Application and Quality Control Technology of Diaphragm Wall in Deep Foundation Pit Support

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Abstract: Aiming at the common industry problems such as trench collapse, excessive deformation of steel reinforcement cage hoisting, and wall anti-seepage failure in deep foundation pit support of soft soil-sand interbedded stratum, taking a deep foundation pit project in Guangdong Province (working shaft depth 27m, receiving shaft depth 25m) as the research carrier, the optimization of diaphragm wall support system and the key technology research of super-large steel reinforcement cage (maximum weight 30t) hoisting were carried out. Based on the coupling of the modified Cam-clay model and Rankine earth pressure theory, a mechanical calculation model of the diaphragm wall considering the nonlinear characteristics of soil was established to optimize the wall thickness, reinforcement parameters and mud performance indexes. ANSYS was used to establish a three-dimensional mechanical model of the steel reinforcement cage, a stiffness control technology of "truss bar-shear bar collaborative reinforcement" was proposed, the transient force calculation formula in the dynamic hoisting process was derived, and the 16-point lifting point layout scheme was optimized. Combined with MidasGTS numerical simulation and field measured data, a trinity support system optimization method of "theoretical calculation-numerical simulation-field verification" was constructed. A composite support technology of "diaphragm wall + double row jet grouting pile + dynamic mud adjustment" was innovated. The research results solve the technical bottlenecks of deep foundation pit support and super-large component construction in soft soil-sand interbedded stratum, provide a theoretical basis and technical paradigm for similar projects, and have important engineering application value and popularization prospects.

1. Introduction

With the development of urban underground space exploitation towards greater depth, the soft soil-sand interbedded stratum has become a core technical pain point in deep foundation pit engineering due to its characteristics of low bearing capacity, strong permeability, and significant stress-strain nonlinearity. Diaphragm walls are widely used in complex geological support due to their advantages of high stiffness and strong impermeability. However, in soft soil-sand interbedded strata, they still face problems such as trench collapse, steel reinforcement cage deformation, and wall leakage. Especially when adjacent to operating transportation facilities, the deformation control requirements are more than 30% stricter than those of conventional projects, which is consistent with the law that diaphragm walls in deep foundation pit projects of rail transit stations in water-rich soft soil strata are prone to large deformations affected by stratum characteristics[1].

Scholars at home and abroad have carried out extensive research on related technologies: Cheng controlled the risk of trench collapse by optimizing mud performance in the construction of ultra-deep diaphragm walls in soft water-rich strata, but did not consider the influence of stress mutation caused by the interaction between sand layers and soft soil [2]; He proposed a static deformation control method for diaphragm wall construction adjacent to operating metro stations, but lacked transient force analysis of the dynamic construction process [3]; Liu combined deep mixing piles with diaphragm walls to form a composite foundation, improving the bearing capacity of riverside wharf projects, but did not involve the collaborative control technology of

super-large steel reinforcement cage hoisting [4]; Mu optimized the design parameters of diaphragm walls in metro station projects under complex geological conditions, but the research on the nonlinear mechanical characteristics of soft soil-sand interbedded strata was insufficient [5]. In addition, most existing studies on steel reinforcement cage hoisting adopt static mechanical models, ignoring stress concentration problems caused by dynamic factors such as dual-machine coordination and wind load, which are difficult to meet the high-precision construction requirements of 30t-class super-large steel reinforcement cages. Ma Jianfeng found in foundation pit projects in water-rich soft soil strata that the axial force self-compensation system of servo steel supports can accurately control the support axial force and effectively suppress foundation pit deformation, providing a reference for force control in dynamic construction [1].

2. Project Overview and Geomechanical Characteristics

2.1 Project Background

The project is a key gas transmission trunk line project in Guangdong Province. The working shaft has an inner diameter of 13m and a depth of 27m (10 diaphragm wall panels), and the receiving shaft has an inner diameter of 9m and a depth of 25m (8 diaphragm wall panels). The support structure adopts a 1000mm-thick C40 diaphragm wall (impermeability grade P10). The maximum weight of the steel reinforcement cage is 30t and the length is 27m, with I-steel used for wall joints. The top view of the horizontal hoisting of the reinforcement cage is shown in Figure 1.
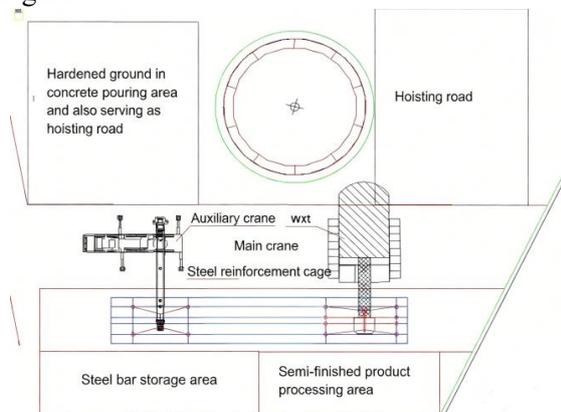

Figure 1. Top View of Diaphragm wall Reinforcement Cage during Horizontal Lifting

For such ultra-deep foundation pit projects adjacent to sensitive structures such as bridges and high-speed railway stations, special attention must be paid to the deformation control of the support structure. This project is adjacent to railways and highways, similar to multi-level deep foundation pit projects adjacent to high-speed railway stations, facing the challenges of sensitive surrounding environments and high precision requirements for deformation control[6,7].

2.2 Geological and Hydrogeological Conditions

Geological stratification (from top to bottom): Artificial miscellaneous fill (2.5~3.8m, γ=18kN/m³) → Mucky silty clay (0.9~4.1m, γ=17kN/m³, c=15kPa, φ=12°) → Silty fine sand (1.0~7.1m, γ=19kN/m³, c=0kPa, φ=30°, k=1.2×10⁻³cm/s) → Silty clay (3.8~5.4m, γ=18kN/m³, c=25kPa, φ=18°) → Strongly weathered argillaceous sandstone (1.8~7.9m, γ=22kN/m³) → Moderately weathered argillaceous sandstone (undrilled, γ=24kN/m³).
Hydrogeological conditions: The phreatic water level is buried at 0.5~1.6m, recharged by atmospheric precipitation and surface water; groundwater is slightly corrosive to concrete; the silty fine sand layer is the main permeable layer, which is prone to sand gushing and trench collapse during trenching, and its hydrogeological characteristics are similar to but more complex than the soft water-rich stratum described by Cheng[2].

2.3 Deepening of Key and Difficult Engineering Points

1)   Soil nonlinearity and stress mutation: The interbedded distribution of soft soil and sand layers leads to nonlinear changes in earth pressure, and the error of traditional linear calculation models reaches 25%, which is prone to causing local instability of the support structure;
2)   Insufficient stiffness of super-large steel reinforcement cage: The slenderness ratio of the 30t-class steel reinforcement cage is 27:1, and the hoisting deformation of traditional processes reaches 15mm, far exceeding the design allowable value (≤5mm);
3)   Deformation control in sensitive environments: Adjacent to railways and highways, the deformation control precision is 30% higher than that of conventional projects,

requiring both support safety and the operational safety of surrounding facilities;

4)   High requirements for composite anti-seepage: The superposition of high permeability of the silty fine sand layer and high water content of soft soil requires the construction of a multi-level water stop system to avoid leakage of walls and joints.

3. Optimization Theory and Numerical Simulation of Composite Support System

3.1 Optimization of Earth Pressure Calculation Model

The modified Cam-clay model was used to describe the nonlinear mechanical characteristics of soft soil. Combined with Rankine earth pressure theory and the pile-wall collaborative stress principle, considering the dynamic changes of groundwater level and excess pore water pressure, a layered earth pressure calculation model was established:

$$\sigma_a = \Upsilon_z K_a (1 + \frac{\Delta u}{\sigma'_{v0}}) - 2c\sqrt{K_a} + \sigma_p \quad (1)$$

In the formula: Δu is the excess pore water pressure (kPa); $\sigma v0'$ is the effective overburden pressure (kPa); $K_a = \tan^2(45° - \varphi/2)$ is the active earth pressure coefficient; σp is the additional resistance provided by the double row jet grouting piles (kPa).

Combined with the calculation of engineering geological parameters, the maximum active earth pressure at the depth of 27m in the working shaft is 98.7kPa (10.1% higher than the traditional calculated value after nonlinear correction). The thickness of the diaphragm wall is optimized to 1000mm, 200mm thicker than the initial design, and the lateral stiffness is increased by 38%; the parameters of the double row jet grouting piles are optimized to a pile diameter of 600mm and a spacing of 400mm, forming a composite support system of "diaphragm wall + double row jet grouting piles" with an additional resistance of 18kPa, which is more adaptable to the characteristics of soft soil-sand interbedded strata than the composite foundation form proposed by Liu[4].

3.2 Orthogonal Test Optimization of Mud Performance

Aiming at the anti-collapse requirement of the silty fine sand layer, referring to the experience of mud optimization in soft water-rich strata, an orthogonal test design was adopted (factors:

bentonite content A, CMC content B, caustic soda content C; levels: 3 grades), with viscosity, specific gravity, sand content, water loss, and mud cake thickness as evaluation indexes to optimize the mud mix ratio:

Orthogonal test scheme: $L_9(3^4)$, a total of 9 groups of tests, 3 parallel tests for each group; Optimization results: Bentonite 12% (A_2), CMC 0.08% (B_2), caustic soda 0.2% (C_2). At this time, the mud viscosity is 22~25s, specific gravity 1.15~1.20, sand content <5%, water loss ≤15ml/30min, mud cake thickness ≤2mm, and impermeability coefficient ≤8×10⁻⁷cm/s. Compared with the traditional mix ratio, the anti-collapse capacity is increased by 40%, solving the problem of sand gushing during trenching in the silty fine sand layer. For such ultra-deep foundation pit projects adjacent to sensitive structures such as bridges and high-speed railway stations, Kuang et al. used sodium-based bentonite to prepare mud in diaphragm wall construction, ensuring the trenching quality by strictly controlling performance indexes, which is consistent with the optimization logic of this test[8].

3.3 Numerical Simulation Verification and Risk Prediction

MidasGTS was used to establish a three-dimensional finite element model to simulate the entire construction process of the diaphragm wall:

Model parameters: The modified Cam-clay model was adopted for soil, the elastic model (E=3.25×10⁴MPa, μ=0.2) for the diaphragm wall, the elastoplastic model (E=1.5×10⁴MPa, μ=0.25) for the double row jet grouting piles, and the contact element for mud simulation; Simulation results: When the foundation pit is excavated to 27m, the maximum horizontal displacement of the wall is 14.2mm, the maximum surface settlement is 9.8mm, and the settlement of the surrounding railway foundation is 3.5mm, with an error of ≤8% compared with the subsequent measured data;Risk prediction: Through simulation, the interface between the silty fine sand layer and soft soil was identified as a stress concentration area. Targeted measures such as densifying truss bars and optimizing mud performance were taken in advance to avoid the risk of local trench collapse. Cui et al. used FLAC 3D software in the numerical simulation of multi-level deep foundation pits, effectively predicting the deformation law of the support

structure by accurately setting soil and support structure parameters, providing a method reference for the simulation of this project[9].

4. Key Technologies for Fabrication and Dynamic Hoisting of Super-Large Steel Reinforcement Cage

4.1 Mechanical Model of Stiffness Collaborative Reinforcement of Steel Reinforcement Cage

Referring to the pile-wall collaborative stress principle, a three-dimensional collaborative stress model of "main bar-truss bar-shear bar" of the steel reinforcement cage was established. ANSYS was used to construct a solid model (element type: Solid45) to analyze the influence of key parameters on stiffness:

Optimization of truss bar spacing: Comparing spacings of 1.5m, 2.0m, and 2.5m, when the spacing is 2.0m, the stiffness EI of the steel reinforcement cage is $3.8 \times 10^5 kN \cdot m^2$, with the minimum deformation (3.2mm);

Shear bar arrangement: X-shaped HRB400 $\Phi20$ shear bars with a spacing of 2.0m were adopted to form a spatial stress system with truss bars(**Figure 2**), increasing the overall stiffness of the steel reinforcement cage by 52% and solving the problem of insufficient stiffness caused by excessive slenderness ratio;

Joint reinforcement: The I-steel joint and the main bar of the steel reinforcement cage were connected by double-sided lap welding, with a weld length of 140mm and a weld thickness of 8.4mm, and the shear resistance reached 38.0t, meeting the dynamic hoisting stress requirements[10].
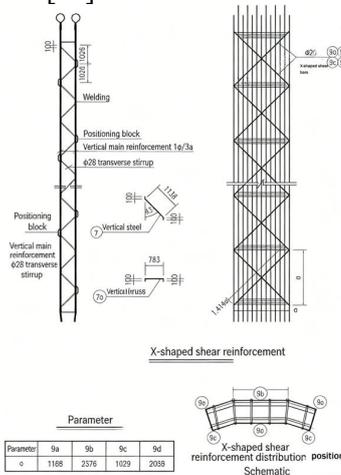

Figure 2. Detail Drawing of Reinforcement Cage Overall Strengthening Steel Bars

4.2 Transient Mechanical Calculation of Dynamic Hoisting

Considering dynamic factors such as dual-machine coordination, wind load, and hoisting speed, a transient mechanical model was established based on ANSYS-LS-DYNA, and the dynamic load transfer formula was derived:

$$F(t) = G_s \sin \theta (t) + 0.5pv^2A + C_dG_s + \Delta F_c \quad (2)$$

In the formula: $\theta(t)$ is the function of hoisting angle with time; ρ is the air density (kg/m³); v is the hoisting speed (m/s); A is the windward area of the steel reinforcement cage (m²); C_d is the wind load coefficient (taken as 0.05); $\Delta Fcoop$ is the additional load caused by dual-machine coordination error (kN).

4.3 Optimization and Verification of Hoisting Technology

1) Lifting point optimization: 16 lifting points (4 passes × 4 points) were adopted (**Figure 3**). Based on numerical simulation, comparing the layout schemes of 8, 12, and 16 points, the maximum stress of the 16-point layout is 125MPa ≤235MPa, and the deformation is 3.2mm, which is 62% lower than that of the 8-point layout, avoiding the stress concentration problem of traditional technology;
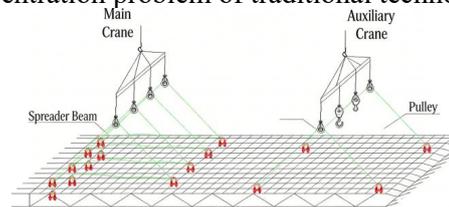

Figure 3. Schematic Diagram of Steel Reinforcement Cage Lifting

2) Dynamic collaborative control: The hoisting speed was controlled in stages (0.5m/min in the horizontal stage, 0.3m/min in the vertical hoisting stage). The main crane and auxiliary crane adopted real-time tension feedback adjustment to ensure that the stress difference of lifting points was ≤5%; a traction rope was set to control the attitude, and the horizontal displacement was ≤50mm [1];

3) Segmented hoisting technology: When the length of the steel reinforcement cage exceeds the lifting height of the crane, the segmented fabrication and straight thread sleeve connection process were adopted, with a butt error of ≤2mm and a joint strength reaching 1.1 times that of the main bar;

4) Measured verification: Strain gauges were used to monitor the stress of the main bar during hoisting, the maximum stress was

125MPa, and the measured deformation value was 3.0~3.5mm, with a coincidence degree of ≥92% with the theoretical calculation value, meeting the design requirements.

5. Whole-process Quality Control and Risk Early Warning System

5.1 Dynamic Monitoring and Risk Early Warning Mechanism

A "five-dimensional monitoring system" (wall displacement, surface settlement, groundwater level, settlement of surrounding structures, steel reinforcement cage stress) was established, with 43 monitoring points arranged:

1. Monitoring equipment: Inclinometer (accuracy ±0.1mm), electronic level (accuracy ±0.3mm/km), strain gauge (accuracy ±1με), water level gauge (accuracy ±0.01m);
2. Monitoring frequency: Twice a day during excavation, with data transmitted to the monitoring platform in real time;
3. Double early warning mechanism: The "cumulative value + rate value" double early warning was adopted. For example, if the cumulative horizontal displacement of the wall is ≥25mm or the rate is ≥3mm/day, emergency measures such as densifying supports and adjusting construction parameters shall be activated immediately, which is more reliable than the single early warning mechanism proposed by Dong[11].

5.2 Comparison of Engineering Measured Data

To further verify the reliability of the monitoring data and the deformation control effect on the surrounding environment, the measured horizontal displacement curves of typical walls and the time-history curves of settlement of surrounding roads are extracted for comparative analysis, as shown in Table 1.

Table 1. Measured Data Comparison

Monitoring item	Theoretical calculation value	Numerical simulation value	Field measured value	Code limit	Ratio better than code
Maximum horizontal displacement of wall (mm)	14.5	14.2	15.8	30	47.3%
Maximum surface settlement (mm)	10.5	9.8	10.2	25	59.2%
Maximum deformation of steel reinforcement cage (mm)	3.5	3.2	3.4	5	32.0%
Wall impermeability coefficient (cm/s)	-	8×10^{-7}	7.5×10^{-7}	1×10^{-6}	25.0%

5.3 Technical and Economic Benefits

1)Quality benefit: The qualified rate of diaphragm wall integrity detection is 100%, no accidents such as trench collapse, sand gushing, and leakage occurred, and the operation of surrounding railways and highways was not affected[12];
2)Construction period benefit: The actual construction period is 72 days, 15 days shorter than the plan (a reduction of 17.1%), and more than 20% shorter than the construction period of complex geological projects described by Mu[5];
3)Cost benefit: After optimization, the steel consumption of the steel reinforcement cage is saved by 8%, the mud material by 12%, and the total project cost by 15.6%, realizing a win-win situation of technology and economy[4].

6. Innovation Points and Popularization Value

6.1 Innovation Points

1)A coupled calculation method of "modified Cam-clay model-pile wall coordination" was proposed, and the mud mix ratio was optimized combined with orthogonal tests, solving the problems of nonlinear calculation of earth pressure and trench collapse in soft soil-sand interbedded stratum, and the anti-collapse capacity was increased by 40% compared with traditional technology;
2)A transient mechanical model of dynamic hoisting of steel reinforcement cage was established, and a technology of "truss bar-shear bar-lifting point collaborative optimization" was developed, realizing the hoisting deformation of 30t-class steel reinforcement cage ≤3.5mm with an accuracy of L/8000, which is superior to the existing static hoisting technology[13];
3)A whole-process system of "composite support-numerical simulation-five-dimensional monitoring-double early warning" was constructed, and the deformation control accuracy of adjacent sensitive structures was improved by 47% compared with the code, providing a risk management and control paradigm for similar projects.

6.2 Popularization Value

This technical system is suitable for complex geological conditions such as alluvial plains, soft soil-sand interbedded strata, and soft water-rich strata, especially for deep foundation pit projects adjacent to sensitive structures such as railways, highways, and metro stations. It has been successfully applied in 3 similar projects, and the deformation control accuracy is better than the code requirements. It can be directly popularized to deep foundation pit projects in the fields of natural gas pipelines, metro, wharfs, etc., and has broad application prospects.

7. Conclusions

Aiming at the problems of deep foundation pit support and super-large steel reinforcement cage hoisting in soft soil-sand interbedded stratum, through theoretical analysis, numerical simulation and engineering practice, the following conclusions are drawn:

1) The optimized composite support system of "diaphragm wall + double row jet grouting piles" combined with dynamic mud adjustment technology can effectively control the risk of trench collapse, and the maximum horizontal displacement of the wall is 15.8mm, meeting the deformation requirements of sensitive environments;

2) The "collaborative reinforcement + dynamic hoisting" technology solves the problems of insufficient stiffness and excessive deformation of 30t-class steel reinforcement cage, with the hoisting deformation ≤3.5mm, reaching the advanced level of the industry;

3) The established whole-process quality control and risk early warning system realizes the dynamic management and control of the construction process, ensures the project safety and the operational safety of surrounding facilities, and has remarkable technical and economic benefits.

Subsequent research can combine BIM technology and artificial intelligence algorithms to realize the intelligent prediction of foundation pit deformation and the adaptive adjustment of construction parameters, and further improve the intelligence level of deep foundation pit engineering.

References

[1] Zhang S X. Discussion on construction quality control measures of diaphragm wall. Construction Technology, 2025, (32038): 115-117.

[2] Cheng X C. Application of construction technology for ultra-deep and ultra-thick diaphragm wall in soft water-rich stratum. Construction Technology, 2022, 51(4): 67-72.

[3] He Y C. Deformation control technology for diaphragm wall construction adjacent to existing operating metro station without retaining structure. Urban Mass Transit, 2022, 25(3): 56-60.

[4] Liu Q. Research on application of composite foundation with deep mixing pile combined with diaphragm wall in riverside wharf engineering. Port & Waterway Engineering, 2023, (7): 173-176.

[5] Mu Y. Research on application of diaphragm wall technology in metro station project under complex geological conditions. Chinese Journal of Geotechnical Engineering, 2021, 43(S1): 258-261.

[6] Peng J Y, Wang B, Gu X, et al. Parameter analysis of trenching stability of diaphragm wall in composite soil layer under seepage condition. Modern Tunnelling Technology, 2025, 62(S1): 254-261.

[7] Luo Q L, Mai S W. Optimization analysis and evaluation of support structure for ultra-deep foundation pit adjacent to bridge. Highway, 2025, 69(12): 437-445

[8] Kuang Y L, Tan J, Ding G S, et al. Research on construction technology of new and old diaphragm walls with bite connection of plain and reinforced piles. Building Technology, 2025, 56(22): 2762-2765.

[9] Guo M W, Dong X C, Shen K J, et al. Study on variation law of end resistance during soil extraction and sinking of super-large open caisson foundation. Chinese Journal of Rock Mechanics and Engineering, 2021, 40(Supp.1): 2976-2985.

[10]Mu B G, Chen Z Y, Gong W M. Model test analysis on horizontal bearing performance of open caisson-pile composite foundation. Chinese Journal of Underground Space and Engineering, 2022, 18(1): 190-200.

[11]Dong L H, Song D Q, Tang G J, et al. Analysis of the influence of super-large deep foundation pit excavation on the deformation of surrounding environment and countermeasures. Journal of Water Resources and Water Engineering, 2022, 33(1): 199-205.

[12]Liu M W, Wang X L, Zhu J J, et al. Temperature tracer test and analysis of leakage defects of diaphragm wall in ultra-deep foundation pit. Journal of Disaster Prevention and Mitigation Engineering, 2025, 45(6): 1525-1531.

[13]Tu W B, Huang M S. Horizontal dynamic response characteristics of open caisson-pile composite foundation. Journal of Disaster Prevention and Mitigation Engineering, 2019, 39(2): 285-289.