Design and Construction

Analysis and Practicality of a Plate Wall and Prestressed Steel Struts in the Interstage Backfill Construction of Deep Foundation Pits

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Abstract: Based on the phase II project of Block 07, District 14 of Shanggang, Baoshan New City SB-A-4, Shanghai, the underground three-layer foundation pits were excavated to the basement at one time. Due to project needs, the backfill construction progress of specific super high-rise building areas needed to be excavated significantly in advance. The calculation method of an elastic ground slab combined with a space frame beam was used to establish an integrated coupling analysis model for the foundation pit and the main structure in the incomplete state and to calculate the interaction mechanism and load distribution between the foundation pit and the main structure under a specific state. Under the premise of non-zoned excavation of the foundation pit, the preliminary removal of the supports in the specific area and the backfill construction of the main structure were achieved. The actual measurement data verify that, as a type of strut structure with a large bearing capacity and high structural stiffness, a plate wall combined with prestressed steel diagonal braces can ensure that the plate wall has better lateral stiffness and overturning resistance through the application of matching prestresses. This meets the conditions of an interstage support replacement system for deep foundation pits. The successful implementation of the project provides certain reference value for deep foundation pits that need backfill construction in advance.

Keywords: elastic ground slab; space frame; finite element analysis; support replacement

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1 Introduction

With the development of urbanization in China, various types of super high-rise buildings have emerged. The construction schedule for this type of project is often relatively tight, and progress can be constrained by commercial needs or the progress of other major municipal projects in the surrounding area. At present, the developmental concept of "excavating by pits and backfill construction by zone" is usually adopted for a core area with higher schedule requirements. However, this technique requires the addition of additional divider piles (walls) and the establishment of an independent supporting system in each zone. The overall construction period and cost are greatly affected. As the depth and scale of foundation pits become increasingly deeper and larger, the construction period for basements tends to increase. If the construction scheme of "excavating by pits and backfill construction by zone" is adopted, the construction period will further increase, and the construction period will be more easily affected by important social activities, major traffic control and other factors. Force majeure factors during this period may prevent basement construction in the core area from backfill construction as originally planned or even cause irreparable losses.

In the conventional method, the backfill construction of the deep foundation pit is accompanied by the removal of the supports and the corresponding replacement of the supports. The commonly used method of support replacement refers to the replacement of the internal support structure system with a certain technical solution to ensure the safety of the foundation pit and structure during the removal of the internal support; its essence is the readjustment, transfer and distribution of the stress in the foundation pit. At present, the traditional means of support replacement for the bracing system in soft soil areas are very mature. Zhu [1] summarized the existing conventional design methods for deep foundation pit replacement in soft soils, including ① a base plate force transfer zone and ② a floor slab force transfer zone; ③ oblique steel support replacement; ④ upturned corbel replacement; and ⑤ rib plate replacement. And through the " Shanghai Armed Police Corps Guesthouse Reconstruction and Expansion Project ", " Shanghai World Expo China Pavilion Project " and other five projects to verify the effectiveness of traditional support replacement. Liu et al. [2] conducted a series of studies on the demolition of pile row and diagonal brace composite systems. They used a collaborative calculation method to replace the support by arranging inclined steel tubes and backfill construction plain concrete outside the wall to achieve the effect of changing the support. The unfavorable factors of steel support through the wall are avoided, but its essence is still a type of diagonal support replacement. Wu et al. [3] proposed a turnable and scalable steel structure replacement beam, which solved the difficulty of the removal and support of the formwork for the replacement beam and slab and was also green and environmentally friendly and required no curing; its essence is the optimized extension of the floor replacement beam. Liu et al. [4] studied the relationship between the deformation of the foundation pit and the length of the piles, the depth of the foundation pit, and the spacing between the piles and the support piles, and from the perspective of the synergic deformation of the support system, they derived an expression for the deformation of the piles. Based on an actual project, Shen et al. [5] described in detail the technology and construction procedures of foundation pit replacement and studied multichannel strut removal and surrounding deformation-controlled construction methods. Based on an actual engineering case in a soft soil area, Fang et al. [6] used finite element calculations to analyze the deformation and internal force of a station. By increasing support replacement, the deformation of the foundation pit is reduced by 48 %. The above cases and studies mainly relied on traditional layer-by-layer or advanced structural transformation systems to ensure the safety of the surrounding envelope structure and control the deformation of the surrounding environment. Zhou [7] used slab-wall support replacement instead of the traditional mid-floor force-transfer belt support replacement method. Under the condition of a zonal foundation pit, the excavation time of the rear area significantly advanced, and the construction period was reasonably compressed. Some breakthroughs have been made in the technical advancement of online strut removal, but the traditional method of layer-by-layer excavation and layer-by-layer backfill construction is still used in the foundation pit of each zone.

In the process of strut removal and support replacement, foundation pits often cross into foundation pit retaining structure construction and main structure construction. Methods such as floor slab support replacement, temporary internal support replacement with partial openings, and diagonal support replacement are often used to replace supports layer by layer. The technical route of the backfill construction is linear and single; that is, the last temporary support is removed after the main structure of the previous layer reaches the design required strength. If there is a locally higher demand for progress, it is difficult to make more flexible adjustments from the design conditions. Therefore, researching a demolition and replacement supporting technique route that maximizes the advance of core area backfill construction progress under without dividing pits condition has great engineering significance and practical demands. In this study, the 3D finite element analysis method is used to establish an integrated analysis model of the interaction of the foundation pit envelope structure, the main structure, the retaining wall, and the supporting structure. The load of the strut structure under the conditions of early demolition and support replacement was calculated, and the shear sheet wall structure + prestressed steel strut technology was used to meet the load transfer requirement. This research and engineering practice has high reference significance for the interstage rapid backfill construction of special areas in deep foundation pits.

2 Engineering Background

This study is based on the phase II project of Block 07, District 14 of Shanggang, Baoshan New City SB-A-4, Shanghai. The foundation pit area is approximately 24,000 m^2, and the excavation depth is approximately 16.0~17.8 m. The construction schedule for this project was very tight. During the construction stage, the G1501 Tunnel, a major project in Shanghai, was completed adjacent to the project. The supporting facilities, the wind tower structure and the emergency command and management center are located at the southeast end of the foundation pit, which are required for synchronous construction by the major municipal office of Shanghai. Due to the increased construction progress of the G1501 tunnel in the mid-construction stage and the difficulty in excavating the foundation pit due to the influence of the China International Import Expo, the construction period for the wind tower and management building area at the southeast end of the foundation pit was obviously insufficient in the backfill construction stage. To meet the progress requirement, the wind tower and management building area should be backfilled construction to ±0.000 m within 2 months after excavation reaches the basement, and the remaining areas should be backfilled construction to ±0.000 m according to the normal schedule (approximately 4 months). Ultimately, a large-scale support replacement system needs to be designed to meet the requirements of early removal and backfill construction of partial foundation pits (180 m wind tower and 5F management building). The detailed planar section conditions of the foundation pit in this project are shown in Figure 1.

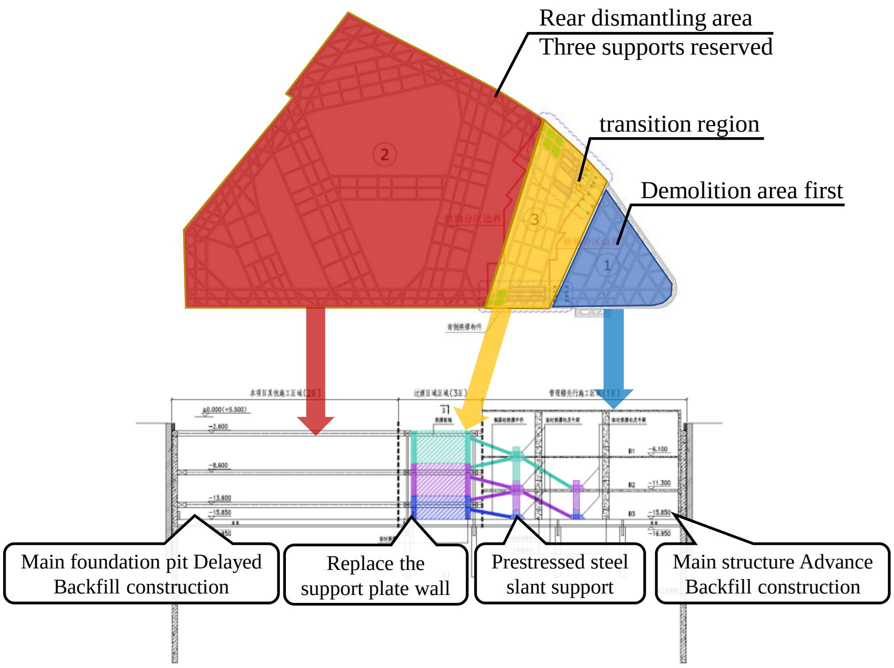

Figure 1 Schematic diagram of the target conditions

3 Creation of the Finite Element Model

To ensure that the interaction between the foundation pit envelope and the main structure can be fully considered in the calculation process, a theoretical model of an elastic ground slab combined with a space frame beam is proposed. Elastic ground

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slab model is usually numerically constructed based on the 3D "m" method. This method can reflect the actual space stiffness of the envelope structure [8]. The water and soil pressure and passive soil stiffness used have already been coded and verified by a large number of projects. The distribution pattern, magnitude of the water and soil pressure on the outside of the underground diaphragm wall and the spring stiffness of inside were the same as those of the elastic foundation beam method in the codes. The load was calculated through the typical cross section of this project, which is shown in Figure 2 below.

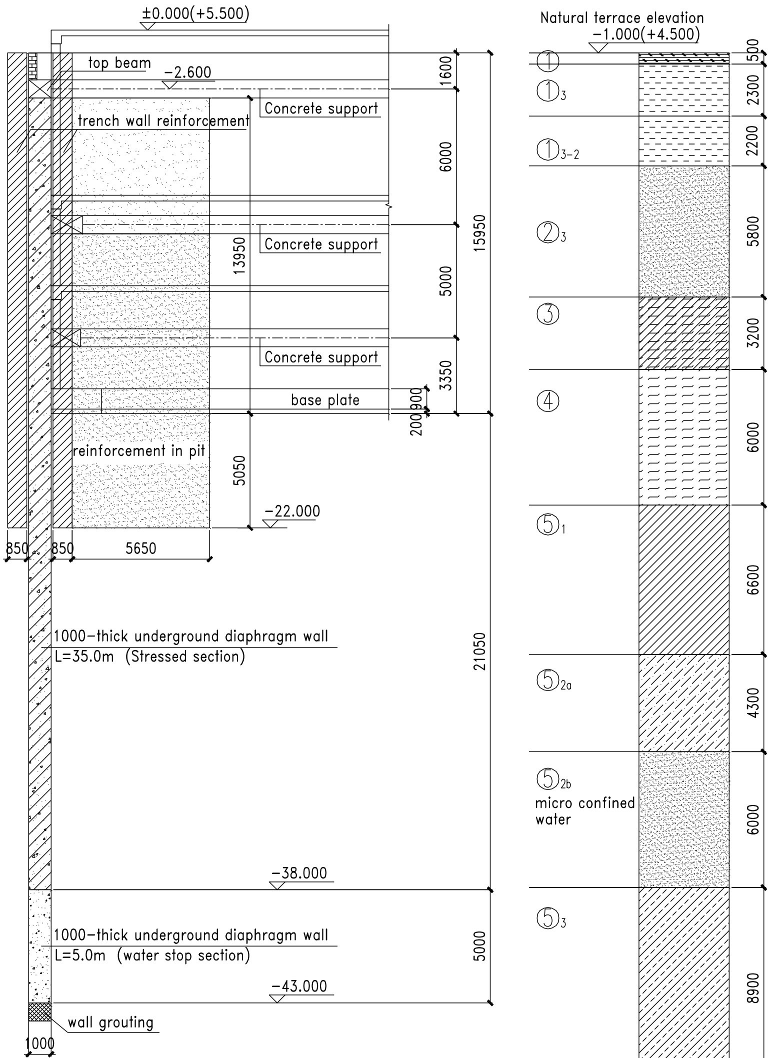


Figure 2 Typical section (Elevation units: m, dimension units: mm)

(1) Hydrogeological conditions

According to the survey report, the soil layer within the foundation pit is a typical soft soil layer in Shanghai, and the physical and mechanical indicators of each soil layer are shown in Table 1.

Table 1 Physical and mechanical parameters of the soil

Layer No.	Name of soil layer	γ (kN/m³)	c (kPa)	φ (°)	m (MPa/m²)
①	Fill	18.0*	5*	10*	1.0
①$_{3-1}$	Dredge fill	18.5	4	28.5	7.0
①$_{3-2}$	Dredge fill	18.5	13	21.5	6.0

Layer No.	Name of soil layer	γ (kN/m³)	c (kPa)	φ (°)	m (MPa/m²)
②$_3$	Sandy silt mixed with silt clay	18.8	4	28	6.5
③	muddy-silty clay	17.8	13	18.5	5.0
④	Silt clay	16.8	11	12	2.0
⑤$_1$	Clay	17.3	13	12	2.5
⑤$_{2a}$	Silt clay mixed with clay silt	18.0	14	20	3.7
⑤$_{2b}$	Sandy silt mixed with silt clay	18.2	7	29.5	7.5
⑤$_{2c}$	Sandy silt	18.3	5	32	3.3
⑤$_3$	Silt clay mixed with clay silt	18.0	14	20	3.3
⑧$_1$	Silty clay	18.0	16	18.5	3.5
⑧$_2$	Sandy silt mixed with silt clay	18.5	20	29.5	8.0

Note: γ is gravity, c is the cohesion force, φ is the friction angle, and m is the soil resistance coefficient

The project site is part of the coastal plain geomorphology. The main source of water is atmospheric precipitation, and the annual water level varies little under the influence of surface water and groundwater. According to the actual measurements, the stable burial depth of the groundwater is approximately 0.3~0.5 m. Before the excavation of the foundation pit, the groundwater level should be no less than 0.5 m below the bottom of the pit. Therefore, based on the physical and mechanical properties of the stratum, in the model, soil and water pressure outside the pit adopted active soil pressure loading to the outside of the ground wall based on soil and water separation calculations.

(2) Structural unit assumption

During the 3D modeling process, the beam and slab elements were assumed to be homogeneous and isotropic. The core tube, ground wall, trestle slab, base plate, and floor slab were simulated using curved surface thick shell elements; the supporting beams, structural beams, columns, and structural columns were simulated using a simulation of a space-linear beam element, and the support rod element was loaded and activated in stages through a life-death element.

(3) Component constraint relationship

The interaction of the monolithic structure was constrained. According to the deformation characteristics of the purlins and the foundation pit, the friction function was used to simulate the relationship between the purlins and the ground wall. With reference to the existing codes [9], the friction coefficient between concrete layers can be set between 0.6 (not chiseled and polished) and 1.4 (one-time cast-in-place), depending on the chiseled degree and connection state between the concrete layers. A low value of 0.6 was set in this design.

For the simulation, a spring unit was set up at the passive area side of the ground wall, and combined with the passive “m” method used in the elastic foundation beam method in the codes, the grounding spring stiffness of the passive soil was set according to the three-dimensional “m” method.

(4) Column system and frame structure

According to a study by Li et al. [10], the deep foundation pit envelope structure system is actually composed of a horizontal support system and a vertical support system, which together resist the horizontal load outside the pit. After the foundation pit reaches a certain scale, the lateral stiffness of the column-bent frame system often reaches a nonnegligible level. Therefore, when overall modeling of the foundation pit is performed, the supporting system model is formed by setting the column-bar unit and the foundation pit supporting system together.

Based on the above structural system analysis, 3D integrated modeling of the full foundation pit was performed using finite element software. The model was composed of 47577 groups of beam elements and 37952 groups of plate and shell elements. The passive soil was simulated using grounded spring elements. The specific meshing is shown in Figure 3.

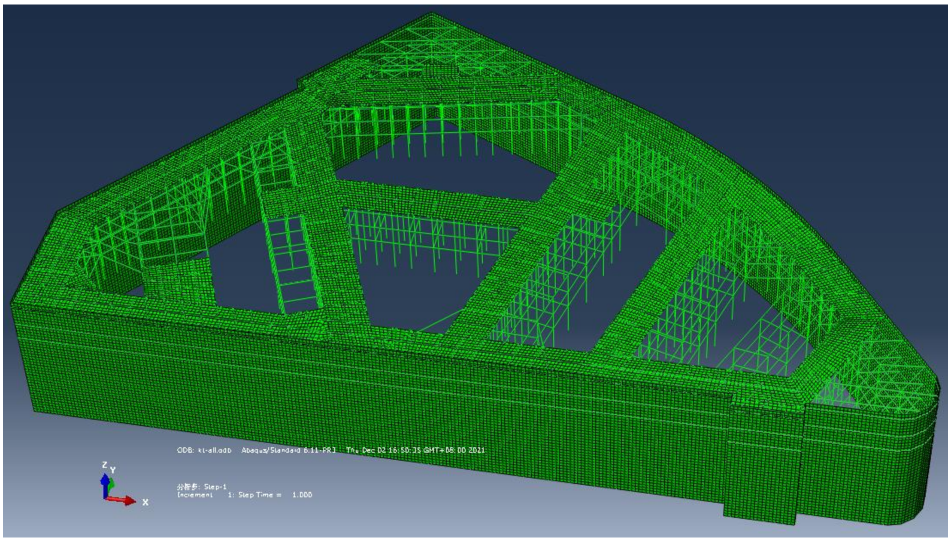


Figure 3 Model grid division

(5) Foundation pit deformation analysis

In analyzing the deformation of the foundation pit, the rationality of the finite element model should be ensured, which lays the model foundation for the analysis of the interaction between the nonholonomic sporting system and the main structure in the subsequent process of partial support removal and rapid backfill construction in specific areas. The deformation contour of the foundation pit of the elastic foundation slab is shown in Figure 4. The effectiveness of the scheme proposed in the present study is verified by comparing the actual measurement data and the calculation results of the elastic foundation beam.

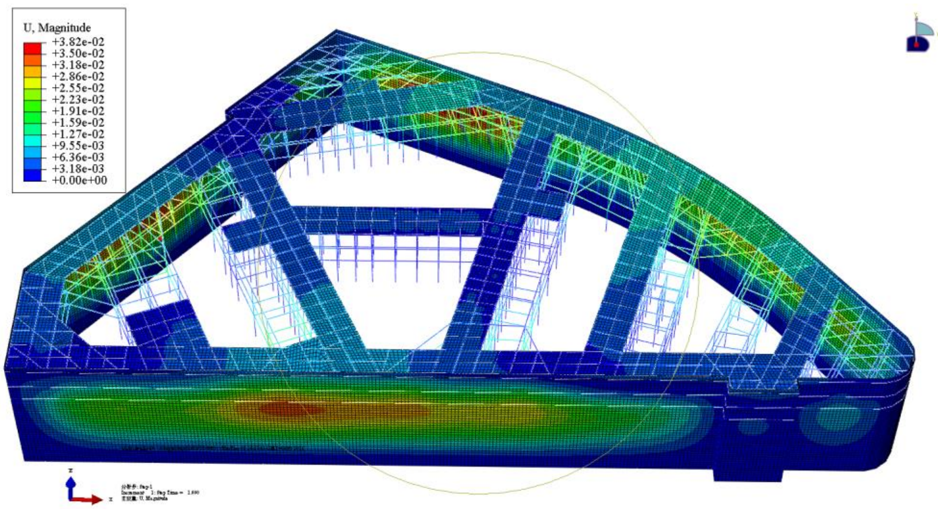
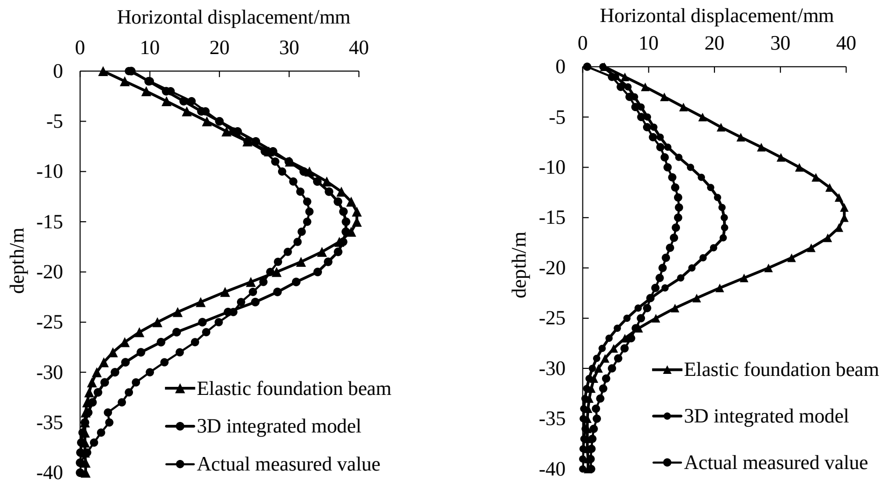


Figure 4 Cloud map of foundation pit deformation (Unit: m)

During the excavation stage of the foundation pit to the basement, the monitoring data of the current period were compared with the calculation results of the conventional elastic foundation beam method. A comparison of the data in different spatial regions is shown in Figure 5.



(a) Maximum deformation of the foundation pit

(b) Deformation of the area to be demolished first

Figure 5 Deformation analysis and comparison

The maximum deformation is located in the middle section of the gussets and opposite braces on the long sides, and the maximum deformation is 3.82 cm. The calculation results are basically consistent with the deformation trend and maximum value of the foundation pit based on the elastic foundation beam calculation [6], but the deformation of the ground wall located in the circular arc segment of the eastern corner of the foundation pit is significantly smaller than that of the elastic foundation beam. The calculation results of the elastic foundation beam method and elastic foundation slab method in the middle of the foundation pit exceeded the measured values by 21.7% and 15.8%, respectively, and the calculation results of the corner area where the wind tower was demolished first exceeded the measured values by 148.1% and 47.2%, respectively. The deformation results of each area show that the location of the wind tower area in this project has an obvious spatial effect. Especially for the individual cross-sections of the circular arc segment on the east side, the maximum deformation of the ground wall was only approximately 14.6 mm, and obvious hoop stress appeared locally. The 3D integrated finite element model based on the elastic foundation slab can more accurately reflect the deformation characteristics of each space region of the actual foundation pit. However, the calculated deformation and internal force results of the traditional elastic foundation beam model are significantly larger than the measured results, and overall, the model is relatively conservative and is not conducive to the exploration of the essential results of foundation pit projects. Therefore, the obvious spatial effect of the wind tower area at the corner makes this interstage replacement possible.

4 Design and Analysis Method for Interstage Support Replacement

The interstage strut removal construction technology has special requirements for theoretical analysis. Through sorting and analysis, the following three main key issues related to zonal interstage strut removal technology were identified in this study:

(1) After the partial support is removed, the remaining incomplete support system still needs to be in a safe state, and the foundation pit deformation needs to be within a controllable range.

(2) Only a small amount of the main structure must be backfilled first; the strength and stiffness requirements of the main structure must be met, and the structural deformation (interstory displacement angle) must be within the allowable value in the codes [9].

(3) The replacement strut system must have sufficient strength and stiffness to meet the replacement load requirements of the three-layers supports.

In the end, based on the 3D integrated finite element model, the weak locations of the support and structure were strengthened, and the strut structure was designed in a targeted manner.

4.1 Load-Bearing Analysis of the Multi-Layer Support System in the Nonintact State

In the overall excavation of the foundation pit, the removal and replacement of multi-layer supports in some areas at one time will cause the stress redistribution of the original support system in a relatively large range. Ensuring that the remaining multi-layer supports can still meet the strength and stability requirements of the foundation pit is one of the prerequisites in this study.

The target work condition of the support area is to retain the three-layers supports and remove the local supports after the base plate and support replacement are completed. In this section, the replacement load at the end of the remaining support system is calculated based on the 3D integrated finite element model, the life-death element method is used to simulate the subsequent incremental work cases, and the results are compared with those of the traditional design method (elastic foundation beam combined with planar frame beam). The replacement loads are shown in Table 2.

Table 2 Calculation results of the support replacement load

Maximum value	Elastic ground slab method (kN)	Elastic foundation beam method (kN)
The first shaft replacement force	1644	4226
The second shaft replacement force	3485	9895
The third shaft replacement force	1328	6041

Because the elastic ground slab method can consider the spatial effect of the foundation pit and the stiffness of the base plate, the calculated shaft replacement force attenuates significantly near the end of the wind tower, and the obtained support replacement is only 1/3~1/4 that of the elastic foundation beam method, and the calculation results obtained by different methods are significantly different. Therefore, in the actual design of support replacement, the spatial shape characteristics of the foundation pit should be considered, and the specific location of the support replacement should be used to conduct a 3D integrated analysis of the coupling of the foundation pit, the support replacement, and the main structure. It can also be seen from the final monitoring results that the trend of the actual support replacement load on the support replacement wall and the calculation results using the elastic floor slab method are basically consistent.

4.2 Main Structure Analysis in the Incomplete State

Usually, in structural design, only the situation of complete basement backfill construction is considered, and the load-bearing safety in the partial backfill construction process is not considered. Therefore, in the present study, it is necessary to consider whether the stiffness, strength, and interstory displacement angle of the main structure under the incomplete condition of the backfill construction phase can meet the requirements of the original design and the subsequent use during the permanent phase [11]. The deformation and load-bearing characteristics under the two conditions of “with support replacement wall” and “without support replacement wall” were compared and analyzed, and the interstory displacement angle was used to determine whether the structure would undergo systematic deflection and whether the structure is safety.

Table 3 Limit values of the interstory displacement angle

Structure type	θ
Reinforced concrete frame	1/550

Structure type	θ
Reinforced concrete frame-seismic wall, frame-core tube	1/800
Reinforced concrete seismic wall, tube-in-tube	1/1000
Reinforced concrete frame and support floor	1/1000
Multi and high-rise steel structures	1/250

Through calculation and analysis, under the condition of partial strut removal first, the displacement contours of the foundation pit and main structure are shown in Figure 6.

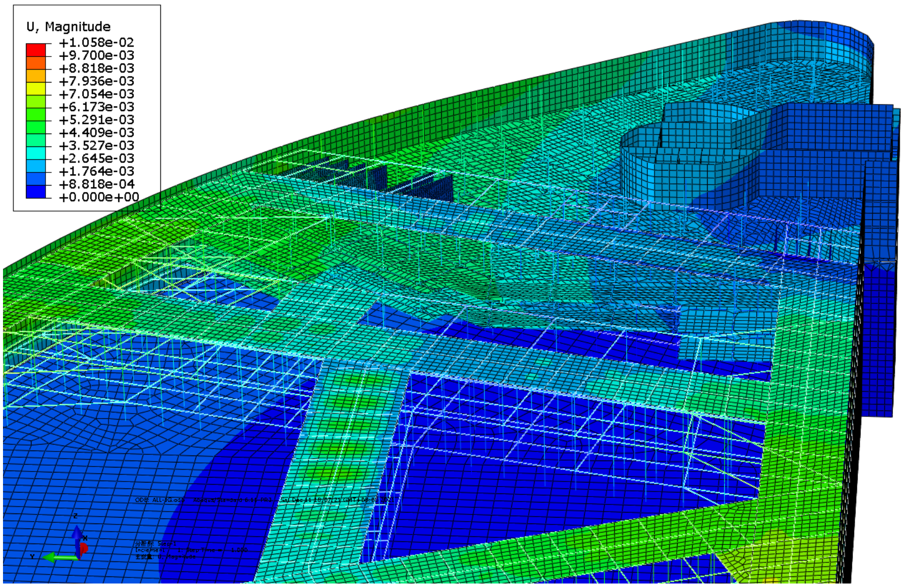


Figure 6 Cloud diagram of the displacement

The stresses and interstory displacements of the nonintact main structure under the two conditions of with the support replacement wall and the condition without the support replacement wall are compared (Table 4).

Table 4 Load-bearing comparison of structure

Structure position	With support replacement wall	Without support replacement wall
Structural displacement	2.24 mm	5.56 mm
Base plate displacement	1.8 mm	4.2 mm
Interstory displacement angle	0.102‰	0.168‰
Core tube structural stress	2.37 MPa	4.34 MPa
Base plate stress	7.69 MPa	4.49 MPa
Floor slab stress	7.87 MPa	5.27 MPa

It can be seen that the support replacement wall can reduce the deformation and interstory displacement angle of the incomplete main structure to a certain extent, but the local base plate and floor slab stress increase, and the stress is still within the safe controllable range after the increase. Analysis of the 3D integrated model of the support replacement wall and support system reveals that the structure will not systematically drift, and its strength and stiffness still have a certain safety margin.

4.3 Design of the Special Support Replacement Structure

Due to the unique circumstances of the advance fillbacking of the main structure in this project and under the premise that nonhomogeneous support and structural analysis are feasible, the primary purpose of the support replacement structure is to ensure that significant deformations do not occur in the nonhomogeneous support during the partial dismantling process, thereby preventing systemic instability of the outer wall system. Additionally, it aims to control interstory displacements of the advanced backfilled main structure. The interaction between the nonhomogeneous support system and the structural system, as well as load calculations, are crucial aspects of this specialized support replacement structure.

Based on actual measurements and analysis, the cast-in-place plate wall, base plate and structural floor slab can be directly used as the conditions for the bound fixed support. The finite element analysis results show that the local compressive stress loading effect on the plate wall heel is obvious under the support load, with the maximum compressive stress reaching 3.51 MPa. Although it is far from the compressive failure limit of concrete, considering the complexity of local stress concentration and node load bearing effect, the joints between the support and the plate wall need to be strengthened during the design process. An obvious tensile stress also appeared at the bottom at the toe of the wall. Therefore, key treatment needs to be carried out at the connection between the plate wall and the base plate. Moreover, if necessary, prestressed steel diagonal braces can be set after support replacement to control the overturning bending moment of the plate wall. Table 5 shows the comparison of the plate wall loading method used by the 3D integrated finite element analysis method and the elastic foundation beam calculation.

Table 5 Summary of plate wall load analysis

Mean stress of plate wall	Elastic foundation beam method	3D “m” method
Maximum tensile stress	15.7 MPa	3.46 MPa
Maximum compressive stress	14.0 MPa	4.67 MPa
Maximum deformation	8.2 mm	4.48 mm

The strut load obtained by the traditional design method acted directly on the plate wall, and the tensile stress reached 15.7 MPa, which is far greater than the tensile strength of the concrete structure. However, the stress at the connection between the base plate and the plate wall was even greater. In view of the risk of overturning under the action of large horizontal thrust, it is necessary to set up prestressed oblique steel supports at the back of the wall to transfer the overturning force of the plate wall to the completed main structure. A total of 609×16 steel tubes are set up between the plate wall and the beam-column joint of the main structure, and the plate wall and beam-column corbels are connected by pre-embedded structures. At the beam-column joints, adding inclined concrete corbels and setting pre-stressed hydraulic jacks at the end of the corbels would provide additional support. Based on the axial forces of the support in the main foundation pit before dismantling, three layers of steel supports are installed from top to bottom. Each layer applies pre-tensioning with forces of 600 kN for the first layer, 800 kN for the second layer, and 800 kN for the third layer, ensuring that the main pit supports in advanced backfilled area have transferred part of the horizontal loads to the main structure before they are removed. Figure 7 shows the structure of the prestressed loading device and the beam-column corbel joint.

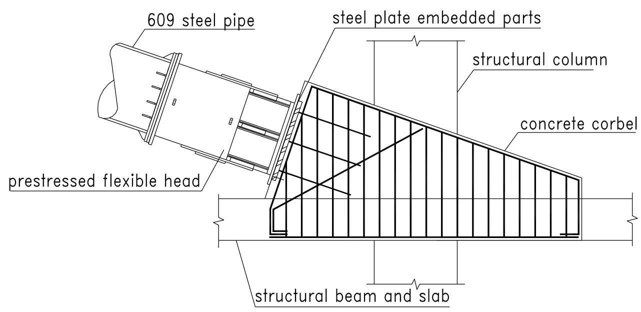


Figure 7 Schematic diagram of node construction

5 Comparison and Analysis of Actual Measurement Results

Through partial interstage removal and support replacement technology, this project completed the roofing of the key nodes of the wind tower approximately 2 months ahead of schedule. The actual scene of early strut removal and support replacement in the eastern area is shown in Figure 8.

Figure 8 Actual picture of early backfill construction

When the elevation of the whole foundation pit was ±0.000 m (the support was not removed in the transition area), the wind tower and management building were constructed to the 5F, and the wind tower core tube was constructed to the 6F, which greatly shortened the total construction period of the project. Figure 9 shows the actual scene of the wind tower backfill construction area.

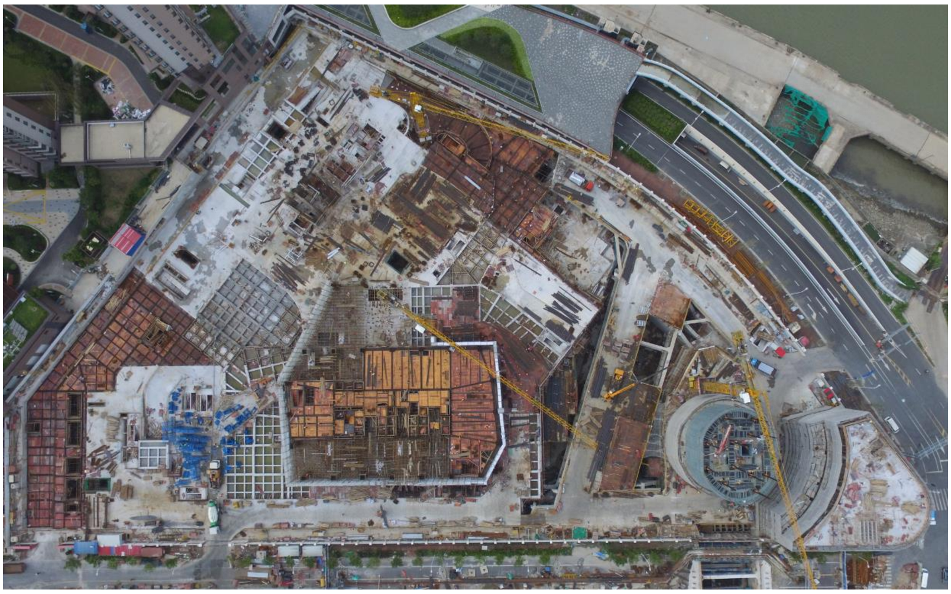


Figure 9 Real view of the project

5.1 Actual Situation and Monitoring Plan

According to the design scheme, in the interstage zonal dismantling and support replacement stage of this project, the internal force and displacement of the temporary support replacement component need to be monitored to ensure the safety of the dismantling and support replacement system under the support replacement condition and to verify the effectiveness of the support replacement scheme. In addition, vertical displacement and crack monitoring were performed on the foundation base plate near the support replacement wall to ensure that the deformation of the foundation base plate under the support replacement condition was within the allowable range.

The specific monitoring steps for support replacement include ① monitoring the positive cross-section stress of the concealed column and the interface between the wall and the existing support and ② monitoring the horizontal displacement, vertical displacement and internal force of the concealed column; ③horizontal displacement (parallel to and perpendicular to the plate wall) and internal force monitoring of the support replacement plate wall; ④ internal force monitoring of the support replacement components; ⑤ horizontal displacement of the temporary support replacement plate wall (parallel to the plate wall direction and vertical to plate wall direction) and internal force monitoring; ⑥ vertical displacement and crack monitoring of the foundation base plate within the range of the plate wall (within 10 m outside the outer profile of the plate wall); and ⑦ crack monitoring of each component of support replacement system (Figure 10).

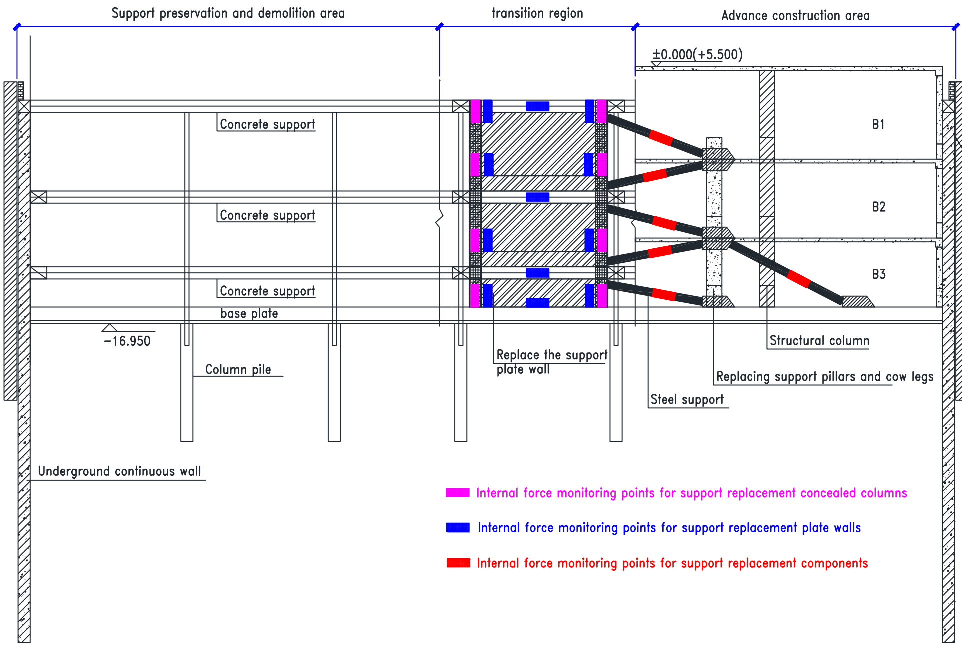


Figure 10 Internal force monitoring points on the plate wall (Elevation Units: m)

5.2 *Stress–Strain Monitoring of the Special Support Replacement Structure*

According to the monitoring of steel stress in the slab body and the original design calculation results, obvious tensile stress appeared in the slab near the toe region, and the maximum steel tensile stress was 17.4 MPa. The longitudinal reinforcement ratio of the plate wall in the monitoring area was 2.46%, and the equivalent average tensile stress of the slab body was 3.12 MPa. Considering the anchorage condition between the concealed column and the base plate, the tensile stress of the slab body can be completely borne by the anchor steel bars, and the bearing capacity meets the tensile capacity of the concealed column. The maximum compressive stress of the plate wall reinforcement was 27.6 MPa, and the average compressive stress of the composite slab body was 4.95 MPa, which was far lower than the compressive strength of the slab structure. The monitoring results of the internal force of the plate wall and the internal force of the support replacement component (partial) are shown in Figures 11 and 12.

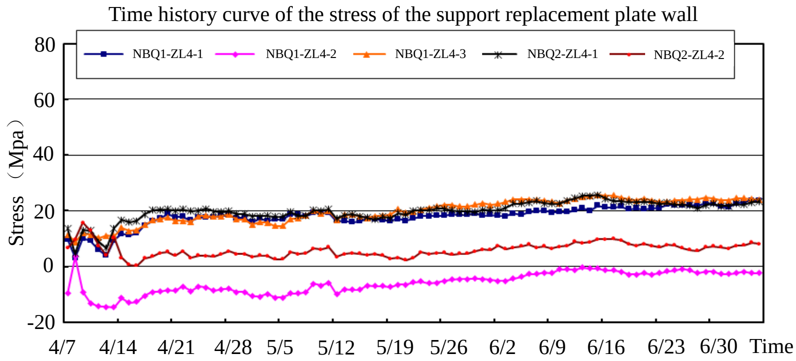


Figure 11 Stress of the support replacement plate wall (Unit: MPa)

The maximum axial load at the end of the diagonal support at the back of the plate wall is 3543 kN. The axial force of the other members is generally approximately 1800 kN~2400 kN, and the overall axial force of the support replacement is less than the design value of the bearing capacity of the diagonal support of the plate wall.

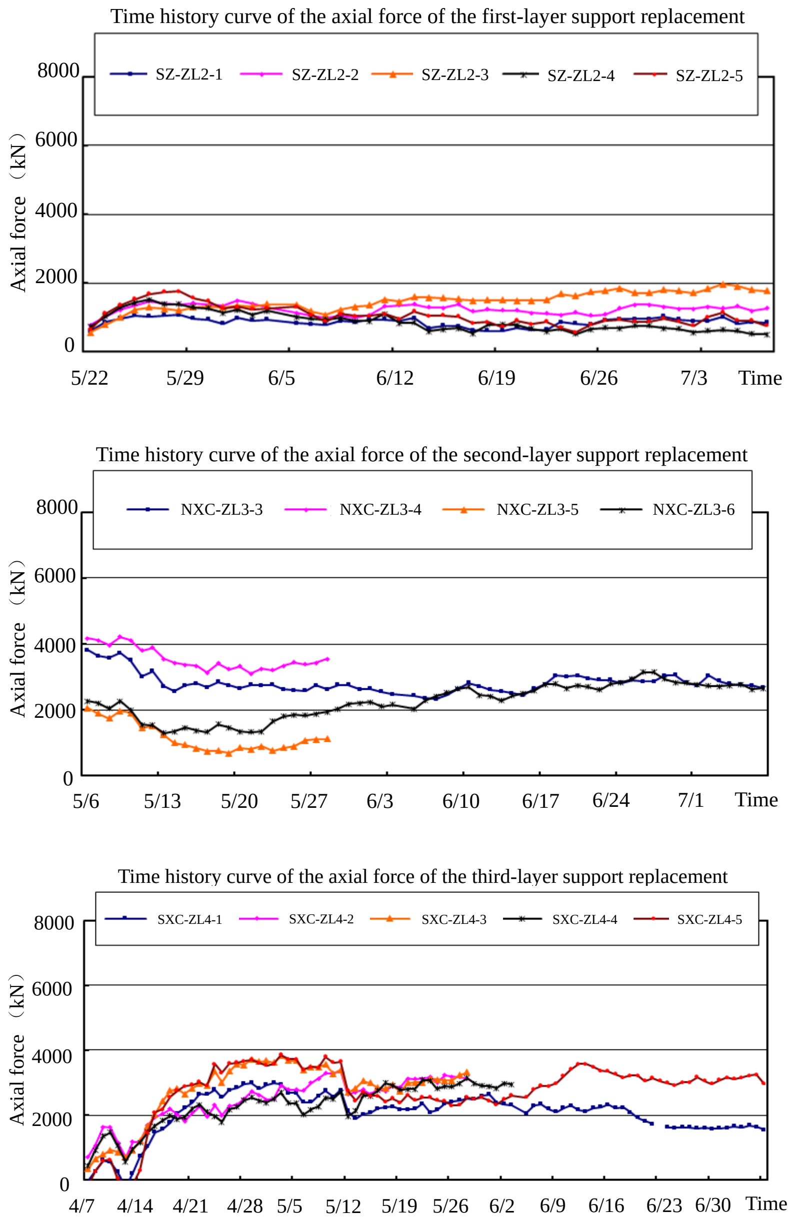


Figure 12 Axial force monitoring data (Unit: kN)

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5.3 Comparison and Validation of the Theoretical Analysis Results

Monitoring of the foundation pit envelope structure and temporary support replacement system reveals that the implementation of subregional and interstage removal and support replacement design for the foundation pit in this project is generally feasible, and the deformation of the foundation pit body and surrounding buildings (structures) are safe and controllable within the range.

From the actual measurement results and calculation analysis, the actual measurement results are closer to the 3D integrated analysis method of the elastic ground plate combined with the space frame beam, but the third-layer support replacement force is generally greater than that of the design scheme, mainly due to the partial quick disassembly in the original design scheme. The support and restorations require the completion of large base plate concrete construction and curing to 80% of the standard strength. However, under actual working conditions, support removal and support replacement in the advance construction area started less than a day after the pouring of the large floor concrete in the slow construction area. Since this is the first time that multistage demolition technology has been used in soft soil areas, a certain design margin was left in the design process, and the replacement load during the construction process did not exceed the actual load design value.

6 Conclusions

The successful implementation of this project shows that a plate wall replacement system can effectively balance the internal force and deformation between a support system and a constructed structure system, creating favorable conditions for the advance backfill construction of local structures and subsequent construction. The structural modeling scheme based on an elastic ground slab combined with a space frame beam can be used to calculate the space effect and interaction relationship of a foundation pit project, which cannot be considered by conventional design methods. The successful implementation of this interstage removal and support replacement technology provides a reference for similar special support replacement projects, and through a series of analyses and practices, the following conclusions can be reached:

(1) For projects with special needs, as a slab (rib) structure with high stiffness and good load-bearing state, it can be applied to a force-transfer system before interstage strut removal under specific conditions.

(2) Before the removal and replacement of the support across stages, the safety of the support system in the incomplete state should be considered to ensure that the support system in the incomplete state in the slow construction area can meet the structural strength and deformation requirements.

(3) Controlling the main structural strength and interstory angle of the advanced construction area is a prerequisite for overall interstage removal, support replacement and backfill construction.

(4) The foundation pit project and the main structure in the interstage process are spatial interaction problems, and the traditional calculation method of elastic foundation beams cannot truly reflect the interaction relationship. The modeling and design method of an elastic slab combined with a space frame beam can relatively accurately calculate the structural internal force and deformation under complex working conditions. For foundation pits with obvious space effects, the overall calculation of the elastic slab combined with a space frame beam is more reliable and reasonable.

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References

1. Zhu, X. Design of Support Replacement for Controlling Deformtion Caused by Support Dismantling of Deep Foundation Pits in Soft Ground. *Chinese Journal of Geotechnical Engineering* **2010**, *32*, 256-260.
2. Liu, Y.; Liu, J.; Xin, Z.; Shen, H. Support Replacement Technology of Bracing System with Oblique Bracing + Piles in Row. *Chinese Journal of Geotechnical Engineering* **2010**, 306-311.
3. Wu, J.; Zhang, B.; Mao, K.; Meng, S. Application of Steel Structure Changing Beams in Inner Supporting Foundation Pit Engineering. *Architecture Technology* **2020**, *51*, 1055-1059, doi:10.3969/j.issn.1000-4726.2020.09.008.
4. Liu, Y.; Liu, J.; Wang, H. Removing First and Supporting Then Method for Diagonal Bracing System. *Chinese Journal of Geotechnical Engineering* **2010**, 77-80.
5. Shen, X.; Zhang, J.; Xu, X.; Wang, Z. Optimization and Construction of Bracing Substitution of Deep Foundation Excavation Support by Stage Construction. *Construction Technology* **2014**, *43*, 45-47, doi:10.7672/sgjs2014010045.
6. Fang, H.; Chai, Y.; An, W.; Xu, X. Numerical Simulation Study on Brace Replacement of Standard Station of Tianjin Metro. *Low Temperature Architecture Technology* **2013**, *35*, 122-123, doi:10.3969/j.issn.1001-6864.2013.12.047.
7. Zhou, S.; Qiu, C.; Zhou, J.; Yu, A.; Sun, Y. Construction Technology of Support Replacement by Rib Wall in Deep Foundation Pit. *Building Construction* **2020**, *42*, 329-331, doi:10.14144/j.cnki.jzsg.2020.03.010.
8. Shen, J.; Wang, W.; Weng, Q. Analytic Method of Diaphragm Walls of Circular Foundation Pits. *Chinese Journal of Geotechnical Engineering* **2008**, 280-285.
9. American Concrete Institute. ACI 318: American Code for Design of Concrete Structures. 2014.
10. Li, M.; Xu, Y.; Zhang, B. Research on Lateral Stiffness of Strutted Retaining Structure for Deep Excavation. *Journal of Engineering Geology* **2020**, *28*, 1116-1122, doi:10.13544/j.cnki.jeg.2020-430.
11. Weng, Z. Discussion on the Control of Interstory Displacement Angle Limit Value of High-Rise Building Structure. Master, South China University of Technology, 2015.

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