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Application Research of Double-Row Pile Retaining Structures in Deep Excavation Projects for Water Conservancy Engineering

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Abstract: *To ensure the safety of deep foundation pit construction and provide scientific basis for controlling surrounding environmental deformation, this study investigates the application of double-row pile support structures in deep foundation pits for water conservancy projects. Based on the principles of synergistic loading, separate calculation of water and earth pressures, and environmental compatibility, Rankine soil pressure theory is employed to calculate water and earth pressures. Design loads are determined by combining permanent loads, live loads, and hydrostatic pressure. The equivalent stiffness method is employed to reduce the double-row piles to a single-row pile equivalent. The elastic foundation beam method is then used to calculate internal forces and deformations within the piles. Stability against overturning and sliding is verified using the moment equilibrium method and sliding plane assumption, respectively. The dewatering design is optimized based on the principles of zoned dewatering and dynamic control, limiting the dewatering rate to a maximum daily water level drop of 0.5m. A three-dimensional numerical model was constructed using FLAC3D software to simulate the coupled effects of deformation in the support structure and seepage field during excavation. The numerical simulation showed that when the pile spacing was optimized, the maximum bending moment in the pile body decreased from 480kN·m to 420kN·m, a reduction of 12.5%. For a deep foundation pit project at a water conservancy hub pump station, a composite system of double-row bored cast-in-place piles and concrete internal bracing was employed, indicating effective deformation control by the support structure. Results demonstrate that double-row pile support structures can significantly enhance deep foundation pit stability through coordinated stress design, refined load calculations, and seepage control measures.*

Keywords: *double-row piles; support structure; water conservancy project; deep foundation pit engineering*

1. Introduction

As a multidisciplinary, comprehensive, and high-risk endeavor, excavation and support methods for foundation pits are fundamental to ensuring timely, high-quality, and cost-effective project completion. During excavation, failure to strictly control deformations—such as displacement of the support structure and settlement of the surrounding ground surface—within safe limits often leads to pit collapse, resulting in engineering accidents including casualties. The fundamental cause lies in the following: unloading the soil disrupts the original equilibrium of earth pressure conditions inside and outside the pit. However, the adopted support structure lacks the necessary stiffness to maintain the pit's safety[1]. When pit deformation progresses to its limit state without reinforcement of the support structure, various foundation pit engineering accidents occur. From a research perspective, the instability of deep excavations in hydraulic engineering not only delays project schedules and incurs economic losses but may also trigger secondary disasters such as pollution of surrounding water systems and embankment seepage, threatening regional water resource security[2]. Double-row pile support structures effectively limit soil deformation through coordinated loading between front and rear rows, thereby reducing impacts on adjacent hydraulic structures. Additionally, its modular construction characteristics make it suitable for confined sites and complex geological conditions, minimizing disturbance to the surrounding environment. However, existing design codes primarily rely on empirical coefficient methods or simplified models, failing to adequately account for the coupled effects of dynamic water pressure changes, soil rheological properties, and construction disturbances.

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This results in insufficient structural safety margins or material wastage.

Extensive research on double-row pile support structures has been conducted globally. Theoretically, scholars have proposed establishing plane strain models and spatial finite element analyses to reveal how parameters like spacing between rows, pile diameter, and girder stiffness influence overall structural rigidity[3]. Experimentally, centrifuge model tests and field monitoring data have validated the superiority of double-row piles in controlling deep horizontal displacement. In engineering applications, some scholars have proposed displacement-controlled dynamic design methods to optimize support effectiveness through real-time adjustment of construction parameters. However, existing research predominantly focuses on geotechnical engineering, with insufficient consideration of special conditions in hydraulic engineering such as high-head seepage, soil softening, and fluctuating water levels during construction. Furthermore, systematic studies on the long-term durability and intelligent construction techniques for double-row piles remain lacking.

This paper aims to apply double-row pile support structures in deep foundation pits for hydraulic engineering[4]. It employs equivalent stiffness methods to calculate pile internal forces and deformations, while verifying stability through methods like moment equilibrium. Building upon this, it proposes a composite system integrating double-row bored cast-in-place piles with concrete internal bracing. Monitoring methods are designed to validate the stability of the support outcomes.

2. Design and Calculation Theory of Double-Row Pile Retaining Structures

2.1 Design Principles and Load Determination

The design of double-row pile support structures must adhere to core principles of safety, reliability, and construction feasibility while meeting the specific demands of deep foundation pits in hydraulic engineering. From the design unit's perspective, the design should satisfy the following principles:

(1) Collaborative Load-Bearing Principle: The double-row piles form a spatial load-bearing system with the front and rear piles and connecting beams. Design must ensure matching stiffness between front and rear piles and rational load distribution to prevent structural failure due to concentrated loading on single rows.

(2) Adaptability Principle for Separate vs. Combined Water-Soil Calculations: Dynamically select water and soil pressure calculation methods based on soil permeability variations. For highly permeable soils, such as sandy and gravelly soils, separate calculations are employed—water pressure and soil pressure are determined independently and then superimposed. For weakly permeable soils, such as clay, combined calculations are considered by converting water pressure into effective soil stress.

(3) Dynamic Adjustment Principle: Deep excavations in hydraulic engineering often face fluctuating water levels and construction disturbances. Designs must incorporate safety reserves and employ phased verification to ensure structural stability throughout the entire lifecycle.

(4) Environmental Compatibility Principle: Design must account for impacts on surrounding hydraulic structures (e.g., levees, pumping stations), mitigating secondary hazards by controlling support structure deformation.

Soil and water pressure constitute the critical loads in double-row pile design, requiring calculations that integrate theoretical analysis with engineering experience[5]. This paper adopts the Rankine soil pressure theory, incorporating soil parameters and excavation depth to determine active and passive earth pressure strengths. The specific calculation formulas are as follows:

$$p_a = \gamma_z K_a - 2c\sqrt{K_a} \tag{1}$$

$$p_p = \gamma_z K_p - 2c\sqrt{K_p} \tag{2}$$

Where γ_z represents the unit weight of the soil, z denotes the depth at the calculation point, K_a and K_p represent the active and passive earth pressure coefficients respectively, and c indicates the cohesion of the soil. Water pressure calculations must distinguish between hydrostatic pressure and seepage pressure[6]. For hydrostatic pressure, this study adopts a triangular distribution for calculation, with the head height h_w determined by the water level difference between the excavation and surrounding ground[7]. For seepage pressure, when a head difference exists between the excavation and surrounding ground, the hydraulic gradient must be determined through seepage analysis. The resulting formulas for hydrostatic pressure u and seepage pressure u_s are as follows.

$$u = \gamma_w h_w \tag{3}$$

$$u_s = \gamma_w iz \tag{4}$$

Where γ_w represents the unit weight of water, and i represents the hydraulic gradient. Designing deep excavations for hydraulic engineering projects requires considering load combinations under various conditions[8]. This paper defines the load combination as comprising three components: dead load, live load, and hydrostatic pressure. The dead load corresponds to the self-weight of the soil, while the live load originates from construction activities, specifically including concentrated or uniformly distributed loads generated by construction platforms, material stockpiles, lifting equipment, etc.

2.2 Structural Internal Forces and Deformation Calculation Methods

Calculating internal forces and deformations for double-row pile retaining structures is central to the design phase, with accuracy directly impacting structural safety and economy. Designers must establish analytical methods balancing computational efficiency and precision based on structural mechanics principles and engineering experience[9]. These methods also provide critical parameters for construction organization, guiding phased construction and monitoring. Calculating internal forces in double-row piles requires considering the spatial interaction between front and rear piles and connecting beams. This paper employs the equivalent stiffness method for this calculation[10]. The double-row pile is modeled as a single-row pile, with pile diameter and spacing adjusted to simulate the combined action of front and rear piles. The core lies in determining the equivalent stiffness coefficient, which relates to the spacing between rows, pile diameter, and soil properties[11]. The derived stiffness coefficient converts the lateral stiffness of double-row piles into that of single-row piles. Subsequently, the elastic foundation beam method is applied to calculate the bending moment $M\left(z\right)$ and shear force $V\left(z\right)$ within the piles. Specific calculation formulas are presented below.

$$M\left(z\right) = \frac{q_0 z^2}{2} \cdot \frac{1}{1 + \frac{z}{z_0}} \tag{5}$$

$$V\left(z\right) = q_0 z \cdot \frac{1}{1 + \frac{z}{z_0}} \tag{6}$$

Where q_0 represents the pile cap load, and z_0 denotes the depth at which the pile body bending moment is zero[12]. Deformation control of double-row piles is a core design objective, requiring calculations that account for both overall lateral displacement and local settlement. This paper adopts the elastic foundation beam theory, treating double-row piles as elastic beams embedded in soil. By solving differential equations, the horizontal displacement at the pile cap is obtained as δ . The specific calculation formula is shown below.

$$\delta = \frac{q_0 H^3}{3EI} \cdot \frac{1}{1 + \frac{k_h H^4}{4EI}} \tag{7}$$

where H represents the excavation depth, EI denotes the bending stiffness of the pile body, and k_h indicates the horizontal subgrade coefficient of the soil. For double-row piles, the coordination condition between the front and rear rows must be considered, with the overall lateral displacement curve determined through iterative calculations. During design, displacement at the pile cap must be constrained to prevent adverse effects on surrounding hydraulic structures.

2.3 Overall Stability Verification

To ensure the overall stability of the double-row pile retaining structure, verification must cover two limit states: overturning resistance and slip resistance[12]. The overturning resistance verification aims to ensure the structure does not experience rotational instability around the pile base or girder joints under lateral earth and water pressure. Designers typically employ the moment equilibrium method, using the pile base as the rotation center to calculate the ratio of overturning resistance moment to overturning moment and verify compliance with the safety factor required by standards. This paper simplifies the double-row pile support structure into a planar rigid frame system subjected to active earth pressure, passive earth pressure, structural self-weight, and hydrostatic pressure[13]. The overturning resistance moment (M_k) is primarily generated by passive earth pressure (E_p) and structural self-weight (G). The overturning moment (M_q) is produced by active earth pressure (E_a) and hydrostatic pressure (U). The safety factor (K_q) is expressed as follows:

$$K_q = \frac{M_k}{M_q} = \frac{E_p \cdot \frac{h_p}{3} + G \cdot x_G}{E_a \cdot \frac{h}{3} + U \cdot x_G} \tag{8}$$

Here, x_G represents the horizontal distance from the point of structural self-weight to the pile base, while x_U denotes the horizontal distance from the point of hydrostatic pressure resultant to the pile base[14]. The purpose of the slip resistance verification is to ensure the retaining structure does not undergo horizontal sliding along its base under lateral earth and water pressure. This paper calculates the ratio of the anti-slip force to the slip force based on the sliding plane assumption. Assuming the sliding plane is a horizontal plane along the pile base, the forces acting on it include the total lateral force F_c , the anti-slip force F_k , and the shear resistance. The anti-slip force is provided by both friction and shear resistance, while the slip force is generated by the total lateral force. Its safety factor K_h is expressed as follows.

$$K_h = \frac{F_k}{F_h} = \frac{\mu \cdot G + c \cdot A}{F_c} \geq 1.3 \tag{9}$$

where A represents the base contact area.

2.4 Seepage Stability and De-watering Design Considerations

Given that hydraulic engineering projects often involve environments with high water levels or dynamic groundwater fluctuations, seepage effects may trigger risks such as soil particle loss, increased lateral pressure on retaining structures, or even sudden surges in excavation pits. Design units must establish a seepage stability analysis framework based on seepage theory, incorporating engineering geological conditions and excavation characteristics. Through optimized dewatering design to control seepage field distribution, they provide scientific basis for construction organization[15]. Seepage impacts double-row pile retaining structures in two primary ways: First, groundwater permeates through soil between piles or beneath pile bases, reducing effective stress and shear strength in the soil. Second, dynamic water pressure generated by seepage directly acts upon the retaining structure, increasing lateral loads.

De-watering design is the key method for controlling seepage field distribution and ensuring stability against seepage. Designers must adhere to the principles of zoned de-watering and dynamic control, achieving coordinated regulation of seepage and stress fields through optimized de-watering well layout, de-watering depth, and de-watering rate. De-watering wells should be arranged along the outer perimeter of the double-row piles to form a closed de-watering curtain, reducing groundwater infiltration into the excavation from the exterior. Rapid dewatering may cause sudden increases in

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effective stress within the soil, leading to additional deformation of the support structure or ground settlement in the surrounding area. To address this, this paper limits the dewatering rate to no more than 0.5m of water level drop per day based on the soil's permeability coefficient and compressibility. Real-time feedback from water level observation wells and settlement monitoring points enables dynamic adjustment of dewatering parameters.

3. Monitoring Plan and Numerical Simulation Analysis

The monitoring plan established in this paper covers three core elements: deformation of the support structure, impact on the surrounding environment, and dynamics of the seepage field. Specific monitoring parameters are shown in Table 1.

Table 1 Monitoring Parameters

Monitoring Items	Monitoring Methods	Monitoring Point Placement Principles	Early Warning Thresholds
Horizontal displacement of piles	Inclinometer + Total Station	Inclination monitoring tubes are installed at intervals of 1.5 to 2.0 meters along the pile shaft. A total station observation point is established at the pile cap, with 3 to 5 monitoring sections arranged on each side.	Pile Top: 30mm (cumulative value)
Groundwater level changes	Piezometer	Set up settlement monitoring points at intervals of 10 to 15 meters around the perimeter of the building.	Deep Layer: 50mm (cumulative value)
Stress and strain in pile bodies	Reinforcement Stress Gauge + Concrete Strain Gauge	Deploy stress gauges at critical pile sections (e.g., 5m, 10m, 15m below ground level), with 4 measurement points per section.	Hydraulic Gradient: 0.6 (critical value 0.8)
Surface settlement around the excavation perimeter	Total Station + Settlement Marker	Place settlement benchmarks along the excavation perimeter at 10–20-meter intervals, prioritizing corners and midpoints of long sides.	Reinforcement Stress: 200MPa

A three-dimensional numerical model was established using FLAC3D software to simulate the coupled effects of deformation in the support structure and seepage field during excavation. Model parameters: Soil elastic modulus 15 MPa, Poisson's ratio 0.35, permeability coefficient 1×10^{-6} cm/s; Double-row pile diameter 1.2 m, pile spacing 2.5 m, row spacing 3.0 m, concrete elastic modulus 30 GPa. Upon excavation to the base, the maximum horizontal displacement at the pile cap reached 28 mm, while the maximum bending moment occurred at 10 m below ground level, valued at 450 kN·m. The discrepancy with field monitoring data was controlled within 8%, validating the model's reliability.

4. Analysis of Engineering Application Case

This project involved a deep foundation pit for a large-scale water conservancy pump station in Zhejiang Province. The pit excavation reached 11.4m deep. The excavation plan formed an irregular polygon with a perimeter of approximately 213m. It was adjacent to a municipal road (12m away), presenting a complex surrounding environment that demanded extremely stringent deformation control.

The project employs a composite support system comprising double-row bored cast-in-place piles with concrete internal bracing. Specific structural parameters are detailed in Table 2.

Table 2 Structural Parameters of Double-Row Drilled Pile Retaining System

Types of Support Structures	Parameter Name	Specific Values
Double-row Drilled Piles	Front Row Pile Diameter	Φ1000mm
	Rear Row Pile Diameter	Φ800mm
	Pile Spacing	1200mm
	Row Spacing	3000mm
	Concrete Strength Grade	C30
	Reinforcement Configuration	Main reinforcement bars: 20Φ25 (HRB400) Stirrups: Φ10@200mm
Concrete Internal Support	Support Cross-Section Dimensions	800mm × 800mm
	Support Spacing	6000mm
	Concrete Strength Grade	C30

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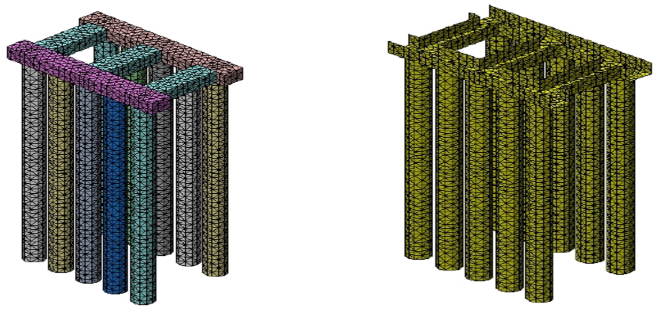
For the aforementioned double-row pile structure, the finite element model established in this paper is shown in Figure 1.



（A）Finite Element Mesh for Double-Row Pile Structure

（B）Double-row pile contact element

Figure 1 Finite Element Model of Double-Row Pile Structure

The double-row pile structure consists of two rows of vertical pile columns and a top transverse connecting beam. The pile columns are arranged at specific intervals and form an integrated structure through the top beam. In this deep foundation pit project, considering the geological conditions of the Qiantang River alluvial plain, the irregular polygonal shape of the excavation, and the complex surrounding environment, this finite element model effectively simulates the mechanical behavior of the double-row pile structure in foundation pit support. It provides a powerful tool for analyzing structural deformation and stress distribution. The numerical simulation results for the maximum bending moment variation of the pile body under different pile spacings are shown in Table 3.

Table 3 Numerical simulation results of maximum bending moment variations in piles at different spacing

Pile spacing (m)	Maximum bending moment of pile body (kN·m)	Bending moment reduction (%)
1.5	480	-
1.3	450	6.25
1.2	420	12.5
1.0	418	12.92

Numerical simulation analysis clearly indicates that as the pile spacing decreases, the maximum bending moment in the pile body drops from 480 kN·m to 420 kN·m, representing a 12.5% reduction. Based on this, the final pile spacing is determined to be 1.2 m. Post-construction monitoring of pile displacement within the foundation pit will be conducted. The specific monitoring results are shown in Figure 2.

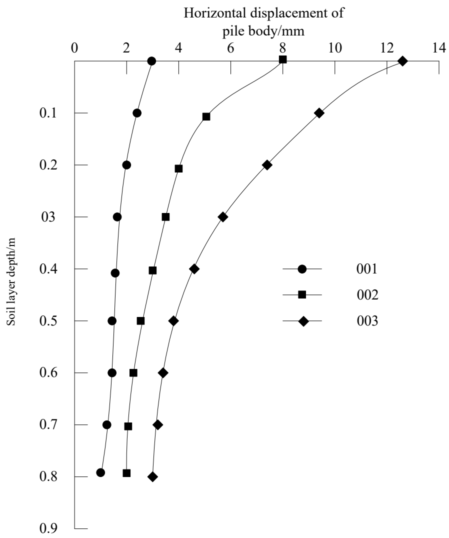


Figure 2 Pile Body Displacement Monitoring Results

The figure 2 shows that the horizontal displacement of the pile body at each monitoring point

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gradually increases with soil depth but stabilizes after reaching a certain depth. The maximum horizontal displacement value of approximately 12 mm occurred near the pile cap, with displacement increments gradually decreasing with increasing depth. This indicates that the double-row pile retaining structure effectively controlled the horizontal displacement of the piles, demonstrating particularly significant displacement control performance in deep soil layers.

5. Conclusions

This study systematically investigates the application of double-row pile support structures in deep excavations for hydraulic engineering. Through theoretical analysis, numerical simulation, and engineering validation, this study demonstrates that the design of double-row piles must be in accordance with the principles of synergistic loading, adaptable water-soil calculation, dynamic adjustment, and environmental compatibility. The equivalent stiffness method simplifies spatial synergistic calculations, while elastic foundation beam theory analyzes deformation, effectively balancing computational accuracy and efficiency. Dynamic selection between separate and combined soil-water calculations, coupled with refined load combination design, enhances the structure's adaptability to complex operating conditions.

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