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Research on Construction Technology and Application of Composite Earth Pressure-Slurry Balance Dual-Mode Shield Machine Push Shield

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Abstract: To address the construction challenges of long-distance urban high-pressure gas pipelines crossing complex strata and sensitive structures, this study takes a high-pressure gas pipeline project crossing an intercity railway as the research object, systematically conducting research on the push shield construction technology of composite earth pressure-slurry balance dual-mode shield machines. By analyzing the engineering geological and hydrological characteristics, special requirements for gas pipeline construction, and protection standards for railway structures, the study focuses on optimizing shield machine selection parameters, innovating the construction process system, establishing key parameter calculation models, and constructing a full-process risk prevention and control mechanism. The results show that the 2868-type dual-mode shield machine (with a cutterhead opening rate of 32% and a maximum torque of 848 kN·m) exhibits excellent adaptability in moderately weathered argillaceous sandstone strata (with uniaxial compressive strength ranging from 8.17 MPa to 18.70 MPa). Adopting the combined technology of "double-liquid grouting for end reinforcement - thixotropic slurry drag reduction - double-liquid grouting replacement" and relay jacking with 8 groups of boosters (arranged at intervals of 50 m to 683 m), the construction of a 938-meter-long gas protection pipe is realized with an axis deviation of $\leq \pm 50$ mm and an elevation deviation of $\leq \pm 30$ mm. The established jacking resistance calculation model (Formula 1) and back wall stability check method (Formula 4) effectively ensure construction safety, with the maximum surface settlement controlled at 28 mm and the railway pier displacement at ≤ 1.2 mm, both meeting the protection requirements for sensitive structures. Compared with traditional shield construction, this technology reduces costs by 23%, achieves a daily average tunneling efficiency of 1.8 m, and shortens the construction period by 4%, providing a technical demonstration and quantitative design basis for similar high-pressure gas pipeline crossing projects.

Keywords: Composite Dual-Mode Shield Machine; High-Pressure Gas Pipeline; Long-Distance Construction; Sensitive Structure Protection; Construction Precision Control; Cost Optimization

1. Introduction

With the rapid development of urban infrastructure construction, underground gas pipelines, as the core carrier of energy transmission, often need to cross sensitive areas such as railways, waterways, and building complexes, facing multiple challenges including "long distance, deep burial, complex strata, and high safety requirements" [1]. Although traditional shield construction has strong adaptability, the cost of segment fabrication and assembly accounts for more than 60%, resulting in insufficient economic efficiency [2]. Traditional pipe jacking machines have low tunneling efficiency in hard rock strata, and are prone to pipe section jamming and excessive surface settlement during long-distance jacking [3]. The push shield technology of composite earth pressure-slurry balance dual-mode shield machines combines the advantages of strong rock-breaking capacity of shield machines and low cost of pipe jacking technology. Through the collaborative mode of "shield tunneling + finished pipe jacking", it eliminates the segment assembly process and has the function of switching between earth pressure and slurry balance modes, which can flexibly adapt to different strata [4].

A high-pressure gas pipeline project needs to cross an intercity extra-large bridge and a waterway, with a 938-meter-long protection pipe crossing complex strata such as moderately weathered argillaceous sandstone. The minimum burial depth is 16 m, the displacement control requirement for railway piers is ±2 mm, and the surface settlement control requirement is ≤ 30 mm, with strict construction constraints [5]. Based on this engineering example, this paper conducts systematic research on engineering overview, shield machine selection and adaptation, construction process system, key parameter calculation, risk prevention and control, and engineering application effects, filling the technical gap of composite dual-mode shield machines in the construction of long-distance high-pressure gas pipelines crossing sensitive areas, and providing reliable technical support for similar projects.

2. Engineering Overview

2.1 Basic Engineering Information

The total length of this crossing project is 938 meters. The protection pipe adopts C50 Grade III reinforced concrete pipe with an inner diameter of 2.2 m, a wall thickness of 220 mm, a pipe section length of 2 m, and an F-type collar + rubber ring seal for the interface, with a designed service life of 50 years. Inside the protection pipe, there is one DN800 natural gas transmission pipeline made of L450M spiral submerged arc welded steel pipe with a wall thickness of 19.05 mm, a designed pressure of 4.4 MPa, and an anti-corrosion grade of enhanced three-layer PE enhanced grade [6].

The construction adopts the push shield method of composite earth pressure-slurry balance dual-mode shield machine. Both the working shaft and the receiving shaft are supported by diaphragm walls. The protection pipe line is a straight section with a slope of 0.0‰, successively crossing the waterway and the intercity railway protection zone. During the entire construction process, it is necessary to ensure that the gas pipeline has no leakage or deformation after construction, meeting the safety requirements for high-pressure operation [7].

2.2 Geological, Hydrological and Construction Constraint Conditions

2.2.1 Geological conditions

The site is located in the Pearl River Delta alluvial plain with a ground elevation of 1.4~6.0 m. The strata from top to bottom are miscellaneous fill, mucky silty clay, silty fine sand, silty clay, strongly weathered argillaceous sandstone, and moderately weathered argillaceous sandstone. Among them, the moderately weathered argillaceous sandstone is gray with an argillaceous structure and layered texture. The rock core is mostly in 10~20 cm columnar shape, with a natural uniaxial compressive strength of 8.17~18.70 MPa, an arithmetic mean value of 14.12 MPa, a standard value of 12.51 MPa, and a rock mass basic quality grade of IV [8], which is the main stratum crossed by the protection pipe.

2.2.2 Hydrological conditions

The groundwater in the site is divided into phreatic water and bedrock fissure water. Phreatic water is confined in the surface miscellaneous fill, recharged by atmospheric precipitation, with a water level depth of 0.5~1.6 m and general water volume. Bedrock fissure water is confined in the strongly weathered and moderately weathered argillaceous sandstone, recharged by lateral groundwater, with limited water volume and a permeability coefficient of 0.02~0.08 m/d. Water quality analysis results show that the groundwater has a pH value of 7.2~7.8 and a chloride ion content of 85~120 mg/L, which is slightly corrosive to steel bars in concrete and reinforced concrete structures and weakly corrosive to steel structures [9].

2.2.3 Core construction constraints

(1) Protection of sensitive structures: The angle between the center line of the protection pipe and the center line of the intercity high-speed railway is 70.2°, the minimum vertical distance between the edge of the protection pipe and the projection line of the railway bridge is 9.32 m, the minimum net distance from the railway pier is 10.69 m, and the minimum burial depth of the top of the protection pipe within the railway area is 20.35 m. According to the "Technical Code for Safety Monitoring of Construction Adjacent to Railway Operating Lines" (TB10314-2021), the control values for vertical and horizontal displacement of piers are both ±2 mm, and the track regularity deviation is ≤ 1 mm/m;(2) Waterway crossing requirements: The minimum distance between the top of the protection pipe and the bottom edge of the waterway is 16.32 m, the water depth of the waterway is 3~5 m, and the navigation grade is Class VI. During

construction, it is necessary to avoid water and sand gushing and river silting to ensure navigation safety;(3) Safety requirements for gas pipelines: The axis deviation of the protection pipe construction is ≤ ±50 mm, the elevation deviation is ≤ ±30 mm, the water seepage of the pipe section interface is < 0.05 L/(m²·d), the pressure test pressure of the protection pipe is ≥ 6.6 MPa (1.5 times the design pressure), and there is no pressure drop for 30 minutes of pressure holding;(4) Environmental protection constraints: During construction, the dust concentration is ≤ 2 mg/m³, the noise is ≤ 85 dB (≤ 55 dB at night), the wastewater is discharged up to the standard after treatment, and the disposal rate of muck transportation is 100% [10].

3 Selection and Construction Process Design of Composite Earth Pressure-Slurry Balance Dual-Mode Shield Machine

3. Selection of Composite Earth Pressure-Mud Water Dual-Mode Shield Machine and Construction Process Design

3.1 Selection and Functional Adaptation Design of Shield Machine

According to the engineering geological characteristics and construction requirements, the 2868-type slurry balance composite earth pressure-slurry balance dual-mode shield machine is selected, with the following core parameters and functional adaptation optimizations [11].

3.1.1 Adaptation of cutterhead and cutting system

(1) The excavation diameter of the cutterhead is φ2868 mm, matching the construction requirements of the DN2200 protection pipe, with an opening rate of 32%, which not only ensures the smooth discharge of muck but also avoids blockage by hard rock blocks (Figure 1.);

(2) Tool configuration: 23 pieces of 12-inch double-edged disc cutters (cutter ring material is wear-resistant alloy, maximum bearing pressure of 150 MPa), 6 pieces of edge scrapers (width 100 mm, tungsten carbide cutting edge), and 18 pieces of face scrapers, forming a collaborative cutting system of "disc cutter rock breaking + scraper slag cleaning", which can effectively break moderately weathered argillaceous sandstone;

(3) The cutterhead speed is infinitely variable between 0~3 r/min, with a working torque of

754 kN·m, a maximum torque of 848 kN·m, and a breakout torque of 942 kN·m. For moderately weathered rock formations, the "low speed + high torque" mode (speed 1.2~1.8 r/min) is adopted to reduce tool wear.
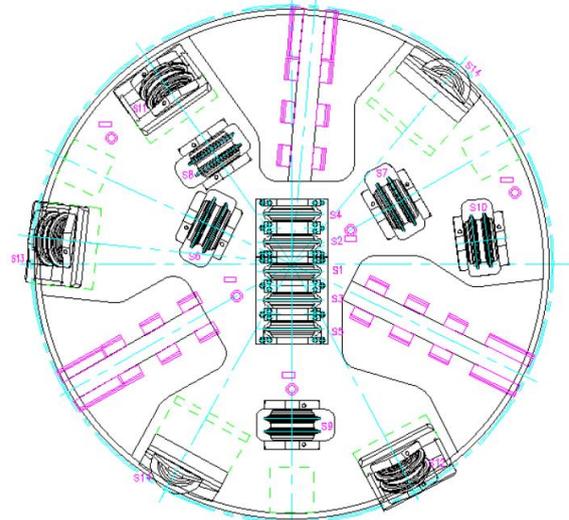

Figure 1. Cutterhead Diagram

3.1.2 Secondary crushing and slag discharge system

(1) The secondary crushing chamber is integrated at the front end of the front shield, forming a shear crushing mechanism with the cutterhead. The maximum particle size allowed to enter through the cutterhead opening is 200 mm, which is crushed to a particle size ≤ 80 mm after secondary crushing to avoid blocking the slurry pipeline;(2) The slurry circulation system adopts a "dual-pipe alternating feeding and discharging" design, with a feeding pipe diameter of DN125 (one divided into three) and a discharging pipe diameter of DN200 (two DN160 converging). It is equipped with a three-stage slurry separation system (primary screen + secondary cyclone + tertiary filter press) with a slurry processing capacity of 200 m³/h to ensure smooth slag discharge.

3.1.3 Sealing and attitude control system

(1) The main shaft seal adopts 3-stage forced lubrication lip-type rubber seal, which can resist a maximum face water and soil pressure of 1 MPa. Forced lubricating grease enters the seal skeleton through the oil channel and is discharged to the excavation chamber, gradually reducing the water and soil pressure to avoid leakage of soil around the gas pipeline;(2) The deviation correction system is equipped with 4 sets of 80T deviation correction cylinders, distributed at 45° angles, with a maximum deviation correction angle of ±3° and a

maximum extension distance of 200 mm for the cylinders. Combined with the SLS-T APD laser guidance automatic measurement system, the positioning accuracy is ±5 mm, meeting the requirements for the axis accuracy control of gas pipelines;(3) The shield tail is equipped with a push shield system (6 sets of hydraulically driven cylinders with a total thrust of 15000 kN) as a backup driving force to cope with sudden increases in resistance such as pipe section jamming and hard rock strata during long-distance jacking.

3.1.4 Safety guarantee functions

(1) Equipped with an automatic tool wear monitoring system, which real-time feeds back the force state of the tools through pressure sensors, automatically generates a wear analysis report every 50 m of advancement, and reduces blind cabin opening;(2) A square cabin door is set at the top of the excavation chamber, with a built-in earth pressure sensor and ball valve, enabling air-pressurized cabin opening for tool change, and a reserved injection port for soil improvement materials to cope with water-rich and loose strata;(3) Integrated with a PLC automatic control system, realizing the linkage control of the main jacking system, boosters, slurry pumps, and deviation correction system, real-time displaying tunneling parameters (thrust, speed, earth chamber pressure, etc.), and automatically alarming and triggering emergency measures in case of abnormalities.

3.2 Special Construction Technology for Gas Pipelines

3.2.1 End reinforcement and portal sealing technology

The strata at the ends of the working shaft and receiving shaft contain silty fine sand and mucky soil, which are prone to water and sand gushing. A combined scheme of "double-liquid grouting reinforcement + composite sealing" is adopted [12], the process flow and details of the grouting pipe are shown in Figure 2:

(1) Reinforcement scope: 3 m outside the left and right edges of the portal, 8 m along the axial direction of the protection pipe, forming a closed reinforcement ring;

(2) Grouting materials: The outer ring adopts cement-water glass double-liquid slurry (cement slurry water-cement ratio 0.6:1, water glass concentration 35Be, volume ratio 1:1), and the inner ring adopts single-liquid cement slurry (water-cement ratio 0.8:1), with a grouting pressure of 0.15~0.25 MPa, a diffusion radius of 1.0 m, and a setting time of 2~3 minutes (double-liquid slurry), ensuring that the bearing capacity of the reinforced stratum is ≥ 350 kPa;

(3) Grouting hole layout: Arranged in a plum-blossom shape with a hole spacing of 0.8 m and a hole depth of 11 m (3 m beyond the reinforcement scope), with a total of 42 grouting holes. After reinforcement, radar detection is used to verify the grouting integrity, and core drilling tests are conducted to verify the strength;

(4) Portal sealing: Install a waterproof annular sealing rubber belt + circular fixed ring plate + fan-shaped pressure plate sealing device. The rubber belt is water-swellable (swelling rate $\geq$ 300%), and FFU glass fiber material is used instead of traditional steel bars pre-embedded in the retaining structure to realize direct cutting by the shield machine, eliminating the portal chiseling process and reducing disturbance to the surrounding strata.
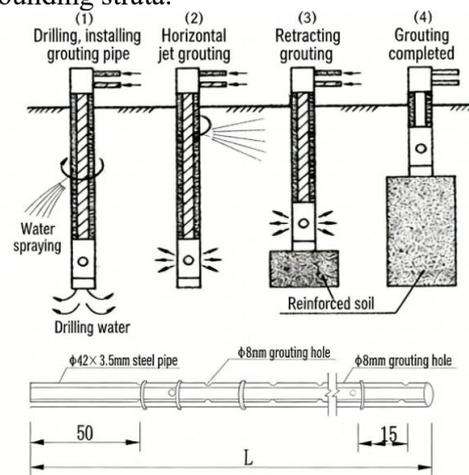
Figure 2. Process Flow and Detail Drawing of Grouting Pipe

3.2.2 Collaborative technology of tunneling and jacking

Construct a three-stage construction process of "shield tunneling - pipe section jacking - slurry replacement", as follows [13]:

(1) Shield tunneling stage:

1) Before tunneling, set the earth chamber pressure according to the stratum parameters, and control the earth chamber pressure at 245 kPa±10 kPa in the moderately weathered rock stratum section;

2) Synchronously inject thixotropic slurry (ratio: bentonite 300kg: CMC 2.2kg: soda ash 11kg: water 870kg) to form a slurry film with a thickness $\geq$ 5 mm, reducing the frictional resistance between the pipe section and the soil.

The slurry viscosity is controlled at 20~23 s, and the water loss rate is ≤ 5%;

3) The rotation direction of the cutterhead is switched every 30 minutes to avoid tool uneven wear, the tunneling speed is 15~20 mm/min, and the single tunneling distance matches the pipe section length (2 m/ring).

(2) Finished pipe jacking stage:

1) The main jacking system adopts 6 sets of 250t-class cylinders, arranged symmetrically, with a total thrust of 15000 kN, equipped with assembled rear backing plates (box-shaped body welded with 20mm thick steel plates) to ensure uniform transmission of jacking force;

2) Pipe section transportation adopts a 25t gantry crane + underground battery car, and the pipe section hoisting adopts double lifting point flexible slings to avoid pipe section damage; before installing the pipe section interface, clean the sealing groove, apply water-based lubricant, and adopt the process of "centered docking - slow jacking - compression sealing" to ensure that the rubber ring is not displaced or reversed;

3) 8 groups of boosters (Figure 3.) are arranged at intervals of "50m, 140m, 231m, 321m, 412m, 502m, 593m, 683m", using PLC linkage control. When the main jacking pressure reaches 80% of the allowable jacking force, the boosters are activated to realize relay jacking.

Figure 3. Booster System

(3) Dual-mode conversion stage:1) When the jacking force exceeds 90% of the maximum allowable jacking force of the pipe material (15104.23 kN) or the monitored stress value of the pipe section continues to rise, start the dual-mode conversion;2) Conversion process: Stop jacking → replace thixotropic slurry with cement slurry (grouting pressure 0.3~0.5 MPa) → remove jacking equipment → install conversion ring (left side connected to the pipe section with F-type interface, right side connected to the segment with bolts) → transport segments → switch to earth pressure balance mode → segment assembly;

3) The segments adopt C50 reinforced concrete segments with a thickness of 220 mm and a ring width of 1200 mm, assembled by staggered joint with six segments, bolt connection torque of 800 N·m, and synchronous grouting with cement-water glass double-liquid slurry, with a grouting volume of 1.5 times the annular gap volume.

3.2.3 Double-liquid grouting replacement technology

After the pipe section is jacked in place, to prevent surface settlement and pipe section floating caused by water bleeding of thixotropic slurry, the double-liquid grouting replacement technology is adopted [14]:(1) Replacement slurry: P.O42.5 ordinary Portland cement slurry with a water-cement ratio of 0.6:1 + 35Be water glass, volume ratio 1:1, setting time 2~3 minutes, diffusion radius 1 m;(2) Grouting process: Adopt the method of "grouting from the middle to both ends, layered grouting", grouting hole spacing 8 m, grouting volume per hole controlled at 0.8~1.2 m³, grouting pressure 0.15~0.25 MPa. When the grouting pressure rises stably to the design value and lasts for 5 minutes, and the grouting volume is < 0.1 m³/h, stop grouting; (3) Quality control: After replacement, geological radar is used to detect the grouting compactness to ensure no cavities, and the pipe section floating is controlled within 5 mm.

3.3 Construction Monitoring and Precision Control System

Establish a "three-layer monitoring + two-level early warning" system to realize dynamic control of the entire construction process [15]:

3.3.1 Monitoring content and frequency

(1) Surface settlement monitoring: Arrange monitoring sections every 30 m along the line, encrypt to 10 m in the sections crossing railways and waterways, and set 5 monitoring points in each section (center line and 10 m, 20 m on both sides). The monitoring frequency is once every 2 days within 50 m before and after the tunneling face, and once a week beyond 50 m. When the data is abnormal, the frequency is increased to once every 6 hours;

(2) Railway structure monitoring: Arrange vertical and horizontal displacement monitoring points on the piers of the 54th~56th holes of the Zhongtang Extra Large Bridge (4 points per pier), and track regularity monitoring points every 5 m. The monitoring frequency is once every 2 hours during construction, and 4 times a

day within 1 month after completion;
(3) Protection pipe monitoring: Use inclinometers to monitor the pipe section axis deviation (one inclinometer hole every 20 m), stress gauges to monitor the pipe section stress (one group every 10 m, 2 sensors per group), and grouting pressure sensors to monitor the replacement grouting effect. Arrange

osmometers at the pipe section interfaces to monitor the sealing performance;
(4) Shield machine attitude monitoring (Figure 4.): Real-time monitoring by the SLS-T APD laser guidance system (data update frequency once every 10 seconds), and manual recheck twice a week (combined measurement with total station + level).
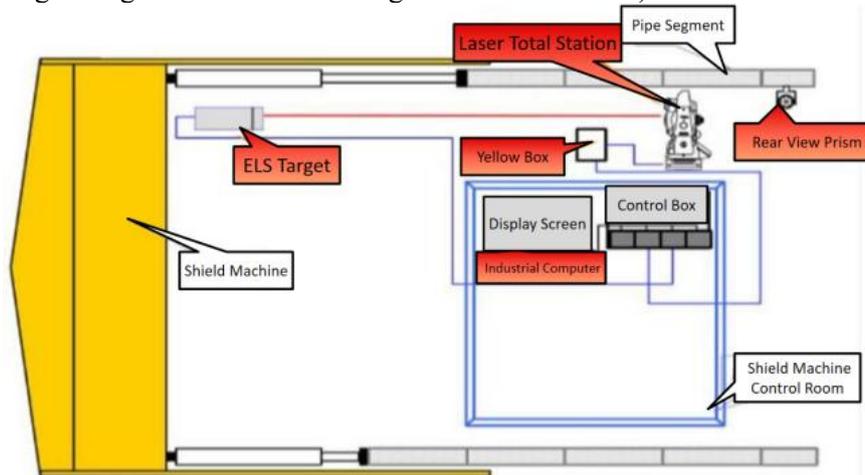

Figure 4. Measurement Guidance System Diagram

3.3.2 Early warning and regulation mechanism
(1) Level 1 early warning (warning value): Surface settlement ≥ 20 mm, pier displacement ≥ 1.2 mm, pipe section axis deviation ≥ 30 mm, activate "slowing down tunneling speed + adjusting grouting parameters" regulation;(2) Level 2 early warning (alarm value): Surface settlement ≥ 25 mm, pier displacement ≥ 1.6 mm, pipe section axis deviation ≥ 40 mm, immediately stop tunneling, take measures of "secondary grouting reinforcement + shield attitude correction" until the monitoring data returns to stability;(3) Regulation principle: The shield attitude correction follows the principle of "frequent and small corrections", with the correction amount per ring not exceeding 9 mm in the horizontal direction and 5 mm in the vertical direction; the grouting parameters are dynamically adjusted according to the settlement data, and when the settlement rate > 2 mm/d, the grouting volume is increased by 20%~30%.

4. Calculation and Optimization of Key Parameters

4.1 Calculation of Jacking Resistance
Jacking resistance is the core basis for determining the thrust of the main jacking system, the number of boosters, and the arrangement spacing, including face slurry pressure (F1) and pipe wall frictional resistance

(F2). The calculation formulas are as follows [16]:

$$F_0 = F_1 + F_2 \tag{1}$$
$$F_1 = \frac{\pi}{4} \times D_1^2 \times \gamma_S \times H_S \tag{2}$$
$$F_2 = \pi \times D_1 \times L \times f_K \tag{3}$$

Where:
D_1=2.64m (outer diameter of the protection pipe);
γ_S=18kN/m³ (stratum unit weight);
Hs=20m (overburden thickness);
L=938m (total jacking length);
f_K =16kN/m² (average frictional resistance per unit area between the outer wall of the pipe section and the soil).
Substituting the data for calculation:
F1=4π×2.642×18×20=1969.61kNF2=π×2.64×938×16=124410.32kNF0=1969.61+124410.32=126379.93kN

4.2 Check Calculation of Allowable Jacking Force of Pipe Material
The allowable jacking force of the DN2200 Grade III reinforced concrete pipe used for the reinforced concrete pipe jacking section is calculated as follows [17]:
F_{dc}=0.5×ϕ₁×ϕ₂×ϕ₃×f_c×A_p/ (γQd×ϕ₅)
Where:
ϕ₁=0.90 (reduction coefficient of concrete compressive strength);
ϕ₂=1.05 (enhancement coefficient of eccentric compressive strength);

ϕ_3=0.85 (material brittleness coefficient);
ϕ_5=0.79 (enhancement coefficient of concrete strength standard value);
fc=23.1MPa=23100kN/m2 (calculated value of concrete compressive strength);
Ap=4π×(D12−D02)= 4π×(2.642−2.22)= 1.672m2 (minimum effective force transmission area of the pipe, D_1=2.64m is the outer diameter of the pipe, D_0=2.2m is the inner diameter of the pipe);
γ_{Qd}=1.3 (jacking force partial coefficient).
Thus: Fdc=0.5×0.90×1.05×0.85×23100×1.672/ (1.3×0.79) =15104.23kN

4.3 Optimization of Booster Arrangement
According to the calculation results of jacking resistance and the allowable jacking force of the pipe material, the total thrust of the main jacking system is 15000 kN, and boosters need to be set for relay jacking. The arrangement principles are as follows [18]:
1. The first booster is arranged 50 m behind the pipe jacking machine head (the resistance is small in the early stage of jacking, with a safety margin reserved);
2. The spacing of subsequent boosters is calculated according to "the jacking force reaches 80% of the allowable jacking force", and the formula is:

$$L_i=L_{i-1}+0.80\times F_{dc}/(\pi\times D_1\times f_k) \qquad (4)$$

Substituting the data to calculate the arrangement positions of each booster: 50m, 140m, 231m, 321m, 412m, 502m, 593m, 683m, with a total of 8 groups of boosters and a maximum jacking distance of 776m. The subsequent 212m adopts the segment assembly mode to meet the requirements of long-distance jacking.

4.4 Check Calculation of Back Wall Stability
The back of the working shaft adopts a combined form of diaphragm wall + backfill soil. The concrete strength of the diaphragm wall is C40, and the formula for checking the stability of the back wall is as follows [19]:

$$R=\alpha B(\gamma H^2 \frac{K_p}{2}+2CH\sqrt{K_p}+\gamma hHK_p) \qquad (5)$$

α=2 (safety factor);

B=3m (width of the back wall);
γ=19.5kN/m3 (soil unit weight);
H=3.5m (height of the back wall);
Kp=1.848 (passive earth pressure coefficient);
c=10kPa (cohesion of the soil);
h=21.63m (height of the soil from the ground to the top of the back wall).
Substituting the data for calculation:
R=2×3.0×(19.5×3.52×1.848/2+2×10×3.5×1.848 +19.5×21.63×3.5×1.848)=18263.9kN
The calculation results show that the allowable thrust of the back is 18263.9kN > the main jacking thrust of 15000kN, meeting the stability requirements.

4.5 Optimization of Tool Rock Breaking Parameters
For moderately weathered argillaceous sandstone (uniaxial compressive strength 12.51MPa), the Roxborough formula is used to calculate the rock breaking thrust of the disc cutter [20]:

$$F_v=4\times\sigma_c\times h\times tan\frac{\theta}{2}\times\sqrt{2Rh-h^2} \qquad (6)$$

Where:
σc=12.51MPa=12510kN/m2 (uniaxial compressive strength of the rock);
h=6~ 8mm (penetration depth of the disc cutter into the rock, corresponding to a tunneling speed of 15~20mm/min);
θ=75∘ (edge angle of the disc cutter);
R=1.434m (radius of the disc cutter, 12-inch disc cutter diameter 304.8mm).
Substituting the data for calculation:
FV=45~ 69kN
The axial force of the main bearing of the shield machine is 752kN, which is evenly distributed to 48 tools (23 disc cutters + 25 scrapers). The average force per tool is 15.67kN < the allowable thrust of the disc cutter of 60kN, and the tool configuration meets the rock breaking requirements.

5. Risk Identification and Control Measures
The project construction faces multiple risks such as stratum stability, pipe section jamming, tool wear, and structural deformation. Targeted control measures are shown in Table 1 [21].

Table 1. Risk Analysis and Control Measures

Risk type	Risk description	Control measures
Stratum stability risk	Excavation face collapse, water gushing and sand inrush (risks are prominent in fine	1. Strictly control the slurry chamber pressure at 245kPa±10kPa, and ensure the synchronous grouting volume is 3–5 times the theoretical gap volume. 2. Adopt double-liquid grout for end reinforcement; conduct radar detection and core drilling verification after grouting to ensure no blind zones in the reinforcement range.

	silty sand layers and around water channels).	3. Adopt the "low speed, high pressure" tunneling mode when crossing the water channel section, with tunneling speed ≤15mm/min and slurry specific gravity increased to 1.25–1.30t/m³. 4. Equip 20 emergency water pumps (5.5kW) and 1000m rubber hoses. Immediately activate drainage and double-liquid grout plugging in case of sudden water inrush.
Risk of pipe segment seizure / Pipe segment jamming risk	During long-distance jacking, the pipe is surrounded and restrained by water and soil pressure, resulting in a sudden increase in jacking force exceeding the allowable value.	1. Use high-quality bentonite for thixotropic slurry to ensure the slurry film thickness is ≥5mm, and supplement slurry every 8m. 2. Arrange water bag counterweights at the inner bottom of pipe segments every 50m, connect them to the head water injection system, and adjust the water injection volume according to the measurement data (control pipe segment uplift <5mm). 3. Real-time monitor the jacking force and pipe segment stress; issue an early warning when the jacking force reaches 80% of the allowable value, and start dual-mode conversion when it reaches 90%. 4. Reserve emergency grouting holes; inject high-pressure clean water + lubricant when seizure occurs, and adjust the jacking parameters after loosening the pipe segments.
Risk of cutter wear	During tunneling in moderately weathered rock strata, cutters wear rapidly, with eccentric wear of disc cutters and mud cake formation on the cutter head.	1. Open the chamber to inspect cutters every 100 m of advance using compressed air chamber opening technology (air pressure 0.12 MPa). Replace cutters immediately when the wear depth exceeds 5 mm. 2. The cutter head adopts a rear-mounted design, allowing disc cutters to be replaced from inside the spoke arms, thus reducing chamber opening time. 3. Inject high-pressure clean water (pressure 7 bar) at the cutter head center during tunneling to prevent mud cake formation. 4. Prepare 2 sets of spare cutters (23 disc cutters, 24 scrapers). Establish a cutter wear log to predict replacement cycles in advance.
Structure deformation risk	Excessive displacement of railway bridges and ground settlement (sensitive areas around bridges and building complexes).	1. Density monitoring points shall be arranged within the railway protection area (one per 5m), with a monitoring frequency of once every 2 hours, and data shall be transmitted to the railway operation unit in real time. 2. Inspect cutters by opening the chamber 200m before crossing the bridge, replace worn cutters, convert the pushing mode to shield mode, and adopt earth pressure balance tunneling. 3. Adopt a "small amount, multiple times" process for double-liquid grout replacement grouting, with grouting pressure ≤ 0.25MPa to avoid disturbing the bridge foundation. 4. Set the settlement early-warning value at 20mm and alarm value at 25mm. Immediately stop tunneling and start secondary grouting reinforcement if exceeding the limits.
Gas pipeline safety risk	Protective pipe leakage and damage at pipe segment joints, affecting the subsequent operation of the gas pipeline.	1.100% visual inspection of pipe segments before delivery; segments with cracks > 0.2 mm or edge breakage > 50 mm are strictly prohibited. 2.Clean the sealing groove and apply water-based lubricant before pipe joint installation; jacking speed ≤ 5 mm/min to avoid damage to the rubber ring. 3.Conduct pressure test (9.45 MPa) after protective pipe construction, stabilize pressure for 30 min with no pressure drop, and joint water permeability < 0.05 L/(m²·d). 4.Use flexible traction head for gas pipeline pulling crossing, traction speed ≤ 1 m/min to avoid scratching the pipeline anti-corrosion layer.

6. Engineering Application Effects

6.1 Construction Quality

6.1.1 Precision control
(1) Protection pipe axis deviation: Horizontal deviation +4.8~-3.9mm, elevation deviation +3.8~-3.2mm, both meeting the design requirement of ≤ ±50mm;(2) Pipe section installation quality: The height difference between adjacent pipe sections ≤ 4mm, the interface seal is good, the pressure test pressure of the protection pipe is 9.45MPa (1.5 times the design pressure), holding pressure for 30 minutes without pressure drop, and the water seepage < 0.05L/(m²·d), reaching the Grade II waterproof standard;(3) Railway structure deformation: The maximum vertical displacement of the pier is 1.2mm, and the maximum horizontal displacement is 0.8mm,

both controlled within the limit of ±2mm; the track regularity deviation ≤ 0.8mm/m, meeting the railway operation requirements;(4) Surface settlement: The maximum settlement is 28mm (waterway crossing section), and the average settlement is 15mm, both ≤ 30mm control standard, without surface cracking or structural damage.

6.1.2 Stratum stability effects

No accidents such as excavation face collapse and water and sand gushing occurred during the entire construction process. The radar detection of the end reinforcement area shows that the grouting compactness ≥ 95%; the slurry chamber pressure is stable in the waterway crossing section, no slurry leakage or river silting occurred, and navigation was not affected.

6.2 Construction Efficiency and Cost

6.2.1 Construction efficiency

(1) The actual construction period of the shield construction stage (938m) is 192 days, 8 days ahead of the planned 200 days, with an average daily tunneling of 1.8m and a maximum daily tunneling of 2.5m (moderately weathered rock stratum section);(2) Dual-mode conversion was implemented 3 times, each conversion taking 6 hours, and the conversion process was safe and stable without excessive settlement;(3) Tools were replaced 4 times, each tool change operation taking 8 hours, the average tool wear amount was 3.2mm, which is lower than the maximum allowable wear amount of 5mm, and the construction period was not affected by tool failures.

6.2.2 Cost saving

(1) Direct cost saving: Using finished pipes instead of segment assembly reduces the cost of segment fabrication (including materials and molds) and assembly construction, reducing the cost per meter by 2860 yuan, with a total cost saving of 2.75 million yuan;(2) Indirect cost saving: Long-distance jacking does not require setting intermediate shafts, reducing the construction cost of 2 intermediate shafts (about 1.8 million yuan); the improved construction efficiency shortens the construction period by 8 days, saving about 450,000 yuan in management fees and equipment rental fees;(3) Total cost saving: 23% lower than traditional shield construction and 15% lower than traditional pipe jacking construction, with significant economic benefits.

6.3 Safety and Environmental Protection

(1) Safety effect: No safety accidents occurred during the entire construction process, achieving the goal of "zero casualties, zero accidents, zero pollution", and passing the safety assessment of construction adjacent to the railway by China State Railway Guangzhou Group Co., Ltd.; (2) Environmental protection effect: A slurry circulation treatment system was adopted, the water content of the waste slurry after three-stage separation is ≤ 30%, and the disposal rate of muck transportation is 100%; during construction, the dust concentration ≤ 1.8mg/m³, and the noise ≤ 82dB (≤ 53dB at night), both meeting the "Emission Standard for Environmental Noise of Construction Sites" (GB12523-2011);(3) Social benefit: The construction process did not affect the normal operation of the intercity railway (68 trains per day) and the navigation of the Liaoxia Waterway, and the gas pipeline was laid on schedule, ensuring the energy supply safety for 120,000 households and 300 enterprises in the region.

7. Conclusions and Prospects

7.1 Conclusions

(1) The push shield technology of composite earth pressure-slurry balance dual-mode shield machines, through the collaborative design of "shield tunneling + finished pipe jacking + dual-mode conversion", effectively solves the construction challenges of long-distance high-pressure gas pipelines crossing complex strata and sensitive structures, balancing construction adaptability, safety, and economy; (2) The optimized design of the 2868-type dual-mode shield machine (cutterhead opening rate 32%), secondary crushing system, and forced lubrication seal adapts to the tunneling of moderately weathered argillaceous sandstone strata, with the tool wear amount controlled within 3.2mm and the tunneling efficiency reaching 1.8m/d; (3) The comprehensive application of end double-liquid grouting reinforcement, thixotropic slurry drag reduction, double-liquid grouting replacement, and laser guidance monitoring achieves high-precision control with a maximum surface settlement of 28mm and a railway pier displacement of ≤ 1.2mm, meeting the protection requirements for sensitive structures; (4) The established jacking resistance calculation model, booster arrangement method, and back wall stability

check formula provide quantitative design basis for long-distance push shield construction, and 8 groups of boosters realize relay jacking of 776m without pipe section jamming; (5) The technology reduces the cost by 23% compared with traditional shield construction, shortens the construction period by 4%, and has been successfully applied in the project, providing a replicable technical scheme for similar high-pressure gas pipeline crossing projects.

7.2 Prospects

The successful application of the push shield technology of composite earth pressure-slurry balance dual-mode shield machines in this project verifies its advantages in urban gas pipeline construction. Further optimization can be carried out in the following aspects in the future: (1) Intelligent upgrading: Integrate BIM + AI technology to establish a coupled model of geology-construction parameters-settlement deformation, realizing real-time intelligent adjustment of tunneling parameters and improving adaptability to complex strata; (2) Optimization of materials and equipment: Develop high-wear-resistant tools (such as diamond-coated disc cutters) and high-performance thixotropic slurry (high-pressure resistant, pollution-resistant) to extend tool life and slurry film stability; (3) Expansion of application scenarios: Explore the application of the technology in gas pipelines of different diameters (DN1500~DN3000) and different pressure levels (6.3~10MPa), optimize the dual-mode conversion device, and shorten the conversion time; (4) Green construction technology: Develop new slurry recycling technology to improve water resource utilization rate, reduce solid waste emissions, and align with the "dual carbon" goal; (5) Standardization system construction: Compile the "Technical Specification for Push Shield Construction of Composite Dual-Mode Shield Machines" based on engineering practice, standardize the construction process, parameter control, and quality acceptance standards, and promote the large-scale application of the technology.

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