that is, it is less than 1.1 times the designed maximum pulling force value. Therefore, the design of supporting anchor bolts for the foundation pit is reasonable and safe.



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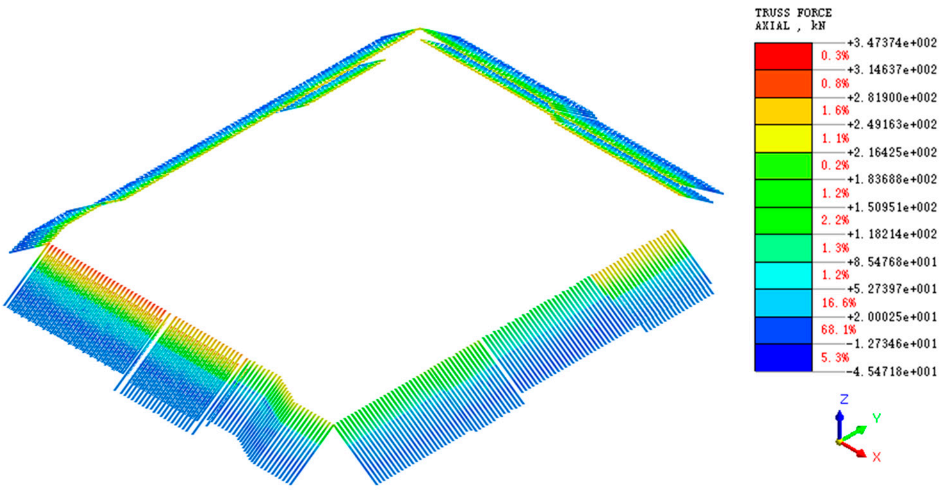


(**b**)

Figure 9. Nephogram of maximum axial force of anchor bolt: (**a**) First layer; (**b**) Second layer.

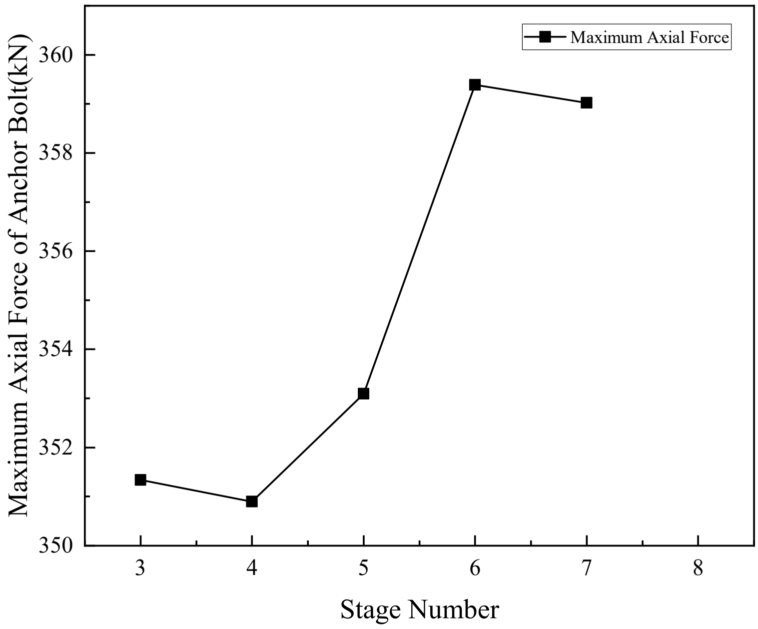


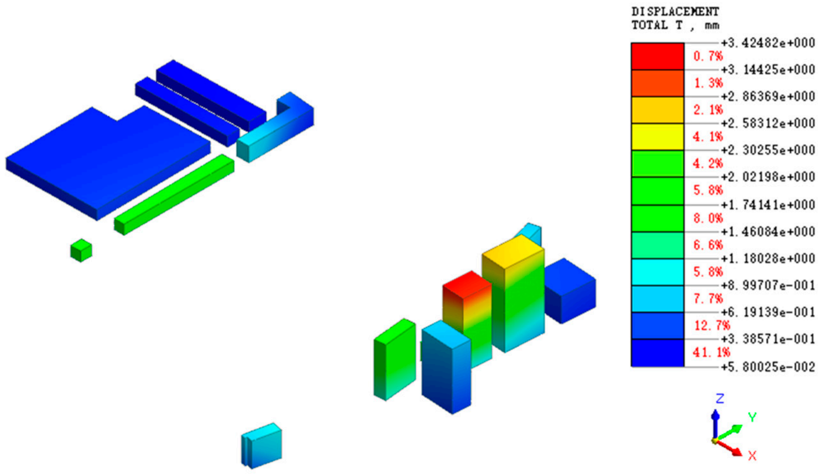
Figure 10. Cartogram of maximum axial force of anchor bolt.

4.3. Analysis of Influence on Surrounding Buildings

According to the main calculation steps of foundation pit excavation described in the previous chapter, a 3D finite element model is applied to simulate the excavation process of the foundation pit. For the results of each step of foundation pit excavation, the displacement nephogram of the surrounding structures of each step is generated (as shown in Figure 11). By checking the displacement results of surrounding structures after each excavation step, it can be found that the maximum value of total displacement of surrounding structures after each excavation step is within the allowable value range, indicating that the 3D numerical simulation can reflect the actual excavation situation well. According to the displacement nephogram of the surrounding buildings, this paper selects a typical building around the foundation pit to make statistics on its displacement at each stage of excavation (as shown in Figure 12).

Figure 13 shows the total displacement, displacement in the X-direction, displacement in the Y-direction, and displacement in the Z-direction of a typical building at different excavation stages. In the total displacement diagram of the surrounding buildings, the displacement gradually increases with the deepening of the excavation, in which the displacement of the second excavation increases more than that of the first excavation, and the displacement increases slowly during the subsequent excavation. In the X-direction displacement diagram of the surrounding buildings, the displacement gradually increases with the deepening of the excavation, in which the displacement of the second excavation increases more than that of the first excavation, and the displacement increases slowly in the subsequent excavation process. In the Y-direction displacement diagram of the surrounding buildings, the displacement generally increases with the depth of excavation, but the displacement decreases in the third excavation process, which is an order of magnitude smaller than the displacement in the X-direction. In the Z-direction displacement diagram of the surrounding buildings, the displacement gradually increases with the deepening of the excavation, in which the displacement of the second excavation increases more than that of the first excavation, and the displacement increases slowly in the subsequent excavation process, and the displacement of the fifth excavation decreases compared with the fourth excavation. The total displacement of a typical building in the five stages, respectively, is 2.56 mm, 12.10 mm, 13.68 mm, 15.82 mm, and 16.47 mm, showing a trend of increasing suddenly in the second stage and then increasing gradually. The X-direction displacement of a typical building in the five stages, respectively, is −2.47 mm, −10.01 mm, −11.09 mm,

−11.78 mm, and −12.64 mm, showing a trend of increasing suddenly in the second stage and then increasing slowly. The Y-direction displacement of a typical building in the five stages, respectively, is −0.65 mm, −2.02 mm, −1.33 mm, −2.02 mm, −2.11 mm, showing a trend of increasing suddenly in the second stage, and then fluctuating. The Z-direction displacement of a typical building in the five stages, respectively, is −0.07 mm, −6.49 mm, −7.84 mm, −10.36 mm, and −10.33 mm, showing a trend of increasing gradually. Since the displacement of the surrounding buildings is mainly in the vertical direction, according to the displacement diagram of the surrounding buildings in the Z-direction, the displacement of the surrounding buildings during the excavation of the foundation pit is less than the limit allowed by the design standard, so the impact of the excavation of the foundation pit on the surrounding buildings is within the safe range.



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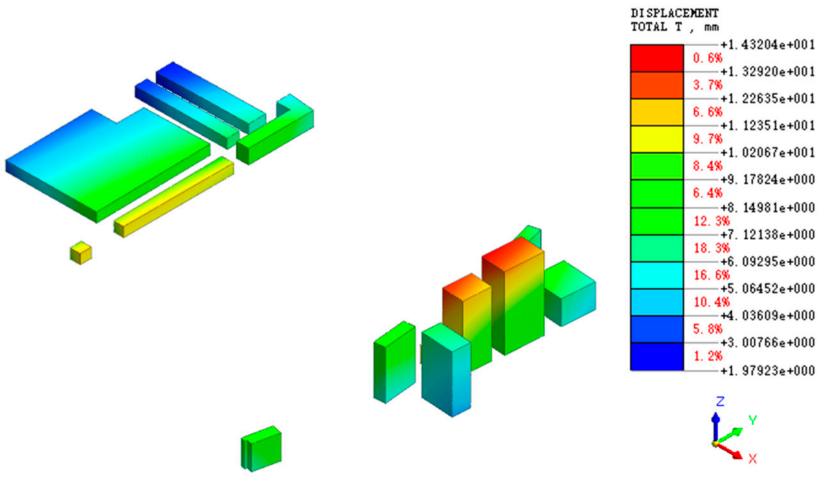

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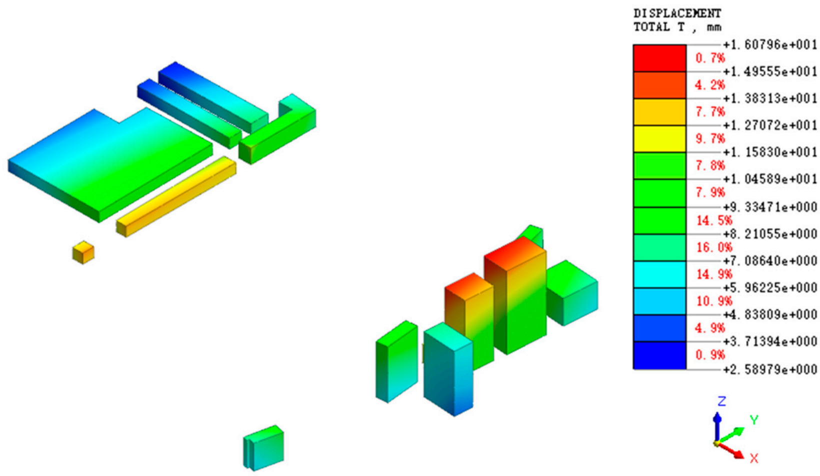
Figure 11. *Cont.*



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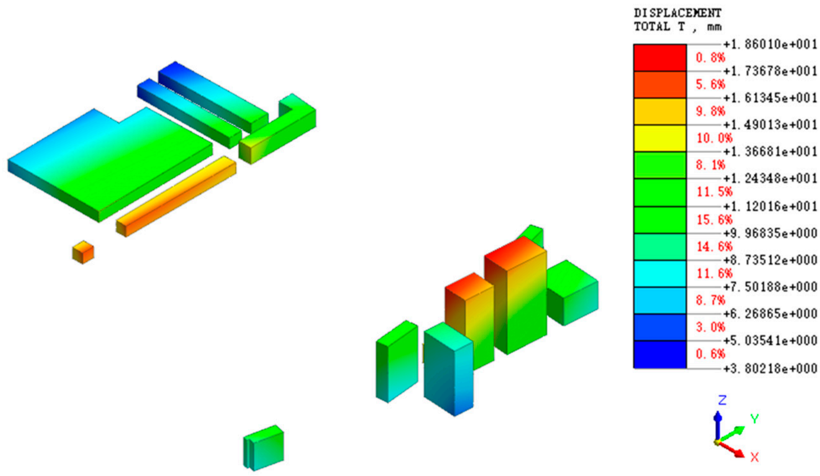
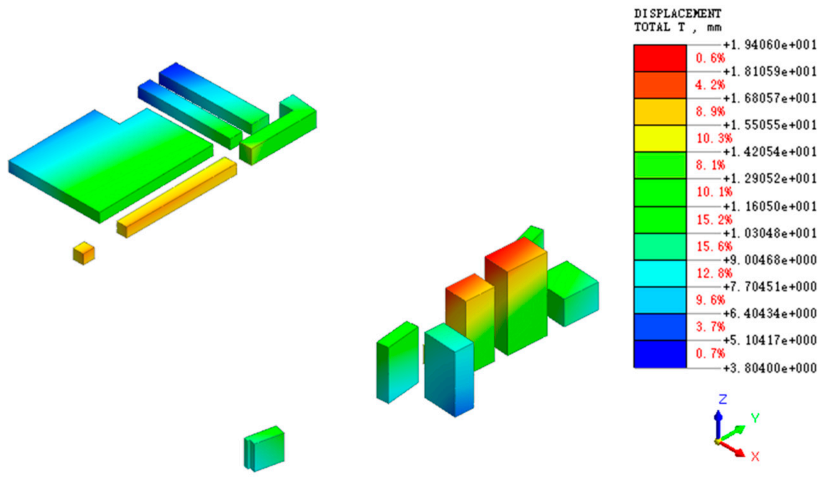


(**d**)



(**e**)

Figure 11. Nephogram of total displacement of surrounding structures at each stage: (**a**) Stage 3; (**b**) Stage 4; (**c**) Stage 5; (**d**) Stage 6; (**e**) Stage 7.

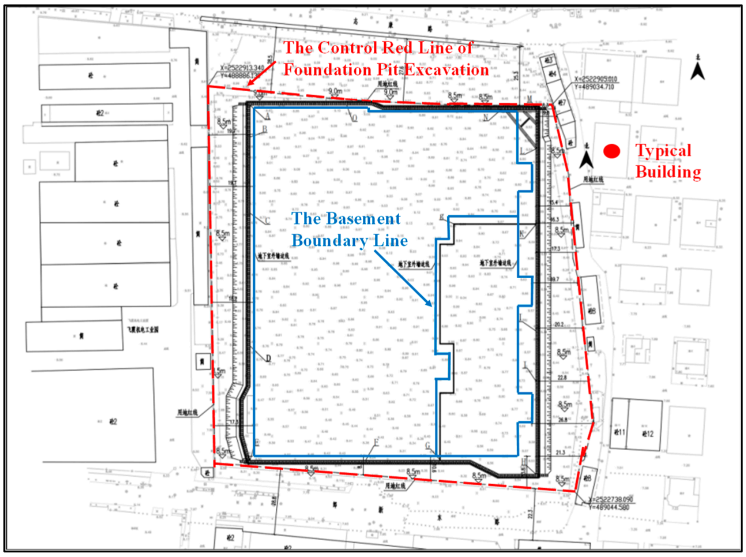
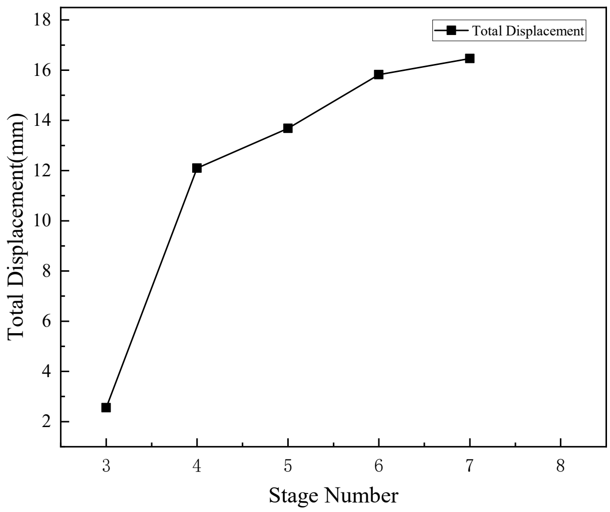
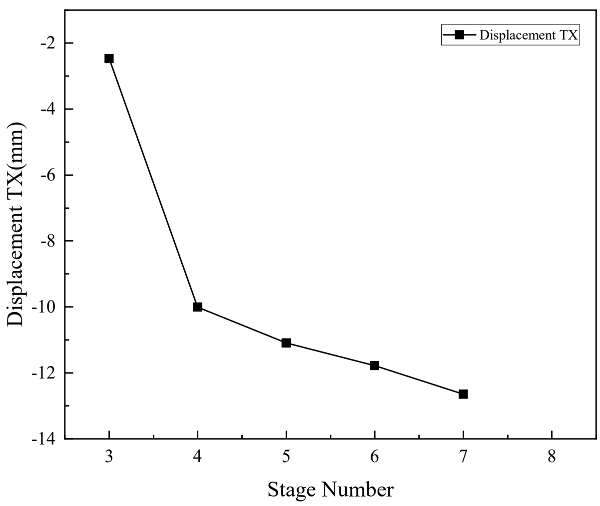


Figure 12. Typical buildings on surrounding buildings.

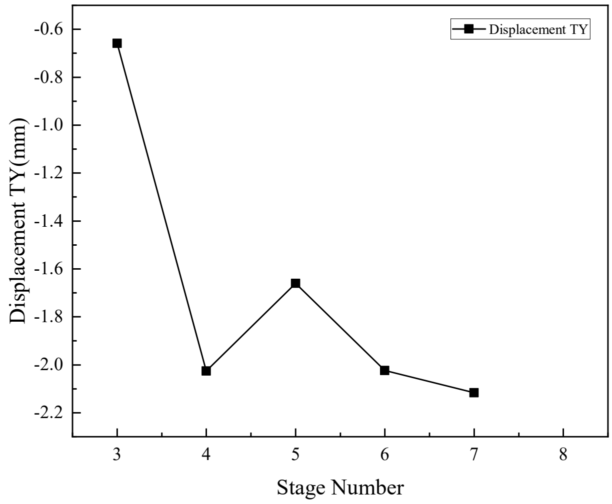


(**a**)

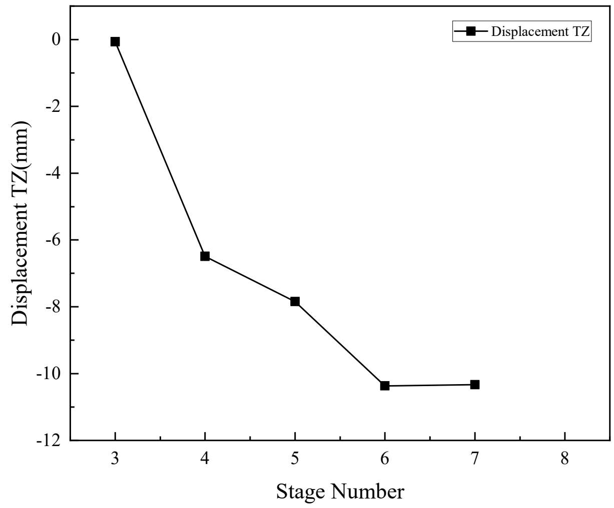


(**b**)

Figure 13. *Cont.*



(c)

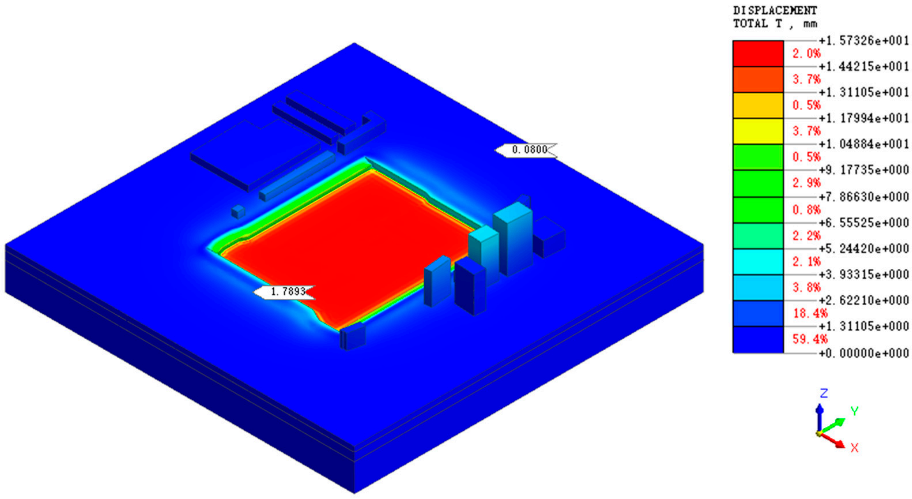


(d)

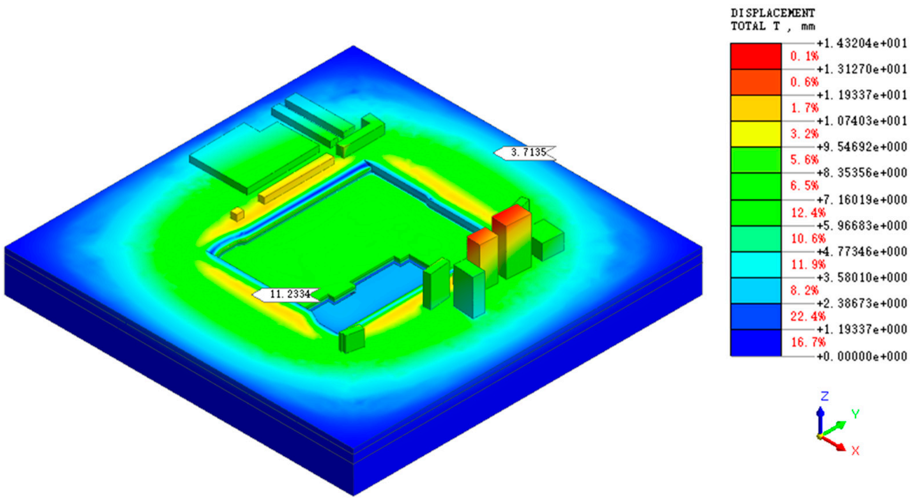
Figure 13. Typical building displacement cartogram: (**a**) Total displacement; (**b**) X-direction; (**c**) Y-direction; (**d**) Z-direction.

4.4. Analysis of Influence on Surrounding Roads

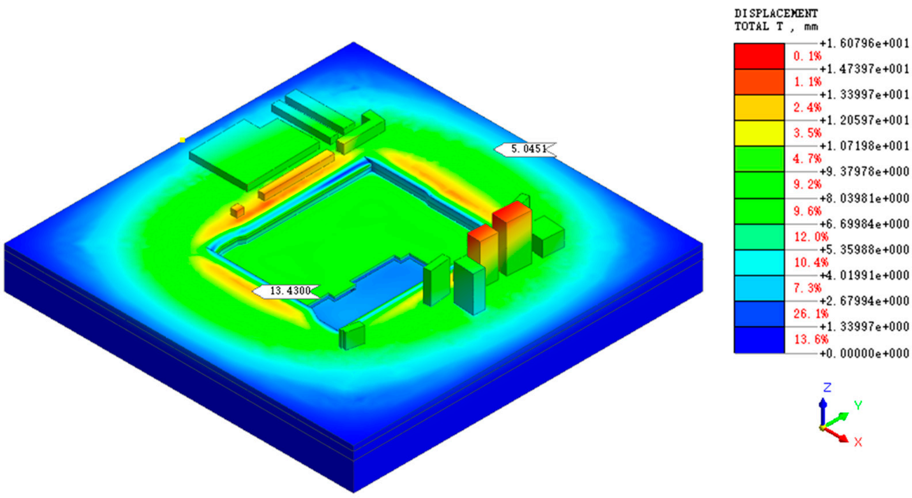
According to the main calculation steps of foundation pit excavation described in the previous chapter, the established 3D finite element model is further used for the analysis of the influence of foundation pit excavation on surrounding roads. For the results of each step of foundation pit excavation, a displacement nephogram of the road around each step is calculated and shown in Figure 14, respectively. By checking the displacement results of the surrounding roads, it can be found that the maximum total displacement of the surrounding roads after each step of excavation is within the allowable value range of the standard. According to the project plan and the actual situation of the site, there are two roads on both sides of the foundation pit. Due to the wide range of roads involved and the different degrees of influence of foundation pit excavation on roads, via the observation and analysis of the excavation displacement cloud map of surrounding roads, the typical large value points on two roads were selected for analysis, and the corresponding two special selected points were marked in the displacement cloud map in Figure 14. By analyzing the two selected critical points, as shown in Figure 15, the corresponding displacements of the roads around the foundation pit at each excavation stage were further analyzed and plotted in Figure 16.



(**a**)

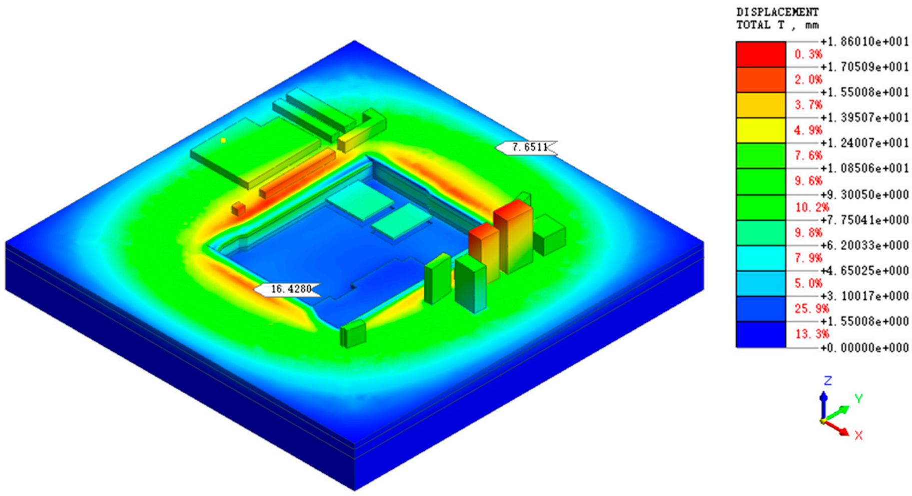


(**b**)

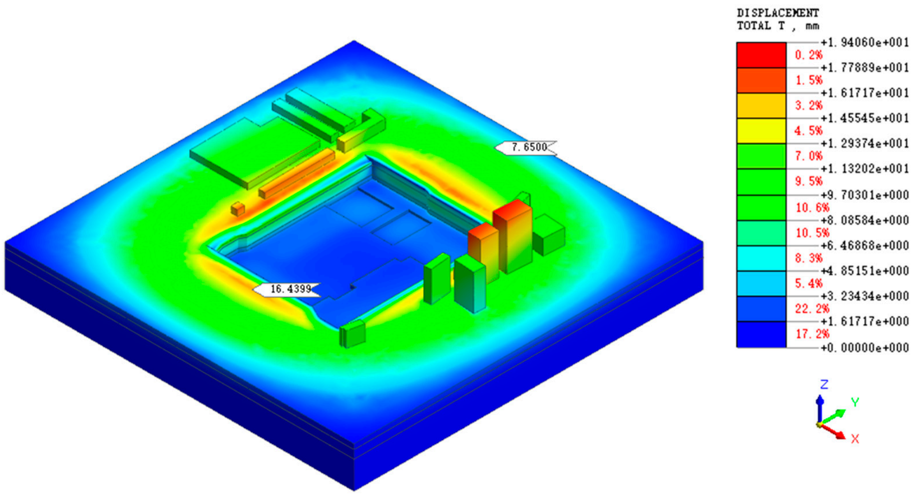


(**c**)

Figure 14. *Cont*.



(**d**)



(**e**)

Figure 14. Nephogram of the total displacement of surrounding roads at each stage: (**a**) Stage 3; (**b**) Stage 4; (**c**) Stage 5; (**d**) Stage 6; (**e**) Stage 7.

Figure 16 shows the total displacement, displacement in the X-direction, displacement in the Y-direction, and displacement in the Z-direction of the typical point on surrounding roads in different excavation stages. In the total displacement diagram of the surrounding road, the displacement of the two points shows a trend of increasing gradually with the deepening of the excavation, in which the displacement of the second excavation increases more than that of the first excavation, and the displacement increases slowly during the subsequent excavation. In the displacement diagram in the X-direction of the surrounding road, the displacement at point E generally increases with the deepening of the excavation, in which the second excavation increases more than the first excavation, while the third excavation decreases a lot compared with the second excavation. The displacement of point F increases gradually with the deepening of the excavation. In the Y-direction displacement diagram of the surrounding road, the displacement of the two points increases gradually with the deepening of the excavation. In the Z-direction displacement diagram of the surrounding road, the displacement of the two points shows a trend of increasing gradually with the deepening of the excavation, and the trend is relatively close, in which the displacement of the second excavation increases more than that of the first excavation. For the displacement of the surrounding roads, the main concern is the settlement of the roads, that is, the displacement in the Z-direction. The Z-direction displacement of typical point E in five stages, respectively, is 1.79 mm, 11.23 mm, 13.43 mm, 16.43 mm, and 16.44 mm, showing a trend of sharp increase and then gradual increase. The Z-direction displacement of typical point F in five stages, respectively, is 0.08 mm, 3.71 mm, 5.05 mm, 7.65 mm, and 7.65 mm, showing a trend of gradual increase. Therefore, according to the displacement diagram of the surrounding roads in the Z-direction, the displacement of the surrounding roads during the excavation of the foundation pit is less than the limit allowed by the standard, so the impact of the excavation of the foundation pit on the surrounding roads is within the safe range.

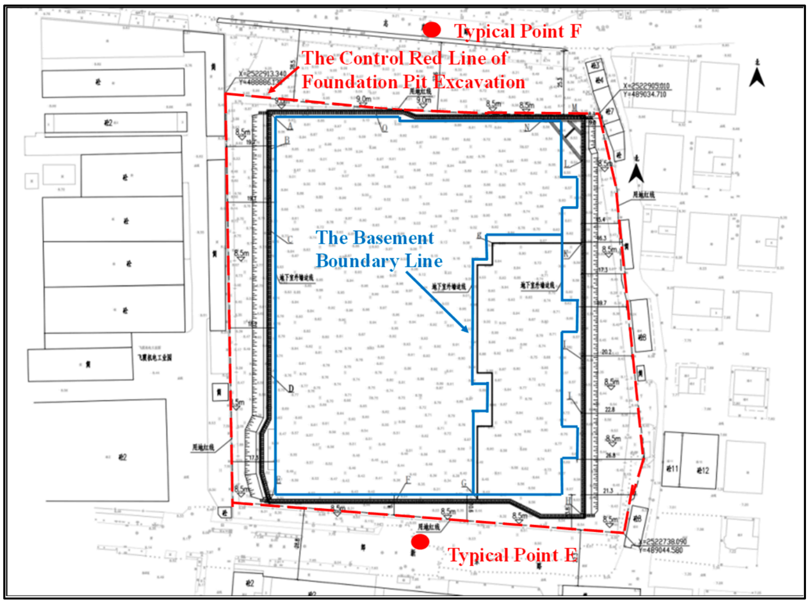
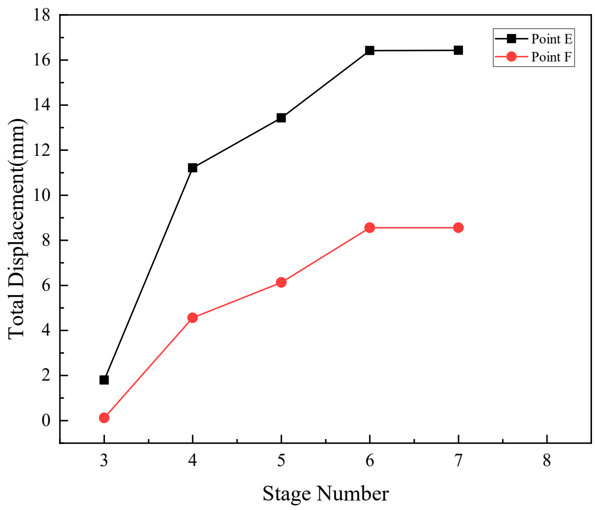


Figure 15. Typical point on surrounding roads.



(**a**)

Figure 16. *Cont*.

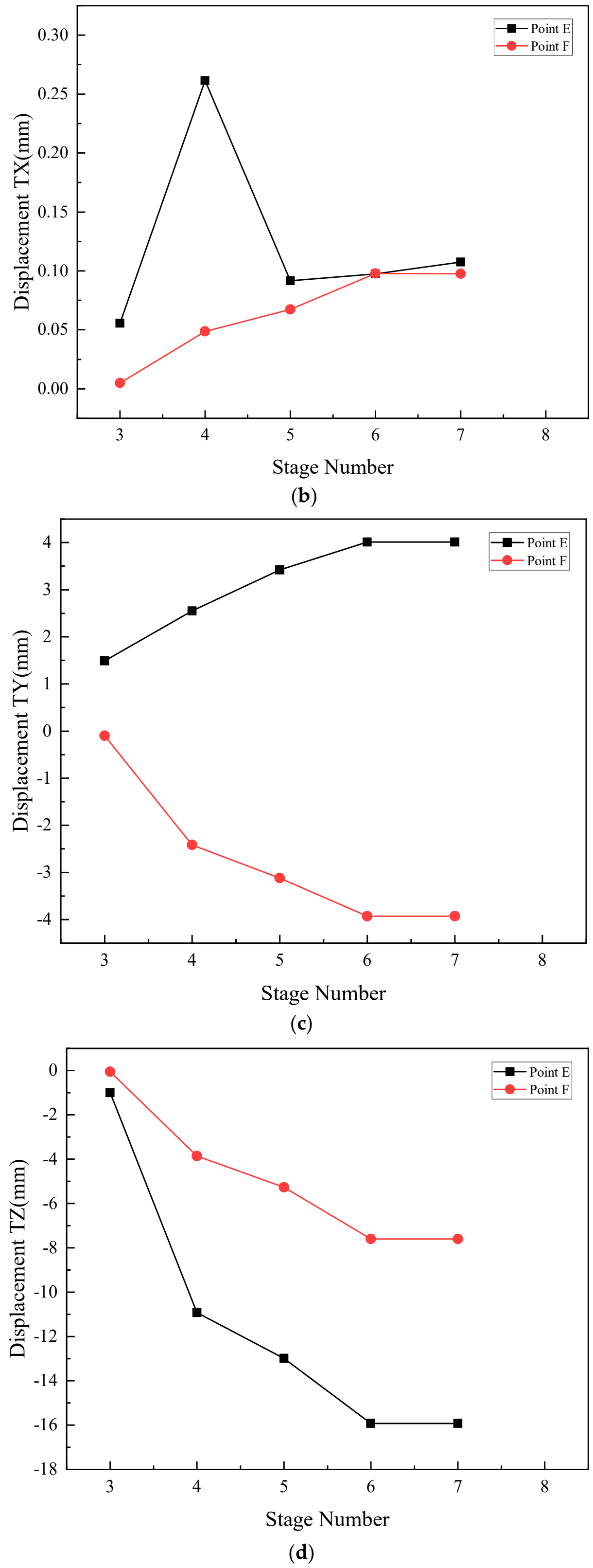


Figure 16. Displacement cartogram of surrounding roads: (**a**) Total displacement; (**b**) Displacement TX; (**c**) Displacement TY; (**d**) Displacement TZ.

5. Discussion

Using the analysis of the numerical simulation results, it can be concluded that the numerical simulation method proposed in this paper is practical and effective and may be used as a reference for similar practical projects in the future. The simulation results of this study are specific to the actual engineering projects and geotechnical parameters of the construction site in the specific construction design scheme. The geotechnical parameters in the neighboring region have similarities, so the findings of simulation results have a certain universality and can be generalized to other similar deep foundation pit excavation projects by using the same model. However, the geological parameters and the construction scheme may vary for different construction projects in different regions, which can have some impact on the fidelity of the 3D FE model. Therefore, it is necessary to adjust the geological parameters and reconstruct the 3D FE model for analysis. The applicability of the results in different contexts needs to consider the specific geotechnical parameters of different locations and the differences in the multi-stage construction process. In the discussion section, the shortcomings of this study will be discussed. We can continue to study the relevant shortcomings in future work as the basis for future research. For the numerical simulation research in this paper, there are two points that can be improved. First, if there is actual monitoring data, it can better confirm the accuracy and persuasiveness of the multi-parameter and multi-stage numerical simulation method proposed in this paper. Second, for the soil constitutive model, the Mohr-Coulomb model is universal, but for different soil conditions in different places, there may be more suitable soil constitutive model for specific projects.

The numerical simulation method proposed in this paper can be verified by using the monitoring data of foundation pit measurement, such as the relevant displacement, stress, and internal force, and it is also helpful to optimize the numerical simulation method of multi-parameter and multi-stage. At the time of writing, the actual foundation pit project had not yet started, and due to the limitations of relevant conditions, real-time monitoring data of foundation pit excavation could not be obtained, which was a pity for this paper. However, by comparing the results of foundation pit design and previous engineering experience, it can be concluded that the multi-parameter and multi-step numerical simulation method proposed in this paper is feasible. If there is an opportunity in the future, this numerical simulation method will be used to compare with the measured data of foundation pit excavation in specific projects to continuously improve the accuracy and applicability of this method.

The Mohr-Coulomb constitutive model is an ideal elastic-plastic model, which is widely used in numerical simulation of foundation pit excavation. The Mohr-Coulomb constitutive model has a certain universality, but it also has some limitations in practical engineering projects. The soil parameters are different in different regions. If we want to analyze the excavation characteristics of the local foundation pit accurately, we should select a specific soil constitutive model according to the local conditions. In the future, we can try to use the modified Cambridge constitutive model to conduct relevant numerical simulation analysis combined with the actual situation of the engineering project, and the results obtained may be more consistent with the actual situation.

6. Conclusions

In this paper, a multi-stage and multi-parameter numerical simulation method is proposed to analyze the influence of excavation on the surrounding environment of buildings, roads, and so on. The three-dimensional geotechnical finite element model is established in the numerical simulation analysis of specific deep foundation pit engineering. By comparing the numerical simulation results with relevant standards, the rationality and accuracy of the foundation pit design are verified.

Combined with the multi-stage simulation construction method, this paper compares and analyzes the numerical simulation results of the actual project from the perspective of multiple parameters such as displacement, stress, and strain and focuses on the influence of foundation pit excavation on the foundation pit supporting structure, surrounding buildings, and surrounding roads. In terms of supporting displacement of the foundation pit, the displacement of the four points A, B, C, and D selected in this paper presents relative regular changes in the three directions of X, Y, and Z. In the Z direction, the final displacement of point A is 8.64 mm, the final displacement of point B is 1.22 mm, the final displacement of point C is 7.23 mm, and the final displacement of point D is 1.05 mm. All are less than the standard limit value of 0.002H = 25 mm. In terms of foundation pit support stress, the displacements of the four points A, B, C, and D selected in this paper show relative regular changes in the three directions of X, Y, and XY, and the corresponding stress change with the change of displacement, but the change of stress shows a certain lag. In terms of the internal force of the anchor bolt, this paper mainly studies the maximum internal force value of the anchor bolt after the completion of excavation. The pulling force value increases with the deepening of excavation, but it is still less than the standard limit, that is, less than 1.1 times the designed maximum pulling force value. In terms of the displacement of the surrounding buildings, the displacement of the typical point A selected in this paper presents relatively regular changes in the X, Y, and Z directions. In the Z direction, the final displacement of a typical building is −10.33 mm, which is less than the code limit of 200 mm. In terms of the displacement of the surrounding road, the displacement of the typical points E and F selected in this paper presents relatively regular changes in the X, Y, and Z directions. In the Z direction, the final displacement of the typical point E is 16.44 mm, and the final displacement of the typical point F is 7.65 mm, which is less than the limit of the specification 300 mm. The results show that the design of the foundation pit is reasonable and safe, and the relevant values are lower than the standard values.

This simulation approach enables engineers to precisely assess the influence of geotechnical factors at the design stage, foresee the effects of excavation and supportive structures on adjacent environments, and refine the design plans accordingly. Simulating various phases of construction facilitates the effective identification and management of risks, including unstable soil regions and groundwater dynamics. Additionally, this method aids in strategic decision-making during construction, allowing for adjustments in construction techniques and schedules to lessen impacts on nearby buildings and infrastructure. The outcomes of this research not only elevate the overall efficiency of engineering projects, mitigating delays and budget overruns but also substantially heighten safety measures, thereby reducing accident risks. Hence, the multi-stage and multi-parameter influence analysis approach based on a 3D FE model is poised to be an essential tool for enhancing both efficiency and safety in future deep foundation pit engineering endeavors.

For future study, different soil constitutive models can be considered according to the actual project situation, combined with relevant measured data, to verify the accuracy of the multi-stage and multi-parameter numerical simulation method and constantly improve the method to enhance its applicability.

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