



Research on Construction and Application of Technical System of Support and Monitoring for Deep and Large Foundation Pit

Chao Cui, Zhiyuan Zhang *, Zequan Yu, Jiantao Jia, Liang Zheng

China First Highway Engineering Co., Ltd, Beijing 100120, China

*Email address: 348268467@qq.com

Abstract. This study investigates a deep foundation pit project on the south bank of the Taiping River in Chang'an District, Shijiazhuang City, Hebei Province. The project features 7–18 floors above ground and 1–2 underground floors, with excavation depths ranging from 5.5 to 9.3 meters under complex geological conditions. A combined “soil nailing wall–pile and anchor” support system was adopted, with upper C20 soil nails (8–12 m) and lower cast-in-place reinforced concrete piles (600–800 mm diameter, 900–1000 mm spacing) combined with prestressed anchor cables. Layered island-style excavation and standardized support procedures were employed to optimize construction. A multi-dimensional monitoring system was implemented, covering slope top horizontal and vertical displacement, deep soil movement, groundwater levels, and road settlement. All measured values remained within alarm thresholds. The maximum cumulative horizontal, vertical, and deep displacements were 5.27 mm, 5.38 mm, and 20.3 mm, respectively. Numerical simulations were performed alongside field monitoring. The simulated results showed similar trends to measured data, with most values slightly lower and a few marginally higher, verifying the model’s accuracy and reliability. A comparative analysis with soldier pile + strut and diaphragm wall systems demonstrated that the adopted scheme offers better cost-effectiveness, adaptability, and environmental performance. The integration of structural monitoring and numerical simulation confirms the safety, stability, and applicability of the support system. These results provide a practical reference for similar urban deep foundation pit projects.

Keywords: Deep and large foundation pit; Foundation pit support; Foundation pit monitoring; Horizontal displacement; Vertical displacement

1 Introduction

With the acceleration of the urbanization process, urban construction is expanding to the upper air and underground, and the scale and number of deep foundation pit projects continue to grow^{1–3}. As the key link of underground engineering construction, the construction complexity and potential engineering risk of deep foundation pit should not be underestimated^{4,5}. On the one hand, the construction of deep foundation pit involves

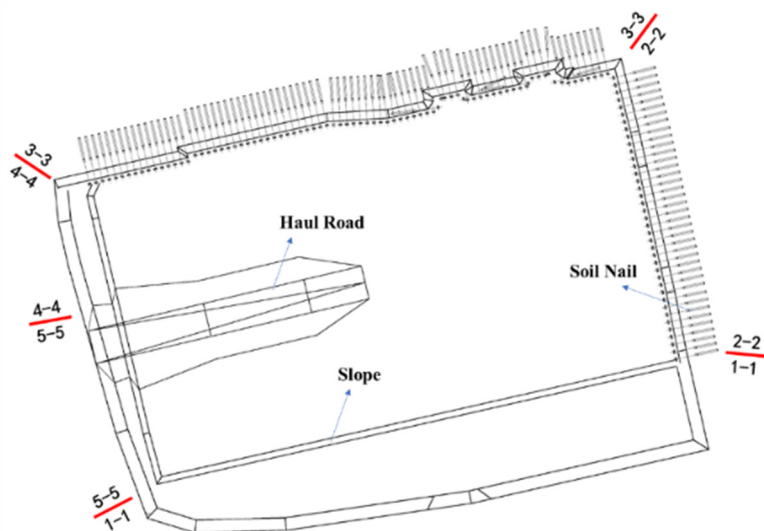
the cross-application of multidisciplinary knowledge such as rock and soil mechanics, structural mechanics, engineering surveying, etc. The diversity of geological conditions in different regions, such as soft soil, sandy soil, rock and other geological types, puts forward strict requirements on the support and construction technology of foundation pit^{6,7}. On the other hand, in the process of foundation pit excavation, the change of soil stress state, the load of surrounding buildings and the dynamic change of groundwater can easily cause the deformation of foundation pit, and even lead to serious engineering accidents such as foundation pit collapse, which not only affects the progress of the project, but also may endanger the life and property safety of surrounding personnel^{8,9}. In recent years, although in deep foundation pit supporting and monitoring technology in our country has obtained certain achievements, new form of supporting structure and methods constantly emerging^{10,11}, but the face of complicated geological conditions and increasingly stringent safety standards, still need to be further in-depth study. This deep foundation pit project on the south bank of Taiping River, Chang 'an District, Shijiazhuang City, Hebei Province, is located on a site with complex geological conditions and large excavation depth, which is a branch project with greater risk of exceeding a certain scale. In view of this, the construction and application research of the support and monitoring technology system of the deep foundation pit of this project not only helps to solve the practical problems of the project, but also provides scientific and effective technical reference for the deep foundation pit engineering under similar geological conditions, and promotes the progress and development of deep foundation pit engineering technology.

2 Project Profile

The project is located in the south bank of Taiping River, Chang 'an District, Shijiazhuang City, Hebei Province. The building layer number is 7-18 above ground, one underground layer/two local layers, the main structure adopts frame-shear wall system, the building height is 21.3-53.75m, and the excavation depth is 5.5-9.3m. The geological survey depth of the site is 60.0m, and the formation is mainly composed of fill, sand, silt and silty clay, which is divided into 12 engineering geological unit layers and 1 sub-layer. The combined support system of "soil nailing wall, pile and anchor" is adopted for the foundation pit. The soil nailing wall (C20 reinforced soil nailing) is adopted for the upper part of the foundation pit, the 600@900 (800@1000) reinforced concrete cast-in-place pile and 6s15.2 steel strand anchor cable are adopted for the lower part, the surface layer is reinforced with C20 concrete, and the drainage hole is arranged with PVC pipe with a diameter of 50mm. Horizontal and vertical spacing 2m. According to the relevant regulations, the foundation pit project is identified as more than a certain scale of dangerous sub-projects, and corresponding safety protection measures are taken. This project mainly divided into six sections to carry on the design of foundation pit, the main design parameters and foundation pit layout **Table 1** and shown in Fig. 1.

Table 1. Main design parameters of foundation pit

Project	Design parameters and results
Foundation pit perimeter	460m
Pit area	13500m ²
Depth of foundation pit	3.8—9.5m
Design service life of foundation pit	1 year
Soil nailing	C20 rebar is used as soil nail
Bar-mat reinforcement	Single-layer bidirectional $\Phi 8@200$
Concrete	C20
Outlet entrance	50mmPVC, vertical spacing 2m.

**Fig. 1.** Foundation pit layout

3 Numerical Simulation

The numerical model was constructed in PLAXIS 2D, with stratified soil layers based on site investigations. The Mohr–Coulomb model was used to simulate soil behavior. Table 2 summarizes the mechanical parameters adopted for the different soil layers and structural elements. The support system, including reinforced soil nails, cast-in-place piles, and anchor cables, was modeled using embedded beam and geogrid elements where appropriate. The interface strength between soil and structure was set at 0.7–0.9 times the corresponding soil strength parameters.

Table 2. Soil and Structural Parameters Used in Numerical Simulation

Material/Element	Unit Weight γ (kN/m ³)	Cohesion c (kPa)	Friction Angle φ (°)	Young's Modulus E (MPa)	Poisson's Ratio ν	Notes
Fill soil	18.0	10	18	10	0.35	Upper layer
Silty clay (Layer 1)	19.5	20	22	25	0.30	Main bearing soil
Sandy silt (Layer 2)	20.0	15	30	35	0.28	Mid-depth
Silty clay (Layer 3)	20.5	25	26	40	0.32	Bottom layer
Soil nail (C20, 8–12 m)	—	—	—	21000	0.20	Modeled as embedded beam
Reinforced concrete pile	—	—	—	30000	0.20	$\varphi 600/\varphi 800$, spacing 900/1000 mm
Prestressed anchor cable	—	—	—	195000	0.15	6-strand 15.2 mm

4 Support Design and Monitoring System Construction

4.1 Construction Technology Optimization

4.1.1 Earthwork Excavation Design. This project adopts a layer-by-layer and section-by-section island excavation method, guided by the construction process of "surveying and marking → layer-by-layer excavation → support construction → cyclic operation". Before excavation, the edge lines and ramp positions are marked according to the designed slope angle, and a two-shift round-the-clock construction mode is adopted to ensure the construction progress. The depth of each layer of excavation is controlled at $\leq 2.0\text{m}$ (0.5m below the soil nails/anchor rods), and a "periphery first, then the middle" cyclic excavation method is used, with a 10m-wide operation zone reserved around the periphery to meet the support construction requirements. The next layer of earth excavation can only be carried out after the support strength of each layer reaches 75%.

During the construction process, manual slope trimming is carried out to keep the slope surface flat. After mechanical excavation reaches 300mm above the base, manual slot clearing is adopted to ensure the accuracy of the base elevation. The ramp area is the last part to be constructed, and a long-arm excavator is used for layer-by-layer slope trimming (each layer $\leq 2.0\text{m}$), with steel plates laid to ensure the safety of construction vehicles, and slope support construction is carried out simultaneously. Safety warning signs are set up throughout the construction process, and the construction principle of

"from top to bottom, layer-by-layer support, and time-limited slot inspection" is strictly followed.

During the earth excavation process, a zoned flow operation mode is adopted to achieve a rapid cycle of "slope support - earth excavation - structure construction", improving construction efficiency and effectively controlling the deformation of the foundation pit and the construction period. After the earth excavation is completed, the slot inspection is carried out immediately and the cushion concrete is poured to avoid long-term exposure of the base soil and ensure the stability of the foundation pit.

4.1.2 Soil Nailing Wall Design. The soil nailing wall support in this project is strictly in accordance with the standardized operation process, including "soil nailing production → slope dressing → hole forming → installation → grouting → net hanging → shotcrete". Soil nailing, must check reinforced performance, make sure no rust and oil, and tie the grouting pipe (exhaust pipe from the bottom of the hole 5 cm), set up check bag, every 2 m welded to ensure the installation precision of stent.

The slope dressing adopts the combination of mechanical excavation and artificial fine repair to control the flatness of slope and elevation Angle. When the water stagnation layer is encountered, $\phi 50\text{mm}$ drainage holes (spacing 2m) are set to ensure smooth drainage. The hole formation operation shall be conducted manually or mechanically. The hole position deviation shall be less than 100mm, the inclination error shall be less than 3° , the total length of the soil nail shall be the hole depth plus 0.2m, and heavy objects shall not be hung at the end within 3 days after construction to prevent uneven force. Grouting adopts p. SA32.5 slurry (water cement ratio, 0.5), the second grouting, at 0.4 MPa recharge after initial setting, recharge quantity 30% ~ 40% for the first time, ensure the slurry and improve cohesive force.

In the mesh hanging operation, welding is performed in the order of "steel mesh → reinforcement → locking reinforcement". C20 fine stone concrete is sprayed, the thickness is 80mm, the mix ratio is 1:2:2:0.5, and stratified spraying is adopted. Each layer is reserved for 45° slope bonding, and the maintenance is not less than 7 days. Cut slope drainage system including phi within 50 mm drain (spacing 2 m², dip Angle of 10°) and blind ditch of 400 x 400 mm at the bottom of the foundation pit and 50 m spacing sump, the top of the foundation pit set 360 mm high MU10 cutoff wall, and take 1:5 reverse slope measures, effectively control the influence of surface runoff on slope. Concrete slope protection constructional detail as shown in Fig. 2.

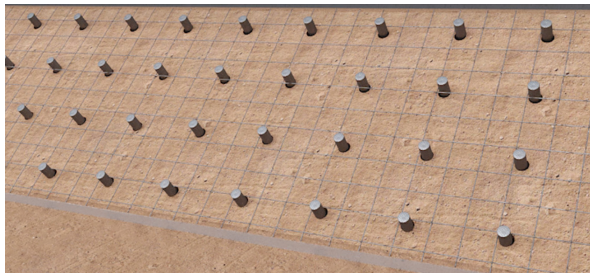


Fig. 2. Schematic diagram of slope hanging net

4.1.3 Support Pile Design. The construction of supporting piles strictly follows the standardized procedures of measurement and pay-off, borehole pile, steel cage installation and quality inspection^{12–14}. First of all, at the stage of measurement and pay-off, Party A, the supervisor and the construction party shall jointly confirm the reference point, and establish the construction control network. The operation can only be carried out after the review by the supervisor. Before, in the process of drilling rig is in place, need to retest the pile location elevation, and on the basis of geological report and design requirements for control drilling depth, to ensure that the perpendicularity of the drilling rig and drilling stability, avoid sticking, offset, or equipment damage. After drilling to the design depth, concrete injection shall be carried out after the supervision and acceptance, and the perfusion process shall be carried out continuously to ensure the density and integrity of the pile.

Reinforcing cage fabrication phase strict quality controls, play material according to the standard sampling inspection, and USES the standard of welding technology, to ensure the quality of main reinforcement concentricity and connection. Hoisting adopts multi-point hoisting mode, and conFigureures stiffening and reinforcing bars to improve the rigidity and stability of the steel cage and prevent deformation. When the steel cage is inserted, the self-weight and vibration hammer are inserted first, and the vibration assisted lifting process is adopted after reaching the design elevation to ensure the concrete compactness.

Construction process, using jump style to pile foundation construction, in order to improve the operation efficiency and ensure the continuity of construction. In terms of quality inspection, the proportion of hole formation detection is not less than 20% of the total number of pile holes, and not less than 10 pile holes; The integrity test of pile body adopts the low strain variation test method, and the detection ratio is not less than 20%, and not less than 5. If abnormal piles are found, the core drilling method should be further verified and the detection range should be expanded. Through strict construction management and quality control, the stability, reliability and durability of supporting pile construction are ensured.

4.1.4 Anchor Bolt Setting Plan. Before large-scale construction, the basic test of anchor cable is carried out according to the design requirements, including the pulling capacity test, in order to verify the performance, construction technology and safety of anchor cable^{14,15}. The test results are used to optimize the construction parameters and schemes. Before construction, clean the soil layer on the surface of the pile, calibrate the hole position to ensure that the error is within $\pm 50\text{mm}$, the hole inclination error is controlled within $\pm 2^\circ$, and adjust the Angle of the rig to ensure the stability of the equipment. High pressure rotary drill bit is used to drill at a depth of no less than the design length, and high pressure injection technology is used to simultaneously cut soil and form anchor solids.

Anchor cable production and installation in strict accordance with the design requirements, the steel strand end fixed by cold extrusion method, free period of PVC tube and sealing, deviation control within plus or minus 50 mm length. The anchor cable and drill pipe walk into the hole together to ensure the anchoring quality. Before installing the anchor, clean the oil on the surface and ensure that the anchor plate is aligned with

the anchor plate. The tensioning work is carried out after the slurry is cured for 7 to 10 days and the strength reaches more than 75% of the design value. The double control method is used to control the tension and check the elongation value, and the influence of the adjacent anchor cable should be considered in the tensioning sequence.

After the construction of anchor cable tensioning locking force monitoring, monitoring to ensure that every layer of not less than three. The basic test should be carried out before construction, and the acceptance test of tensile strength should be carried out after formal construction, and the detection proportion should not be less than 5%. Through strict test verification and monitoring, the construction quality and structural safety of anchor cable are ensured.

4.1.5 Cap Beam Design. The soil excavation between piles is carried out in two phases, with the mechanical excavation depth of 0.8m, the remaining 0.1m completed by manual excavation, the excavation width of 1.8m, and the working face of 0.5m on both sides of the cap beam. The ring splitting method was used to determine the elevation and mark the ring tangent. After the ring cutting by a small cutting machine, the drill hole was drilled in the symmetrical position of the elevation of the pile head and the hydraulic splitting machine was inserted for splitting. Finally, the concrete of the pile head was lifted out and part of the pile points were ground to match the integrity testing of the pile body. Pour 100mm thick C20 concrete cushion between piles, cap beam area and formwork support area, and place positioning line according to cap beam side line. After the top of the pile is chiseled to the design elevation, the reinforcement is cleaned and bundled. The main reinforcement is mechanically connected with straight thread, and the number of joints is controlled within 50%. Before binding the bar of the cap beam, place the pad evenly at the bottom of the beam. The formwork is reinforced with wood formwork, wood square and 14 pairs of pull screws, screw spacing $\leq 500\text{mm}$, as shown in Fig. 3. The concrete was poured with truck pump and C30 commercial concrete in sections, each length about 27m. Diagonal stubble was left at the construction joint, which should be chiseled and cleaned before subsequent pouring. After the concrete strength reaches 1.2MPa, the formwork is removed and covered with quilts for maintenance for 14 days.

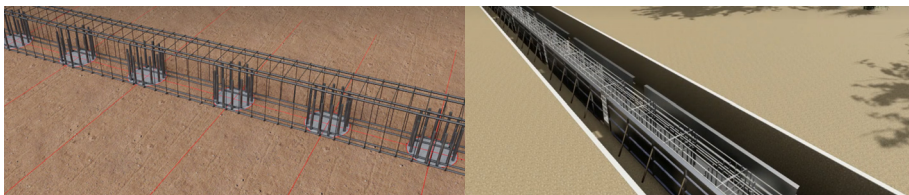


Fig. 3. Installation diagram of cap beam template

4.1.6 Soil Design Between Piles. The construction of interpile net shotcrete is carried out simultaneously with the excavation of foundation pit. The method of "digging and spraying" is adopted, and the construction is carried out in sections and layers¹⁶. The length of each section is consistent with the excavation of soil, and the height of the

layers is controlled within 2 meters. Pile joint excavation mainly relies on mechanical work, manual assistance to clean up excess earth and trim slope, remove loose soil and debris. After the completion of earthwork excavation, A8@200 steel mesh should be laid immediately and bound with transverse reinforcement bars. C18 concrete should be used for planting reinforcement bars of cast-in piles and C16 reinforcement bars should be used for transverse reinforcement bars with a spacing of 1500mm.

The steel mesh is hung according to the design requirements, and is bound and fixed with the fluctuation of the initial spray surface. The lap of the mesh is welded or tied. The welding length is $10D=80\text{mm}$, and the lashing and lap length is 400mm. Shotcreting machine is used for the sprayed concrete construction, the spray gun and slope 0.6 ~ 1.0 m distance, ensure that the vertical injection, strength of concrete is C20, jet thickness of 50 mm. 2 hours after the final solidification of concrete, cover the quilt for curing, keep the surface wet, and the curing period is 7 days to ensure the strength and stability of the concrete.

4.2 Construction of the Monitoring System

The monitoring contents of the project mainly include: (1) the horizontal displacement of the top of the slope; (2) Vertical displacement at the top of the slope; (3) deep soil horizontal displacement; According to the monitoring results, combined with the site construction situation, timely grasp the deformation of the enclosure wall and the surrounding buildings (structures), and analyze and judge the safety and stability of the foundation pit supporting structure, so as to ensure that the foundation pit is always in a safe operation state.

4.2.1 Slope Top Horizontal Displacement Monitoring. The horizontal displacement monitoring of this project adopts the small Angle method, and the reference point buried should meet the "second class" accuracy requirements of "Building Deformation Measurement Code" (JGJ8-2016). The monitoring datum point can be used by sight line method, small Angle method, drop point method, etc. When the measuring point and the datum point cannot be seen, GPS measurement and other comprehensive measurement methods can be combined. 12 pile top displacement monitoring points and 24 slope top displacement monitoring points are planned to be arranged along the perimeter of the foundation pit, and monitoring points should be set up in the middle of the side, the sun corner and near the protected object.

The horizontal spacing is not more than 20m, and no less than 3 on each side should be set at the top of the foundation pit pile. When the small Angle method is used, the station should be forced to the center pier as far as possible to reduce the centering error and orientation error. If the conditions are not available, the "three-point collinear" or multi-directional orientation method can be used to improve the accuracy of the station setting, and maintain the appropriate aiming distance to improve the Angle observation accuracy.

4.2.2 Vertical Displacement Monitoring of Slope Bottom. The vertical displacement monitoring mainly involves the monitoring of the main supporting structure of foundation pit engineering, the surrounding surface settlement and the settlement of underground pipelines, and adopts the unified leveling network system or the independent elevation system according to the site conditions. The leveling network is composed of reference points and working base points, and the layout of the reference points and working base points is graded according to the distribution density of surrounding buildings, risk level and the specific situation of the construction site, so as to ensure that at least 3 level points are set in each measuring area.

The leveling network adopts the form of a loop to ensure the monitoring accuracy of vertical displacement and deformation in the monitoring area. The base point can be selected as a normal base point or a stable building, located in an area that is not affected by construction and the surrounding environment, and 3 base points are planned. In order to ensure the stability of the leveling network, the stability of the reference point is checked every time the monitoring is carried out, and it is regularly reviewed.

The monitoring shall be carried out in accordance with national standards to ensure that the error of elevation measurement is controlled within the specified range. The elevation measurement shall be carried out in the loop mode. The monitoring points shall strictly follow the principle of "two fixed and one consistent" to ensure reliable results. Retest the benchmark network twice a month to ensure the accuracy and stability of the monitoring work

4.2.3 Deep Horizontal Displacement Monitoring. Deep horizontal displacement monitoring points are arranged in the middle of the pit, the sun corner and representative parts around the pit. The horizontal spacing of the monitoring points is 20-60 meters, and at least one monitoring point is set on each side. Before hoisting the steel cage, the inclinometer pipe shall be connected and bundled in segments, once every 1 meter, and the guide groove shall be perpendicular to the side line of the foundation pit. By measuring the Angle change between the axis of the inclinometer and the plumb line, the horizontal displacement of soil and pile can be calculated.

The accuracy of the inclinometer is 0.02mm/0.5m. During operation, the probe is placed in the tube, measured along the depth and recorded, ensuring that the cable is aligned with the mark at each reading. The inclinometer pipe shall be tied with supporting piles. When installing the inclinometer pipe, ensure that the deviation of perpendicularity is not more than 1.5%, and take appropriate sealing and protection measures. The inclinometer pipe generally uses $\phi 70$ PVC pipe, ABS pipe or aluminum alloy pipe, and the inner wall has two pairs of perpendicular guide grooves.

In order to further clarify the applicability and engineering advantages of the "soil nailing wall-pile anchor" combined support system adopted in this project, this paper selects two common mainstream support systems -- row pile + internal support and underground diaphragm wall for systematic comparison and analysis. The results show that the soil nail wall and pile-anchor combined support has significant advantages such as mature construction technology, significant structural synergy, and application to complex geological conditions. In particular:

In terms of construction convenience, the system does not rely on large-scale deep foundation pit supporting equipment, and can use medium-sized machinery and manual work, especially suitable for the rapid construction requirements of small and medium-sized urban sites.

The structure synergism and the flexibility and rigidity complementarity are prominent, the soil nail wall plays the role of in-plane active support, and the pile anchor system provides rigid constraint and vertical water stop protection, which effectively controls the overall displacement and deep sliding risk. The economy and material utilization efficiency are better than pile row + internal support system. Although the latter has large structural stiffness and strong deformation control ability, it often has high cost and long construction period due to complex structure and large construction interference.

Compared with the diaphragm wall, the combined system is suitable for the soft clay area with medium and low groundwater level and no high permeability sand layer. Its construction disturbance is small and the process is flexible, which is more suitable for the demand of the medium and shallow unsaturated site, while the diaphragm wall is suitable for the high groundwater area with see-proof and inrush prevention.

Based on multiple factors such as stratum conditions, site restrictions and environmental protection, the "soil nailing wall-pile anchor" combined support system has both economic and technical feasibility, and is an efficient support scheme with promotion potential in urban environment.

5 Interpretation of Result

5.1 Monitoring Alarm and Detection Frequency

The pit monitoring alarm value and monitoring frequency are shown in Table 3 and Table 4.

Table 3. Monitoring alarm values

Monitoring program	change frequency	Cumulative value /mm
Slope top horizontal displacement monitoring	Continuous 3 d is greater than 3 mm/d or the same day more than 5 mm/d	Greater than 30
Vertical displacement monitoring of slope bottom	Continuous 3 d is greater than 3 mm/d or the same day more than 5 mm/d	Greater than 30
Deep horizontal displacement monitoring	Continuous 3 d is greater than 3 mm/d or the same day more than 5 mm/d	Greater than 40

Table 4. Monitoring frequency

Monitoring program	Frequency of monitoring		
	Pile foundation construction	Excavation of foundation pit	After the bottom plate is poured

Slope top horizontal displacement monitoring	2 times/week	1 times /1d	1 times /3d
Vertical displacement monitoring of slope bottom	2 times/week	1 times /1d	1 times /3d
Deep horizontal displacement monitoring	2 times/week	1 times /1d	1 times /3d

The construction and monitoring system developed in this study is applied to the project plot. The vertical displacement, horizontal displacement and peripheral displacement of each block were observed. The measured and simulated values are coded as MOV and SOV.

5.2 Displacement Monitoring

5.2.1 Slope Top Horizontal Displacement Monitoring. The monitoring results of the horizontal displacement at the top of the slope indicate that, as the excavation depth of the foundation pit increases, the horizontal displacement shows a gradual upward trend and eventually tends to stabilize upon the completion of excavation. Throughout the entire construction process, none of the monitoring points triggered any alarm thresholds, as detailed in Table 5.

In addition to the field measurements, numerical simulation was conducted to further analyze the deformation behavior. The simulated horizontal displacements exhibit a similar overall trend to the measured data, reflecting a consistent response pattern of the slope top under excavation-induced stress. However, the simulated values are generally slightly smaller than the corresponding measured values across all excavation stages.

This deviation is likely due to the simplified assumptions regarding boundary conditions and soil parameters within the numerical model, which tend to yield conservative deformation estimates. Nevertheless, the strong agreement in overall trend between simulation and field data enhances confidence in the reliability and predictive capability of the numerical analysis.

Table 5. Cumulative value of horizontal displacement change of slope top

Observation point	Cumulative value of horizontal displacement (mm)		Observation point	Cumulative value of horizontal displacement (mm)	
	MOV	SOV		MOV	SOV
P01	4.51	4.32	P19	4.9	4.95
P02	4.05	4.21	P20	4.57	4.52
P03	4.13	4.01	P21	5.27	4.96
P04	4.07	3.98	P22	4.43	4.21
P05	4.43	1.31	P23	4.51	4.38
P06	4.57	4.36	P24	4.48	4.31

P07	4.55	4.21	ZD1	0.03	0.04
P08	4.74	4.45	ZD2	0.01	0.04
P09	4.25	4.31	ZD3	0.18	0.23
P10	4.65	4.58	ZD4	0.16	0.21
P11	3.98	4.13	ZD5	0.24	0.22
P12	3.4	3.49	ZD6	0.16	0.19
P13	4.25	4.17	ZD7	0.08	0.07
P14	4.8	4.77	ZD8	0.22	0.31
P15	4.4	4.33	ZD9	0.16	0.21
P16	4.53	4.30	ZD10	0.02	0.04
P17	4.23	4.21	ZD11	0.1	0.16
P18	3.93	4.35	ZD12	0.06	0.03

5.2.2 Vertical Displacement Monitoring of Slope Top. During the foundation pit construction, the settlement at the top of the slope serves as a direct indicator of the overall safety of the excavation. The monitoring team reported real-time data, enabling the construction team to promptly adjust construction speed and parameters.

As a result, both the daily variation and the cumulative vertical displacement at the top of the slope remained within the preset alarm thresholds throughout the monitoring period. The cumulative vertical displacements after 30 consecutive measurements at each monitoring point are presented in Table 6.

In addition to the measured data, numerical simulation was carried out to further analyze the vertical displacement behavior of the slope top. The simulation results exhibit a similar trend to the measured values, reflecting the same general pattern of gradual settlement stabilization.

However, the simulated displacements are slightly smaller than the measured values across all measuring points. This discrepancy may be due to simplifications in the numerical model, such as idealized boundary conditions or material parameter assumptions. Nevertheless, the close agreement between the simulation and monitoring results confirms the validity of the model and supports its use in guiding construction safety assessments.

Table 6. Cumulative value of vertical displacement change of slope top

Observation point	Cumulative value of vertical displacement (mm)		Observation point	Cumulative value of vertical displacement (mm)	
	MOV	SOV		MOV	SOV
P01	4.94	4.58	P19	4.88	4.33
P02	4.99	4.47	P20	3.49	3.01
P03	3.89	3.52	P21	4.54	4.13
P04	4.11	3.76	P22	4.37	3.88
P05	3.91	3.41	P23	4.58	4.16
P06	4.33	4.02	P24	5.02	4.61
P07	4.37	3.91	ZD1	3.79	3.33

P08	4.28	3.85	ZD2	3.71	3.22
P09	4.07	3.66	ZD3	3.12	2.81
P10	4.24	3.92	ZD4	3.75	3.48
P11	3.98	3.62	ZD5	3.01	2.77
P12	3.94	3.51	ZD6	3.26	2.91
P13	3.89	3.38	ZD7	3.04	2.84
P14	5.38	4.97	ZD8	2.26	2.06
P15	3.79	3.24	ZD9	2.92	2.65
P16	4.63	4.12	ZD10	3.53	3.17
P17	4.32	3.79	ZD11	2.72	2.38
P18	4.38	3.95	ZD12	2.68	2.41

5.2.3 Deep Horizontal Displacement Monitoring. During the excavation of the foundation pit, monitoring and measurement were conducted at each inclinometer borehole. As shown in Fig. 4, the cumulative horizontal displacement of the deep soil mass at each monitoring point generally exhibited a displacement trend toward the foundation pit. The maximum cumulative horizontal displacement recorded was 20.3 mm at measuring point Z10. Thanks to the effective support system, the horizontal displacements at all monitoring points remained below the alarm thresholds throughout the monitoring period.

In addition to the field monitoring data, numerical simulation was carried out to analyze the horizontal displacement behavior of the deep soil mass. The simulation results are overall in good agreement with the measured data, capturing the same displacement trend toward the excavation. In most cases, the simulated displacements are slightly smaller than the measured values, reflecting a conservative prediction from the numerical model. However, at certain points, the simulated values were marginally higher, which may be attributed to local variations in soil properties or limitations in boundary condition assumptions. Despite these minor differences, the close alignment between simulated and measured results confirms the reliability of the numerical model and supports its application in assessing and predicting deformation behavior during construction.

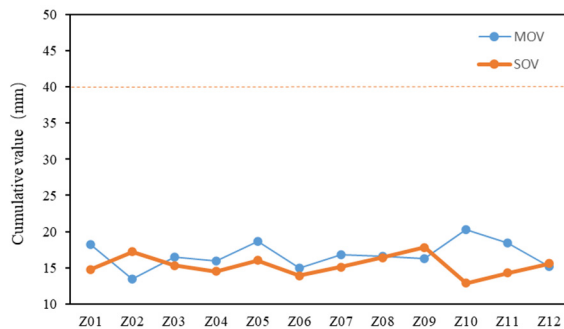


Fig. 4. Cumulative value of deep displacement

5.2.4 Groundwater Level Monitoring. With the excavation of the foundation pit, the difference between the external and internal water pressures gradually increases, which may lead to water leakage and a subsequent drop in the groundwater level outside the pit. The variation in water level is influenced not only by excavation-induced deformation but also by external environmental factors such as weather conditions and precipitation within the pit. Table 7 presents the cumulative changes in water level at each monitoring point, where a positive value ("+") indicates a rise in water level and a negative value ("-") indicates a decline.

According to Table 7, the maximum cumulative change in water level during the entire construction period reached 1500 mm, which remained within the safety threshold and did not trigger any alarms.

To further assess groundwater behavior, numerical simulation was conducted in parallel with field monitoring. The simulation results generally follow the same trend as the measured data, capturing the overall pattern of water level fluctuation associated with the excavation process. In most monitoring points, the simulated water level changes are slightly smaller than the measured values, indicating a conservative estimation by the model. At a few points, however, the simulation slightly overestimates the actual water level change, possibly due to idealized assumptions regarding boundary seepage or hydrogeological parameters. Despite these minor differences, the simulation outcomes align well with the field data, reinforcing the credibility of the model and supporting its application in groundwater behavior prediction during deep excavation projects.

Table 7. Cumulative values of water level changes at each measurement point of the foundation pit

Observation point	Cumulative value of vertical displacement (mm)		Observation point	Cumulative value of vertical displacement (mm)	
	MOV	SOV		MOV	SOV
P01	-870	-1085	P09	-1340	-1440
P02	-1130	-1020	P10	-1480	-1350
P03	-1090	-1105	P11	-1360	-1300
P04	-1060	-970	P12	-1320	-1490
P05	-1030	-1070	P13	-1500	-1210
P06	-1040	-1055	P14	-1320	-1340
P07	-1040	-1015	P15	-1150	-1380
P08	-1060	-1120	P16	-1320	-1310

5.2.5 Monitoring of Settlement of Surrounding Roads. During the construction of the foundation pit, the settlement of the surrounding roads serves as a more intuitive indicator of the excavation's impact on the surrounding environment. As shown in Fig. 5, the cumulative settlement values at all monitoring points on the surrounding roads remained within the alarm thresholds, with the maximum recorded settlement being -5.1 mm at point CL2. This indicates that the foundation pit excavation has had a minimal impact on the surrounding environment.

To further verify the deformation behavior of the surrounding ground, numerical simulation was also performed. The simulation results display a consistent settlement trend with the monitoring data, showing deformation directed downward toward the pit. Overall, the simulated settlement values are slightly smaller than the measured ones, which is likely due to conservative assumptions in model parameters or boundary conditions. Despite the slight underestimation, the close agreement in the settlement pattern confirms the reliability and accuracy of the numerical model. This consistency between simulation and field measurements further supports the conclusion that the excavation caused only limited influence on the surrounding roads and environment.

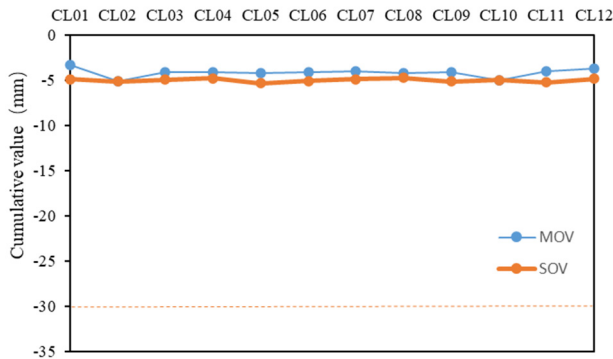


Fig. 5. Cumulative settlement values of each measurement point on the surrounding roads

6 Conclusions

1. The combined support system of "soil nailing wall-pile anchor" and supporting construction technology constructed in this study have been verified by practice, effectively guaranteeing the stability of deep foundation pit under complex geological conditions and meeting the requirements of the design service life of foundation pit.
2. The established contains top level and vertical displacement and horizontal displacement of deep soil construction monitoring system, real time and accurately reflect the deformation condition, the combination of reasonable monitoring alarm value and frequency setting, realize the effective control of foundation pit safety status.
3. The application of this study support and monitoring technology system, the foundation pit displacement cumulative value of various monitoring items and change frequency are controlled within the alarm value, the validation of the technical system in deep foundation pit engineering science, reliability and practicability. reference.

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