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Investigating the Construction Procedure and Safety Oversight of the Mechanical Shaft Technique: Insights Gained from the Guangzhou Intercity Railway Project

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Abstract: Currently, subway and underground engineering projects are vital for alleviating urban congestion and enhancing citizens' quality of life. Among these, excavation engineering for foundation pits involves the most accidents in geotechnical engineering. Although there are various construction methods, most face issues such as a large footprint, high investments, resource waste, and low mechanization. Addressing these, this paper focuses on a subway foundation pit project in Guangzhou using mechanical shaft sinking technology. Using intelligent cloud monitoring, we analyzed the stress–strain patterns of the cutting edge and segments. The results showed significant improvements in construction efficiency, cost reduction, safety, and resource conservation. Based on this work, this paper makes the following conclusions: (1) The mechanical shaft sinking method offers advantages such as small footprint, high mechanization, minimal environmental impact, and cost-effectiveness. The achievements include a 22.22% reduction in construction time, a 20.27% decrease in investment, and lower worker risk. (2) Monitoring confirmed that all cutting edge and segment values remained safe, demonstrating the method's feasibility and rationality. (3) Analyzing shaft monitoring data and field uncertainties, this study proposes recommendations for future work, including precise segment lowering control and introducing high-precision total stations and GPS technology to mitigate tunneling and assembly inaccuracies. The research validates the mechanical shaft sinking scheme's scientific and logical nature, ensuring safety and contributing to technological advancements. It offers practical insights, implementable suggestions, and significant economic benefits, reducing project investment by RMB 41,235,600. This sets a benchmark for subway excavation projects in South China and beyond, providing reliable reference values. Furthermore, the findings provide valuable insights and guidance for industry peers, enhancing overall efficiency and sustainable development in subway construction.

Keywords: cutting edge; segment; underground engineering projects; monitoring data

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1. Introduction

As global urban populations surge dramatically, the disparity between urban carrying capacity and high-standard human habitation is becoming more apparent. Addressing this challenge, underground engineering presents a viable solution, prompting the advent of numerous extensive and deep excavation ventures. However, these projects are often confronted with intricate geological formations and unpredictable ambient conditions, making them prone to geotechnical engineering accidents, as illustrated in Figure 1a,b.


(**a**) (**b**)

Figure 1. Subway pit collapse with extensive damage: (**a**) Singapore MRT foundation pit; (**b**) Nanning Greenland deep foundation pit.

To mitigate accidents in deep excavation projects, academics have explored various excavation techniques and support systems for foundation pits. For instance, Tan et al. [1] introduced a central island construction plan for the Shanghai World Financial Center (SWFC) tower, which involved the excavation of the central cylindrical shaft from the base to the top, followed by the construction of the surrounding rectangular pit in a descending sequence. Xiong et al. [2] applied a method combining soil nailing support and prestressed anchor support to design foundation pit support and found that this method was safe, reliable, economical, and effective. Addressing the shortcomings of the open caisson method, Gao et al. [3] suggested a suspended excavation technique for deep pits. In collaboration with the Juzizhou Island Station foundation pit project, Wang et al. [4] incorporated high-pressure grouting for waterproofing in high-pressure zones, underground continuous wall construction in soft upper and hard lower layers, and safety protocols for blasting excavation of foundation pit floors. Liu et al. [5] introduced an innovative excavation technique leveraging the time–space effect principle, demonstrating its effectiveness in controlling ground uplift deformation in a Shenzhen subway project. This method significantly reduced subway tunnel deformation. Regarding excavation support, Deng et al. [6] outlined the arrangement, structural measures, and construction methods for artificial bored pile supports in a Ningbo foundation pit project. Zhang et al. [7] implemented a support system combining an underground continuous wall with internal braces for deep and thick silty soil layers in foundation pit engineering. Wu et al. [8] proposed a construction scheme of combined support technology based on a deep foundation pit project in Changsha City. Chunyan Gao et al. [9] employed the pre-excavation, blasting, and anchoring (PBA) method to manage arching effects and surface settlement during excavation. Zhong et al. [10] proposed a novel double-diaphragm wall support and excavation method for a large-scale soft soil foundation pit in Shanghai. Feng et al. [11] designed a construction scheme for a deep foundation pit in a residential area, integrating top slope support, bottom pile foundations, and prestressed anchor cables to minimize construction risks. Diao et al. [12] studied the deformation and load transfer mechanism of pile group foundations under asymmetric excavation conditions using two construction methods—"tunnel before foundation pit" and "foundation before foundation pit"—starting from the relative position of tunnel, pile, and foundation pit.

Construction monitoring is an important means for studying the effectiveness of new construction methods and ensuring the safety of foundation pit construction, and it has received significant attention. Yang et al. [13] conducted on-site monitoring of 21 foundation pit projects in Fuzhou Metro and analyzed the deformation characteristics of subway station foundation pits in the soft soil area of Fuzhou. Lv et al. [14] obtained real-time deformation data for various monitoring sections of the foundation pit through on-site monitoring at Beijing Daxing International Airport. Li et al. [15] dynamically monitored the horizontal displacement of the crown beam, surface settlement, anchor rod forces, and groundwater level during the construction of a specific foundation pit, obtaining deformation patterns of deep excavation and assessing the impact of foundation pit construction on surrounding structures. Through real-time monitoring of the excavation process of a deep foundation pit in a soft soil area, Zhang et al. [16] obtained the variation patterns of deformation in the diaphragm walls and the displacement of support columns during the construction of the pit. Ren et al. [17] employed Brillouin optical frequency domain analysis and distributed fiber-optic monitoring technology. They used this technology to monitor the lateral displacement of an ultra-deep circular foundation pit. The monitoring took place in a test section of a tunnel buried deep under the Suzhou River. Their objective was to obtain the deformation patterns of the ultra-deep excavation. Based on BIM technology, combined with sensor technology, an SQL Server database, and the BIMFACE lightweight platform, Sun [18] realized an integrated management process for deep foundation pit monitoring using automatic data collection, intelligent processing, and foundation pit early warning. Liu et al. [19], relying on the actual project, used the self-developed measurement robot technology to carry out automatic monitoring of the foundation pit; detailed the monitoring content and monitoring requirements such as monitoring cycle, frequency, control value, and early warning value; assembled the monitoring equipment; built the system platform; and conducted real-time monitoring of the deformation of the foundation pit. Chen et al. [20] greatly improved the efficiency of foundation pit monitoring, the accuracy of monitoring results, and the timeliness of information feedback through the practical application of automatic monitoring technology for foundation pit support and earthwork in Dongguan City. Chen [21] adopted automatic monitoring technology based on the actual foundation pit engineering of a certain block in Hangzhou, Zhejiang Province, and analyzed the advantages of automatic monitoring. Li et al. [22] took the construction project of a fully buried sewage plant in a wash tile weir as an example and used Internet of Things technology to monitor changes in anchor stress and pile deep displacement during foundation pit construction in real time. Liu et al. [23] proposed a GIS technology-based method for monitoring the construction safety of deep foundation pit support in urban open-cut tunnels, obtained the pile body moment through calculation, built a three-dimensional finite element model based on it, and used the model to analyze and monitor the supporting pile structure, the side earth pressure of the supporting wall of the deep foundation pit, and the wall mechanical model of the supporting wall. Li et al. [24] studied and analyzed the expanded application of BIM technology and 3D laser scanning in complex deep foundation pit monitoring based on the advantages of BIM and 3D laser scanning, and conducted secondary development based on the construction of a cloud platform to realize a foundation pit safety monitoring platform for efficient collection, storage, input, analysis, and display visualization of deep foundation pit monitoring data so that all parties involved in the construction can work together in the same information platform, greatly improving the timeliness of pit safety supervision. Furthermore, Wang et al. [25], Huang et al. [26], Lin et al. [27], Ding et al. [28], Zhou et al. [29], Wu et al. [30], and Zheng et al. [31], based on different projects and utilizing various on-site monitoring technologies, have successfully conducted field monitoring of specific foundation pit construction processes, yielding valuable conclusions.

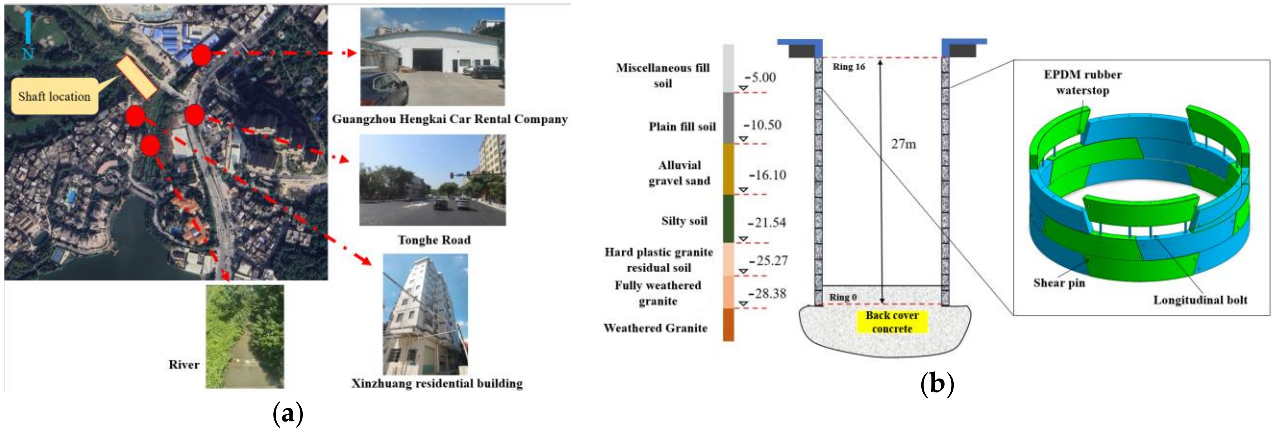
In the field of mechanical shaft construction, an increasing number of experts and scholars have begun to conduct research on this, and the engineering sector is gradually adopting this construction method. Zhang et al. [32] introduced a new shaft construction technology and the construction method of prefabricated circular shafts constructed by fully automatic mechanized equipment. Jiang et al. [33] proposed a prefabricated shaft construction technology based on the German Herrenknecht vertical shaft excavator (VSM) and the construction project of a caisson parking facility (Phase 1) in Jianye District, Nanjing. Zou [34] designed a set of installation and adjustment devices for a super large shaft boring machine and applied the device in practical projects. The on-site use further verified the reliability and safety of the construction method. Xu et al. [35] developed a submersible shaft boring machine. The new construction method and the boring machine can realize the simultaneous operation of excavation, slag extraction, and support, and the construction is automatic and efficient. Zhao et al. [36] proposed a mechanical excavation caisson boring machine and summarized a set of construction methods matching the boring machine. Finally, through simulating different working conditions and geological conditions and the whole process of the whole machine functional test verification, the test results prove that the performance and reliability of the whole machine meet the design requirements. Chen [37] introduced the vertical excavation excavator invented by Herrenknecht in Germany based on the Shanghai Zhuyuan Bailong Port sewage connecting pipe project and elaborated a new suspended shaft excavation technology in depth. Sun et al. [38], combined with the Wenzhou sinkhole underground garage project constructed by the press-in sinkhole method for an ultra-deep underground garage, using on-site measurements, studied the change characteristics of the ratio of blade footing and inclined end resistance and overall end resistance in the process of sinking press-in sinkhole. Huang et al. [39], in order to investigate the force and structural response law of the VSM sinkhole wall during the construction process, obtained the load effects and structural response law of the VSM sinkhole wall by monitoring the external soil and water loads, the structural main reinforcement stress, and the inter-annular pressure of the tubular sheet on the wall during the construction process.

Nevertheless, these traditional construction techniques still face problems such as the overuse of land, environmental degradation, resource depletion, and increasing occupational hazards. In view of these challenges, this study introduces an innovative method for the construction of deep foundation pits, the first of its kind in South China, called mechanical shaft excavation technology. The method combines the subway shield technology with the immersed tube method to realize the automatic underwater excavation controlled by ground personnel remotely. In addition, it helps to separate excavator operation, mud circulation, and mud settling processes. However, the application of this technology remains confined to a limited number of engineering projects, and existing research primarily focuses on the specific steps and operational procedures of technical implementation. In-depth analyses of mechanical characteristics during the construction process and cost control aspects are still lacking. Furthermore, current research has failed to provide effective solutions for mechanical shaft construction strategies under complex geological conditions that effectively address uncertainties during the construction process. In light of this, the objective of this work is to comprehensively and thoroughly explore the application of mechanical shaft sinking methods in actual engineering projects. By monitoring and analyzing the mechanical properties of shaft structures, we aim to uncover the key influencing factors during the construction process and ultimately propose corresponding optimization measures. Additionally, this study is dedicated to evaluating the economic benefits of mechanical shaft sinking methods, providing more scientific and reasonable construction strategies for future subway excavation projects. Most importantly, this work exhibits notable novelty in research methods. By introducing advanced monitoring technologies and automated data analysis, we are able to conduct real-time and precise monitoring of key parameters of shaft structures during the mechanical shaft sinking process, thereby more accurately assessing its construction effectiveness and safety. This provides robust support for theoretical research and practical applications in related fields.

2. Construction Materials and Methods

2.1. Project Overview and Shaft Materials

This submission pertains to the construction of a reception pit for a shield tunnel of the Guanghua Inter-city Metro project, situated in Guangzhou, China. Positioned 15 m away from two residential structures, 150 m from a major urban roadway, and 200 m from commercial edifices, the reception pit is also adjacent to a river, located just 30 m from the site, as depicted in Figure 2a. The excavation of the pit features a circular cross-section, measuring 14 m in diameter and extending to a depth of 27 m. It traverses various grades of granitic residual soil, from fully weathered to slightly weathered granite.



(**a**)

(**b**)

Figure 2. Construction area surrounding environment and formation conditions. (**a**) Surrounding environment of construction site; (**b**) geological condition.

The excavation process for this pit is mechanized and fully automated. The shaft's structural support comprises prefabricated concrete segments and a cutting edge, resulting in an internal diameter of 13 m and an external diameter of 14 m. Upon reaching the prescribed excavation depth, grouting is employed to integrate the shaft wall with the adjacent soil for stability. The shaft's base is constructed through the integration of the cutting edge and poured concrete, achieving a thickness of 3 m.

Structurally, the shaft body encompasses 17 ring segments, accompanied by a cutting edge at the bottom. Each ring segment consists of six prefabricated concrete segments that are wedge-shaped, with dimensions of 1.5 m in height and 500 mm in thickness. These segments possess a compressive strength of C50 and a permeability rating of P12. The cutting edge, standing 2 m tall, is composed of C30 concrete cast within a 3 mm steel formwork. Bolts are utilized to secure connections between segments and the cutting edge. Furthermore, longitudinal alignment is maintained through continuous spiral reinforcement, while shear keys are incorporated to prevent displacement between segments, as illustrated in Figure 2b.

The excavation pit is situated within a typical layer of weathered granite. The specific physical attributes and design specifications for each soil layer are detailed in Table 1.

Table 1. Soil physical and mechanical annotation.

Rock ID	Rock Name	Thickness/m	Unit Weight (kN/m3)	Cohesive Force (kPa)	Poisson's Ratio	Permeability Coefficient (m/Day)	Internal Friction Angle (°)	Void Ratio
<1-1>	Fill soil	2.00~10.00	18.62	12	0.32	0.1~2	7	0.757
<4N-1>	Soft plastic silty clay	1.70~2.30	15.97	6	0.35	0.02	6	52.0
<4N-2>	Plastic silty clay	1.70~2.70	18.03	16	0.32	0.02	16	35.8
<3-3>	Alluvial gravel sand	0.50~4.00	19.60	--	0.24	30	34	--
<5H-2>	Hard plastic residual soil of granite	1.60~5.40	18.52	21.6	0.28	0.3	19.4	0.86
<6H>	Fully weathered granite	2.00~4.50	18.72	28	0.27	0.3	22	0.774
<7H-A>	emi-rock semi-soil weathered layer of granite	0.70~8.80	19.01	36	0.25	0.5	25	0.661
<7H-B>	Broken granite weathered layer	0.60~5.50	19.11	40	0.23	1.6	25	0.550
<8H>	Moderately weathered granite	0.70~8.00	24.01	400	0.20	1	35	--
<9H>	Slightly weathered granite	0.30~2.20	25.77	1000	0.18	0.3	42	--

2.2. Construction Equipment and Methods

2.2.1. Mechanical Shaft Excavation System

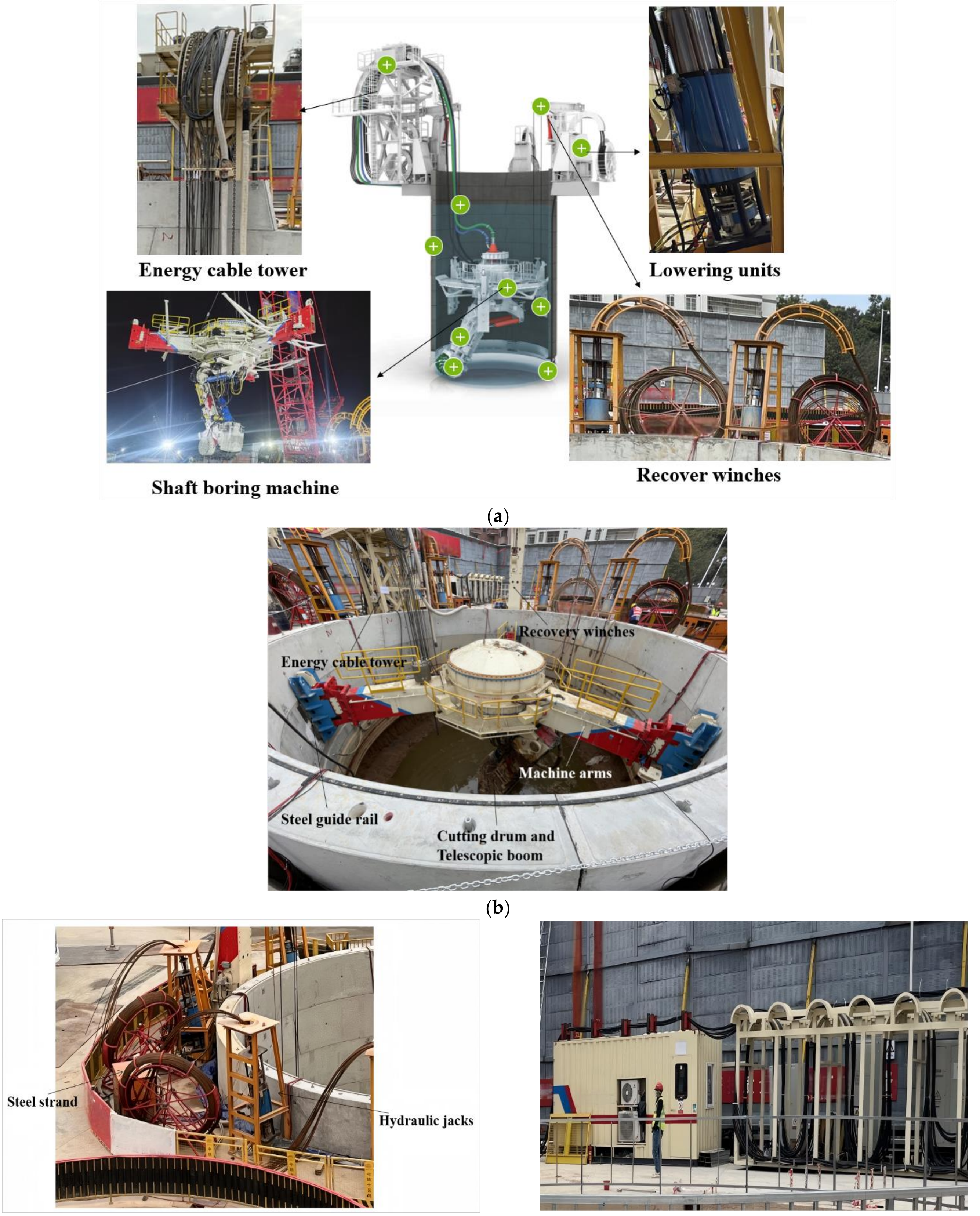
The excavation shaft for the project employs a specialized machine, comprehensively outlined in Figure 3a, which primarily comprises the excavation machine, supply winch system, recovery winch, and separation plant. Here is a detailed breakdown of how each component operates:

(1) Excavation Machine: At its core, the excavation machine features a mainframe equipped with three machine arms, an extendable digging arm, and a cutting drum. The machine arms are anchored to pre-installed steel guide rails on the shaft segments, ensuring stability during operation. The recovery winch enables vertical movement of the mainframe. The telescopic boom, capable of 360-degree rotation, allows for precise downward excavation, while the cutting drum at its tip facilitates the cutting and crushing of rock and soil.

(2) Supply Winch System and Recovery Winch: This system employs hydraulic jacks to facilitate smooth vertical movement of the excavation machine within the shaft, as illustrated in Figure 3b.

(3) Settlement System: The settlement system makes use of steel wire ropes connected to hydraulic jacks for lowering the shaft segments, as depicted in Figure 3c.

(4) Separation Plant: Within the mud system, the rolling cutters of the cutting drum disintegrate the soil mass into mud. This mud is extracted by a mud pump through pipelines embedded in the cutting drum and transported to the separation facility. After filtering and allowing the mud to settle to a specified concentration, it is recycled back into the shaft. This process ensures a balanced water pressure and mud concentration both inside and outside the shaft, crucial for maintaining stability, as shown in Figure 3d.



(**a**)

(**b**)

(**c**) (**d**)

Figure 3. The mechanical shaft excavation system: (**a**) overall schematic diagram of mechanical shaft machine; (**b**) the shaft excavation machine; (**c**) settlement System; (**d**) separation plant.

2.2.2. Construction Plan and Method

1. The grouting method is employed to reinforce the foundation. A 2 m thick layer of C20 concrete is poured onto the ground, which doubles as the top ring beam for the shaft. Concurrently, welding, joining, and sensor placement activities are conducted for the cutting edge. Furthermore, sensors are installed both internally within the concrete segments and during the pouring process of these segments.
2. The initial stage of foundation pit excavation is carried out manually to a depth of approximately 2 m. Upon reaching the designed depth, the cutting edge is lifted and installed within the pit. Concrete is then poured into the cutting edge. Once the concrete attains the necessary strength, the settling system is utilized to fine-tune and position the cutting edge as specified in the design. Simultaneously, the installation of the supply winch system, recovery winch, and separation plant proceeds, as illustrated in Figure 4a.

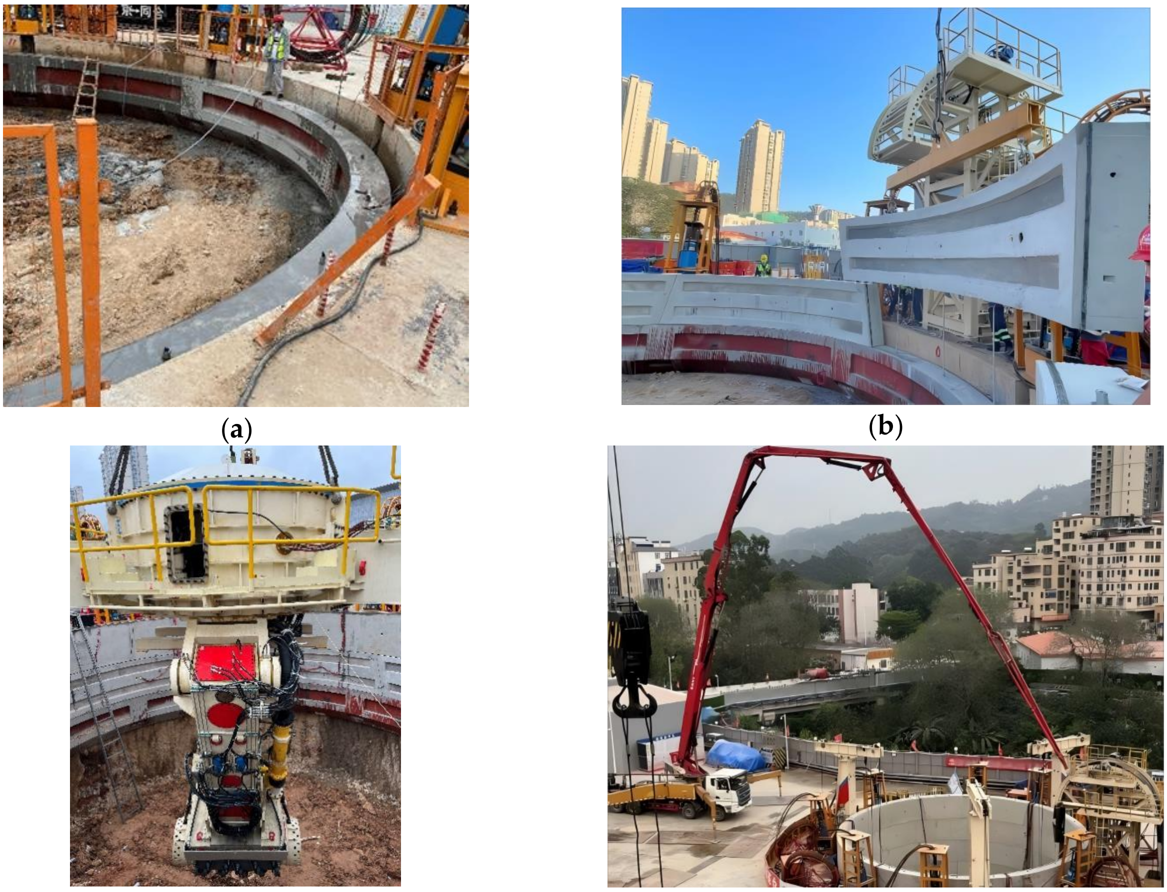


Figure 4. Mechanical shaft sinking method construction process: (**a**) cutting edge positioning; (**b**) 0-ring segment splicing; (**c**) shaft excavation machine installation; (**d**) underwater grouting.

3. Concrete prefabricated segments are lifted and positioned using locating bolts and shear keys on the cutting edge to ensure precise alignment. These segments are then joined together, and the connecting bolts are tightened. Manual excavation of the foundation pit continues, followed by the lowering and assembly of the shaft and cutting edge for subsequent segment installation, as depicted in Figure 4b.
4. Once the foundation pit is excavated to a depth of 5 m, the excavation machine is lifted and installed onto the guide rail of the segments. It is then connected to the recovery winch system. Additionally, grouting operations commence inside the shaft. Upon

completion of grouting, the shaft excavation machine is utilized for excavation. This process involves simultaneous excavation and segment assembly, followed by the lowering of additional segments and the cutting edge. This cyclic process continues, as shown in Figure 4c.

5. Upon reaching the designed depth of excavation, the shaft excavation machine is lifted out of the shaft using the recovery winch. Subsequently, the shaft is sealed at the bottom through underwater grouting. After the sealing process is completed, the accumulated silt and slurry within the shaft are pumped out, marking the completion of the entire shaft structure, as illustrated in Figure 4d. Throughout this construction process, the arrangement of monitoring instruments and the collection of monitoring data are conducted in a systematic and orderly manner.

In summary, the excavation process utilizing the mechanical shaft sinking method initiates with the assembly and commissioning of the mechanical shaft system, along with the installation of the cutting edge. Subsequently, the mechanical shaft commences operation. As the excavation depth attains the design height for one ring of segments, installation of a new ring of segments begins; if not, the excavation proceeds further. This process of segment assembly and installation is repeated until the entire structure of the shaft reaches the designated elevation, at which point concrete sealing and grouting of the shaft base can be carried out. Upon completion of the base sealing grouting, the mechanical shaft excavation system is removed, marking the successful conclusion of the construction work. The construction process and methodology are illustrated in Figure 5 below.

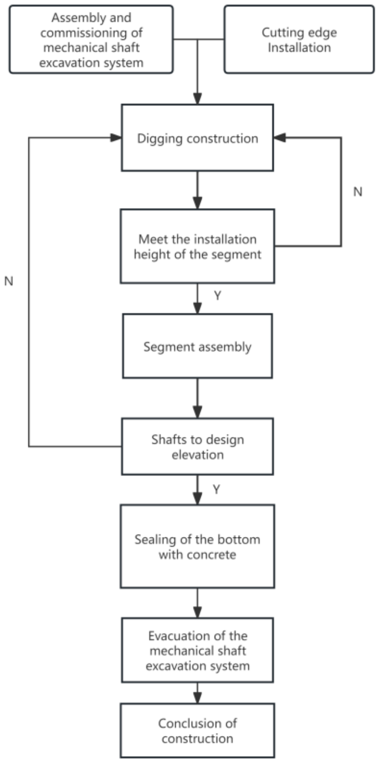


Figure 5. Construction process and method.

The sinking of the shaft is primarily achieved by using equipment and the self-weight of the shaft to compress the soil. When sinking becomes difficult, ground-based thrust cylinders can be utilized to assist in the shaft's descent. After each 0.5 m excavation, steel strands are lowered through the shaft's lifting system, and the shaft sinks by 0.5 m. This process is repeated with another 0.5 m excavation followed by another 0.5 m sink. When the excavation distance reaches 1.5 m, which matches the width of one segment ring, one segment ring is assembled above ground. This cycle is repeated. This process is shown in Figure 6 below.

Figure 6. Shaft sinking method and schematic diagram of the sinking system.

2.3. Monitoring Equipment and Methods

2.3.1. Monitoring Equipment

The automated monitoring and data acquisition technology for excavation pits employs sophisticated measurement instruments to enable automatic, real-time collection, transmission, calculation, and alerting of monitoring data. This technology facilitates superior risk prevention and control at the construction site, ensuring the safety of construction operations. In complex environments, automated monitoring and data acquisition not only guarantee the real-time conduct and transmission of monitoring activities but also safeguard the safety of monitoring personnel and the timeliness of data acquisition. For monitoring parameters such as segment internal forces, segment crack widths, and lateral earth pressures, this research project utilized fully automated data acquisition instruments, specifically the JTM-MCU Automated Data Acquisition Box, as shown in Figure 7 below. The sensors for each monitoring parameter are connected to wireless nodes, and with the assistance of the built-in wireless transmission module, the data are uploaded to the control center of the intelligent safety monitoring system's cloud platform. The cloud platform offers functionalities such as real-time display, automatic alerting and warning, and data storage. Monitoring personnel can access the server via mobile phones or computers to modify the monitoring frequency and view current monitoring data at any time.

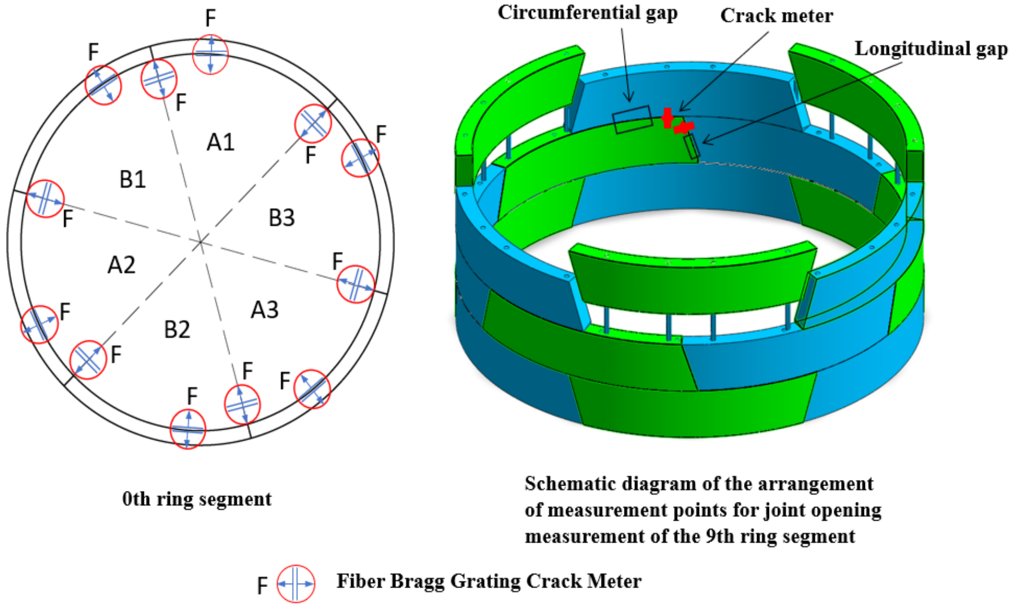
Figure 7. JTM-MCU automated data.

2.3.2. Monitoring Method

A tailored monitoring plan has been formulated, taking into account the unique attributes of the project, the construction party's contractual specifications, and pertinent regulations. This plan prioritizes the shaft structure and encompasses the following monitoring indicators: displacement at segment joints, soil pressure acting on segment joints, strain in the concrete segments, soil pressure exerted on the cutting edge slope, and strain in the steel plates forming the cutting edge. Below is the detailed arrangement for each of these monitoring indicators:

1. Monitoring Opening Displacement of Segment Joints:

A key emphasis is placed on monitoring the changes in joint width, both horizontally and vertically, throughout the entire construction process. This is accomplished using an enhanced crack gauge capable of measuring both elongations and contractions within a range of 2 cm, with a precision of 0.001 mm. Based on geological layer distribution, segments at rings 0, 5, 9, and 13 have been chosen for this monitoring task, as illustrated in Figure 8.



0th ring segment

Schematic diagram of the arrangement of measurement points for joint opening measurement of the 9th ring segment

F **Fiber Bragg Grating Crack Meter**

Figure 8. Crack gauge monitoring.

2. Monitoring Soil Pressure at Segment Joints:

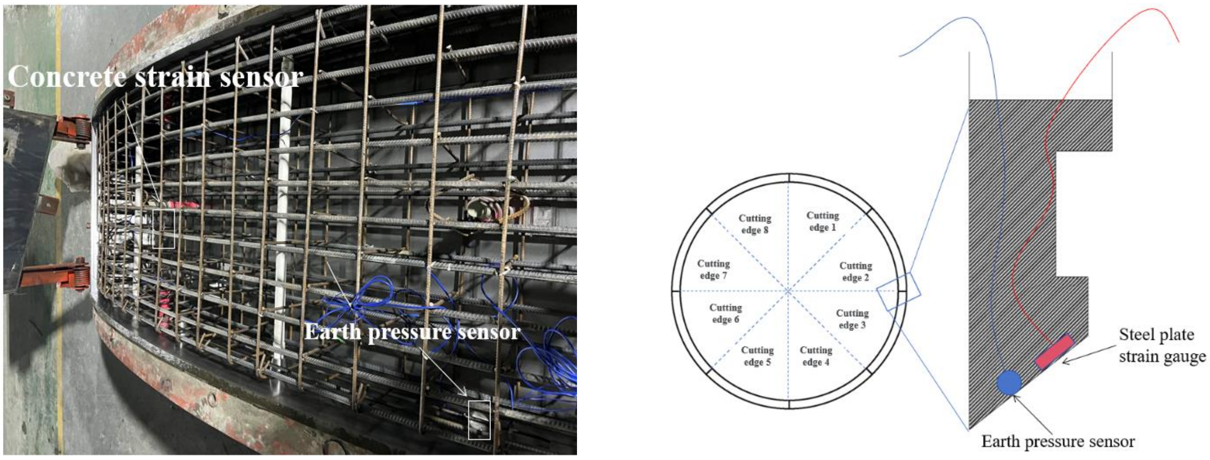
Soil pressure is monitored in both circumferential and longitudinal directions using fiber optic grating soil pressure sensors, offering a measurement accuracy of 0.01 MPa. Segments at rings 0, 5, 9, and 13 are selected for this purpose. The layout of monitoring points is depicted in Figure 9a.

3. Monitoring Concrete Strain in Segments:

The primary focus is on longitudinal internal concrete strain. This is measured using fiber optic grating concrete strain sensors with a precision of 0.01 $\mu\varepsilon$. Segments at rings 0, 5, 9, and 13 are chosen for monitoring concrete strain in reinforced concrete segments. The layout of monitoring points is shown in Figure 9a.

4. Monitoring Soil Pressure on the Cutting edge Slope:

A significant focus is on monitoring variations in soil pressure at the bottom of the cutting edge during shaft construction. This is achieved using fiber optic grating soil pressure sensors with a measurement accuracy of 0.01 MPa. The arrangement of soil pressure sensors at the cutting edge is illustrated in Figure 9b.



(**a**) (**b**)

Figure 9. Segment and cutting edge stress and strain monitoring: (**a**) segment sensor layout; (**b**) cutting edge sensor layout.

5. Monitoring Steel Plate Strain at the Cutting Edge:

This aims to track deformation of the cutting edge on the sidewall during shaft construction and lowering. A steel plate strain gauge with a measurement accuracy of 0.01 με is employed for this purpose. The placement of strain gauges on the cutting edge steel plates is shown in Figure 9b.

3. Monitoring Results and Data Analysis

3.1. Monitoring Results

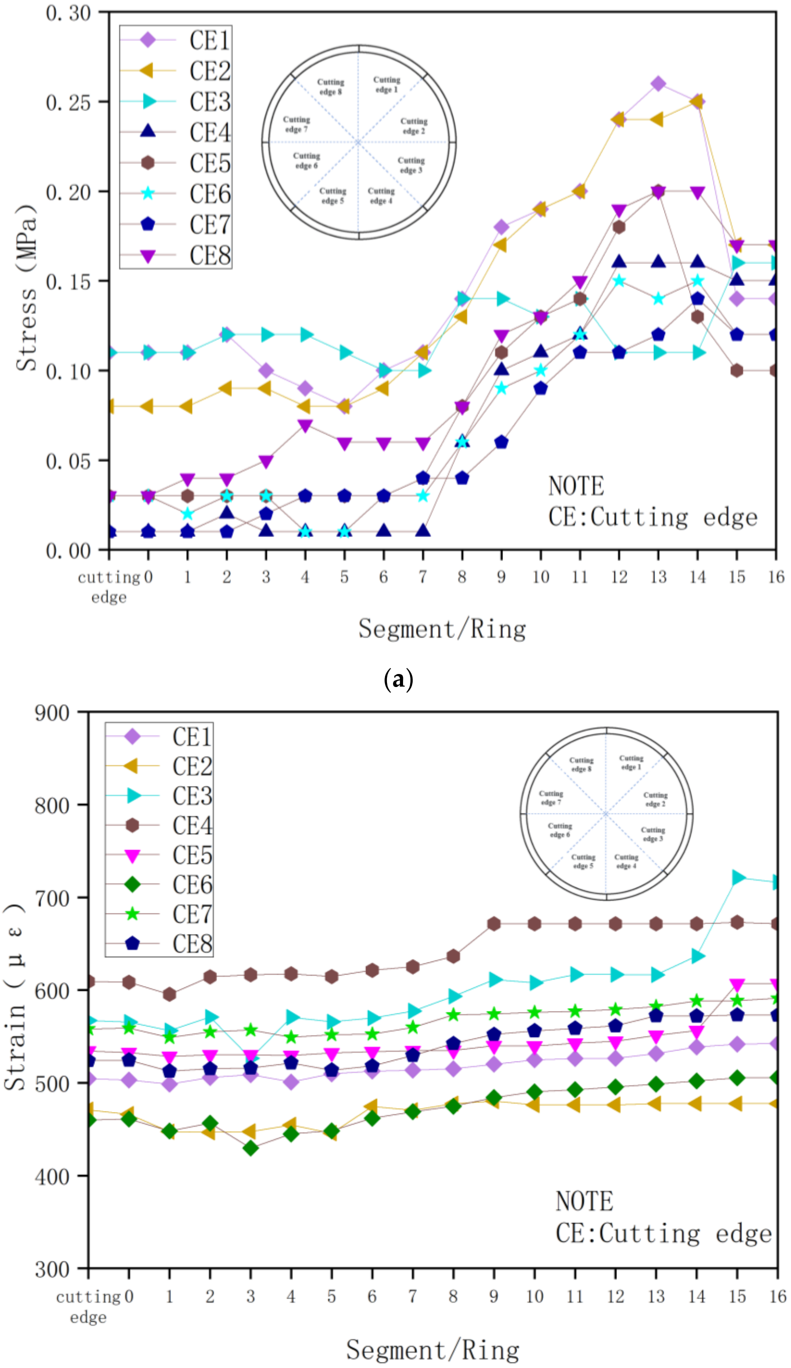
(1) Cutting edge slope contact soil pressure and steel plate strain

The contact soil pressure between the cutting edge and the slope, as well as the strain conditions of the steel plate at the cutting edge, are detailed in Figure 10. In this chart, compressive stresses and compressive strains are designated as positive values, while tensile strains are correspondingly annotated as negative values. This representation method aids in a more intuitive understanding and analysis of the stress–strain state of the cutting edge under various loading conditions.

As evident from Figure 10a,b, during the process of segment assembly within the shaft, the contact soil pressure between the cutting edge and the slope exhibits a unique trend: Initially, the pressure undergoes a period of minor fluctuations, followed by a significant and abrupt increase overall, with a fluctuation range maintained between 0 and 0.30 MPa. Meanwhile, the strain conditions of the steel plate at the cutting edge remain relatively stable, showing only a trend of minor increases and fluctuations within a narrow range, with strain values approximately falling between 400 and 800 uε.

(2) Contact Soil Pressure and Segment Concrete Strain on the Fifth Ring

The contact soil pressures of the fifth ring segment are subdivided into two categories: ring joint contact soil pressure and longitudinal joint contact soil pressure of the fifth ring segment. Correspondingly, the concrete strains of the fifth ring segment are also distinguished into a circumferential concrete strain and a longitudinal concrete strain. Under this definition, compressive stresses and compressive strains are assigned positive values, while tensile strains are marked as negative values. This classification and labeling method facilitates a more precise analysis and understanding of the behavior of the fifth ring segment under different loading conditions.

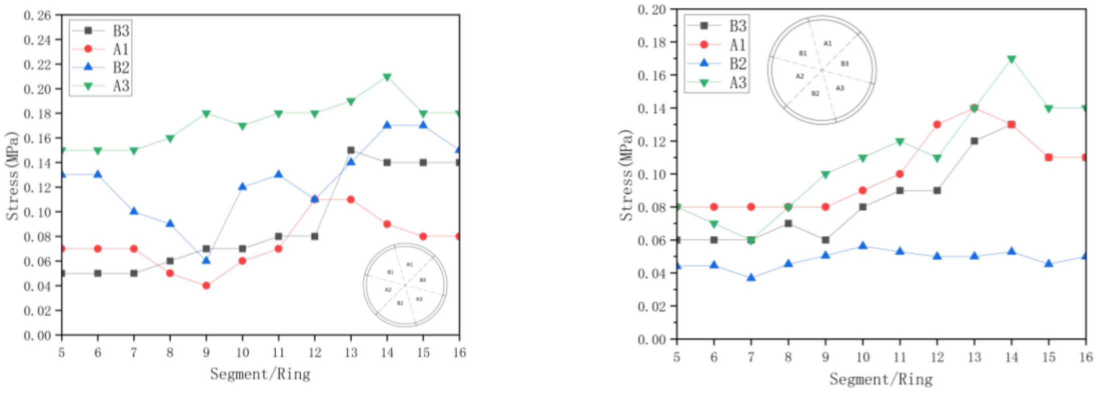


(**a**)

(**b**)

Figure 10. Cutting edge force monitoring: (**a**) cutting edge slope contact soil pressure; (**b**) cutting edge steel plate strain.

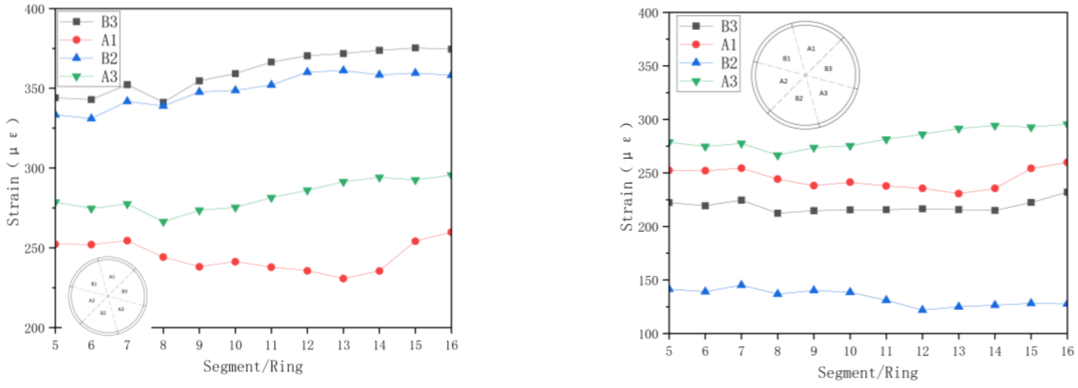
From Figure 11a,b, it is clearly observable that during the sinking process of assembling the fifth ring segment within the shaft, as the construction progresses, the pressure values between the ring joints and longitudinal joints of the fifth ring segment exhibit a notable increasing trend. Specifically, the soil pressure at the ring joints of the segment initially remains stable and then gradually increases in a slow and steady manner. In contrast, the soil pressure at the longitudinal joints of the segment continues to rise with fluctuations. Notably, the variation range of the contact pressures, whether at the ring joints or longitudinal joints, is strictly controlled within 0 to 0.26 MPa.



(**a**) (**b**)

Figure 11. Contact soil pressure of fifth ring segment: (**a**) ring joint contact soil pressure; (**b**) longitudinal joint contact soil pressure.

As seen in Figure 12a,b, the longitudinal concrete of the segment exhibits a trend of increasing toward compressive strain, showing an overall gentle upward trend. Meanwhile, the transverse concrete strain of the segment remains relatively stable with no significant fluctuations. Taken together, the strain range of the entire segment's concrete primarily falls between 100 and 400 uε.



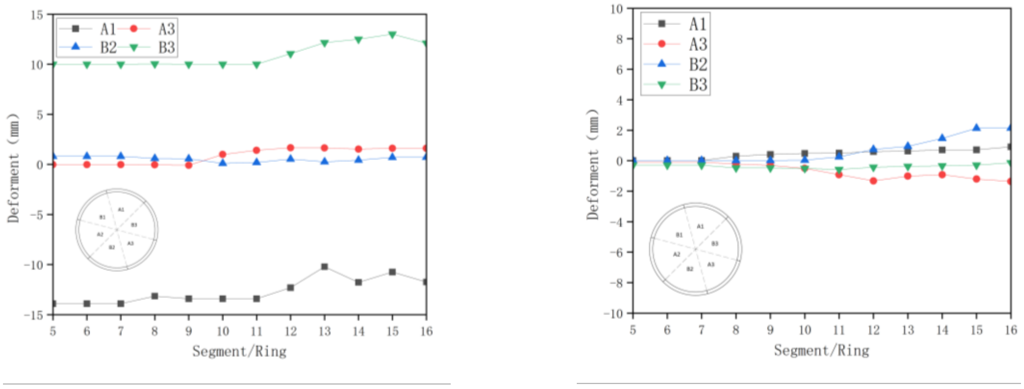
(**a**) (**b**)

Figure 12. Concrete strain of fifth ring segment: (**a**) segment longitudinal concrete strain; (**b**) segment circumferential concrete strain.

(3) Opening Width of Segment Joints

The opening width of the joints in the fifth ring of concrete segments is illustrated in Figure 13 below. Positive values indicate an increase in the width of the segment joints, while negative values indicate a decrease in the width of the segment joints.

As demonstrated in Figure 13, during the assembly process of segments from the fifth to the ninth rings at the construction site, it was observed that the opening widths of both the ring joints and longitudinal joints of the fifth ring segment maintained a relatively stable trend. However, as the assembly progressed to the ninth to sixteenth rings, the opening widths exhibited significant fluctuations, characterized by alternating periods of decline, stability, and sudden increases. Further inspection of the details in Figure 13a reveals a clear and consistent trend of stability in the opening width of the ring joints of the fifth ring segment.



(**a**)

(**b**)

Figure 13. The opening width of fifth ring segment: (**a**) the opening width of segment ring joint; (**b**) the opening width of segment longitudinal joint.

Overall, the opening width of the ring joints of the fifth ring segment was controlled within a range of −15 mm to 15 mm, while in comparison, the variation range of the opening width of its longitudinal joints was narrower, maintained between −2 mm and 2 mm.

3.2. Results Analysis

Field monitoring results indicate that the stresses and displacements of the segments remained relatively stable throughout the construction process, with only some fluctuations observed at certain monitoring points. This phenomenon can be comprehensively analyzed in terms of geological conditions, construction uncertainties, construction methods, and the construction process.

(1) Construction method and construction process

As previously elaborated, the mechanical shaft construction process for this project is unique. It begins with the meticulous excavation of the required space below the cutting edge using a mechanical excavation head, followed by the assembly and lowering of the segments. Given that this mechanical shaft construction method is being applied for the first time in South China, the project faces the dual challenges of lacking relevant normative technical manuals and mature engineering case studies for reference. Therefore, a highly conservative construction strategy was adopted. Specifically, the lifting equipment stably suspends the concrete segments and cutting edge using steel cables, rather than relying on the segments' self-weight to facilitate the cutting of soil by the cutting edge. After the robotic arm successfully excavates the space, the entire segment structure is carefully and slowly lowered. During this entire process, neither the cutting edge nor the segments come into contact with the shaft bottom or adjacent soil, as evidenced by the fact that there is no significant surge in the strain value of the steel plate of the cutting edge during the milling and sinking process, as shown in Figure 10. Additionally, throughout the construction process, the segment structure primarily bears its own weight, the pressure from the mud inside the shaft, and the tensile force applied by the steel cables. As subsequent segments are continuously added, the pressure on the bottom segments from the upper segments gradually increases, leading to an overall increasing trend in both the pressure values at the segment joints and the strain in the segment concrete, as illustrated in Figures 11 and 12.

In this project, high-strength bolts are utilized for precise connection between tunnel segments. Additionally, specialized waterproof strips are installed between segments within the shaft to ensure that both horizontal and vertical seams during assembly exhibit superior sealing performance. However, the accuracy of waterproof strip placement and minor errors during the assembly process may hinder the achievement of a perfect, tight fit between the circumferential and longitudinal seams. As assembly progresses with the addition of upper segments, the contact pressure between segments gradually increases. This escalating pressure further compresses the waterproof strips, leading to an overall decreasing trend in the amount of joint opening as more segments are assembled. This phenomenon is visually demonstrated in Figure 13.

Additionally, the design characteristic of the tunnel segment structure lies in the fact that the width of its circumferential seams is typically narrower than that of the longitudinal seams. This design results in a relatively smaller stress area for the soil between longitudinal seams, thereby increasing the soil pressure per unit area. Furthermore, during the construction process, the assembly of segments may introduce localized axial force concentration, which makes the forces experienced by the segments in the vertical direction more significant compared to those in the horizontal direction. Consequently, during the process of segment settlement, the soil pressure values between the circumferential seams are generally higher than those between the longitudinal seams. This difference is clearly illustrated in Figure 11.

(2) Geological conditions and uncertainties

Throughout the entire construction process, it is inevitable that monitoring data for certain projects exhibited a degree of fluctuation, primarily attributed to the inevitably occurring contingent factors during construction. Taking the stage of sinking the cutting edge down to the splicing of the seventh ring segment as an example, this phase coincided with the shaft boring machine operating deep within the granite formation, leading to a particularly frequent slurry replacement within the shaft. This change not only increased the complexity of the construction environment but also induced frequent collisions and vibrations among the segments. This series of dynamic changes directly resulted in significant enhancements in the fluctuations of key parameters such as segment joint pressure, contact pressure between the cutting edge and soil, and segment joint opening, as illustrated in Figures 10–13. These fluctuations visually reflect the complexity and uncertainty inherent in the construction process.

Starting from the construction phase of the 7th ring segment, there was a sudden and significant increase in the soil pressure on the slope of the cutting edge and the strain on the steel plate. Specifically, when the 13th ring segment was assembled at the construction site, the soil pressure at the cutting edge of CE1 increased from 0.24 MPa to a maximum of 0.26 MPa, and the steel plate strain increased from 526.49 $\mu\varepsilon$ to 540.46 $\mu\varepsilon$. For CE2, the soil pressure reached a maximum of 0.24 MPa when the 14th ring segment was assembled, with the strain value suddenly increasing from 480.55 $\mu\varepsilon$ to 498.55 $\mu\varepsilon$. The correlation between these values, combined with the actual conditions at the construction site, provides insight into the fact that these phenomena stem from the combined effects of numerous uncertain factors in actual construction. Specifically, as the excavation depth of the shaft boring machine gradually increased, by the time the 13th ring segment was being excavated, the cutting edge had already penetrated the granite stratum. At this stage, the interaction between the cutting edge, the boring equipment, and the rock significantly intensified, with collisions becoming more violent. Additionally, due to the incomplete crushing of a small amount of rubble, the contact force with the bottom of the cutting edge increased, resulting in significant abrupt changes in stress and strain values, as illustrated in Figure 10.

Additionally, factors such as installation errors during construction and uneven placement of waterstop gaskets made it difficult for the segments to achieve a completely fitted state. During the excavation process, the inclination of the segment's posture would increase the friction contact surface between the segment surface and the sidewall, while construction operations such as slurry replacement would cause changes in water pressure. Under the combined effects of these factors, the monitoring results of the segments were significantly influenced by external factors, resulting in variations in pressure and strain values among different measurement points. Meanwhile, the segment joint opening was also significantly affected. However, as construction progressed, it was observed that the pressure values at various monitoring points gradually converged and decreased somewhat, as illustrated in Figure 11.

Furthermore, as the construction progress accelerates, the monitoring results for the longitudinal joint opening of tunnel segments exhibit a certain degree of fluctuation; yet, overall, they display a slight upward trend. Considering factors such as the interaction between the mechanical shaft boring system and the sidewalls during construction, the construction disturbance caused by the mechanical milling head, the impact of adjacent excavation pit construction and blasting, and the contact and collision between harder underground formations like granite and the cutting edge, these elements collectively exert a significant influence on the overall internal force monitoring of the segments. Consequently, the monitoring results demonstrate substantial variations in their trends, as illustrated in Figure 13.

4. Discussion

4.1. Limitations in the Application of Mechanical Shaft Construction Method

In the field of underground engineering, the mechanical shaft construction method has proven to be a pivotal technology, exhibiting unparalleled advantages. It has significantly enhanced construction efficiency, fortified safety standards, and optimized cost–benefit ratios. However, despite its widespread application and numerous achievements in practical settings, we must not overlook the inherent limitations of the mechanical shaft construction method. These limitations can stem from the complexity of geological conditions, limitations in equipment performance, technical challenges during operation, and potential impacts of environmental factors on the construction process. Therefore, while fully acknowledging the positive effects of the mechanical shaft construction method, we should also scrutinize the potential issues that may arise during its application in order to provide more rigorous guidance and reference for future technological innovations and practical implementations.

1. Geological Limitations: Geological conditions represent the foremost challenge faced by the mechanical shaft construction method. In rock formations with high hardness or complex geological conditions, the efficiency of this method may decrease and the construction difficulty may increase. Currently, the equipment is only suitable for strata with a rock strength of less than 60 MPa, as higher strength conditions can cause wear on the cutting disk of the shaft sinking equipment, leading to a decline in equipment performance and construction efficiency and subsequently increasing time and costs.
2. Equipment Constraints: Another limitation of the mechanical shaft construction method lies in the performance of available equipment. Current technology cannot accommodate all shaft diameters and depths, limiting its versatility. Additionally, the high initial investment and maintenance costs of specialized equipment may hinder the implementation of smaller-scale projects.

4.2. Comparative Analysis of Construction Cost of Mechanical Shaft Sinking Method

Compared with the open-cut shield initiation scheme, the mechanical shaft construction method saves 22.6% of the construction site, reduces building demolition by about 3000 m^2, saves the amount of reinforced concrete by more than 30%, reduces earthwork by more than 50%, saves about 20% of project investment, and realizes low-cost and efficient construction. The cost comparative analysis is shown in Table 2 below. It can be seen that the construction method does not require a large mining area on the ground, thus reducing the cost of land acquisition and ground facility construction. And because the shaft structure doubles as support, there is no need to carry out foundation pit support and dewatering separately, thus reducing the material cost and improving the overall economic benefit.

Table 2. Cost comparison.

Project	Open-Cut Shield Initiation Scheme	Mechanical Shaft Construction Method	Analysis and Comparison
Pre-demolition works (m^2)	13,647.31	10,566.02	−22.58%
Concrete Engineering (m^3)	29,270.67	19,762.65	−32.48%
Steel Engineering (t)	6597.84	4098.66	−37.88%
Earthwork (m^3)	233,549.90	110,696.6	−52.60%
Waterproof works (m^2)	9538.24	5890.23	−38.25%
Project investment (ten thousand yuan)	20,344.80	16,221.24	−20.27%

5. Conclusions

This paper, leveraging a subway excavation project in Guangzhou as a case study, aimed to delve into and examine the mechanical shaft construction technique, which was implemented for the first time in South China. By providing a detailed analysis of stress–strain monitoring data throughout the entire construction process, with a special emphasis on the cutting edge and the fifth ring of segments, this study achieves its formulated goal. The following key conclusions underscore the novelty and significance of the adopted construction scheme:

1. The innovative mechanical shaft construction method for foundation pit excavation exhibits remarkable superiority compared to traditional methods. Its compact footprint, high level of mechanization, minimal environmental impact, and cost savings have streamlined the construction process. Notably, its ability to operate in all weather conditions allows for a significant reduction in construction time by at least 22.22%, ensuring timely project completion. Additionally, this method not only accelerates construction but also realizes significant cost savings of 20.27% on engineering investments. Importantly, this method significantly reduces worker risks, as confirmed by monitoring data. Overall, this method offers substantial economic benefits and promises excellent application prospects, marking a significant step forward in the construction industry.
2. The monitoring results for the cutting edge and segments during excavation indicate that all recorded values stayed within the acceptable control range, demonstrating the effectiveness of the construction scheme. During excavation into granite formations, sudden increases were observed, but the joints in the fifth ring consistently exhibited compression response characteristics, adhering to safety standards. These findings underscore the robustness and reliability of the mechanical shaft construction technique.
3. Based on a thorough analysis of shaft monitoring data and the uncertainties encountered at the construction site, this study recommends implementing measures such as precise control of tunnel segment lowering rates and the integration of high-precision total stations and GPS positioning technology. These recommendations aim to mitigate adverse effects from tunneling operations and ensure accuracy in segment assembly and lowering. The exceptional stability and manageability maintained throughout the construction process validate the effectiveness of distributed optical fiber monitoring and intelligent safety systems. These innovations not only guided

construction precisely but also ensured dual safeguards for construction safety and quality, constructing a solid technical defense for project progression.

In summary, this study fully validates the scientific and rational construction scheme of mechanical shafts and provides valuable practical engineering case references and feasible suggestions regarding construction technology for subway excavation projects in South China and beyond. Future research should prioritize the development of adaptable excavation techniques leveraging numerical simulation and machine learning for shaft performance optimization. Additionally, there is a need to refine equipment design for mechanical shaft sinking to bolster versatility, durability, and reliability. Concurrently, optimizing concrete segment materials, encompassing design, material choice, processing, waterproofing, and intelligent construction methods, will enhance efficiency, stability, and overall performance while minimizing costs.

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