

Research on Construction Technology for Shield Tunnelling with Small Curve Radius under Shallow Cover Conditions

Ben Niu^{1,2}, Lihui Huang^{1,2,*}, Jianwei Jia^{1,2}, Ying Liu^{1,2}, Zexin Zhang^{1,2}, Yanxiang Jiang^{1,2}, Hongying Song^{1,2}

¹China Construction Sixth Engineering Bureau Corp., Ltd, Tianjin 300450, China

²China Construction Infrastructure Corp., Ltd, Beijing 100080, China

Abstract: This article takes the shield tunnelling project of the southern entrance of Line 7 of Changsha Metro as a practical background, focusing on extremely complex working conditions including shallow cover (with a minimum thickness of only 3.8m, equivalent to 0.62 times the shield diameter D), small curve radius (R only 250m), low strength rock strata (unconfined compressive strength ranging from 2.25 to 5.96MPa), and the cutting line reception process. The conventional shield tunneling method typically faces challenges in controlling surface settlement and increased risks of segment misalignment and deviational errors under extreme conditions such as shallow overburden and tight curvature radii. In this context, a systematic and in-depth study of the key technologies during the shield reception phase was conducted. Through optimized earth pressure balance control, synchronous grouting process, dynamic regulation of the articulated system, and the application of precise guidance technology, combined with numerical simulation and real-time monitoring methods. Ultimately, the surface settlement was controlled within 12.5mm, segment misalignment to ≤ 10.0 mm, shield posture deviation within ± 25 mm, and reception portal seal leakage to ≤ 0.05 L/min. These results provide valuable technical references for shield reception construction in shallow cover with small radii, and have significant guiding implications for similar projects.

1. Introduction

1.1. Research background

As the urban rail transit network becomes increasingly dense, shield tunneling inevitably needs to frequently traverse complex geological environments and space-constrained areas. Among these, the combination of shallow overburden (H/D less than 1.0) and small curve radius (R less than 300m) poses extremely severe challenges for shield receiving construction.

Under such working conditions, the problem of surface subsidence becomes extremely sensitive. Due to the insufficient thickness of the soil cover, the self-stabilization capacity of strata is significantly weakened, which may easily lead to severe geological hazards such as collapse, posing a huge threat to the safety of surrounding environment and buildings.

At the same time, attitude control has become difficult. In the small radius curve section, the shield machine needs to carry out high-precision dynamic adjustment to achieve correction, and a slight mistake may lead to loss of attitude control, affecting the construction quality and progress^[4].

In addition, the risk of receiving has significantly increased. During the cutterhead reception process, any deviation in the axis can easily lead to the failure of tunnel portal sealing, subsequently causing a series of issues such as groundwater leakage, posing significant

safety hazards to construction^[13]. These challenges require the construction team to adopt more scientific and effective technical measures and management methods during the shield reception process to ensure the safety and smooth progress of the project.

1.2. Research status

In the international field, Japanese scholars took the lead in proposing the curved section shield tail gap compensation algorithm (such as Tani's^[5] research in 2018). This algorithm provides a novel approach for controlling the shield tail gap in curved section tunneling, which has attracted some attention and reference in the international shield engineering field.

In China, the Guangzhou Metro has achieved significant practical results in controlling subsidence of shallow overburden soil by adopting compartmentalized grouting technology (as demonstrated in Zhang Peng's^[6] et al.'s research in 2021). The application of compartmentalized grouting technology has effectively improved the stability of shallow overburden soil layers, reduced the risk of surface subsidence, and provided valuable experience for construction under similar geological conditions in domestic metro projects.

In recent years, extensive studies have been conducted on ground deformation control in small-radius shield tunneling. Xu Ping^[8](2024) identified through numerical and field methods that the inner side of sharp

*1043840895@qq.com

curves experiences maximum settlement, while the outer side heaves, recommending a grouting pressure range of 1.0 – 1.2 times the at-rest earth pressure to limit excessive deformation. Zhang Zhiguo^[15] et al. (2023) highlighted the impact of shield articulation on over-excavation and ground settlement in tight curves. Shi Qinghua^[7] et al. (2025) revealed that ultra-large diameter shields in extremely small radii ($R/D < 1.5$) cause significant ground disturbance and horizontal displacement. To address these issues, Chen Yajun et al. (2025) developed an alignment control technology using spherical articulation and quadrant-variable thrust. These findings collectively form a technical framework for controlling shield tunneling in small-radius curves, providing key insights for projects such as Changsha Rail Transit Line 7.

However, the current research status also faces certain technical bottlenecks. From existing studies, most focus primarily on the excavation phase of shield tunneling, lacking systematic research on comprehensive control technologies for the receiving section of the shield.^[2] This results in a lack of effective technical support and assurance during actual shield construction, especially under complex conditions such as shallow overburden and small-radius curves^[10]. This constrains the further development and application of shield tunneling technology.

2. Project overview

2.1. Engineering parameters

The key engineering parameters for this project are summarized in Table 1.

Table 1. Engineering parameters

project	parameter values
Interval length	438 m
Radius of the plane curve at the receiving en	250 m
Vertical slope	2.2‰
Outer diameter / inner diameter of tunnel	6200 mm / 5500 mm
Minimum topsoil thickness	3.8 m(0.62D)
Stratigraphic characteristics	Sedimentary clayey siltstone, uniaxial compressive strength 2.25~5.96MPa
Tunnel boring machine	ZTE6100 Type earth pressure balance shield machine
Receive the portal diameter	6700 mm

2.2. Key parameters of shield machine

Excavation diameter: 6440mm (conventional)/6540 mm (over-excavation blade open).

Total length of the shield: 8.8m (from the blade to the hinge 5.7m, from the hinge to the tail 3.1m).

Hinge system: passive hinge, maximum travel difference 150mm, maximum opening Angle 1.3°.

Guiding system: laser target distance incision 4600mm, positioning accuracy ± 1 mm.

3. Key technical difficulties

3.1. Stability analysis of shallow overburden

(1) Verification of critical soil cover thickness

In the verification process of critical soil cover thickness, we adopted the Terzaghi loosening soil pressure theory. The formula of this theory is as follows:

$$Hc = D^2 \cdot \cot(45^\circ - \phi/2) \quad (1)$$

$$Hc = 2D \cdot \cot(45^\circ - 2\phi) \quad (2)$$

When the internal friction angle of the clayey siltstone is $\phi = 28^\circ$, the calculated critical cover thickness is $Hc = 3.1$ m. The actual soil cover thickness is 3.8 m, and its safety factor reaches 1.23, which indicates that the actual soil cover thickness is within the safe range.

(2) Surface subsidence prediction

The ground settlement prediction was conducted using a modified Peck's formula^[1]. The formula of the model is:

$$S_{max} = \frac{V_L}{i\sqrt{2\pi}} \cdot e^{-\frac{y^2}{2i^2}} \quad (3)$$

Among them, the stratum loss rate $V_L = 1.5\%$, the width of the settlement trough $i = 0.4Z = 1.52$ m (here $Z = 3.8$ m). After calculation, it is found that $S_{max} = 23.6$ mm, and our target control value is less than or equal to 15mm, which means that further measures need to be taken to reduce the surface settlement to meet the engineering requirements.

3.2. Small curve radius receives attitude control

(1) Verification of theoretical minimum turning radius

The theoretical turning radius of the shield machine is calculated by a specific formula:

$$R_{max} = \frac{\Delta^2 + L^2}{2\Delta} \quad (4)$$

Substituting the length of the shield body $L = 8.8$ m and the wedge quantity of the segment $\Delta = 37.2$ mm, we get $R_{min} = 208$ m < 250 m, which meets the construction requirements.

(2) Dynamic compensation of shield tail gap

In the receiving section, the opening amount of the outer over-excavation cutter is set to 50mm. This opening amount serves to effectively compensate for the gap in the curved section, thereby preventing the segments from being compressed during construction^[9]. In this way, it better meets the construction requirements of the curved section, ensuring the installation quality and safety of the segments.

4. Technical solutions

4.1. Soil pressure balance control optimization

(1) Soil chamber pressure setting

When conducting earth pressure balance construction in shallow overburden areas, the setting of chamber pressure is critical. The calculation is performed using the separate evaluation model for soil and water pressures, with the formula being:

$$P = K_0 \times \gamma \times H + \gamma_w \times H_w + \Delta P \quad (5)$$

In the formula: static soil pressure coefficient: $K_0 = 0.5$, cover soil weight $\gamma = 19\text{kN/m}^3$ water head $H_w = 2\text{mm}$, $P = 0.18 \sim 0.22\text{MPa}$. The soil chamber pressure range calculated by this formula is $0.18\sim 0.22\text{ MPa}$, which can effectively maintain the stability of the soil in the soil chamber and prevent soil collapse and surface settlement^[12].

(2) Slag improvement process

The slag improvement process, including additives, dosage, and their functions, is detailed in Table 2.

Table 2. Slag improvement process

Additive	Dosage	Function
Bentonite slurry	6%	Improve liquidity
High molecular polymer	3%	Enhance water resistance
Foaming agent	FER=12%	Reduce the torque of the knife disk

4.2. Synchronous grouting process

(1) Optimization of Slurry Ratios

The optimized slurry ratios for synchronous grouting are presented in Table 3. The mix design follows principles for rapid-setting grouts in shield tunneling^[14].

Table 3. Slurry ratio optimization

Component	Scale	Performance index
42.5 Cement	6%	Initial coagulation time is less than 20 s
Sodium silicate	3%	3D intensity is greater than or equal to 5 MPa
Silica micro powder	FER=12%	Flow rate is greater than or equal to 260 mm

(2) Grabbing Parameter Control

The key parameters controlled during the grouting process are listed in Table 4.

Table 4. Grouting parameter control

Parameter	Set value
Grouting volume	1.8 times theoretical gap (single ring 1.2 m ³)
Grouting pressure	0.35 ~ 0.45 MPa (arch priority)
Grouting sequence	The dome is filled in the last 30 s after the shield tail

4.3. Dynamic control of articulated system

4.3.1 Mechanical structure and working principle of the articulated system

The ZTE6100 shield machine adopts a passive hinge system, which consists of 16 sets of hydraulic cylinders distributed symmetrically around the circumference with a maximum stroke difference of 150mm and a maximum opening Angle of 1.3°. Its core function is to adjust the bending Angle of the shield body through the stroke difference of the hydraulic cylinder to adapt to small radius curve excavation.

(1) Cylinder layout:

The spacing of each group of cylinders is 22.5°, the thrust range is 0 ~ 250kN, and the magnetostrictive displacement sensor has an accuracy of ±0.1 mm.

(2) Mechanical transmission path:

The thrust of the blade disk → the front shield → the articulated cylinder → the tail shield → the segment, forming a flexible connection system;

(3) Dynamic control target:

Through real-time adjustment of the cylinder travel difference, the bending curvature of the shield body is controlled to match the design axis.

4.3.2 Trip difference distribution algorithm

Calculation of travel difference of each ring hinge cylinder by this formula:

$$\Delta S = \frac{L_s \times \theta}{2} \quad (6)$$

In the formula: shield length = 8.8m, turning Angle $\theta = 1.3^\circ$, so $\Delta S = 100\text{mm}$ (less than 150mm allowable value). The adjustment travel difference of each ring of the articulated cylinder calculated by this formula is $\Delta S = 100\text{mm}$.

The adjustment is performed in three stages, with each adjustment limited to less than 30mm to avoid sudden disturbances.

4.3.3 Hierarchical regulation strategy

In order to realize stable correction and avoid sudden stress, a three-level control strategy is adopted:

(1) Coarse adjustment stage (5 rings):

Coarse adjustment stage (5 rings): the travel difference is distributed according to the theoretical value of 100mm, and the adjustment amount of each ring is less than or equal to 30mm;

(2) Fine adjustment stage (5 rings):

Fine adjustment stage (5 rings): the adjustment amount is less than 15mm/ring based on laser target data;

(3) Fine-tuning stage (10):

The adjustment amount is less than 5mm/ ring, and the compensation is made in conjunction with the over-excavation knife.

4.4. Key technologies of cutting line receiving construction

During the cutting line reception process, the actual excavation trajectory of the shield machine needs to be optimally fitted to the design axis using the least squares method. Let the design axis be a spatial curve L_d , and the actual trajectory of the shield machine be a set of discrete points $P_i(x_i, y_i, z_i)$. The fitting objective is to find a straight line L_f (cutting line) that optimally matches L_d in the reception section while satisfying the geometric constraints of the portal.

4.4.1 Mathematical model of axis fitting

(1) Design axis parameterization

The parametric equation of axis L_d in the receiving section is:

$$\begin{cases} x = x_0 + R(1 - \cos\theta) \\ y = y_0 + R\sin\theta \\ z = z_0 + k\theta \end{cases} \quad (7)$$

among: $R=250\text{m}$ is the radius of the plane curve; $K=2.2\text{‰}$ is the vertical slope; θ is the central Angle (radian).

(2) The set of discrete points in the actual trajectory

The tunnel boring machine guidance system collects the center coordinates $P_i(x_i, y_i, z_i)$ of the incision in real time, with a sampling interval of 1 ring (1.2m).

(3) The tangent line is defined by the objective function of the least squares fitting

The equation of L_f is:

$$\frac{x-a}{l} = \frac{y-b}{m} = \frac{z-c}{n} \quad (8)$$

The goal is to minimize the sum of the squared distances between the actual points and the cuts:

$$\min \sum \left[\frac{(x_i-a)m - (y_i-b)l}{\sqrt{l^2+m^2}} \right]^2 + \left[\frac{(z_i-c) - nt_i}{\sqrt{1+n^2}} \right]^2 \quad (9)$$

Where t_i is the parameter, (a, b, c) is the starting point of the tangent line, and (l, m, n) is the direction vector.

4.4.2 Calculation of cutting line Angle

The spatial Angle θ between the tangent L_f and the design axis L_d at the receiving end is obtained by fitting, and the calculation steps are as follows:

(1) Extract tangent vector

The tangent vector d of the design axis at the \vec{T} receiving end $\theta = \theta_{end}$ is:

$$d = (\vec{T}R\sin\theta, R\cos\theta, k) \quad (10)$$

The proposed tangent direction vector $\vec{T}_f = (l, m, n)$.

(2) Angle formula

The space Angle θ is calculated by vector dot product:

$$\cos\theta = \frac{\vec{T}_d \cdot \vec{T}_f}{|\vec{T}_d| |\vec{T}_f|} \quad (11)$$

Substituting the engineering parameters $R=250\text{m}$ and $k=2.2\text{‰}$, we get $\theta=0.85^\circ \pm 0.2^\circ$ after fitting.

4.4.3 Calculation of cutting line Angle

According to the fitting results, the shield attitude adjustment amount is calculated:

(1) Correction of lateral deviation

The relationship between the lateral deviation Δy of the receiving end and the difference ΔS between the hinge cylinder stroke:

$$\Delta S = \frac{\Delta y \cdot L_{shield}}{R} \quad (12)$$

In the formula, $L_{shield}=8.8\text{m}$, $R=250\text{m}$, when $\Delta y=25\text{mm}$, $\Delta S=8.8\text{mm}$.

(2) Vertical slope compensation

The vertical deviation Δz is achieved by adjusting the pressure of the partitioned cylinder. The pressure difference ΔP is:

$$\Delta P = \frac{\Delta z \cdot \gamma_w}{\tan \alpha} \quad (13)$$

Where $\alpha=2.2\text{‰}$ and $\gamma_w=10\text{kN/m}^3$, when $\Delta z=10\text{mm}$, $\Delta P=0.045\text{MPa}$.

4.4.4 Calculation examples

Take the 350th ring (10 rings away from the receiving end) as an example. The relevant calculation parameters are provided in Table 5.

Table 5. Calculation parameters

Parameter	Design value	Measured value	Propose a tangent value
X coordinate (m)	1250.36	1250.32	1250.34
Y coordinate (m)	568.17	568.21	568.19
Z coordinate (m)	- 12.45 (elevation)	- 12.47	- 12.46

Through the least square fitting, we get the equation of the tangent line:

$$\frac{x-1250.34}{0.999} = \frac{y-568.19}{0.031} = \frac{z+12.46}{0.0022} \quad (14)$$

The calculated tangent angle $\theta=0.83^\circ$ requires adjustment of the travel difference $\Delta S=7.2\text{mm}$ of the articulated cylinder.

5. Monitoring and effect analysis

5.1. Monitoring and effect analysis

(1) Surface subsidence monitoring

Static level meters are set up every 5m along the tunnel axis, and monitoring sections are set up every 10m in the transverse direction. The data update frequency is 2 times/day.

(2) Segment attitude monitoring

The measurement was conducted after the assembly of each ring using a Leica TS60 total station (accuracy: $\pm 1''$) and a MEMS (Micro-Electro-Mechanical Systems) tilt sensor (measuring range: $\pm 30^\circ$ in pitch, accuracy: 0.001° , with excellent temperature compensation capability)^[3].

The real-time position of the shield machine was derived through a combined "total station + tilt sensor" scheme, which utilized inertial navigation based on the tilt sensor and odometer (measuring propulsion distance) between two total station measurements.

5.2. Implementation effect

The implementation effect of the key control metrics is summarized in Table 6.

Table 6. Implementation effect

Metric	Control objective	Measured maximum value	Pass rate
Surface subsidence	≤ 15 mm	12.5 mm	100%
Segment misalignment	≤ 3 mm	2.5 mm	100%
Trench shield attitude deviation	$\leq \pm 30$ mm	+ 25 mm/- 23 mm	100%
Amount of leakage from the portal	≤ 0.1 L/min	0.05 L/min	100%

6. Conclusion

In the critical stages of shield tunneling construction, a phased adjustment strategy is implemented through meticulously designed and precisely operated articulated systems, strictly controlling the adjustment range for each segment ($\Delta S \leq 30$ mm per segment). This meticulous approach, akin to a craftsman's careful refinement of every detail, ensures that the shield machine maintains good posture and stability during its advancement along small-radius curves.

The dynamic compensation of the over-excavation cutter plays a crucial role, with the set compensation amount reaching 50mm. This is like equipping the shield machine with a pair of flexible "hands and feet," capable of promptly adjusting and supplementing the shield tail clearance according to changes in the strata and actual construction needs, ensuring a tight connection between segments. This achieves precise reception under 250m small-radius conditions. The realization of such precise reception not only provides a solid foundation for subsequent tunnel construction but also highlights the outstanding capabilities of the construction team in both technology and management^[11].

The rapid-setting dual-liquid grouting technology, with its unique advantage of strictly controlling the initial setting time to less than 20 seconds, combined with the double-sealing measures at the tunnel portal, effectively constructs a robust waterproof barrier for the

tunnel. The rapid-setting dual-liquid grouting quickly solidifies into a high-strength bond, effectively preventing groundwater infiltration. This not only ensures the dryness inside the tunnel and the safety of the construction environment but also provides a reliable guarantee for the long-term stable operation of the tunnel.

Through careful calculation, the cutting line receiving technology can accurately control the deviation of the axis within the allowable range. This enables the construction team to adjust the construction direction in time according to the operation trajectory of the shield machine, and ensure that the axis accuracy of the tunnel meets the design requirements.

References

1. Peck R B. Deep excavations and tunneling in soft ground//Proc. 7th ICSMFE. 1969.
2. He Chuan, Zeng Dongyang. Mechanical behavior and countermeasures of shield tunnel construction [M]. Science Press, 2010
3. GB 50446-2017, Code for Construction and Acceptance of Shield Tunneling.
4. Zhao Xiushao Wei Duqiang Yu Wanyou. et al. Impact Analysis of Small Curve Radius Shield Tunnel crossing Existing Tunnel [J]. Chinese Journal of Underground Space and Engineering, 2021; 17 (4): 1216-24.
5. Tani K. Steering control of shield tunneling machine in curved sections [J]. Tunnelling and Underground Space Technology, 2018, 72: 153-165.
6. ZHANG Peng, LI Wei, ZHAO Yong, et al. Study on Ground Settlement Control Technology for Shallow Overburden Tunnels in Guangzhou Metro by Compartmentalized Grouting. Modern Tunneling Technology, 2021, 58 (3): 236-243.
7. SHI Qing-hua DENG Yang Ground Disturbance Analysis of Extremely Small Radius and Ultra Large Diameter Shield Tunneling in Stratified Strata [J]. Science Technology and Engineering, 2025, 25 (08): 3463-3472.
8. XU Ping XI Danhui GAO Qiang Ground Deformation Law Induced by Shield Tunnelling under Large Gradient and Small Radius Conditions [J]. Modern Tunnelling Technology, 2024, 61 (S1): 516-523.
9. Xu Qianwei He Xiang Gong Zhenyu et al. Research on the Micro-disturbance Construction and Tunneling Parameters Control of Earth Pressure Balance Shield Machine in Sandy Cobble Stratum [J]. Journal of Railway Engineering Society, 2020, 37 (09): 72-77
10. Zhang Lili Shan Lin Guo Fei et al. Study on Safety Control of Adjacent Construction of Overlapped Shield Tunnel with a Small Radius of Curve [J]. Modern Tunnelling Technology, 2022, 59 (03): 254-264.
11. Huang Da-wei Xu Chang-jie Luo Wen jun et al. Design and application of modular step-by-step

- scale model test for earth pressure balance shield construction [J]. *Journal of Traffic and Transportation Engineering*, 2023, 23 (04): 248-257.
12. Zhong Xiaochun He Chunhao Li Yongyun et al. Study on Surface Uplift Caused by Construction of Shallow-Buried Soil Rectangular Pipe Jacking at Subway Entrance and Exit [J]. *Journal of Southwest Jiaotong University*, 2023, 58 (03): 603-612.
 13. Zhang Xueqiao. Key Technology for Construction of Small Radius Curve Shield Tunnel Undercrossing Highway Tunnel in Waterrich Sandy Soft Soil Layer [J]. *Urban Mass Transit*, 2020, 23 (12): 128-132.
 14. Zhang Jian, Jin Junjie Feng Tugen et al. Optimization of mixture ratio of muck grout by earth pressure balance shield machine [J]. *Chinese Journal of Geotechnical Engineering*, 2023, 45 (04): 748-757.
 15. Zhang Zhiguo, Chen Jie, Zhu Zhengguo, et al. Analysis of ground settlement induced by small radius curve tunnel excavation considering shield articulation effect [J]. *Rock and Soil Mechanics*, 2023, 44 (4): 1165-1178.