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Research Article

Shield Equipment Optimization and Construction Control Technology in Water-Rich and Sandy Cobble Stratum: A Case Study of the First Yellow River Metro Tunnel Undercrossing

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The Lanzhou Yellow River Tunnel is the first metro shield tunnel that undercrosses the Yellow River in China. It was completed after successfully overcoming several construction challenges, including strata with a high proportion of large-sized sandy cobble stratum being saturated, large-scale sand pits along the bank of the Yellow River, and a combination of boulders and erratic blocks of rock. Given the difficulties in constructing the tunnel, this paper summarizes the scheme employed to transform the cutter and cutter head design to be applicable to sandy cobble stratum and the key technology used to form the slurry film to facilitate crossing the sand pits in a systematic way. The transformation scheme primarily involved the addition of an adjusting device to control the aperture ratio of the shield on the cutter head, a protective device for the hob hub, and a protective device for the piston rod in the oil cylinder of the crusher. The implementation of measures mentioned above guarantees the safe completion of the tunnel, which can provide a reference for similar projects.

1. Introduction

With the acceleration of urbanization, shield tunnelling methods have been widely applied to traverse various types of strata, facilitate rapid construction, and cause less interference to the surroundings. A review of the literature shows that the associated tunnelling machinery typically encounters a wide range of geological conditions, such as soft strata, loess strata, mixed ground, soft fluid-plastic strata, and sandy cobble strata. Among these, sandy cobble strata are typical mechanically unstable strata that have been encountered as a problem of shield construction in recent years. The mechanical and physical properties of this type of strata are uncommon and characterized by a loose structure, high permeability coefficient, high strength of single cobbles, poor plastic fluidity of the soil mass, and low cohesion. Traversing this type of strata during shield tunnel construction is extremely difficult and risky. The undercrossing of the Yellow River by Lanzhou Metro Line 1 is the first urban rail transit traffic tunnel along the Yellow River and is located in an area with a high content of large-sized sandy cobble stratum being saturated, which presented many technical challenges to the construction project.

At present, the research into shielded construction on such strata has been primarily focused on innovating the construction technology, the stability of the excavation surface, and the configuration and wear of the cutter and cutter head. Yang [1] proposed a systematic method of using shield construction technology on sandy cobble stratum being saturated in the Chengdu Metro. Wang et al. [2] and Bai et al. [3] investigated the stability of the excavation surface for shield construction on sandy cobble stratum by a discrete element program and analysed deformation and damage to the surface of the excavation surface. Fargnoli et al. [4] considered the influence of different excavation parameters on the estimated volume loss and shape of subsidence troughs based on monitoring the twin tunnelling-induced settlements of the Milan Metro Line 5 in coarse-grained soils. Yuan et al. [5] and Ye [6] studied the influence of the slurry shield mud fluid properties on the stability of the excavation surface. The property indicators of slurry in sandy cobble stratum were determined based on experience and testing.

At the same time, some researchers have focused on the performance of tunnel-boring machines (TBMs) in soft ground conditions and have introduced new tests for the measurement of soil abrasivity in a laboratory environment [7–9]. Zhang et al. [10] developed a mathematical model for the extent of wear and the tunnelling parameters as well as the wear and tunnelling distance, incorporating statistical methods based on the monitoring of the shield cutter for Beijing Metro Line 4. Song [11] and Huang [12] investigated the interaction between the shield cutter head and soil based on a theoretical analysis, empirical formulae, and field tests on shield tunnelling in sandy cobble strata and also made suggestions regarding the type of cutter head and the optimum configuration of the cutter for sandy cobble strata. By investigating the tool wear of an earth pressure balance-TBM (EPB-TBM) in Tehran Metro Line 7, Amoun et al. [13] observed that soil conditioning plays an important role in controlling cutter wear and that the tool wear can be reduced even in coarse-grained soils by improving the soil-conditioning parameters.

However, as the characteristics of sandy cobble strata vary greatly, the applicability of existing research to a particular location is somewhat limited. Many researchers have paid close attention to certain typical strata: the strata through which the Shenyang Metro passes are primarily composed of medium and coarse sand and gravel sand layers [14]; the southwest of Beijing contains unique sandy cobble boulder strata that are characterized by large grain sizes of boulders and are free of water over the entire section [15–17]; the strata of the Chengdu Metro are characterized by a high cobble strength and high groundwater table, but with a small permeability coefficient and a poor groundwater recharge [1]. In contrast, the sandy cobble strata in the riverbed of the Yellow River are characterized by a high cobble content, poor cementation, large permeability coefficient, and high water content, which make it more difficult for the Lanzhou Metro Tunnel to pass through.

The paper presents a systematic analysis and summary of a series of problems that were encountered when the shield method was used to undercross the Yellow River for the Lanzhou Metro Tunnel with the intent to improve shield construction technology, to document our experience in sandy cobble stratum, and to provide a foundation for subsequent similar projects.

2. Project Overview

The left-hand track of the section between Yingmen Beach and Ma Beach (hereinafter referred to as Ying Ma) of Lanzhou No. 1 Metro Line is 1908.029 m in length, and the right-hand track is 1906.567 m in length. The entire section was constructed using the shield method, and the inner and outer diameters of the tunnel are 5500 mm and 6200 mm, respectively. The shield tunnel passes through the Yellow River within this section and is the first urban metro along the Yellow River. The main section of the tunnel is located 50 m away from the upper reaches of the main bridge, Silver Beach Yellow River Bridge, which is enough to provide a reasonable distance from the piles of the bridge. The plane layout of the line is as shown in Figure 1. The total length of the tunnel undercrossing is about 404 m, of which the water surface of the Yellow River is about 200 m in width, the tunnel roof is about 18.1–24.1 m from the river bottom plate, and the minimum spacing between the two tracks is 6.8 m. A profile diagram of the tunnel is shown in Figure 2.

2.1. Hydrogeological Condition. The stratum in the Ying Ma interval is primarily composed of Quaternary Holocene mixed backfill soil (Q_4^{ml}) and a medium sand layer (Q_4^{al}), cobble layer (Q_4^{al}), and Quaternary Low Pleistocene cobble layer (Q_1^{al}). The distribution of the strata is as shown in Figure 3. The ground along the alignment of the Yellow River Tunnel undercrossing is mostly Q_1^{al}, and the percentage content of boulders and cobbles with a grain size more than 2 cm in the layer accounts for 77.69% of the total. Generally, the grain size ranges from 2 to 6 cm, while the maximum grain size of the boulders is up to 500 mm. In general, the ground is characterized by poor gradation and better rounding, poor separation, and either weak calcareous cementation or no cementation in the local area. The parent rock of the cobble primarily composed of hard rock, such as quartzite, granite, etc.

The water table of the site through which the tunnel passes is 1521.4 m above sea level, the groundwater table is from 1519.10 to 1524.00 m above sea level, and the cobble layer (Q_1^{al}) through which the tunnel passes has a permeability coefficient of up to 1.15×10^{-1} cm/s with rapid groundwater recharge. The permeability coefficient is determined by the combination of the pumping test, hydrogeological condition, composition of the material, and engineering experience. In addition, as the groundwater table is higher than the tunnel roof in elevation, there was a risk of water surge during construction. It was estimated that the maximum water yield may be up to 1603 m^3/d.

2.2. Difficulties in Shield Tunnel Construction. The difficulties encountered when constructing the shield tunnel undercrossing of the Yellow River for the Lanzhou Metro were as follows:

2.2.1. High Percentage of Large Grain Size Cobbles. Grains with sizes ranging from 40 to 60 mm accounted for 32.73% by volume of the sandy cobble stratum (Q_1^{al}) through which the tunnel passed, while the grains with sizes larger than 60 mm accounted for 6.44% by volume (Table 1). The sampling in the stratum was as shown in Figure 4. The stratum was unstable and it was therefore difficult to control the tunnel face, which increased the likelihood of a collapse and the subsequent blockage of the circulation system for the shield tunnelling machine.

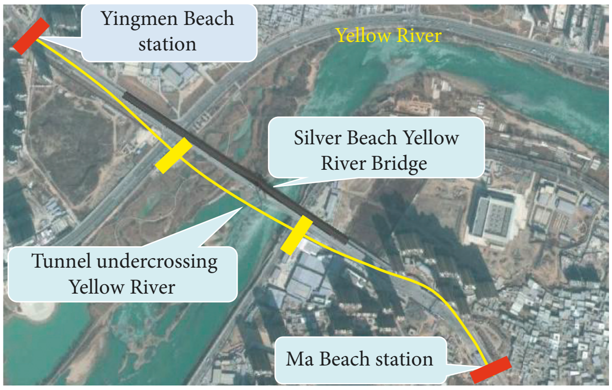


Figure 1: Plane layout of the Lanzhou No.1 Metro Line.

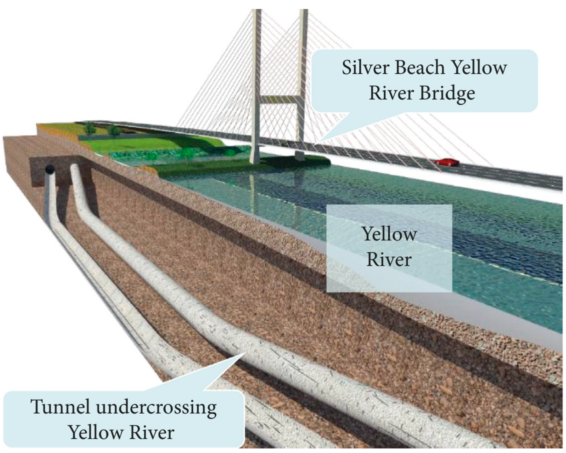


Figure 2: Profile diagram of the tunnels under the Yellow River bed.

2.2.2. High Percentage of Quartz. The maximum saturated compressive strength of the cobble at the tunnel site was 200 MPa, and the quartz content was as high as 70–90%; thus, it was crucial to significantly increase the wear resistance of the cutter head, cutter, and slag tapping system.

2.2.3. Water Saturation and High Permeability. The permeability coefficient of the stratum through which the shield tunnel undercrossed was from 7.5×10^{-2} cm/s to 1.15×10^{-1} cm/s, which is extremely high. Based on our previous construction experience and research, the slurry is more likely to run off in cases of a high-permeability coefficient and macropores, and it is therefore difficult to ensure the stability of the excavation surface by maintaining a balance between the water, earth pressure, and slurry pressure. As the groundwater pressure was above 0.3 MPa, the seal for shield tail was likely to be penetrated. Therefore, water resistance was essential.

2.2.4. Complex Geological Conditions of the Sand Pit. After undercrossing the north bank of the Yellow River, the tunnel entered two sand pits with a total length of 110 m and a backfill thickness ranging from 12 to 15 m, and the undisturbed soil above the tunnel was only 7.7–10 m. Therefore, the slurry was more likely to flow into the ground through the covering soil and result in a loss of pressure at the tunnel face. Cobbles with large diameters in the section were more common and more concentrated in distribution, which made it difficult to ensure pressure stability on the tunnel face compared with other sections. In addition, aged silt stratification prevailed along the top, which provided poor stratum stability.

2.2.5. Unpredictable Engineering Geological and Hydrological Conditions. It was observed from the geological surveys as well as the supposition and analysis of the geological data in history that there was a possibility to encounter an underground barrier, such as boulders at the river bottom. Moreover, the groundwater table on the tunnel site was higher than the tunnel roof in elevation; accordingly, there was a risk of water surge in tunnel construction by the shield method.

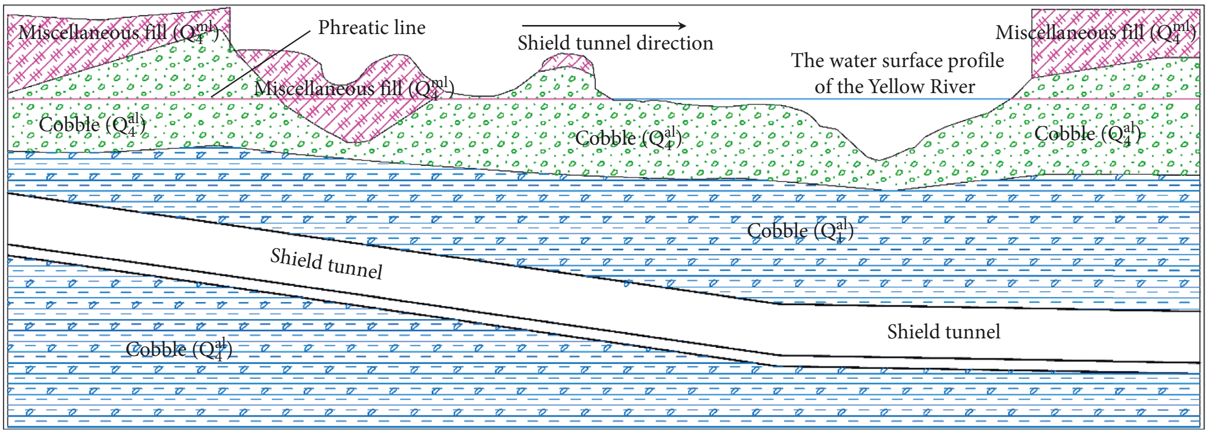
3. Shield-Type Selection as Well as Modification and Optimization of Equipment

3.1. Analysis of the Selection of the Shield Type. The project adopted two composite-type slurry-balanced shield machines that were produced by the China Railway Construction Heavy Industry Co., Ltd. The shield machines were about 96 m in total length, with a main body of about 8.5 m in length and an auxiliary bogie about 87.5 m in length. The type of shield machine was similar to that used in other engineering projects, and the relevant facts are shown in Table 2 and Figure 5.

The permeability coefficient of the sandy cobble layer through which the shield tunnel undercrossed was from 7.5×10^{-2} cm/s to 1.15×10^{-1} cm/s. Based on previous experience in shield-type selection in similar projects and an analysis of various factors, we determined that the project should adopt a slurry-balanced shield at the very end so as to ensure the project could be completed safely.

3.2. Analysis of the Adaptability of the Shield Machine. The slurry shield machines used for the project employed a spoke-type cutter head, with composite and wear plates welded on the panel of the cutter head. And alloy wear plates were welded and inset on the outer contour, which provided wearproof functionality and ensured the performance of the machines. It was similar to that of a wearproof cutter and to ensure the proper diameter of the cutter head. Wearproof compact mesh was welded on the transition zone of the edge of the cutter head, slag inlet of the cutter head, and back of the cutter head, while the opening surface of the cutter head was subjected to a hardening treatment.

The cutter head was equipped with 8 centre disc cutters, 23 front disc cutters, 10 edge disc cutters, 36 front slicers, 16 edge scrapers, 4 shell cutters, and 28 guide cutters, and was capable of performing a full-face excavation of the tunnel, including a two-way rotation for forward and backward excavation. The layout of the cutter head and cutter were as shown in Figure 6. All cutters were constructed of boron steel tungsten carbide with high wear resistance properties.



Miscellaneous fill (Q_4^{ml}): The composition is complex, mainly composed of silt, medium and coarse sand, and pebbles and round gravel, including bricks, cement blocks (boards), coal cinders, domestic garbage, etc.
Cobble (Q_4^{al}): The colour is steel grey. In the composition, boulders and pebbles account for 55% to 70%, and the general particle size is 20 mm to 60 mm; the content of boulders is less, while the maximum particle size can reach 500 mm; gravels account for 10% to 25%; Cobble (Q_1^{al}): The colour is earthy yellow. In the composition, boulders and pebbles account for 55% to 70%, and the general particle size is 20 mm to 50 mm; the content of boulders is less, while the maximum particle size can reach 450 mm; gravels account for 10% to 25%;

Figure 3: Profile of the geological section of the Lanzhou Yellow River Tunnel.

Table 1: Cobbles of particle-size distributions.

Type	Statistical indicators	Grains composition (%) Grains sizes (mm)								Uniformity coefficient (C_U)
		100~60	60~40	40~20	20~2	2~0.5	0.5~0.25	0.25~0.75	0.75~0.005	
Cobble (Q_4^{al})	Minimum value	0	8.8	9.4	3.1	0.6	0.5	0.2	0	2.21
	Maximum value	42.3	68.3	32.7	25.7	13.9	12.5	9.4	12	310.73
	Average value	11.63	30.84	22.11	15.19	7.09	5.36	4.87	2.91	113.1
	Standard deviation	12.890	11.166	5.802	4.905	3.506	3.033	2.458	2.763	66.129
	CV	1.109	0.362	0.263	0.323	0.494	0.566	0.504	0.949	0.585
	Count	37								
Cobble (Q_1^{al})	Minimum value	0	13.4	7.5	2.3	0.5	1	0.8	0.01	9.18
	Maximum value	34.5	75.1	38.7	21.24	13.7	11.8	8.5	13.6	1027.13
	Average value	6.44	32.73	24.65	13.87	7.7	5.56	4.09	4.87	213.06
	Standard deviation	8.6	12.9	6.33	5.39	4.1	2.89	1.69	3.71	239.56
	CV	1.335	0.394	0.257	0.389	0.533	0.511	0.412	0.762	1.24
	Count	24								

Figure 4: Representative photograph of the cobble stratum.

Table 2: Comparison of similar engineering projects.

Name of tunnel	Engineering hydrogeology			Construction requirements		Shield type selection	
	Geological conditions	Permeability coefficient (cm/s)	Groundwater pressure (MPa)	Tunnel diameter (m)	Tunnel length (m)	Shield type	Cutter head
Zhengzhou section of the Middle Line works for the South-to-North Water Transfer Project (undercrossing the Yellow River)	Passing through a single silty loam layer, single medium sand layer, and composite stratum with sand on the top and soil at the bottom	Loam: 1×10^{-5} Sand layer: 10^{-3}~10^{-2}	About 0.4	8.7	3450	Slurry-balanced shield	Panel-type cutter head
Beijing railway underground connecting Line Project (undercrossing a moat)	The stratum through which the tunnel passes is predominantly cobble	Maximum: 1.74×10^{-3}	Maximum 0.3	11.6	5227	Slurry-balanced shield	Spoke-type cutter head
Slurry shield works in the second main line project in Shirahata of Yokohama in Japan	The stratum through which the tunnel passes is a sandy gravel layer, with the percentage content of silt and clay up to 6%	1.0×10^{-2}~1.0×10^{-1}	—	3.49	1497	Slurry-balanced shield	Panel-type cutter head
Interval from Qiushui Square to West Zhongshan Road for Nanchang Metro Line 1 (undercrossing the Ganjiang River)	The stratum through which the tunnel passes is a sandy cobble layer and a medium and weakly weathered politic siltstone layer	Sandy cobble: 1×10^{-1} Silt layer: 1×10^{-5}	Maximum 0.2	6.0	1889.52 (1245)	Slurry-balanced shield	Panel-type cutter head
Interval from Wulihe to the Olympic Sports Centre Gymnasium for Shenyang Metro Line 2 (undercrossing the Hunhe River)	The stratum through which the tunnel passes is a sandy cobble layer mixed with a localized round cobble layer	8.25×10^{-2}~1.93×10^{-1}	About 0.19	6.0	1423.45 (500)	Slurry-balanced shield	Spoke-type cutter head
Interval from Nanning Theatre to Chaoyang Square for the Nanning Metro Line 2 (undercrossing the Yongjiang River)	The stratum through which the tunnel passes in the full section is a round cobble layer composite stratum characterized by a soft top and hard bottom and a mudstone layer	Cobble layer: 2.3×10^{-2}	—	6.0	1487.3 (350)	Slurry-balanced shield	Panel-type cutter head
Interval from Jinxiang station to Xiangban station for Fuzhou Metro Line 2 (undercrossing the Minjiang River)	The stratum through which the tunnel passes is a mucky soil layer and a medium fine sand layer	1.45×10^{-9}~3.10×10^{-3}	Maximum 0.33	6.2	1579.9 (490)	Slurry-balanced shield	Panel-type cutter head
Interval from Houting station to Juyuanzhou station for Fuzhou Metro Line 2 (undercrossing the Wulongjiang River)	The stratum through which the tunnel passes is a coarse and medium sand layer, cobble layer, and mucky soil layer	3.75×10^{-5}~2.21×10^{-3}	—	6.2	2619.30 (1700)	Slurry-balanced shield	Panel-type cutter head

3.2.1. Adaptation to Long Distance Tunnelling. The tunnelling was completed over the course of a single operation and was a total of approximately 404 m in length. Experience in similar strata, including those at Chengdu and Wuhan, indicated that it was advisable to check and replace the cutter every 200 m when tunnelling in sandy cobble stratum; however, this was difficult to accomplish when the cutter was under normal pressure in this project.

On this point, we determined that it was advisable to reduce the wear on cutter by making use of a lubricating

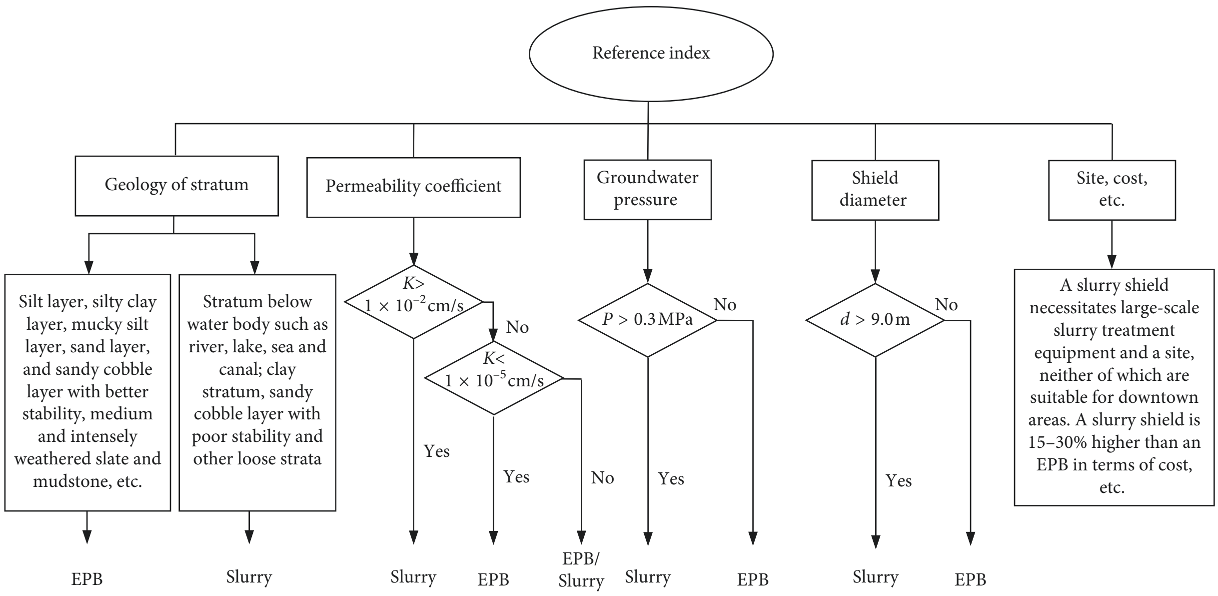


Figure 5: Main considerations underpinning the shield type selection [18, 19].

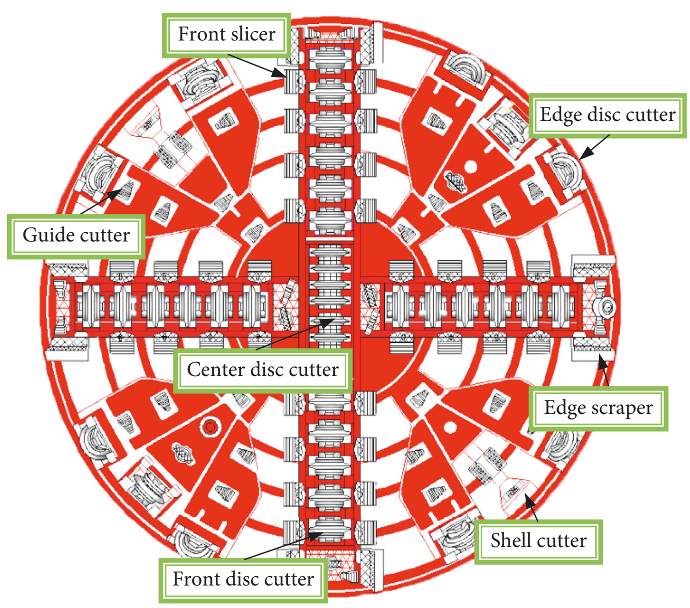


Figure 6: Layout of the shield cutter head and cutter.

slurry on the cutting surface of the shield so as to prolong service life of cutters; therefore, the project adopted a slurry-balanced shield. Moreover, two factors were considered in the design of the shield machine: first, a large-sized cutter was designed with overlapping cutters to provide mutual protection when cutting soil mass so as to reduce the wear. Second, the leading cutter, cutter, and edge scraper were integrated, the leading cutter being higher than the cutter so that the leading cutter would disturb the soil mass on the tunnel face in advance and then enable the cutter to cut the soil mass so as to protect the cutter and prolong its service life and ensure long distance tunnelling without having to replace the cutter.

3.2.2. Improvement of the Blockage of the Delivery Pipeline. The cobbles in the stratum through which the shield passed had various grain sizes, including sizes of 20 mm and 500 mm. When a large amount of broken stone with a large grain size was encountered during tunnelling, it not only aggravated the wear of the pipeline in the slurry system, but was also more likely to result in the blockage of the delivery pipeline. To address this problem, the shield machines used in the project were equipped with jaw crushers on the front end of the slurry drainage pipe so as to crush large pieces of broken stone. A heavy-duty grille was installed in front of the slurry drainage pipe, the opening of which was 150 mm × 150 mm, to prevent large blocks from entering the pipe, and the discharge opening was equipped with two flushing pipes to flush the broken area and avoid blockages.

3.3. Adaptability Improvements Applied to the Shield Machine

3.3.1. Adjustment Device Controlling the Opening Ratio of the Shield Cutter. The shield machine entered into the riverbed from the terrace of the Yellow River, in particular, as the probability that boulders will be encountered increased when passing through the sand pit, the shield machine had the opening ratio of the cutter head in the inspection shaft (centre mileage: YCK13 + 727.106 and ZCK13 + 723.896) adjusted from 35% to 32%. Since there was high risk when conducting welding operations in the shield machine during the shutdown period, improvements were applied to the cutter head.

The improvements were as follows. The cutter head was equipped with five ring beams, and each ring beam contained the number of bolt holes shown in Figure 7. The spacing between the ring beam and panel as well as between the spokes and the adjacent ring beam formed openings of various sizes and shapes. The steel cover plate could be installed inside the opening and connected to the ring beam using a grade 10.9 high-strength bolt. The steel cover plate was 35 mm thick with a wear-resistant composite plate welded on the surface, and the edge of the plate was subjected to a hardening treatment. This measure could overcome the limitation of the conventional method, in which it was necessary to weld a wear-resistant steel plate on the cutter head to adjust the opening ratio.

Since the sizes of the openings varied, we prefabricated suitable cover plates for each opening prior to construction so that the opening ratio of the cutter head could be adjusted by changing the coverage area through adjustment of the number and position of the cover plates. The cover plates were installed as shown in Figures 8(a) and 8(b). After these improvements were applied, the opening ratio of the cutter head of the shield could be flexibly adjusted based on the stratum conditions over time to ensure rapid construction and a high-safety factor.

3.3.2. Protective Device for the Disc Cutter Hub. After the shield machine arrived in the inspection shaft for the maintenance and replacement of the shield cutter head and cutter, it was observed that most of the cutter ring of the hob that did not perform the rock-crushing function showed uniform but low levels of wear, while the cutter hub that contacted the rock and the cutter ring on the same side thereof exhibited serious wear, which in turn exposed the cutter axis, as shown in Figure 9. Upon analysis, the reason the cutter hub was subjected to excessive wear was due to the failure of the sealing-bearing ring of the cutter, which allowed foreign matters, including slag, soil, and slurry, to enter the bearing. Consequently, the bearing was unable to operate properly, which resulted in excessive wear and significantly shortened the service life of the cutter.

In order to mitigate such problems, improvements were made to the cutter box and cutter hub as follows. Four high-strength wear-resistant blocks were welded to both sides of

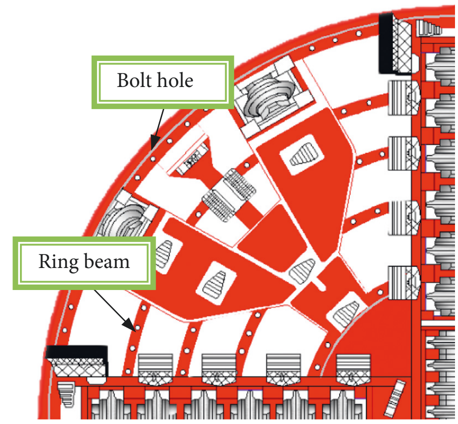


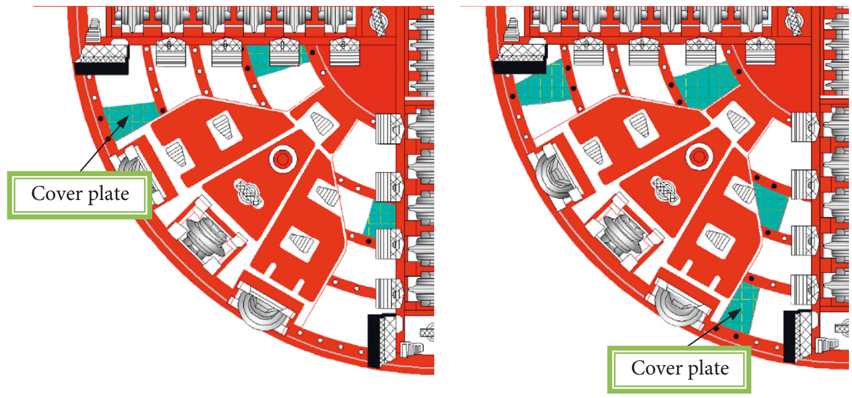
Figure 7: Layout of the bolt holes.

the cutter hub on the cutter box by an oxyacetylene flame overlay with the wear-resistant blocks higher than the cutter hub, and the outer surface of the wear-resistant blocks were covered with a high-chromium cast iron layer, as shown in Figure 10(a).

The following improvements were made to the cutter hub. The outer surface of the cutter hub was inlaid with carbide alloy cylindrical teeth arranged in a single row, which had hardness higher than HRA85. The radius of each cylindrical tooth was 0.5 cm, as shown in Figure 10(b). In order to improve the overall wear resistance, it was necessary to overlay a wear-resistant layer on the outer surface of the cutter hub and alloy. The wear-resistant layer was made of high-chromium cast iron. The carbide alloy and wear-resistant layer constitute the wear-resisting unit to effectively reduce the wear of the cutter hub.

3.3.3. Protective Device for the Piston Rod in the Oil Cylinder for the Crusher. The shield crusher system was positioned in front of the slurry drainage port at the bottom of the air-cushioned cabin because the piston rod of the hydraulic cylinder for the crusher was exposed to poor working conditions. During operation, stones continually impacted and rubbed against the piston rod, resulting in severe wear and deformation of the piston rod and causing the oil cylinder to fail and the oil to leak. As it was time-consuming to change the oil cylinder, this had an adverse effect on the construction schedule.

Consequently, the following improvements were applied. The piston rod was equipped with a steel protective outer sleeve, and one end of the protective sleeve was fixed to the base of the piston rod, while the other end made contact with the oil cylinder to reciprocate along with the piston rod. The inner diameter of the protective sleeve was slightly larger than the outer diameter of the oil cylinder, and its length was between the maximum extension length of the piston rod and the cylinder length. With a seal wire brush welded to the inside of the end of the sleeve, the seal brush and oil cylinder formed a sealed structure to prevent slurry and stones from entering the protective sleeve, as shown in Figure 11.



(a) (b)

Figure 8: Diagram showing the adjusting device that controls the opening rate and position of the cutter head.

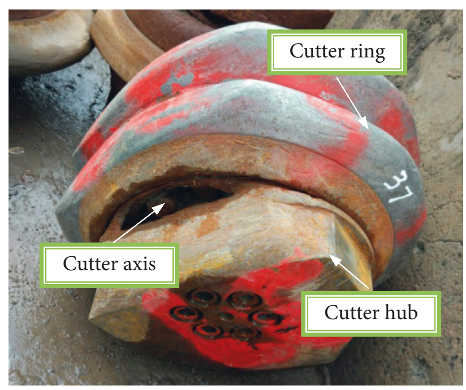
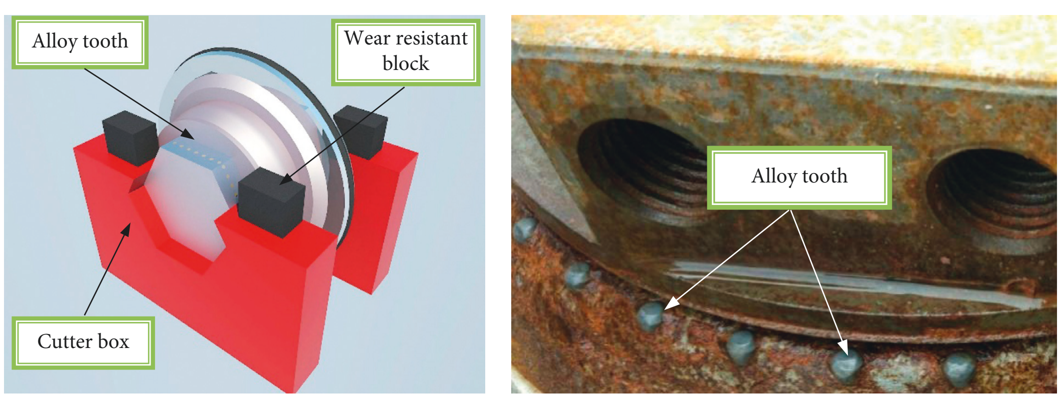


Figure 9: Picture of the wear on the cutter hub.



(a) (b)

Figure 10: Schematic diagram of the hub protection device.

3.3.4. External Mixer for Crusher. Soil and stone enter into the slurry cabin during shield tunnelling, and the broken stones with larger grain sizes are deposited at the bottom of the cabin; however, since the space around the crusher is narrow and small, it is difficult for the shield mixer to function properly, resulting in a pileup of broken stones in large quantity. This has an adverse effect on the slurry discharge.

To mitigate this problem, the following improvements were applied. Mixers were welded to the bottom of the rotating plate of the crusher. The mixers were staggered by 7 cm in the vertical direction. Under the drive of the hydraulic cylinder, the rotating plate begins to rotate, then, the mixers move and collide with broken stones that have been deposited; therefore, they are mixed and large-sized broken stones being deposited are prevented.

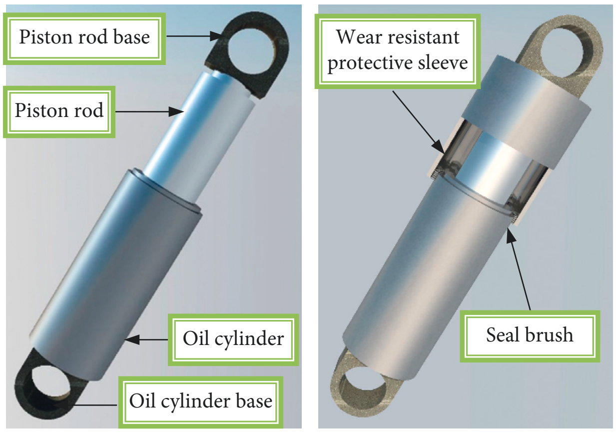


FIGURE 11: Schematic diagram of piston rod protection device.

3.3.5. Improvements in the Joint Hose. The slurry transfer hose is a key part of the slurry transfer system for the slurry shield and was more likely to be locally worn and damaged during tunnelling, causing the slurry to drain away and result in the failure of the entire hose. In particular, the hose was more likely to need changing in sandy cobble stratum, which not only delayed the construction schedule but also considerably increased the cost.

To mitigate these problems, the following improvements were applied. The conventional slurry transfer hose was divided into three segments, and adjacent hoses were connected by a flange and waterproof gasket installed at the connection, as shown in Figure 12. In the case where the slurry transfer hose is damaged and fails to operate properly, all that needs to be done is to change the worn hose. This operation is simple and reduces the cost of the hose and prolongs the service life.

4. Key Control Technique in Shield Construction

4.1. Parameter Control in Shield Construction

4.1.1. Setting the Tunnelling Parameters. The tunnelling parameters for the shield are the shield thrust, incision slurry pressure, tunnelling rate, cutter head torque, cutter head speed, shield posture control, etc. These parameters are related to each other; therefore, the shield construction was completed while considering the relationship between them.

After the shield machine entered the riverbed of the Yellow River, the tunnelling operation was subject to control by the following tunnelling parameters:

(1) The normal tunnelling rate for the shield was 15–25 mm/min; however, if an obstruction was encountered by the front face, the tunnelling rate may have been lower than 10 mm/min.

(2) The set value of the slurry pressure at the cutter head incision was between the theoretical maximum and minimum calculated values and was adjusted based on the conditions of the riverbed and geology. The slurry pressure for the shield in the section was between 0.22 and 0.30 MPa.

(3) The amount of excavation was subject to strict management, and the slag amount discharged per ring was limited to 42 m^3 so as to reduce soil disturbance.

(4) The cutter head speed was from 1 to 1.3 r/min; the total thrust for the shield was from 10,000 to 15,000 kN; and the cutter head torque was from 700 to 1600 kN m.

(5) The maximum horizontal deviation for the cutter head centre from the design axis was within 40 mm, the vertical deviation of the same was within 30 mm, and the deviation correction value per ring was no more than 10 mm. A SLS-T tunnel autoguide system was employed along with manual measurements as an auxiliary means by which to monitor the shield posture during construction, as it was important to operate the thrust cylinder of the shield machine on an area basis so as to control the tunnelling direction of the shield.

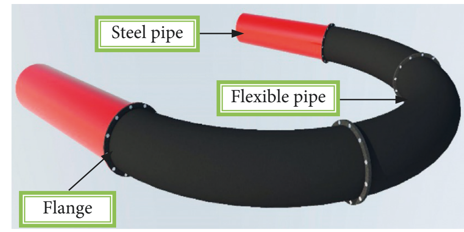


FIGURE 12: Schematic diagram of the improved device for slurry transfer hose.

4.1.2. Control of the Performance Index of the Slurry. While considering the film-forming properties of the slurry and the specifications of the equipment, the proposed mix ratio for the slurry of bentonite-CMC-soda-water per cubic meter was 330 : 2.2 : 11 : 870 (kg). The mix ratio for the slurry was adjusted based on the geological conditions and stability of the tunnel face over time. The main performance parameters were as follows: the specific gravity of the slurry was adjusted from 1.05 to 1.18 g/cm^3, the viscosity was maintained from 25 to 35 s, and the water segregation rate was below 12%.

4.1.3. Grouting Index Control

(1) Synchronous Grouting. The mass ratio of the main material for the synchronous grouting of the cement-fly ash-bentonite-sand-water per cubic was 150–200 : 190–300 : 100–120 : 620 : 360–380 (kg), and the grouting pressure was from 0.2 to 0.32 MPa. The theoretical grouting amount per ring (1.2 m) was $V = 1.2 \times \pi\ (6.45^2 - 6.2^2)/4 = 2.98\ m^3$, and the actual grouting amount was 1.2–1.6 times the theoretical grouting amount. The grouting parameters were adjusted when the stratum pores changed. When necessary, it was increased to 2.0 times. The synchronous grouting speed matched the tunnelling speed, and the average grouting speed was

determined based on the time to tunnel one ring and the complete grouting amount of the ring.

(2) Backfilling Grouting. After the shield passed through the relevant stratum, the soil mass was reinforced by backfill grouting based on the subsidence. The material used for grouting contained cement, fly ash, and bentonite, and the mass ratio of cement-fly ash-bentonite-water per cubic was 450 : 400 : 25 : 400 (kg).

4.2. Control Technique for Construction in the Sand Pit

4.2.1. Risk That the Shield Will Pass through the Sand Pit

(1) Frequent Collapse of the Tunnel Face. The undisturbed soil on the top of the shield machine was thin loose soil and was likely to collapse under the disturbance of shield tunnelling and combine with the cobble accumulated at the bottom of excavation and work cabins, resulting in an increase of the cutter head torque and jamming therein. After cobble accumulated in the cabin, it took a long time to clear the blockage. In addition, a prolonged standstill causes the tunnel face to further collapse, resulting in a vicious cycle.

(2) Tunnel Face Fails to Hold the Pressure. The section was characterized by a high content of coarse and loose grains with a permeability coefficient up to 1.15×10^{-1} cm/s, which was more likely to result in the filtration of slurry in large quantities. Thus, it was impossible to establish a pressure balance on the excavation surface. Moreover, the frequent collapse of the tunnel face also constantly damaged the integrity of the slurry film, which prevented the film from protecting the wall of slurry.

4.2.2. Treatment

(1) Prereinforcement. The reinforcement by grouting was based on a sleeve valve pipe for construction. The grout was made of cement mixed with sodium silicate, and the grout index was as follows: the ratio of water and cement (W/C) was 0.8 : 1–1 : 1, and the volume ratio between the cement and sodium silicate (C/S) was 1 : 0.8, with a setting time within approximately 1 min 45 s. The depth of the reinforced zone was within the range of 5.0 m above the shield machine (including a 1.0 m allowance for the buffer layer of undisturbed soil), the width of which was in the range of 3 m on the left and right sides of the tunnel, as shown in Figure 13. After the reinforcement by grouting was completed, the permeability coefficient of the soil mass that was subjected to reinforcement was lower than 1.0×10^{-6} cm/s, with an unconfined compression strength after 28 d that was more than 1.2 MPa.

(2) Improvement in the Slurry Index. In order to ensure the stability of the tunnel face, it was decided to increase the consumption of a special slurry preparation agent and macromolecular polymer. The resulting slurry index had a viscosity more than 40 s (maximum was up to 60 s), the density was from 1.13 to 1.4 g/cm^3, the rate of water loss was about 14 ml, and the sand percentage was lower than 2%.

(3) Enhancement of the Slurry Film. Excavation surface was filled with chemical slurry to enhance the quality of the slurry film. The chemical slurry was delivered to the excavation surface by the central flushing pipe, and the mass ratio of chemical slurry was HS1 : HS2:HS3: water = 0.15 : 0.5 : 0.1 : 1.

(4) Advanced Grouting. An HS3 plugging agent was employed to carry out advance grouting from the preserved grouting pipe on the shield. The mass ratio of the grout per cubic was HS3: water = 0.5 : 1.

(5) Isolation Ring for Construction. Polyurethane was delivered into the upper semicircle in the rear of shield tail from the grouting holes in the shield tail at intervals of 1.2 m. The mass ratio per cubic was polyurethane: catalyst = 10 : 1.

4.3. Difficulties in and Countermeasures for Passing through the Inspection Shaft. There was an inspection shaft in the place marked with mileage pile number of YCK13 + 727.106 and ZCK13 + 723.896 before the shield undercrossed the Yellow River. Its planar dimensions were up to 6.0 m (along the direction normal to the line) × 21.4 m (along the direction of the line) × 27.822 m. The main risk in passing through the inspection shaft was the water surge at the tunnel exit, poor reinforcement of the soil mass at the end, damage to the sealing at the tunnel exit, etc.

The enclosure system for the inspection shaft consisted of an underground diaphragm wall and interior bracing. The continuous wall at the front of the shield access tunnel was constructed of glass fibre-reinforced polymer rebar, which replaced the common reinforcing steel bar, so as to facilitate cutting by the shield cutter head. The soil used for the launch and arrival of the shield machines underwent reinforcement by a jet-grouting pile at high pressure based on Φ800 double-wall pipe on the ground. The spacing in the layout was 600 mm. The reinforcement range for ends was as follows. The arrival was in the range of 10 m along the forward direction of the shield, and the launching was in the range of 8 m along the forward direction of shield. Both ends were within the range of 12 m in the horizontal direction and 12.2 m in the vertical direction. The grouting material was ordinary Portland cement with a water-cement ratio of 1 : 1. After reinforcement and improvement, the soil mass was uniform. The main technical parameters of the stratum were as follows. The unconfined compression strength was more than 1.0 MPa, and the permeability coefficient was no more than 10^{-8} cm/s.

The tunnelling parameters were subject to strict controls when the shield machine launched, namely, the cutter head rotation speed was within 1.0 r/min, the incision of slurry pressure was set to 98 kPa, the advancement speed was within 3 mm/min, and the driving axis was 30 mm lower than the design axis.

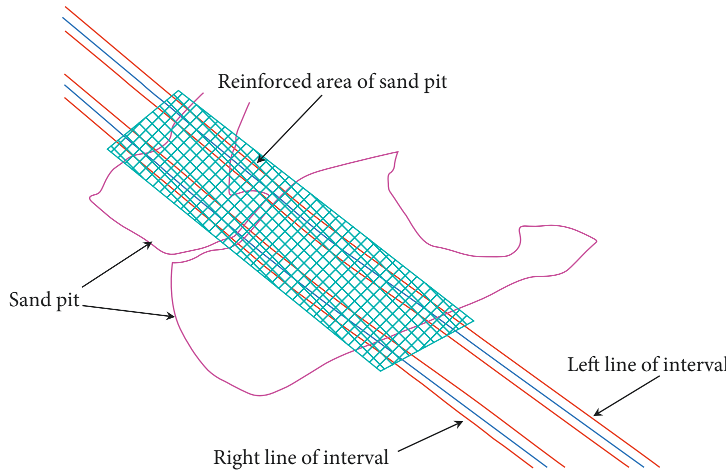


Figure 13: Diagram of the reinforced zone.

4.4. Risk and Disposal of Boulders at the Bottom of the River. There were a large number of boulders in the riverbed of the Yellow River that were random in spatial distribution, and due to distribution of the drilling holes, it was difficult to locate them in a geological survey. Thus, this caused great difficulty during construction of the shield, including severe wear of the cutter, deformation of the cutter holder, and abrasive wearing of the cutter head, all of which reduced the strength and rigidity of the cutter head and even deformed the cutter head. In addition, nonuniform stress on the cutter head damaged the main bearing or sealing of the main bearing, and large-sized boulders could not be broken, which caused blockages of the shield tunnelling or deviations in the tunnelling route.

These challenges were mitigated as follows:

(1) The geological forecast was enhanced to carry out inspection of the cutter head and cutter before the shield arrives in sections with large-sized boulders to ensure that the cutter head and cutter are in good condition.

(2) The tunnelling parameters were adjusted to reduce the cutter head speed, increase the thrust, control the penetration of the cutter within 10 mm/r, and limit the torque variation of the cutter head within the range of 10%. Then, the cutter head was controlled to achieve forward and reverse rotation and thereby slowly cut large-sized boulders.

(3) The slurry performance and slurry pressure were properly controlled during the large-sized boulder cutting process to ensure that the slurry film was able to stabilize the tunnel face and reduce the wear of the cutter head and cutter. In addition, it was necessary to check the crusher system to ensure that the crusher was in good condition to crush large-sized stones and slag in time to prevent the slurry pipe from being blocked.

5. Conclusion

By summarizing the measures adopted to address the problems in the process of the construction of Lanzhou Yellow River Tunnel, including the strata with a high proportion of large-sized sandy cobble stratum being saturated, large-scale sand pits along the bank of the Yellow River, and a combination of boulders and erratic blocks of rock, the following conclusions are listed:

(1) The success of the shield type selection for the interval from Yingmen Beach to Ma Beach for the Lanzhou Metro is suitable for use as a reference in strata with a high content of large-sized sandy cobbles and water.

(2) A set of control programs for construction technology that are applicable to stratum with a high content of large-sized sandy cobble stratum being saturated and to traversals of sand pits have been prepared during the construction of a shield tunnel that undercrosses the Yellow River for the Lanzhou Metro. These control programs provide valuable experience for the construction of urban commuter rail tunnel systems in similar strata.

(3) A series of improvement programs were developed based on the adaptation of the opening rate to stratum with sandy cobbles of various grain sizes and the wearing of the cutter head and cutter by sandy cobble while shield tunnelling in this type of stratum. These improvement programs will prove valuable for reference purposes.

(4) The construction parameters that were determined for the current shield tunnelling process may offer engineering experience for the construction of urban commuter rail tunnel systems in similar strata and may facilitate improvements in the construction efficiency and increase the construction speed, thereby ensuring construction quality.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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