Case Study of the Largest Concrete Earth Pressure Balance Pipe-Jacking Project in the World

Jiang, Xi; Zhang, Xuehui; Wang, Shuai; Bai, Yun; Huang, Baoshan

DOI
10.1177/03611981221076842

Publication date
2022

Document Version
Final published version

Published in
Transportation Research Record

Citation (APA)
Jiang, X., Zhang, X., Wang, S., Bai, Y., & Huang, B. (2022). Case Study of the Largest Concrete Earth Pressure Balance Pipe-Jacking Project in the World. *Transportation Research Record*, *2676*(7), 92-105. https://doi.org/10.1177/03611981221076842

Research Article

TRR
JOURNAL OF THE TRANSPORTATION RESEARCH BOARD

Transportation Research Record
2022, Vol. 2676(7) 92–105

DOI: 10.1177/03611981221076842
journals.sagepub.com/home/trr
SAGE

Case Study of the Largest Concrete Earth Pressure Balance Pipe-Jacking Project in the World

Xi Jiang[1,2,3], Xuehui Zhang[4], Shuai Wang[5], Yun Bai[1,2], and Baoshan Huang[3]

Abstract

Pipe jacking has been the dominant trenchless technology for constructing small (<2 m) to medium-diameter (<4 m) tunnels. Uncertainties and construction difficulties increase significantly when the diameter of the tunnel exceeds 4 m. This paper presents a case study of the largest concrete pipe-jacking tunnel project in the world, the sewerage tunnel along Jinshan Lake, Zhenjiang, China. In this project, an underwater tunnel with a diameter of 4.67 m was constructed by the earth pressure balance (EPB) pipe-jacking method. The case study reports project background, and geological and hydrogeology conditions. The key techniques such as the selection of pipe-jacking machine, jacking force estimation and control, design of intermediate jacking station, grouting process control, launching, and reception of the tunnel boring machine, trajectory control of pipe jacking, and ventilation and gas monitoring during the construction period were investigated and discussed. Furthermore, to overcome the technical difficulties associated with the oversized jacked tunnel, the corresponding countermeasures were adopted point by point, so that the safety of the whole project could be guaranteed. This study filled the knowledge gap of technical know-how for large-diameter (over 4.5 m) pipe-jacking tunnel and is expected to provide practical guide for future large-diameter pipe-jacking tunnels.

Keywords

pipe jacking, grouting, infrastructure, lining, tunnels and underground structures

With the intensive development of urban cities, the exploitation of underground space plays a vital role in mitigating space shortage and improving urban resilience. The tunnel is one of the most popular underground structures to connect different districts and improve the integrity of the metropolis. Metro and road tunnels have been an essential part of the infrastructure system, which can meet the demand for more reliable transportation, energy efficiency, and society's environmental awareness (*1*). Besides traffic tunnels, tunnels for utilities, such as sewerage, water, and electrical cables are also of great importance to the sustainable development of metropolises such as Shanghai, Tokyo, and London (*2*). The development of utility tunnels worldwide has a history of over a hundred years, and it was only in the late 1990s that the great significance of utility tunnels in boosting urban resilience was recognized. With more and more utility tunnels constructed and in operation in recent decades, their design and construction have been much improved.

In China, many utility tunnel projects are underway, especially in the construction of "sponge cities," which improve the drainage for rainwater underground in cities. The city drainage system can be much strengthened

[1]Department of Geotechnical Engineering, College of Civil Engineering, Tongji University, Shanghai, China
[2]Key Laboratory of Geotechnical and Underground Engineering, Ministry of Education, Tongji University, Shanghai, China
[3]Department of Civil and Environmental Engineering, University of Tennessee, Knoxville, TN
[4]Department of Geoscience and Engineering, Delft University of Technology, Delft, the Netherlands
[5]Shanghai Road and Bridge (Group) Co., Ltd., Shanghai, China

Corresponding Author:
Xuehui Zhang, X.Zhang-10@tudelft.nl

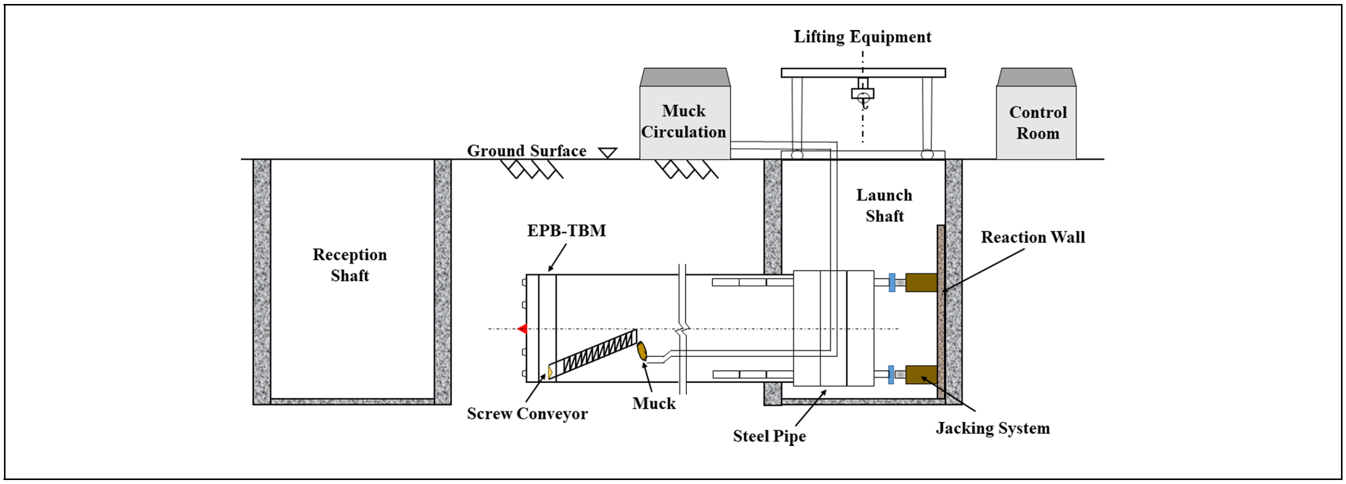

Figure 1. Schematic of EPB pipe-jacking method.
Note: EPB = earth pressure balanced; TBM = tunnel boring machine.

by constructing utility tunnels to reduce urban flooding risks. In general, ordinary utility tunnels for gas, water, and cables usually have small diameters of less than 1.5 m and are of shallow burial depth. Thus, these tunnels are mostly constructed with the traditional trench method (or cut & cover method), which is not eco-friendly because of its influence on the surrounding environment. In contrast, advanced trenchless methods, such as the shielding tunneling method and pipe-jacking, are more advantageous because of their reduced negative effect, especially in dense urban areas. The shield tunneling method relies on the costly tunnel boring machine (TBM) and it is applied mainly to segmented tunnels whose diameter is more than 5 m. Pipe-jacking (or micro-tunneling method) is used to construct small-diameter utility tunnels such as sewerage, gas and water mains, oil pipelines, electricity and telecommunications cable ducts, and drainage culverts (*3–7*).

The pipe-jacking method outperforms traditional trench methods in many aspects, such as lower environmental disturbance, lower overall cost, shorter construction period, and less rehabilitation (*4*, *8*). As shown in Figures 1 and 2, the schematic of the earth pressure balance (EPB) pipe-jacking method is presented, and the main construction process consists of the following steps: (a) The TBM machine is installed at the launch shaft by lifting equipment and positioned at the designated distance ahead of the hydraulic jacking system; (b) the first tunnel segmental ring is put between the TBM machine and the jacking rigs, and is then pushed into the ground. At the same time, the TBM does soil excavation and discharges the soil when thrust forward; (c) the hydraulic jacking rigs retract and the next segmental ring is placed (after the first segmental ring) and subsequently pushed into the ground; (d) the process repeats until the TBM reaches the reception shaft. For the longer pipelines by the pipe-jacking method, the accumulated interface friction between segmental lining and ground will challenge the pipe-jacking system, and usually an intermediate jacking station will be set up to ensure that the segmental ring can be thrust forward smoothly.

In recent years, tunnels constructed by pipe-jacking method have attracted more and more interest from the tunneling industry and academia. Many studies on pipe-jacking tunnels can be found from the past several years. For instance, Mok et al. highlighted the planning, design, and construction of pipe-jacking tunnels with a diameter of smaller than 2 m in Hong Kong (*9*, *10*). The performance of works, lessons from the projects, and improvements were presented in this study. Zhen et al. studied the remedial treatment of a steel pipe-jacking accident in the complex ground strata, where large deflection and local buckling of segmental ring and water intake occurred (*8*). The outer diameter of this tunnel was 1.8 m. With the development of the pipe-jacking method, it is used to construct larger-diameter and longer-distance utility tunnels. Cui et al. investigated the field performance of concrete pipes during the jacking process under the Guan River in China (*3*). The external diameter of the TBM was 4.17 m, and the longest jacking distance was 450 m. Sun et al. presented two underground pedestrian passages by pipe jacking in Nanjing, China (*11*). This study investigated the rectangular pipe-jacking technology and proposed measures such as increasing grouting mortars and pressure to reduce the adverse surface settlement. Sun et al. made a numerical analysis of soil deformation behind the reaction wall induced by horizontal parallel pipe-jacking construction (*12*). The tunnel in this study had an outer diameter of

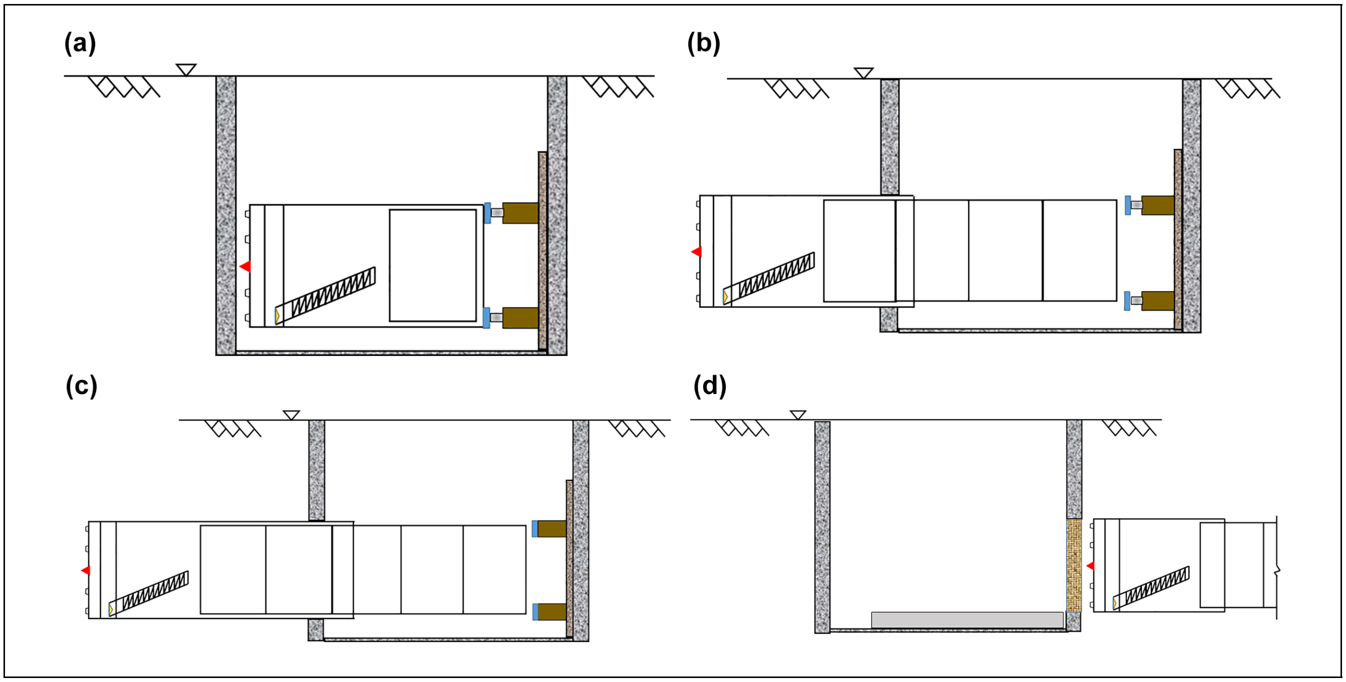

Figure 2. Construction process of pipe jacking.

4.16 m and an internal diameter of 3.50 m. The longest jacking distance was 450 m. Wang et al. investigated the steel pipe-jacking tunnel project in Shanghai, China (*13*). The pipe diameter was 4 m, and the longest jacking distance was 969.94 m.

Although the pipe-jacking method has been much investigated, based on the literature review, the diameters of all the studied tunnels are less than 4.50 m, and their longest jacking distances were less than 1,000 m. Meanwhile, many large-diameter steel pipe-jacking tunnels have relatively poor durability compared with concrete tunnels, leading to greater cost for maintenance and rehabilitation in the service phase. And most previous studies have focused on the slurry-TBM pipe jacking. To meet the usage demand, the larger-diameter pipe-jacking tunnel with a longer jacking distance is urgently needed. However, uncertainties and construction difficulties increase significantly when the diameter of the tunnel exceeds 4 m, and there is no published literature on the technique of pipe-jacking tunnel with a diameter of more than 4.50 m.

To fill this knowledge gap, this study conducts a case study of the largest concrete pipe-jacking tunnel project in the world, the sewerage tunnel along Jinshan Lake, Zhenjiang, China. In this project, a sewerage pipeline with a diameter of 4.67 m constructed by the pipe-jacking method was presented comprehensively. The key technologies and challenges of this case study are investigated and discussed, and can provide experience for the pipe-jacking tunnel industry.

Project Information

Project Background

The pipe-jacking tunnel in this study is designed and constructed for overflow discharge and pollution control, which is a sub-project of the main "Sponge City" project in Zhenjiang, Jiangsu Province, China. The first section of the pipeline construction (referred to as the CS0 section) is located along the bank of Jinshan Lake, consisting of four shafts and three interval tunnels. As shown in Figure 3, the tunnel starts from the Y-1 shaft in Jiangnan pumping station and goes to the Y-4 shaft on Jiefang Road, with a total length of 2,716 m. Of these four working shafts, three serve as launch shafts for pipe jacking, whereas Y-2 works only as a reception shaft. The lengths of these three interval tunnels are 750 m, 633 m, and 1333 m, respectively. More information can be found in Table 1.

Geological Conditions

The project area is located in the eastern area of the Ningzhen Mountain Range and faces the Yangtze River in the north. The ground strata of the site mainly consist of miscellaneous fill, plain fill, silt, and silty clay. The corresponding geological investigation was conducted according to the Chinese standard GB 50021-2001 (*14*). In addition, the parameters of soil properties were tested based on the Chinese standards (*15*). Table 2 shows the detailed properties of site soil layers, and Figure 4 shows the geological profile along the pipe-jacking route. Based

Table 1. Details of CS0 Sections

Shafts	Diameter (m)	Depth (m)	Construction method
Y-1 shaft	16	22.45	High-pressure jet grouting piles, bored piles
Y-2 shaft	16	23.61	High-pressure jet grouting piles, bored piles
Y-3 shaft	16	20.88	Caisson, triaxial mixing pile, high-pressure jet grouting piles
Y-4 shaft	16	23.71	Caisson, triaxial mixing pile, high-pressure jet grouting piles
Intervals	Jacking length (m)	Burial depth (m)	Soil layer
Y-1–Y-2	750	9.82–18.08	Silty clay
Y-2–Y-3	633	10.53–18.45	Silty clay
Y-4–Y-3	1,333	8.42–18.39	Silty clay
Total	2,716		

Table 2. Soil Properties of the Main Formations

Layer no.	Name	Thickness (m)	Unit weight (kN/m^3)	Cohesion (kPa)	Internal friction angle (°)
1-1	Miscellaneous fill	0.30–13.70	20.0	5.0	10.0
1-2	Plain fill	1.50–12.70	18.6	15.0	8.0
1-3	Silt	0.40–11.40	17.2	10.0	5.0
2-2-1	Silty clay	0.9–43.70	18.0	16.1	15.2
2-2-2	Sandy silt	1.40–25.00	18.5	16.1	18.8
2-3	Silty sand with silt	1.20–25.90	18.7	9.0	24.0
5-2-1	Coarse sand	0.80–4.30	20.6	4.6	35.2
6-5	Round gravel	1.40–6.80	na	na	na

Note: na = not applicable.

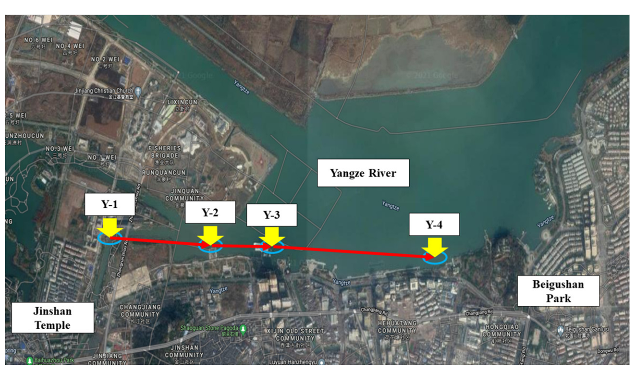

Figure 3. Schematic route of program construction.

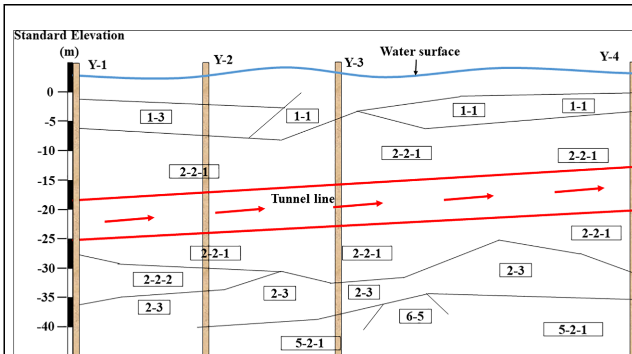

Figure 4. Geological profile of the project.

on the geological information, it can be found that the tunnel is mainly laid in the silty clay layer. A high driving resistance on the cutterhead of the TBM could be generated as a result of the properties of the excavating layer. During the construction, relevant countermeasures should be taken to deal with the potential problems.

Hydrogeology Conditions

Zhenjiang city is located in the mid-latitude and belongs to the northern subtropical monsoon climate zone. The hydrogeology conditions are significant to the safety of the construction because the CS0 sewerage pipeline was built under Jinshan Lake. The types of underground water mainly consist of phreatic water and micro-confined water. The phreatic water occurs in the pores of the 1-2 layer of plain fill soil, 2-2-1 layer of silty clay and 2-2-2 layer of sandy silt. The micro-confined water can be found in the 2-3 layer of silty sand with silt. Groundwater receives replenishment from atmospheric precipitation, and the drainage methods include natural evaporation and stratum seepage. The pipeline project is

Table 3. Parameters for DN-4000 Pipe-Jacking Machine

Items	Parameters	Value
Size of tunnel boring machine	Diameter of incision ring (R_a)	4,680 mm
Cutterhead	Diameter of cutterhead	4,670 mm
	Torque coefficient	$\alpha = 2.03$
	Rotating speed	0–1.03 r/min
	Opening ratio	38%
	Power	6×37 kW
Correction system	Hydraulic jacks	8×200 t
	Total thrust	1600 t
Main jacking system	Hydraulic jacks	10×200 t
	Total thrust	2,000 t
	Length of pipe-jacking machine	6,672 mm
	Weight of pipe-jacking machine	70 t

under Jinshan Lake and the lake water level varies with the tides. Watertightness is a key issue in the pipeline tunnel design, and the high water pressure on the excavation face may bring safety concerns to the jacking process.

Selection of Pipe-Jacking Machine and Segmental Lining Design

Pipe-Jacking Machine. The suitable selection of pipe-jacking machines is the key issue to guarantee the safety of tunnel construction. The primary considerations for selecting pipe-jacking machines are geotechnical parameters, stability of the excavation surface, tunnel segment types, cost, construction duration, and tunnel route. EPB shield, slurry-shield, and multi-mode shield are the most commonly used TBM types (*16*). Multi-mode shield TBM can be switched to slurry and EPB modes according to the geological conditions, but the higher expense of the machine and the time-consuming switching process limit its utilization in pipe-jacking projects. Slurry-TBM can be applied to more complex strata but the high costs for slurry treatment plants constrain its application in small-diameter utility tunnels. In addition, the environmental problem induced by the slurry operating process also limits its wider usage. Thus, EPB TBM outperforms other options after a consideration of the economic, technical, and geological conditions in this project.

In this project, a DN-4000 EBP TBM designed by Shanghai Road and Bridge Company, with an outer diameter of 4,670 mm, was selected and its technical parameters were determined based on the requirement of excavating in silty clay strata. The detailed parameters of the TBM are presented in Table 3. Figure 5 shows the schematic of the TBM cutterhead. A spoke-type

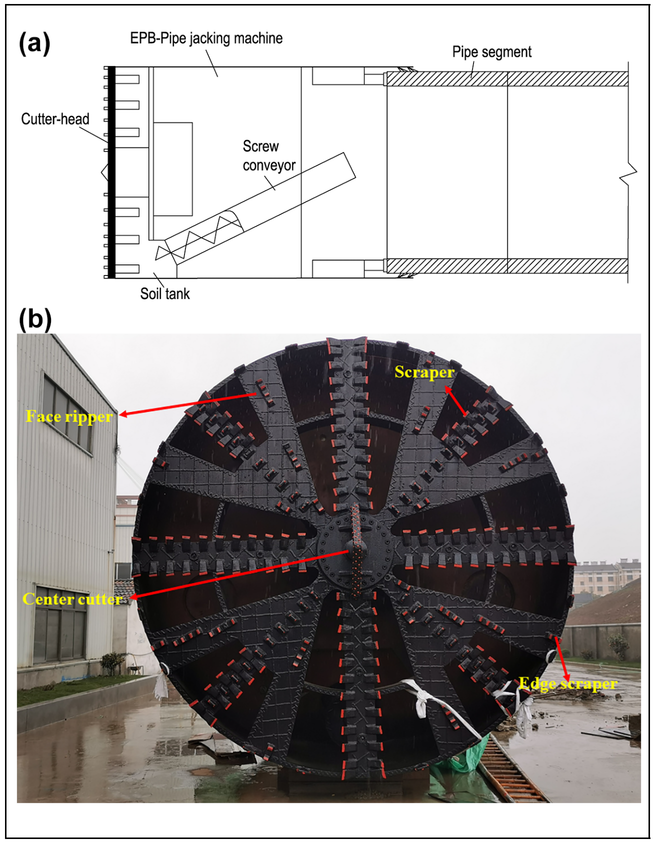

Figure 5. Schematic of the earth pressure balance (EPB) tunnel boring machine (TBM): (*a*) EPB TBM and (*b*) cutterhead.

cutterhead was used to stir the soil and lead the excavated soil to have good plasticity and fluidity. The pressure in the soil tank will increase with the advance of pipe jacking. When the pressure in the soil tank rises to the designated limit value, the extra soil is discharged inside the TBM by a screw conveyor located at the lower section of the soil tank to keep the pressure of the soil tank within an acceptable range during the jacking process. The proper control of the pressure gap between the soil tank and excavating face ensures the stability of face, and therefore a safe advancing process. Thus, the EPB TBM is able to control surface settlement with higher precision, which can reduce its negative influence on the surrounding environment, such as damage to existing nearby infrastructure. Meanwhile, it can improve the construction efficiency, and less slurry treatment can reduce the environmental impact.

During the pipe-jacking process, attention should be paid to the following issues:

(1) The main jacking system has ten 2,000 kN-double-stroke thrust cylinders with a total thrust force of 20,000 kN. The center position of the cylinders is supposed to be consistent with the

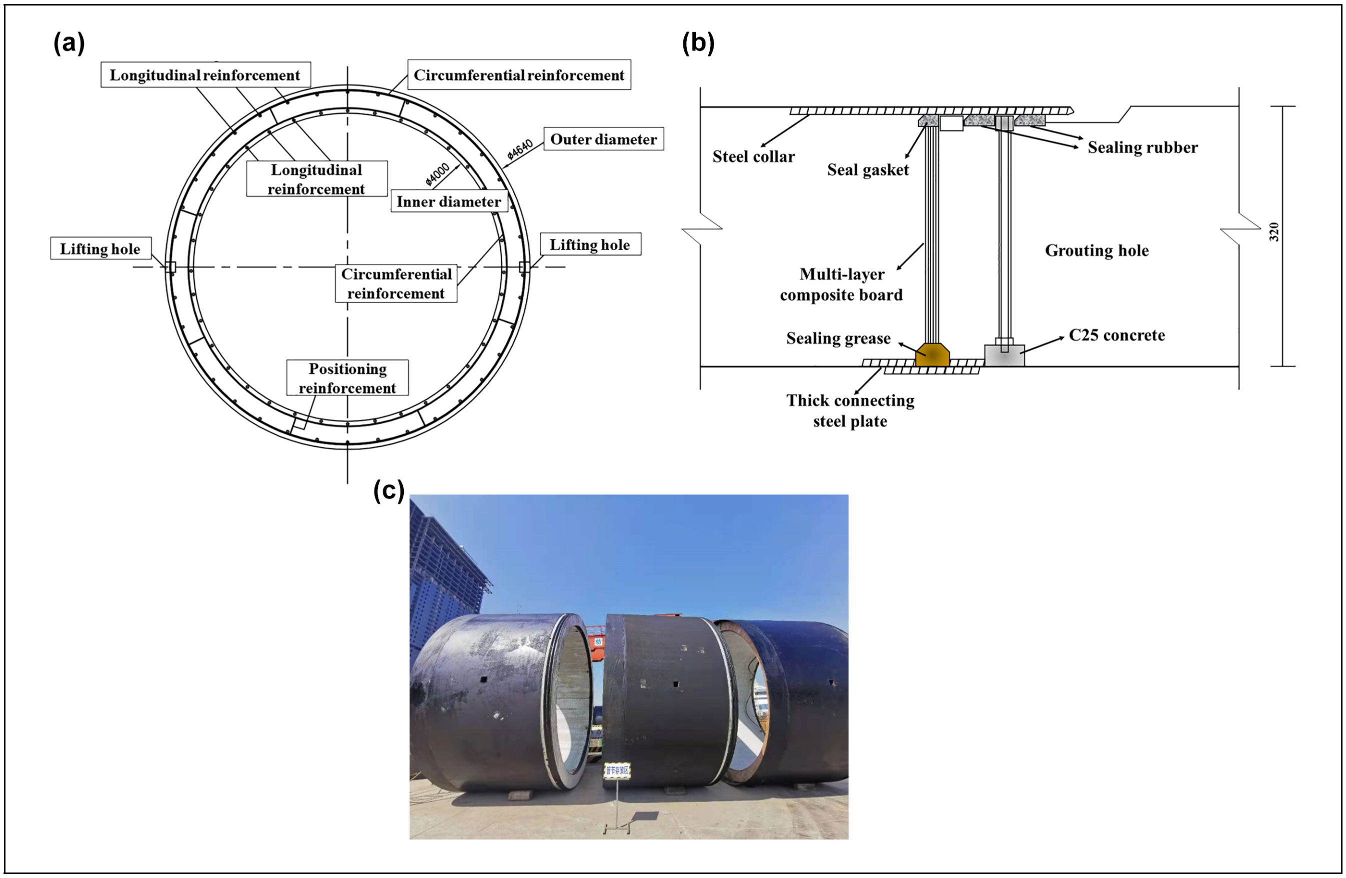

Figure 6. Segmental ring design: (*a*) segment cross-section, (*b*) segmental joint, and (*c*) precast segment with waterproof coating.

design, which can keep the jacking point and the rear contact point in good condition. Meanwhile, the error of the cylinder center should be less than 5 mm.

(2) To reduce interface friction along the jacked length, bentonite is injected into the tunnel–ground interface through the holes on the segment. Four grouting holes are evenly distributed at the end of the tool pipe for circumferential synchronous grouting during the jacking process. The gap between the ground and TBM shield is backfilled by synchronous grouting, and a diaphragm pressure gauge should be installed at the shield to check the grouting quality.

Segmental Lining Design. The design of segmental linings is supposed to be based on the structure safety and operation requirements. The tunnel segment must be strong enough to withstand ground loading as well as external forces in the construction phase, such as the bending moment in the lifting and the large jack forces. The segment cross-section should keep safe under uneven compression during the jacking process. The design of reinforcement should consider all anticipated loading scenarios and provide adequate strength. As shown in Figure 6*a*, the concrete tunnel lining is 320 mm thick and a segmental ring has an outer diameter (R_s) of 4,640 mm. The concrete used for the segment has a compressive strength of 55 MPa.

Besides structure strength, watertightness design is also vital in underground tunnels, as many incidents caused by water inrush and joint leaking are attributable to the unreliable sealing problem in tunnel structures (*17*, *18*). The longitudinal joint is the weak point for water leakage, and multiple sealing rubber layers are fixed at the circumference of segmental ring to prevent water inrush, as shown in Figure 6*b*. In addition, the interface of two adjoining segmental rings is paved with composite board to assure an even distribution of contact forces. For watertightness of the segmental ring, the concrete has a high resistance to water permeability. A waterproof coating is painted externally to provide additional water resistance. Figure 6*c* shows the “black” surface of the precast segment after painting with waterproof materials. In the segment manufacturing process, the inner and outer surfaces of the precast segment should be flat and perpendicular to its axis. No cracking is allowed on the

Table 4. Number and Location of Inter-Jacks

		Distance from the cutterhead/Number of inter-jacks								
Section	Length (m)	50	200	350	500	650	800	950	1100	Total
Y-1-Y-2	750	1	1	1	1	1	na	na	na	17
Y-3-Y-2	633	1	1	1	1	na	na	na	na	
Y-4-Y-3	1,333	1	1	1	1	1	1	1	1	

Note: na = not applicable.

outer surface of the lining, and the width of the cracks on the inner surface should be controlled within 0.05 mm.

Key Challenges and Countermeasures in Long-Distance Pipe Jacking

Many technical challenges were faced for the first time in this project because of the complex geological conditions and difficulty in controlling such a large-diameter TBM during the jacking process. The key challenges and corresponding countermeasures during the construction are summarized and clarified in this section.

Jacking Force Estimation and Earth Pressure Control

During the tunneling process, the thrust force should counterbalance the longitudinal circumferential friction and the face resistance at cutterhead (*19*). Equations 1 and 2 show the calculation of the total jacking force and face resistance of the cutterhead.

$$F_0 = \pi * D_1 * L * f_k + N_F \tag{1}$$

where F_0 represents the total jacking force (kN), D_1 represents the outer diameter of segment; L represents the jacking length; f_k represents the average friction between the outer pipe and the soil (3.5 kN/m^2); N_F represents the face resistance of the cutterhead.

The maximum face resistant force can be estimated by Equation 2:

$$N_F = \frac{\pi * D^2 * \gamma_s * H_s}{4} \tag{2}$$

where D is the outer diameter of TBM, γ_s is the soil weight (18kN/m^3 in this project), H_s is the thickness of overburden ground.

The Y-3 to Y-4 section with the longest length of 1,333 m was selected to calculate the total jacking force. The total jacking force F_0 is 73,413 kN, which is much larger than the maximum allowable jacking force (9,000 kN) of the launch shaft. Thus, the intermediate jacking station is needed during the advancing process.

In the jacking process, the earth pressure *P* at the soil tank is important to control the stability of the excavating face. While *P* is smaller than the active earth pressure P_a on the face, settlement will occur on the ground. While if *P* is larger than the passive earth pressure P_p, uplift will occur on the ground. Settlement during construction is a relative slower process compared with the uplift process, especially in cohesive soil formation. It will take a long time to reach the final settlement. *P* is supposed to be controlled between P_a and P_p. In the practical construction, *P* is adjusted as equal to the static earth pressure (P_0) with a variation of 20 kPa according to the soil type, as shown in Figure 7. The soil tank pressure is controlled by soil discharge rate and a dynamic balance is kept as much as possible to minimize ground disturbance.

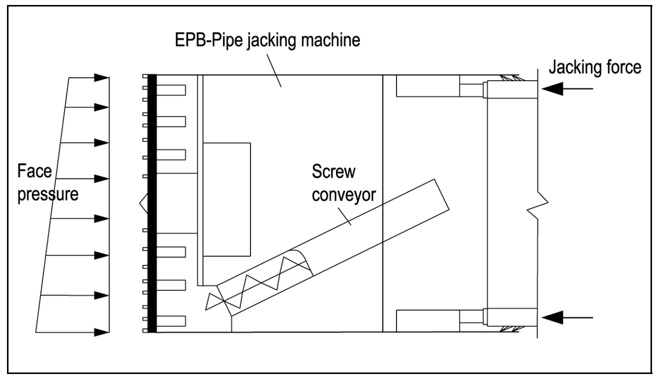

Figure 7. Face stability of earth pressure balance (EPB) pipe-jacking machine.

Design of Intermediate Jacking Station

To increase the maximum jacking length and reduce the thrust forces that are transmitted to the shaft structure or reaction wall, the intermediate jacking station (inter-jack) is applied in the pipe-jacking process. As shown in Figure 8, the inter-jack is a steel cylinder equipped with hydraulic jacks which are installed between the leading and trailing pipes. The inter-jack is not activated in the ordinary jacking process, and moves forward along with the pipeline. When the thrust force provided by the jacking system is not adequate to push the whole pipe forward, hydraulic jacks at inter-jack start working to push the leading pipe section forward. The designed bearing force of the reaction wall in the shaft is 9,000 kN, and

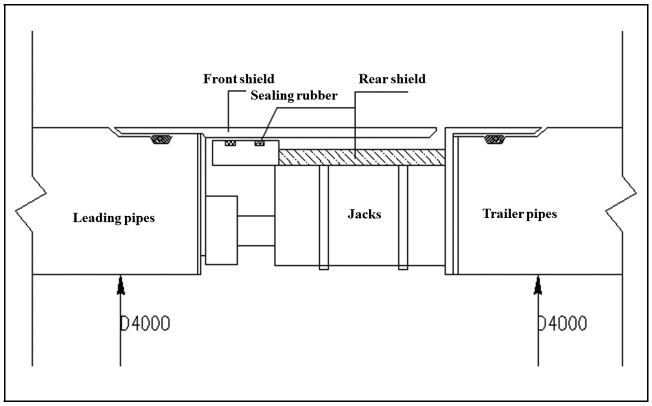

Figure 8. Intermediate jacking station.

the designed jacking force of a single inter-jack is set as 10,000 kN when determining the number of inter-jacks needed. Table 4 shows the number and location of inter-jacks in this project. During the coordination of multiple inter-jacks, the inter-jacks should be marshaled, and the pipes are jacked forward from the head according to the procedures. When one inter-jack works, others should stop and the main jack completes the final jacking operation after all inter-jacks are deactivated.

Grouting Process Control

To minimize the friction resistance between the pipes and ground, synchronous grouting is necessary. The grouting material is injected into ground through the preset holes distributed evenly along the circumference of segment ring. The grouting mortar forms an annular mud lubrication sleeve between the outer segment and the ground soil. A proper grouting material design and grouting process control contribute to the smoothness of pipe jacking.

In this project, a type of thixotropic mortar was used for synchronous grouting. Besides friction reduction, the setting of the grouted mortar can prevent the settlement caused by the existing void left by TBM. There are five precast grouting holes on each segment ring, as shown in Figure 9, *a* and *b*, and the angle between two grouting holes is 60°. Under a proper injection pressure, the grouting mortar will flow longitudinally and circumferentially to coat the ring evenly.

To ensure the stable and effective grouting process, the quality of the thixotropic mortar should be guaranteed. Table 5 shows the mixture ratio of the grouting mortar and its properties. After determination of the properties of the grouting mortar, the theoretical

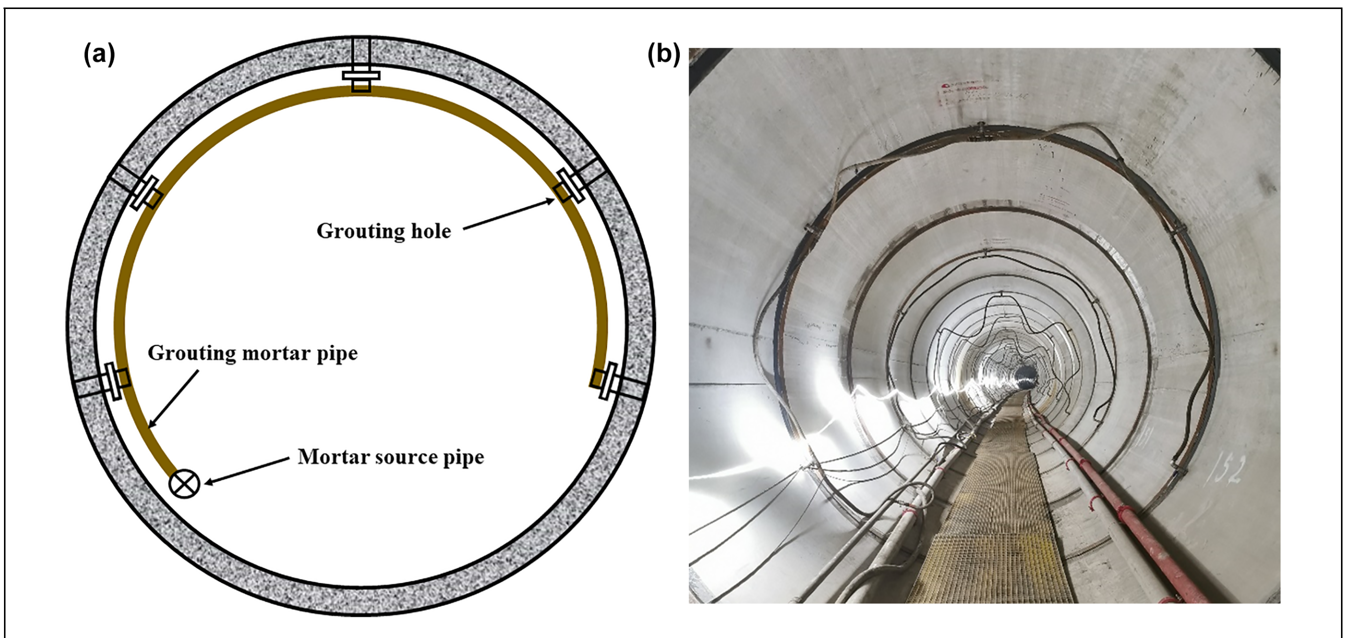

Figure 9. (a) Grouting holes of the segment and (b) inner structure.

Table 5. Mixture Ratio and Properties of the Grouting Mortar

Raw materials	Bentonite	Sodium carbonate	Carboxymethyl cellulose (CMC)	Water
Weight	100 kg	5 kg	1.2 kg	550 kg
Properties	Funnel viscosity (s)	Fluid loss (ml)	Effective viscosity (CP)	Specific gravity (kg/m^3)
Values	80	12.6	21	1.05

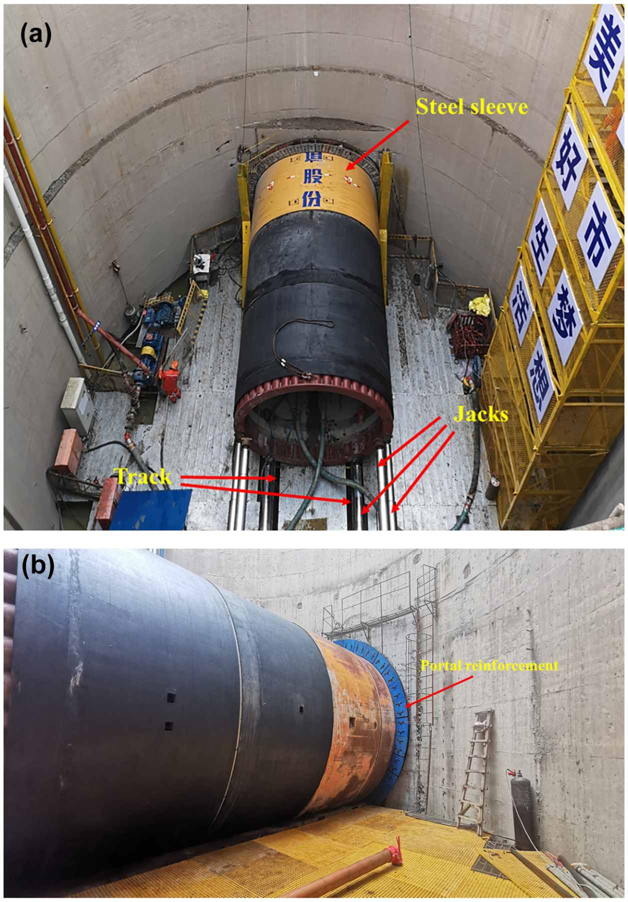

Figure 10. (*a*) Pipe-jacking machine in the launch shaft and (*b*) tunnel portal in the shaft.

grouting volume is five times the theoretical void volume between the pipe and ground based on the construction experience (*13*). The outer diameter (R_a) of the TBM cutterhead, the outer diameter of the segment, the size of the unilateral gap, and the length of a single segment is 4,680 mm, 4,640 mm, 20 mm, and 2.5 m, respectively. Thus, the volume of grouting mortar in theory is 1.46 m^3/m. Because of the seepage loss in silty clay, the actual grouting volume is generally 1.5 to 3 times the theoretical value. Therefore, the quantity of grouting mortar for a single segment ring is between 2.20 and 4.40 m^3/m. During the grouting process, the pressure of the pump should be controlled at 0.3 to 0.4 MPa, and appropriate adjustments should be made based on the actual ground condition and jacking process.

Launching of Pipe-Jacking Machine

Launching of the pipe-jacking machine means the start of jacking process. Figure 10, *a* and *b*, shows the launching of TBM pipe-jacking machine, where the TBM head is pushed into ground through the circular portal installed at the launch shaft wall. Before the launching process, the circumference of the portal is instrumented with sealing rubber ring, and the rubber will be stuck on the external of pipes, which can guarantee that the potential gap in the portal is sealed. Furthermore, lubrication grease is spread on the outer cutterhead to reduce rubber seal damage when the cutterhead is pushed through the portal. The TBM machine and the jacking system should be tested beforehand. The first 50 m distance is used as a trial section to adjust the parameters of the TBM and jacking system, and more field monitoring is conducted to acquire the effects of construction on the surrounding ground.

The soil at the excavating face was cut by the cutterhead and discharged from the soil tank by screw conveyor, and further transported to the shaft by vehicles and lifted up to the ground. The soil discharge control is the key to maintain reliable face support pressure. Meanwhile, ground disturbance mitigation during pipe jacking is an important aspect of construction safety. The main causes of ground deformation are: (1) ground loss caused by excessive face excavation at the cutterhead edge; (2) the correction of pipeline axis deviation; (3) insufficient grouting at the gap between the segment and ground; (4) friction between the TBM and surrounding ground; (5) water inrush from the ring joints and inter-jacks. Thus, it is essential to adjust the earth pressure in the TBM according to different soil properties, the burial depth of the tunnel, and nearby infrastructure to reduce the ground deformation. The jacking speed should be controlled and dynamically adjusted based on the monitoring of ground deformation.

Trajectory Control of Pipe Jacking

For jacking such a large pipe with outer diameter of 4.68 m, the trajectory control of TBM is difficult. For the TBM for conventional shield tunneling, the reaction force is directly on the completed segmented tunnel. Its trajectory control is more flexible because of the rear hydraulic jacks, and the already assembled tunnel section will stay static. In pipe jacking, the reaction force is provided by the reaction wall at the shaft, and the pipe sections that have been thrusted into ground will move as an entirety. The trajectory of the head TBM is affected by the whole finished pipeline, and it will be harder to control for the curved pipeline.

The deviation of the jacking direction can be affected by: (1) setting difference in jacks; (2) uneven frictional resistance between the jacking machine and surrounding soil; (3) the pressure difference at the excavating face; (4) the complex soil properties at the excavating face. These complex aspects usually result in a difficult alignment control during the jacking process. Pipe rolling and snaking are

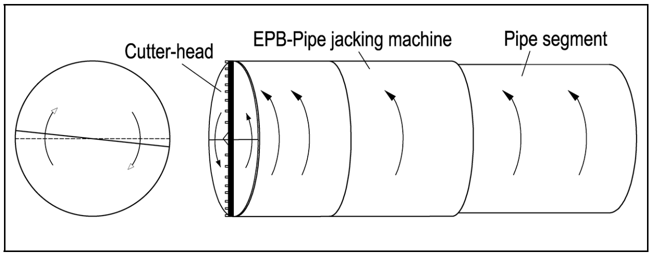

Figure 11. Torsion deviation of pipe jacking.

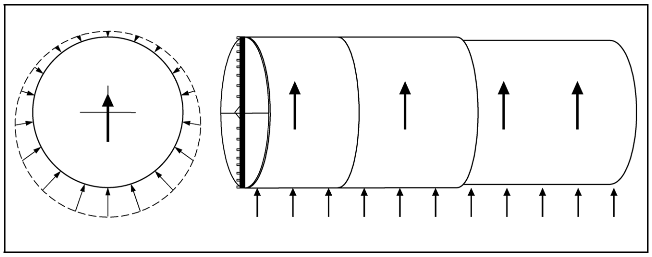

Figure 12. Uplift deviation of pipe jacking.

the most frequent problems. When the cutterhead rotates to excavate soil, the induced torque tends to roll the TBM and the adjoining pipe section. Then the torsion deviation will occur, as shown in Figure 11. Excessive rolling deviation will affect the navigation accuracy and the trajectory of correction cylinder, resulting in deviation of jacking direction. As TBM torsion is unavoidable and increases with diameter, proper correction is very important to mitigate the deviation. If large torsion of the TBM is detected, the cutterhead rotates to the reverse direction so that the machine posture can recover to designed position.

Besides the TBM torsion, snaking is also a common problem of pipe jacking, especially for long-distance jacking. Pipe snaking refers to the cyclic axial drifting transversely and vertically, and finally results in a cumulated deviation of the alignment. The snaking is predominantly caused by inadequate warping forces on the pipe by the surrounding soil. Usually the surrounding ground near the pipe is deeply disturbed and the grouting is not stiff enough to provide very solid confinement for the pipe. The insufficient confinement leads the pipeline to drifting a little (left and right or upwards and downwards) when thrust forward. When the grouting mortar flows downwards and is concentrated on the bottom of the pipe, the resultant uplift forces will float the pipe gradually and the large accumulated alignment deviation forms, as shown in Figure 12. The snaking movement must be carefully monitored and be corrected before too large an error occurs.

Therefore, an automatic navigation system is required for a long pipe-jacking tunnel, so that dynamic trajectory measuring is conducted, and correction can be done promptly. As shown in Figure 13*a*, the navigation system combines the multiple advantages of the automatic total station: (1) Coordinate measurement function can control the jacking direction in real-time; (2) trigonometric elevation measurement function can control the tunnel's elevation and the designed alignment of the tunnel can be maintained; (3) the portable processing software can plot the real-time trajectory deviation and display the current mileage and the center position of the jacking machine, as shown in Figure 13*b*. The real-time measurement can provide information such as jacking distance and direction, and deviation in horizontal and vertical directions, which can well assist the deviation control of pipe-jacking process. Figure 14 displays the measured vertical tilting angles of the EPB pipe-jacking machine during the jacking process (Ring 200 to 220). The positive values indicate the front head of the TBM drifts upwards a little, but the tilting angle is controlled within an acceptable range.

The calculation results by the software are automatically compared with the designed pipe alignment. The deviations in each direction will be plotted, and the measuring time and corresponding jacking distance will be recorded at the same time. The whole process can be set by the engineer at the beginning, and the system will continue to complete the measurement automatically without manual intervention. Each measurement process only takes 1 to 3 minutes, which can improve the construction efficiency. When snaking occurs, axis deviation correction is necessary. The snaking correction is achieved by adjusting the jacking cylinders at the interjack to provide slightly different thrust forces, and thus pipe tilting is induced to force the pipe to drift back to the designed alignment. The correction of the snaking should be slow and gentle, and the maximum correction for a single segment ring cannot exceed 2 mm. Otherwise, a hasty adjustment will exacerbate this problem, as shown in Figure 15.

Reception of the Pipe-Jacking Machine

Reception of the pipe-jacking machine is vital to the success of the whole jacking section construction. When the TBM is thrust closer to the reception shaft, the navigation must be accurate enough so that the TBM can push through the designated portal. An alignment survey is conducted through the whole pipeline from the launching shaft when the TBM head reaches about 30 m before the receiving shaft. The last 30 m length will be an important chance for final alignment correction. The corresponding thorough alignment surveying is to: (1) accurately determine the distance between the cutterhead and the

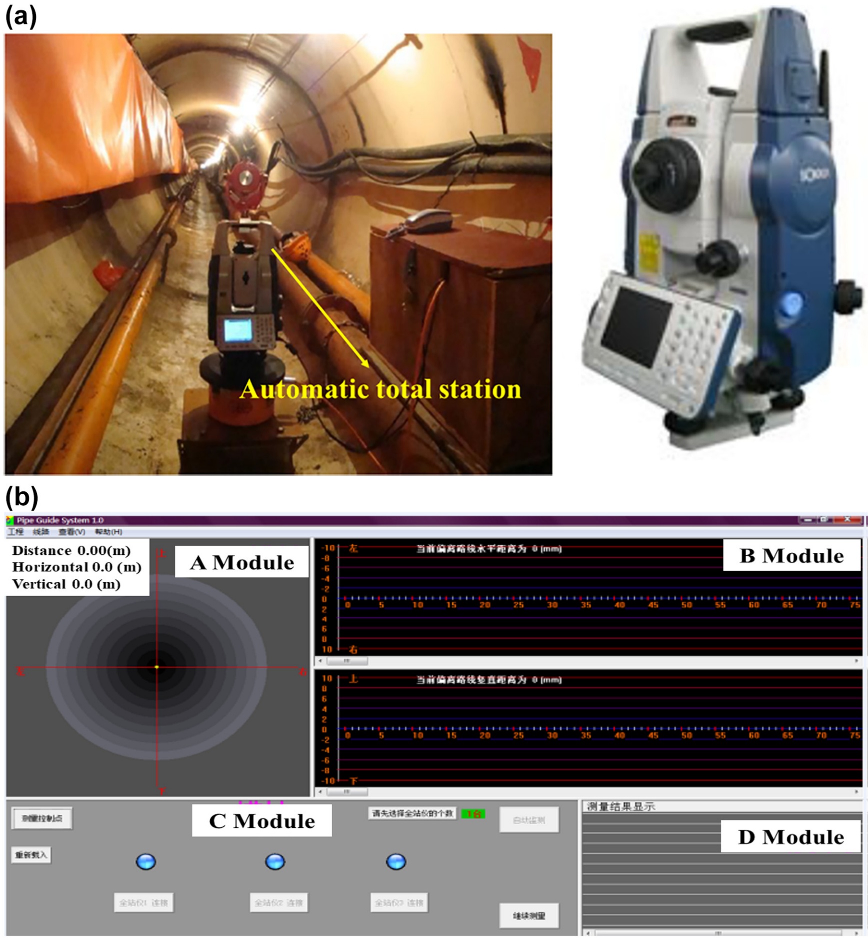

Figure 13. (*a*) Automatic total station and (*b*) measurement processing system.

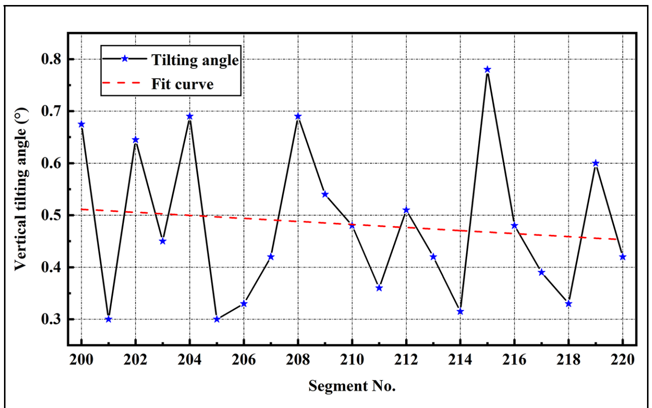

Figure 14. Vertical tilting angle of segments.

reception shaft wall; (2) check the trajectory of the jacking machine so that the timely adjustment can be made before the final reception process.

Besides thorough surveying to make tunnel alignment as accurately as possible, the ground disturbance control and water inrush prevention are also very important during the final TBM reception. The soil between the cutterhead and outer shaft wall is compressed hard, which may cause high thrust forces on the shaft wall. In addition, water inrush may occur if the small gap between the portal and external TBM is not sealed properly. To solve these safety concerns, two small holes (with diameter of about 1 in.) are preset on the portal wall, which can serve as soil relief channels and help to mitigate the inrush of water and soil when the cutterhead breaks the portal. Large settlement usually occurs on the ground near the entry portal because of the large soil disturbance induced by the TBM deviation correction and insufficient synchronous grouting. To mitigate the settlement, it is necessary to properly strengthen the grouting when the TBM is approaching the portal. Furthermore, high-pressure jet grouting from ground surface is used to

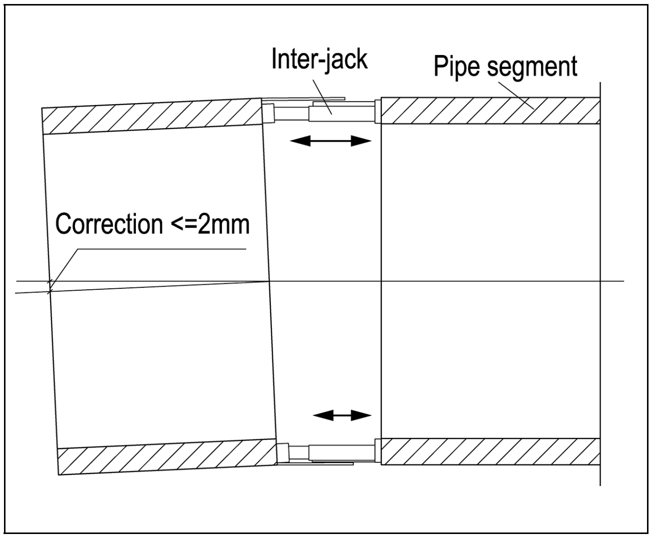

Figure 15. Alignment correction by inter-jack.

reinforce the soil outside the portal, as this grouting can greatly improve the stiffness of soil and reduce ground permeability.

Ventilation and Gas Monitoring

During jacking under water, there are possible combustible biological gases embedded into the rotten materials in the underwater shallow ground (*20*). The shallow biogas may penetrate the pipeline from the joints of the segmental lining, the head and the shield tail of the jacking machine, which could result in casualties and property loss (*21–24*). Therefore, a system for monitoring harmful gas is required during the pipe-jacking construction. As shown in Figure 16, a gas monitoring and alerting system is installed inside the jacking machine, and can detect potential harmful gases and issue prompt alarms. Furthermore, as a double precaution, workers should take a portable combustible gas detecting device with them when they enter the tunnel. Ventilation of the head working space inside the tunnel is important; the following requirements on ventilation must be followed.

(1) The oxygen concentration in the tunnel should be above 20%, and the concentration of harmful gases and dust should meet the healthy standards ($CO\% \leqslant 30\,mg/m^3$; $NO_2 \leqslant 50\,mg/m^3$; $CO_2 \leqslant 0.5\%$; $SO_2 \leqslant 0.0005\%$). Meanwhile, the noise of ventilation equipment should not exceed 80 decibels.
(2) The fresh air used for ventilation should be clean, and the amount of fresh air at the head working space should be more than $4\,m^3$ for one person in 1 min. The ventilation speed should be greater than 0.15 m/s and less than 6 m/s.
(3) The temperature at the working space should not exceed 28°C, and the relative humidity is controlled to be below 80%.

Besides ventilation, cables for power supply and equipment control cables in the tunnel should be arranged in conjunction, and fixed in isolated channels in the tunnel cross-section. As the TBM advances, more and more cables and other supply pipes have to be arranged. An emergency lighting system should be set at the tool pipe in the tunnel to ensure that workers can evacuate quickly in a power failure situation.

Conclusions

In this paper, a case study of the largest-diameter concrete EPB pipe-jacking project in the world was presented. This jacked tunnel has an excavating face of 4,670 mm in diameter and passed through the silty clay

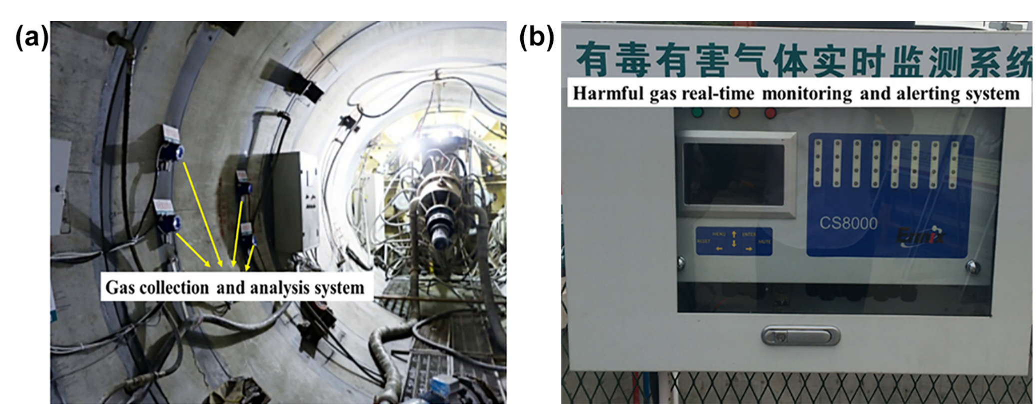

Figure 16. (a) Harmful gas real-time monitoring and (b) alerting system.

layer under Jinshan Lake in Jiangsu Province, China. Key challenges and problems of this project were described in detail, and corresponding countermeasures were also summarized in this study, which can provide engineering experience for other large pipe-jacking projects in future. The primary experience and technologies of this project can be summarized as follows:

(1) Selection of TBM type is of great importance to the pipe jacking. Based on the geological condition and construction requirements in this project, the EPB pipe-jacking method was chosen to construct the 4.64 m-diameter sewerage tunnel.
(2) Segmental lining design should consider strength and watertightness. The concrete of the segmental ring has a high resistance to water permeability, and the waterproof coating is painted externally to provide additional water resistance. At the segment joint, multiple sealing rubber layers are placed at the circumference of the segmental ring joint to prevent water inrush.
(3) Inter-jacks are important parts to support long-distance pipe-jacking construction. In this project, a total of 17 inter-jacks were set based on the analysis of the maximum thrust force, and the coordination of adjoining inter-jacks was well considered for jacking process control.
(4) Pipe rolling and snaking are the most frequent problems. Rolling can be corrected by rotating the cutterhead to the reverse direction, whereas pipeline snaking correction is by adjusting the jacking cylinders at the inter-jack to provide slightly different thrust forces. The correction of the snaking should be slow, and the maximum correction for a single segment ring cannot exceed 2 mm.
(5) Reception of the pipe-jacking machine is vital to the success of the whole jacking section construction. Thorough alignment surveying should be performed to check the trajectory of the jacking machine. Besides, the ground disturbance control and water inrush prevention are also important, and two small soil relief holes (with a diameter of about 1 in.) are preset on the portal wall to mitigate the inrush of water and soil as the cutterhead breaks the portal.
(6) The harmful gases monitoring and alerting system can reduce risks caused by potential combustible or harmful gases such as biogas and CO. Meanwhile, this system can guarantee that the workers are working in a safe condition with good ventilation, proper temperature and relative humidity.

The pipe-jacking process of this sewerage tunnel has been finished, and field monitoring showed the whole jacking process was controlled well. Therefore, the countermeasures used in this study can provide helpful experience for future large-diameter pipe-jacking projects.

Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: Xi Jiang, Yun Bai, Baoshan Huang; data collection: Shuai Wang; analysis and interpretation of results: Xi Jiang, Xuehui Zhang; draft manuscript preparation: Xi Jiang, Xuehui Zhang.
All authors reviewed the results and approved the final version of the manuscript.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) received no financial support for the research, authorship, and/or publication of this article.

ORCID iDs

Xi Jiang https://orcid.org/0000-0002-0403-8618
Yun Bai https://orcid.org/0000-0002-5246-1402

Data Accessibility Statement

The data that support the findings of this study are available from the first author, Xi Jiang, on reasonable request.

References

1. Wang, T., L. Tan, S. Xie, and B. Ma. Development and Applications of Common Utility Tunnels in China. *Tunnelling and Underground Space Technology*, Vol. 76, 2018, pp. 92–106. https://doi.org/10.1016/j.tust.2018.03.006.
2. Wang, W., Z. Zhu, Z. Jiao, H. Mi, and Q. Wang. Characteristics of Fire and Smoke in the Natural Gas Cabin of Urban Underground Utility Tunnels Based on CFD Simulations. *Tunnelling and Underground Space Technology*, Vol. 109, 2021, p. 103748. https://doi.org/10.1016/j.tust.2020.103748.
3. Cui, Q.-L., Y.-S. Xu, S.-L. Shen, Z.-Y. Yin, and S. Horpibulsuk. Field Performance of Concrete Pipes During Jacking in Cemented Sandy Silt. *Tunnelling and Underground Space Technology*, Vol. 49, 2015, pp. 336–344. https://doi.org/10.1016/j.tust.2015.05.005.
4. Chen, X., B. Ma, M. Najafi, and P. Zhang. Long Rectangular Box Jacking Project: A Case Study. *Underground Space*, Vol. 6, No. 2, 2021, pp. 101–125. https://doi.org/10.1016/j.undsp.2019.08.003.

5. De, A., T. F. Zimmie, T. Abdoun, and A. Tessari. Physical Modeling of Explosive Effects on Tunnels. *Proc., 4th International Symposium on Tunnel Safety and Security*, Frankfurt, Germany, 2010, pp. 159–168. http://www.divaportal.org/smash/get/diva2:962530/FULLTEXT01.pdf#page = 352%0A; http://www.diva-portal.org/smash/get/diva2:962530/FULLTEXT01.pdf%23page = 160.
6. Milligan, G. W. E., and P. Norris. Site-Based Research in Pipe Jacking - Objectives, Procedures and a Case History. *Tunnelling & Underground Space Technology*, Vol. 11, Supplement 1, 1996, pp. 3–24. https://doi.org/10.1016/0886-7798(95)00041-0.
7. Sterling, R. L. Developments and Research Directions in Pipe Jacking and Microtunneling. *Underground Space*, Vol. 5, No. 1, 2020, pp. 1–19. https://doi.org/10.1016/j.undsp.2018.09.001.
8. Zhen, L., J. J. Chen, P. Qiao, and J. H. Wang. Analysis and Remedial Treatment of a Steel Pipe-Jacking Accident in Complex Underground Environment. *Engineering Structures*, Vol. 59, 2014, pp. 210–219. https://doi.org/10.1016/j.engstruct.2013.10.025.
9. Mok, W. W. S., M. K. W. Mak, and F. H. T. Poon. Sewer Installation by Pipejacking in the Urban Areas of Hong Kong Part I–Planning, Design, Construction and Challenges. *HKIE Transactions Hong Kong Institution of Engineers*, Vol. 14, No. 1, 2007, pp. 17–30. https://doi.org/10.1080/1023697X.2007.10668065.
10. Mok, W. W. S., M. K. W. Mak, and F. H. T. Poon. Sewer Installation by Pipejacking in the Urban Areas of Hong Kong Part II–Performance of Works, Lessons Learned and Improvements Proposed. *HKIE Transactions Hong Kong Institution of Engineers*, Vol. 14, No. 1, 2007, pp. 31–43. https://doi.org/10.1080/1023697X.2007.10668066.
11. Sun, Y., F. Wu, W. Sun, H. Li, and G. Shao. Two Underground Pedestrian Passages Using Pipe Jacking: Case Study. *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 145, No. 2, 2019, p. 05018004. https://doi.org/10.1061/(asce)gt.1943-5606.0002006.
12. Sun, Y., J. B. Su, X. H. Xia, and Z. L. Xu. Numerical Analysis of Soil Deformation Behind the Reaction Wall of an Open Caisson Induced by Horizontal Parallel Pipe-Jacking Construction. *Canadian Geotechnical Journal*, Vol. 52, No. 12, 2015, pp. 2008–2016. https://doi.org/10.1139/cgj-2015-0024.
13. Wang, J., K. Wang, T. Zhang, and S. Wang. Key Aspects of a DN4000 Steel Pipe Jacking Project in China: A Case Study of a Water Pipeline in the Shanghai Huangpu River. *Tunnelling and Underground Space Technology*, Vol. 72, 2017, pp. 323–332. https://doi.org/10.1016/j.tust.2017.12.012.
14. GB 50021-2001. *Code for Investigation of Geotechnical Engineering*. National Standard of the People's Republic of China, 2009.
15. GB/T 50123-2019. *Standard for Geotechnical Testing Method*. National Standard of the People's Republic of China, 2019.
16. Haghshenas, S. S., S. S. Haghshenas, R. Mikaeil, T. Ardalan, Z. Sedaghati, and P. K. Heris. Selection of an Appropriate Tunnel Boring Machine Using TOPSIS-FDAHP Method (Case Study: Line 7 of Tehran Subway, East-West Section). *Electronic Journal of Geotechnical Engineering*, Vol. 22, No. 10, 2017, pp. 4047–4062.
17. Tan, Y., and Y. Lu. Forensic Diagnosis of a Leaking Accident During Excavation. *Journal of Performance of Constructed Facilities*, Vol. 31, No. 5, 2017, p. 04017061. https://doi.org/10.1061/(asce)cf.1943-5509.0001058.
18. Wu, H. N., R. Q. Huang, W. J. Sun, S. L. Shen, Y. S. Xu, Y. B. Liu, and S. J. Du. Leaking Behavior of Shield Tunnels Under the Huangpu River of Shanghai With Induced Hazards. *Natural Hazards*, Vol. 70, No. 2, 2014, pp. 1115–1132. https://doi.org/10.1007/s11069-013-0863-z.
19. Ji, X., W. Zhao, P. Ni, M. Barla, J. Han, P. Jia, Y. Chen, and C. Zhang. A Method to Estimate the Jacking Force for Pipe Jacking in Sandy Soils. *Tunnelling and Underground Space Technology*, Vol. 90, 2019, pp. 119–130. https://doi.org/10.1016/j.tust.2019.04.002
20. Jiang, X., Y. Zhang, Z. Zhang, and Y. Bai. Study on Risks and Countermeasures of Shallow Biogas During Construction of Metro Tunnels by Shield Boring Machine. *Transportation Research Record: Journal of the Transportation Research Board*, 2021. 2675: 105–116.
21. He, S., L. Su, H. Fan, and R. Ren. Methane Explosion Accidents of Tunnels in SW China. *Geomatics, Natural Hazards and Risk*, Vol. 10, No. 1, 2019, pp. 667–677. https://doi.org/10.1080/19475705.2018.1541826.
22. Ayhan, M., D. Aydın, M. Ş. İmamoğlu, M. Çoğalan, and A. Karakuş. Investigation of a Methane Flare During the Excavation of the Silvan Irrigation Tunnel, Turkey. *Bulletin of Engineering Geology and the Environment*, Vol. 78, No. 4, 2019, pp. 2641–2652. https://doi.org/10.1007/s10064-018-1265-y.
23. Zhang, J. Z., H. W. Huang, D. M. Zhang, M. L. Zhou, C. Tang, and D. J. Liu. Effect of Ground Surface Surcharge on Deformational Performance of Tunnel in Spatially Variable Soil. *Computers and Geotechnics*, Vol. 136, 2021, p. 104229. https://doi.org/10.1016/j.compgeo.2021.104229.
24. Zhang, Y., H. Zhu, Q. Guo, R. Carvel, and Z. Yan. The Effect of Technical Installations on Evacuation Performance in Urban Road Tunnel Fires. *Tunnelling and Underground Space Technology*, Vol. 107, 2021, p. 103608. https://doi.org/10.1016/j.tust.2020.103608.