

Design Principles and Three-Dimensional Finite Element Numerical Analysis of Ultra-Deep Large Foundation Pit Support: Postprint

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Abstract

With the rapid development of China's economy, available urban space is becoming increasingly scarce, necessitating that more construction projects extend underground. Deep excavation support systems are extensively employed in urban construction, and ensuring the safety and rationality of deep foundation pits has become a critical issue in their design. This study, based on an engineering case, utilizes the geotechnical calculation software Lizheng Deep Foundation Pit 7.0 and the finite element analysis software Midas GTS to analyze foundation pit safety. The support structure design and three-dimensional finite element analysis results can provide valuable references for design optimization and construction, offering guidance for similar projects.

Full Text

Super Deep Foundation Pit Supporting Design Principle and Three-Dimensional Finite Element Numerical Analysis

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Abstract

With rapid economic development in China, available urban space is becoming increasingly scarce, necessitating the expansion of buildings underground. Deep foundation pit support is frequently employed in urban construction, making the assurance of safety and rationality critical issues in deep foundation pit design. This paper analyzes the safety of a foundation pit using the geotechnical calculation software Lizheng Deep Foundation Pit 7.0 and the finite element analysis software Midas-GTS, based on an actual engineering case. The analysis

results provide valuable references for optimization of design and construction, offering guidance for similar projects.

Keywords: Deep Foundation Pit; Support; Lizheng; Finite Element Simulation

3. Analysis of Deep Foundation Pit Support Principles

The fundamental requirements for deep foundation pit support structures are “safety, low cost, and construction convenience,” which collectively reflect the overall performance of the main structure under varying conditions such as water level fluctuations and site environmental changes. By comparing multiple support structure designs, the most suitable support form can be selected for the specific construction conditions. Since deep foundation pit engineering involves significant risks, any oversight can severely impact life and property safety, with potentially catastrophic consequences. Therefore, in deep foundation pit projects, bored piles combined with triple-axis mixing piles are often employed. To prevent excessive lateral displacement of the bored piles and ground deformation caused by excavation, it is crucial to properly determine the excavation sequence and support installation procedures. The excavation depth should not be excessively large relative to the distance from the lowest steel support to the pit bottom.

After comprehensive evaluation, the deep foundation pit can be excavated vertically in four stages with three levels of steel supports. The support material consists of steel pipes with a diameter of 106 mm and wall thickness of 16 mm. The layout of the deep foundation pit support is shown in [Figure 1: see original paper].

The mechanical parameters of the soil and rock are presented in .

During pit excavation, it is essential to fully consider the displacement and stability caused by excavation, particularly for deep and large pits. Ensuring control of displacement and stability during excavation represents the greatest construction challenge.

The principle and computational model for analyzing sheet pile structures using the finite element method are illustrated in [Figure 2: see original paper]. The fundamental approach involves rotating the elastic foundation beam by 90° about its central axis and relocating the soil spring units above the excavation surface to the non-working structure. The supporting structure behind the wall simultaneously bears the active earth pressure while providing support. The soil to be excavated in front of the wall and the steel support structure are modeled as elastic foundations. Based on the principle of proximity to the element, the earth pressure acting on the wall is discretized and simplified to concentrated nodal loads. A similar approach is applied to analyze the spring loads of the soil below the excavation, where the loads are simplified to concentrated forces

at nodes that bear elastic support reactions. The finite element method is then employed to analyze the loads and stability of the supporting wall, as shown in [Figure 2: see original paper].

This analysis process can be summarized as follows: First, the structural configuration of row piles with internal bracing is established. Determining the excavation construction sequence is a prerequisite for ensuring project execution. Based on the actual construction progress, the computational diagram for structural forces during the support installation process can be determined.

4. Finite Element Analysis of Deep Foundation Pit Support

Soil is a complex material composed of three phases: solid, liquid, and gas. Its constitutive relationship primarily refers to the relationship between stress and strain. Due to the complex composition and significant discreteness of its components, coupled with substantial differences in physical properties among these elements, soil exhibits nonlinear and viscoplastic behavior. Researchers worldwide have studied soil constitutive relationships for decades, proposing hundreds of models. While many of these theoretical models have been incorporated into engineering practice through advanced computer programming and numerical analysis techniques, only a limited number of mature theories and models have gained widespread acceptance and practical application.

4.1 Finite Element Simulation Process of Deep Foundation Pit Excavation The construction simulation is conducted using the “empty element” method to model the excavation process. The computational procedure is as follows:

First, gravitational loads are applied to the deep foundation pit to calculate the initial stress and displacement fields, as shown in [Figure 3: see original paper]. The first excavation reaches a depth of 1.2 m, after which the excavated elements are represented as “empty elements” and the resulting stress and displacement fields are analyzed. Following the installation of the first support level, the second excavation proceeds to 6.7 m depth, with subsequent analysis of stress and displacement fields. After installing the second support level, the third excavation reaches 12.2 m depth, followed by corresponding analysis. Finally, after the third support level is installed, the fourth excavation advances to the final depth of 15.5 m, with final analysis of the stress and displacement fields.

4.2 Finite Element Analysis Results of Deep Foundation Pit Excavation Analysis of the displacement diagram in [Figure 4: see original paper] reveals that the horizontal displacement of the retaining pile system remains within acceptable limits. In this simulation, the maximum horizontal displacement is less than 30 mm. During the first excavation, virtually no horizontal displacement occurs. The second excavation induces approximately 8 mm of horizontal displacement near the pit bottom. The third excavation results in a significant displacement of 18 mm, concentrated at a depth of approximately

6 m below the surface. By the fourth excavation, the horizontal displacement reaches about 23 mm, occurring primarily at a depth of 8 m from the pit bottom.

The bending moments in the retaining piles evolve during each excavation stage, as illustrated in [Figure 5: see original paper]. In practical engineering applications such as this deep foundation pit project, the bending moments induced by horizontal soil loads on the retaining piles increase progressively with excavation depth, as do the moments in the supporting structures. The maximum bending moment occurs during the fourth excavation, reaching a value of $-1839 \text{ kN} \cdot \text{m}$. Comparison with the ultimate bending moment capacity of the retaining piles indicates that the structural performance remains adequately protected throughout the excavation process. As excavation depth increases, both positive and negative bending moments in the supported piles continue to grow. To ensure construction safety, it is necessary to increase the cross-sectional dimensions and reinforce the piles with steel bars. Additionally, double reinforcement in the retaining piles enhances safety performance by effectively resisting the effects of moment variations.

The primary cause of bottom heave during excavation is the change in the original stress state due to soil unloading. The heave development curve throughout the excavation process is presented in [Figure 6: see original paper], where the pit center represents the zero point of horizontal distance and the total pit width is 18 m. Analysis of the curve indicates that bottom heave increases with excavation depth, reaching its maximum near the mid-depth of the pit. Heave at the pit sidewalls is relatively small and can be neglected due to the restraint provided by the retaining piles. During the fourth excavation, the maximum heave at the mid-depth position is 7.86 mm. The heave development in this project is relatively uniform without significant fluctuations, indicating that the pit bottom remains in an elastic working state throughout construction, and overall safety is not compromised by heave.

The deformation curve for soil outside the retaining piles during construction is shown in [Figure 7: see original paper]. Under horizontal pressure, the excavated pit causes deformation of the supported retaining piles, resulting in settlement of the soil mass within the construction area but outside the piles. Settlement increases with excavation depth, reaching a maximum of 21 mm. Soil settlement near the piles is insignificant due to protection from the retaining or support piles. Conversely, the influence of excavation on settlement diminishes with distance from the pit, becoming stable at approximately three times the pit depth.

Water is a critical factor affecting pit safety. In the finite element analysis model, water levels were incorporated to investigate the influence of water table variations on the displacement of the retaining structure and settlement of soil outside the pit.

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