Influence of Deep Foundation Pit Support on the Stability of Underground Structures and Design Optimization

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Abstract: This paper discusses the influence of deep foundation pit support on the stability of underground structures and design optimization from the perspectives of problem causes and optimization paths. It proposes methods such as strength parameter calculation based on detailed geological surveys, multi-dimensional waterproofing system design, selection of appropriate support forms, and coordinated excavation planning. Corresponding research on the influence mechanisms of support and optimization strategies is conducted. The results aim to demonstrate that these optimization paths can effectively solve problems such as displacement caused by insufficient support strength and seepage failure due to waterproofing failure, thereby ensuring the stability and durability of underground structures.

1. Introduction

With the increasing intensity of urban underground space development, the scale and complexity of deep foundation pit projects continue to rise, and the impact of support systems on the stability of underground structures has become increasingly prominent. Issues such as insufficient support structure strength and waterproofing failure can easily lead to safety hazards such as displacement and seepage damage to underground structures, threatening the overall safety of the project. To address these problems, it is necessary to systematically sort out the key links of support affecting the stability of underground structures and propose scientific optimization plans based on actual engineering conditions, providing theoretical and practical support for the design of deep foundation pit support and the safety assurance of underground structures.

2. Influence of Deep Foundation Pit Support on the Stability of Underground Structures

2.1 Displacement of Structures Caused by Insufficient Support Structure Strength

In the design of deep foundation pit support, if strength parameters are determined solely based on conventional geological survey data without fully considering the heterogeneity of soil layers and the dynamic changes in loads during construction, the strength reserve of the support structure will be insufficient. During actual excavation, the active earth pressure of the soil on the side of the foundation pit will increase non-linearly with the increase in excavation depth. When the flexural and shear strengths of the support structure cannot resist this dynamic pressure, micro-cracks will first appear at the weak parts of the structure. As the cracks expand, the support structure will produce lateral displacement towards the inside of the foundation pit. This displacement will be transmitted to the underground structure through the support system, causing additional bending moments and shear forces in the walls of the underground structure and affecting its long-term safety.

2.2 Seepage Damage to Structures Caused by Waterproofing Failure

If the design of the deep foundation pit waterproofing system ignores the differences in the occurrence forms of groundwater and the anisotropy of soil permeability, it is prone to poor waterproofing effects. In sandy gravel strata, if a single waterproof curtain is used and the depth of

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the curtain does not penetrate the confined water layer, or if there are defects such as poor lap joints or holes in the curtain during construction due to the complexity of the stratum, groundwater will form concentrated seepage along these defects in the curtain. The concentrated seepage will generate hydrodynamic pressure on the soil around the foundation pit, causing fine particles in the soil to be carried away by the water flow and forming piping channels. As the piping develops, the soil below the foundation of the underground structure will gradually be excavated, forming local cavities and causing the foundation to lose effective support, resulting in settlement deformation.

2.3 Aggravation of Structural Vibration Caused by Insufficient Support Stiffness

If the stiffness design of the deep foundation pit support structure does not conduct dynamic analysis in combination with the characteristics of vibration sources in the surrounding environment, it is easy to cause the natural frequency of the support structure to be close to the external vibration frequency, resulting in resonance phenomena. When the stiffness of the support structure is relatively small, its anti-vibration ability is weak. Under the action of high-frequency vibrations generated by construction machinery operations, the support structure will have a large-amplitude vibration response. This vibration will be transmitted to the underground structure through support piles, underground diaphragm walls, and other components. In underground structures, thin-walled components such as floors and walls are more sensitive to vibrations. Long-term vibrations can loosen the embedded parts at the connections of components, reducing the connection stiffness. At the same time, they can expand the micro-pores inside the concrete, reducing the crack resistance of the components.

2.4 Influence of Improper Excavation Sequence of Foundation Pits on Structural Forces

If the excavation of deep foundation pits does not follow the principle of "layered excavation and layered support" or if the excavation sequence is not coordinated with the construction progress of the support structure, it is easy to cause disordered stress states in the soil around the foundation pit[1]. Excavating deep soil first and then carrying out shallow support will cause the upper soil of the foundation pit to lose timely support, and the soil stress will be redistributed, forming relatively large lateral unloading stresses. These stresses will be transmitted to the underground structure, causing the underground structure to bear additional horizontal thrusts and vertical additional stresses. When the additional stresses exceed the design limit of the structure, the beams and columns of the underground structure will show obvious bending deformations and shear cracks, destroying the force balance of the structure.

3. Optimization Design Paths for the Influence of Deep Foundation Pit Support on the Stability of Underground Structures

3.1 Precise Calculation to Determine Strength Parameters of Support Structures

Conduct detailed geological surveys to enhance the accuracy of parameter calculations. During the survey stage, not only should conventional physical and mechanical indicators such as soil layer distribution, natural unit weight of soil, cohesion, and internal friction angle be obtained, but also special soil layers within the influence range of foundation pit excavation should be subject to special tests[2]. The strength characteristics of soil under different stress paths should be determined through triaxial shear tests, and the horizontal bearing capacity parameters of soil should be obtained through pressuremeter tests to ensure that the survey data can truly reflect the site geological conditions. Classify and quantitatively analyze load conditions, clarify various types of loads that may occur during foundation pit excavation, including active earth pressure, passive earth pressure, construction machinery loads, ground loads, and groundwater pressure. The calculation of active earth pressure should be determined layer by layer in combination with the excavation depth, considering the pressure transmission characteristics of different soil layers to avoid calculation deviations caused by using single soil layer parameters. Select appropriate calculation models and software. According to the type of support structure, choose the corresponding theoretical model.

For example, the elastic foundation beam method can be used for row piles support, and the finite element method can be used for underground diaphragm walls. At the same time, use professional software such as MIDAS GTS and FLAC3D for numerical simulation. During the simulation process, multiple working conditions should be set up to analyze the internal force distribution and deformation of the support structure under different working conditions to ensure the comprehensiveness of the calculation results. Verify and optimize the adjustment of strength parameters[3]. Compare the required strength of the support structure calculated with the actual strength of the selected materials. If the calculated strength is close to the ultimate strength of the materials, the strength reserve should be improved by adjusting the cross-sectional dimensions of the support structure or optimizing the support layout. At the same time, multiple plans should be compared and selected based on engineering economy to finally determine the support structure parameters that meet both strength requirements and economic rationality.

3.2 Optimize the Design of the Waterproofing System to Enhance Anti-seepage Capacity

Conduct a special assessment of hydrogeological conditions. Determine the type of groundwater, water level depth, permeability coefficient, and recharge source at the site through pumping tests and pressure tests, with particular attention to the distribution range and water head height of the confined water layer to avoid waterproofing design failure due to ignoring the effect of confined water[4]. Select appropriate waterproofing methods and determine the basic plan. Design according to the hydrogeological conditions: for thin layers aquifers with unconfined water with weak permeability, a high-pressure rotary jet grouting pile waterproof curtain can be used; for sandy gravel layers with strong permeability, a composite waterproofing method combining an underground diaphragm wall and a waterproof curtain should be adopted. The depth of the underground diaphragm wall should penetrate the layer and enter a relatively impermeable layer, and the waterproof curtain should be tightly lapped with the diaphragm wall; for sites with confined water, pressure relief wells should also be set up to control the water head of the confined water through pressure relief and dewatering to prevent piping. Optimize the construction parameters and node design of the waterproofing system. For the waterproof curtain, determine the pile diameter, pile length, lap length, and grouting pressure. The grouting pressure should be adjusted according to the permeability of the stratum to ensure that the grout fully fills the pores; for the underground diaphragm wall, optimize the groove section division and joint treatment. Use I-beam joints or rubber waterstops to prevent leakage at the joints; for the pressure relief wells, determine the well depth, well diameter, and filter pipe layout. The filter screen wrapped around the filter pipe should be selected according to the particle size distribution of the soil layer to avoid filter screen blockage affecting the dewatering effect[5]. Set up monitoring and redundant safeguard measures for the waterproofing system. After the construction of the waterproofing system is completed, pressure tests or pumping tests should be carried out to inspect the anti-seepage effect. At the same time, water level observation wells should be arranged around the foundation pit to monitor the changes in the groundwater level in real-time; design multiple waterproofing lines and add drainage ditches outside the waterproof curtain and collection wells inside to control the seepage volume and prevent the expansion of seepage damage even if local leakage occurs.

3.3 Reasonably Select Support Forms to Improve Structural Stiffness

Conduct a pre-condition analysis for the selection of support forms. Comprehensively collect basic engineering data, including the excavation depth of the foundation pit, surrounding environment, geological conditions, and construction period requirements, and quantify these factors into evaluation indicators to establish an index system for the selection of support forms. Conduct a technical and economic comparison of multiple support forms. List feasible support forms and compare them from four dimensions: stiffness performance, construction difficulty, construction period and cost, and environmental impact. For example, row piles support has medium stiffness and flexible construction but poor integrity; underground diaphragm walls have high stiffness and good integrity but high construction cost and long construction period; steel sheet pile support has fast construction speed but relatively low stiffness and is suitable for shallow foundation pits; soil nailing wall support has low cost but low stiffness and is suitable for strata with weak permeability[6]. Through the analytic hierarchy process or weighted scoring method, comprehensively score each support form and preliminarily screen out 2-3 appropriate support forms. Optimize the stiffness design for the initially selected support forms. Taking row piles support as an example, if row piles support is initially selected, the following steps should be taken to improve the stiffness: determine the pile diameter and pile spacing. The pile diameter should be selected according to the excavation depth. For an excavation depth of 10-15 m, a pile diameter of 800-1000 mm can be selected, and the pile spacing should be controlled at 1.2-1.5 times the pile diameter; set internal supports or anchors. Steel supports or concrete supports can be used as internal supports, and the number of support layers should be determined according to the excavation depth. If the excavation depth exceeds 12 m, 2-3 layers of supports should be set up, and the support spacing should be determined through calculation to ensure that the supports can effectively transmit horizontal forces; optimize the design of the pile top crown beam. The cross-sectional dimensions of the crown beam should meet the flexural requirements and be rigidly connected with the row piles to enhance the overall stiffness of the row piles. Verify and dynamically adjust the stiffness of the support structure[7]. Calculate the stiffness parameters of the support structure using structural mechanics software and simulate the deformation of the support structure during foundation pit excavation. If the deformation exceeds the allowable value, further optimize the support parameters, such as increasing the pile diameter, adding support layers, or adopting a support form with higher stiffness to ensure that the stiffness of the support structure can effectively control the vibration and deformation of the underground structure.

3.4 Scientifically Plan the Excavation Sequence to Control Structural Forces

Conduct a pre-force analysis for the design of the excavation sequence. Establish a whole mechanical model of the foundation pit-support-underground structure through finite element software, simulate the stress distribution of the soil around the foundation pit, the internal force changes of the support structure, and the additional stresses of the underground structure under different excavation sequences, clarify the influence law of the excavation sequence on the forces of the underground structure. For example, excavating the soil in the middle of the foundation pit first and then excavating the surrounding soil can reduce the lateral pressure of the surrounding soil on the underground structure, providing a theoretical basis for the planning of the excavation sequence[8]. Determine the basic parameters of layered and segmented excavation. Determine the layer thickness according to the excavation depth of the foundation pit and the stiffness of the support structure. Generally, the layer thickness should not exceed the cantilever height of the support structure to avoid excessive deformation of the support structure due to over-thick layers; determine the segment length according to the plane size of the foundation pit. If the length of the foundation pit exceeds 50 m, it should be excavated in segments, with a segment length controlled at 20-30 m. The support structure should be constructed in a timely manner after each segment of excavation is completed to form a closed support system; at the same time, determine the excavation speed. The excavation speed in soft soil layers should be controlled at 0.5-1 m per day to avoid excessive stress release in the soil due to too fast excavation. Formulate a coordinated construction process for excavation and support. Clarify the time sequence and spatial coordination of each process: first excavate the first layer of soil, construct the first layer of support in a timely manner after the excavation is completed, and then excavate the second layer of soil after the support structure reaches the design strength; follow the principle of "support first, then excavate" during the excavation process, and over-excavation is strictly prohibited. When the excavation reaches 0.5 m below the construction surface of the support, stop the excavation and start the support construction; for the parts connected to the underground structure, construct the support structure first and then excavate the soil around the structure to avoid direct exposure of the structure to the soil stress[9]. Establish a force monitoring and dynamic adjustment mechanism during the excavation process. Arrange monitoring points on the soil around the foundation pit, the support structure, and the underground structure to monitor soil settlement, support structure displacement, and underground structure stress. The monitoring frequency should be adjusted according to the excavation progress, with 1-2 times of monitoring per day during the excavation period; adjust the excavation parameters according to the feedback from the monitoring data. If the displacement of the support structure exceeds the warning value, slow down the excavation speed, increase the support stiffness, or construct the next layer of support in advance; if the stress of the underground structure is abnormal, adjust the excavation sequence and excavate the soil at the stress concentration part first to reduce the additional stress on the structure and ensure that the forces of the underground structure are always within a safe range.

4. Conclusion

Through the above research, it is clear that insufficient support structure strength, waterproofing failure, insufficient stiffness, and improper excavation sequence are the core factors affecting the stability of underground structures, and each factor has a specific action mechanism. The corresponding optimization design paths proposed, through precise calculation of strength parameters, optimization of the waterproofing system, reasonable selection of support forms, and scientific planning of the excavation sequence, can specifically solve the above problems, effectively control risks such as displacement and seepage damage of underground structures, and ensure the stability of underground structures during the construction and use stages.

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