Research on the Rapid Maintenance Spatial System of Shield Machine Based on Auxiliary Piles

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Abstract. In the process of tunneling through conglomerate formations containing abundant water and pebbles, disc cutter wear is an unavoidable issue for shield tunneling. To effectively alleviate this problem, a constant-pressure cutter replacement technique utilizing hollow piles tailored for water-rich sandy conglomerate formations is proposed. Simultaneously, a rapid maintenance spatial system is established through the use of hollow and isolation piles. This cutter replacement technique ensures safety, shortens the cutter replacement period, and offers flexibility in application. The rapid maintenance spatial system provides a spacious construction area, reduces construction risks, and promotes personnel well-being, demonstrating significant potential for widespread adoption.

Keywords: Prefabricated Construction; Water-Rich Sandy Conglomerate; Auxiliary Piles; Rapid Maintenance Spatial System; Constant-pressure cutter replacement technique

1 Introduction

Blade wear is an inevitable issue in shield tunneling operations. In the case of the Water-Rich Sandy Conglomerate, the unique characteristics [1] of the soil make blade maintenance operations face greater challenges.Compared with clayey stratum, the mechanical properties of the sandy stratum are more complex and less stable: (1)Strain localization.Strain localization on a shear band induced by post-peak softening is one of the most important deformation and strength characteristics [2] of sand, as verified by triaxial tests [3] .(2)Seepage mechanism.Model tests in a centrifuge and three-dimensional stress-pore pressure coupled numerical simulation [4] have shown that seepage in sandy soil is one of the most important factors leading to ground instability. Additionally, the water content in sandy soil has a significant effect on both the profile and magnitude of ground surface settlement [5] .

The successful operation of a space system of rapid maintenance relies on efficient maintenance and upgrades to ensure its continuous performance. One of the key features of such a system is its rapid maintenance capability, enabling quick repairs or

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replacements of critical components when necessary, thus minimizing downtime to the maximum extent. This contributes to enhancing production efficiency and the reliability of the system. Common repair works in shield tunneling [6, 7] are classified into two categories: non-pressurized and pressurized, depending on the pressure. Non-pressurized repairs [8, 9] primarily involve dewatering and stratum reinforcement to create a space directly accessible to the cutterhead for repair, usually performed in conjunction with cutter replacement. Common reinforcement methods include vertical shafts [10], isolation piles [11], hollow piles [12], sheet piling [13], etc., conducted in front of the cutterhead to ensure the water level is below it. These methods require surface operations, have certain environmental requirements for ground construction, and come with significant limitations. Additionally, they have long preparation times and can impact construction progress. In conglomerate formations, significant thrust fluctuations and ground settlements are likely to occur during shutdown periods.

High-pressure repairs [14] involve creating a high-pressure environment in the space in front of the stopped cutterhead, where maintenance personnel can conduct hot repairs. This method is suitable for situations where it is not feasible to excavate vertical shafts or reinforce the ground due to environmental constraints. It serves as an effective complement to non-pressurized repairs, but it comes with greater technical difficulty and has fewer documented applications. Currently, this method is used in Beijing for addressing damaged cutterheads in tunneling.

For conglomerate formations, effective auxiliary measures must be selected to complement shield cutter replacement and cutterhead maintenance to meet production demands. The construction of Chengdu Metro Line 17 utilizes a combination of hollow piles and isolation piles for auxiliary reinforcement during the breakthrough process, rapidly establishing a stable and spacious breakthrough environment. This construction technique [15] is an extension of the conventional non-pressurized cutter replacement technique based on vertical shaft construction, effectively reducing the construction period and occupying less surface space.

2 Rapid Maintenance Spatial System for Shield Tunneling Machine Based on Auxiliary Piles

2.1 Wear Analysis of Shield Tunneling Equipment in Conglomerate Formations

As shown in Fig. 1, in the shield tunneling construction process in water-rich conglomerate formations, geological conditions directly or indirectly impact the equipment, leading to the following common issues: 1) Severe ground settlement with noticeably delayed settlement; 2) Severe wear of tools and cutterhead; 3) Severe wear of the screw conveyor; 4) Screw conveyor jamming; 5) Surge of the screw conveyor; 6) Complex preparation for breakthrough cutter replacement and other inspection tasks; 7) Cutterhead jamming, etc.

Analyzing the aforementioned issues, due to geological factors, the contact surface between the cutterhead and the sandy soil ahead of it experiences significant friction under the enormous thrust of the shield tunneling machine. As the cutterhead rotates, it generates substantial friction. Moreover, the cutterhead requires sufficient crushing capacity to deal with high-strength conglomerate stones. The impact force on the cutterhead and tools is significant, inevitably resulting in severe wear of tools and the cutterhead. Additionally, the degree of wear increases with the larger particle size and density of the gravel in the soil layer. It is also closely related to the material and installation position of the tools themselves.

The outer edge of the cutterhead is more prone to wear due to cutting through the soil. This situation becomes more severe after the wear of the surrounding scrapers and leading cutters. The outer edge plate and the gap in the front shield tend to trap conglomerate stones, leading to continuous wear of the outer edge plate. When encountering oversized conglomerate stones, higher torque and thrust are needed, causing more frequent fluctuations in thrust and torque, which can easily lead to ground uplift or settlement. The composition of the spoils mainly consists of conglomerate stones, gravel, and sand, leading to significant wear on the screw conveyor. The accumulation of spoils inside the screw conveyor can result in the screw conveyor getting “jammed.”

(a) Roller Wear (b) Screw Conveyor Wear (c) Cutterhead Wear

Fig. 1. Shield Tunneling Equipment Wear Diagram

2.2 Hollow Pile + Isolation Pile Assisted Breakthrough

The construction of the hollow pile-assisted breakthrough mainly includes three aspects: hollow pile installation, dewatering construction, and breakthrough inspection, as illustrated in Figure 2. The construction points for pile foundations are determined through measurement and layout. Isolation piles are constructed using rotary drilling, reinforcing the face of the cutterhead. They are arranged on both sides from the centerline of the tunnel, with the pile bottoms extending at least 1 meter below the tunnel bottom. The schematic diagram of the Hollow Pile + Isolation Pile is shown in Figure 3.

The method for creating holes for hollow piles is the same as that for isolation piles. During the segment crossing of the shield tunneling machine, glass fiber bars of corresponding diameters are used in the reinforcement cage, connected with threaded steel bars using clasps. After piling, an auger is employed to excavate, ensuring that the center of the drilling rod aligns with the center of the already installed pile, thereby guaranteeing the concrete wall thickness of the hollow pile.

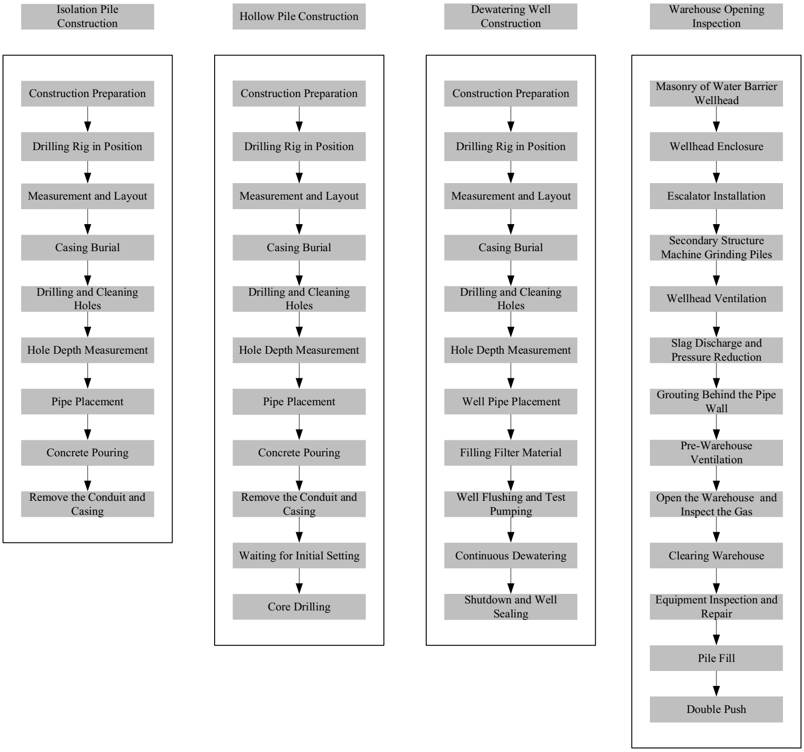
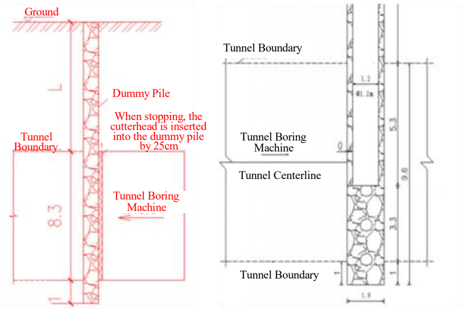


Fig. 2. Flowchart for Hollow Pile + Isolation Pile Assisted Breakthrough

(a) Diagram of Hollow Pile Reinforcement Cage (b) Hollow Pile Drilling



(c) Isolation Pile (d) Hollow Pile

Fig. 3. Hollow Pile + Isolation Pile Schematic Diagram

At the same time as the construction of the isolation piles, construct dewatering wells and set up drainage routes. After completing the construction of the dewatering wells, initiate the dewatering process and monitor it to ensure it meets the requirements for breakthrough inspection

2.3 Hollow Pile Assisted Breakthrough Technique

After the construction of the hollow and isolation piles is completed, the shield tunneling machine advances to the designated position for pile grinding. The grinding continues until the cutterhead is positioned within the hollow part of the hollow pile. This hollow portion serves as the operational space for activities such as cutter replacement and repairs after breakthrough. At this point, the conditions for a hollow pile-assisted breakthrough are met. The hollow pile-assisted breakthrough technique has specific requirements for details like pile placement. To ensure the effectiveness of hollow pile construction, we should pay attention to the following matters during the construction process, as shown in Fig. 4.

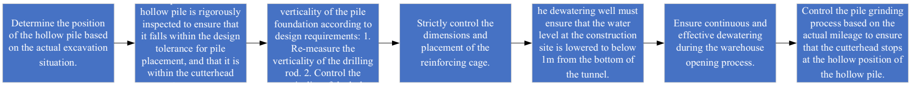


Fig. 4. Construction Precautions Diagram

2.4 Analysis of Hollow Pile Strength Calculation

At the optimized points of the cutterhead on the shield tunneling machine, a support system consisting of hollow piles and plain concrete piles is employed, as shown in Fig. 5. There are three hollow piles and four plain concrete piles. The outer diameter of the hollow pile is 1.8 meters, with an inner diameter of 1.6 meters, providing the optimized working space for the shield tunneling cutterhead. The diameter of the plain concrete piles is 1.2 meters. The calculation and analysis results for annular piles, as well as the section parameters of the annular pile, are respectively shown in Figure 6 and Figure 7.

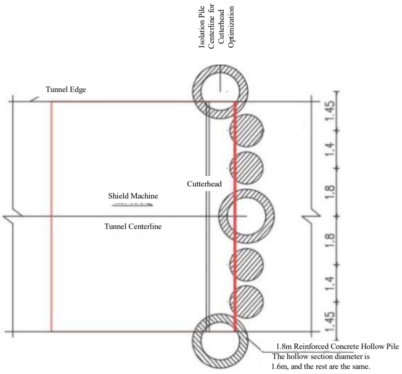
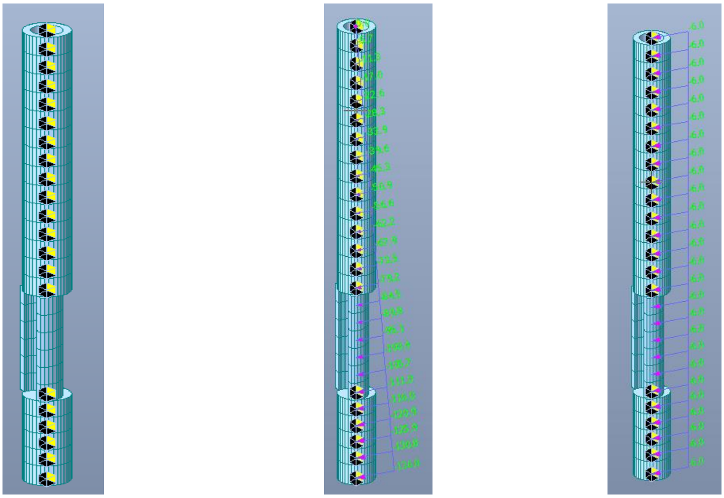


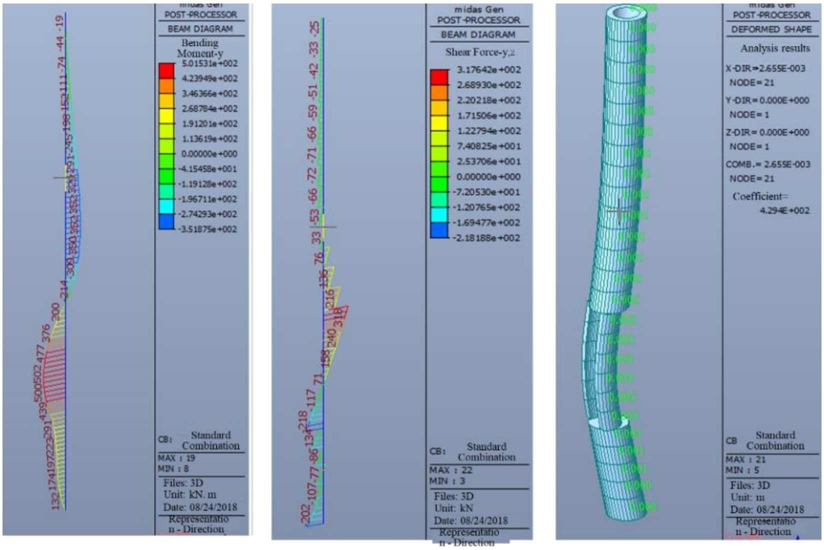
Fig. 5. Layout Plan of Isolation Piles

The soil density is assumed to be 20 kN/m³, the lateral pressure coefficient is taken as 0.3, and the horizontal base coefficient is set at 90 MPa. The soil load on the pile top is 0 kN/m², while the soil load at the pile base is calculated as 22.8 × 20 × 0.3 = 136.8 kN/m². An additional overload of 20 kPa is considered at the ground level. The horizontal live load is calculated as 20 × 0.3 = 6 kN/m²



(a)Finite Element Model (b) Soil Load (c)Live Load

Fig. 6. Calculation and Analysis Model for Annular Piles

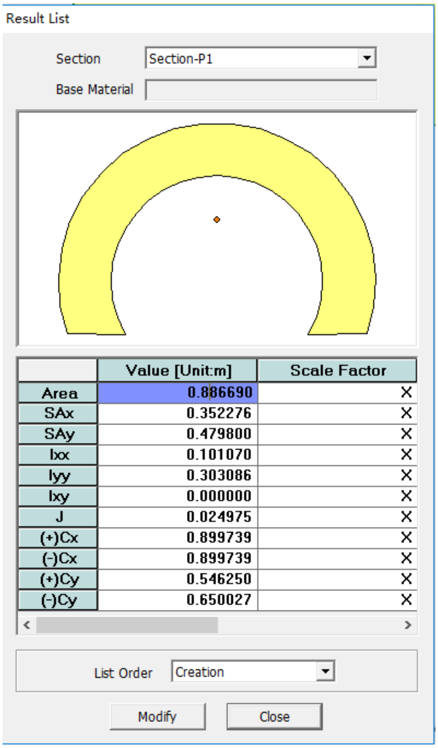


(a) Annular Pile Bending Moment / kN·m (b) Annular Pile Shear Force / kN (c) Annular Pile

Fig. 7. Calculation and Analysis Results for Annular Piles

The calculation results show that the maximum bending moment at the cutterhead position of the shield tunneling machine is 501 kN·m, and the maximum shear force is 318 kN. The maximum deformation of the annular pile is 2.6 mm.

The allowable internal force check for the annular pile section parameters is shown in Figure 8 (post-pile grinding position):



Section: Section-P1

Base Material:

	Value [Unit:m]	Scale Factor
Area	0.886690	×
SAx	0.352276	×
SAy	0.479800	×
Ixx	0.101070	×
Iyy	0.303086	×
Ixy	0.000000	×
J	0.024975	×
(+)Cx	0.899739	×
(-)Cx	0.899739	×
(+)Cy	0.546250	×
(-)Cy	0.650027	×

List Order: Creation

Fig. 8. Annular Pile Section Parameters

Area $\mathrm{A} = 1.75\mathrm{m}^2$; Inertia Moment $\mathrm{I_{xx}} = 0.44\mathrm{m}^4$, $\mathrm{I_{yy}} = 0.46\mathrm{m}^4, \mathrm{y_{min}} = 0.409\mathrm{m}$

The maximum bending moment can be meted as follows:

$$\sigma = \frac{M \cdot y}{I_{xx}} = \frac{501 \times 0.65}{0.010107} = 3.25MPa < [\sigma] = 9.6MPa \quad (1)$$

The maximum shear force verification is satisfied as follows:

$$\tau = \frac{F}{A} = \frac{318}{0.88699} = 0.36MPa < [\tau] = 1.1MPa \quad (2)$$

According to the calculation results, using a diameter of 1.8 meters with a central aperture of 1.2 meters, the annular piles extending to the axis of the shield cutterhead meet the stress requirements.

3 Analysis of the Application Effect of Shield Tunneling Equipment Rapid Maintenance Technology

The application of hollow pile-assisted breakthrough technology can provide a favorable operating environment for breakthrough construction, facilitating construction operations. However, it requires sufficient ground construction space and completion of related preparatory work. In order to better analyze its application effect, we planned to conduct an effectiveness comparison using four methods: hollow pile-assisted breakthrough, plain pile-assisted breakthrough, breakthrough under pressure, and non-reinforced breakthrough under normal pressure, as shown in Table 1.

Table 1. Effectiveness Comparison of Conglomerate Stone-Assisted Breakthrough Techniques

Construction Method	Hollow Pile	Plain Pile	Pressure Entry	Unreinforced Entry Under Normal Pressure
Site Preparation	Preparations include early site enclosure and traffic clearance.	Preparations include early site enclosure and traffic clearance.	Early safety enclosure of the site is conducted.	Early safety enclosure of the site is conducted.
Dewatering Preparation	Dewatering wells are set up to ensure effective dewatering.	Dewatering wells are set up to ensure effective dewatering.	Dewatering is not required.	Dewatering wells are set up to ensure effective dewatering.
Personnel Deployment (Excluding Dewatering)	Planned construction personnel: 15	Planned construction personnel: 15	Planned construction personnel: 5	Planned construction personnel: 2
Equipment Preparation	Rotary drilling rig *1, crane *1, forklift *1, loader *1, dump truck *1, emergency water pump *1	Rotary drilling rig *1, crane *1, forklift *1, loader *1, dump truck *1, emergency water pump *1	Mud film prefabrication equipment *1 set	/
Material Preparation	Concrete, reinforcing bars, glass fiber bars	Concrete, reinforcing bars, glass fiber bars	Bentonite, soda ash, water	/
Duration Comparison (With Auxiliary Measures)	Estimated preparation time: 18 days	Estimated preparation time: 18 days	Estimated preparation time: 2 days	Estimated preparation time: 3 days
Duration Comparison (With Breakthrough Construction)	Estimated preparation time: 7 days	Estimated preparation time: 10 days	Estimated preparation time: 18 days	Estimated preparation time: 20 days

Through comparative analysis, it is found that the economic cost of the hollow pile-assisted breakthrough technology is higher than that of the other methods. However, it has a shorter construction period and, combined with its user-friendliness for construction personnel, it possesses unique value.

4 Conclusions

Although the hollow pile-assisted breakthrough technology requires advanced preparations for auxiliary measures and has a higher economic cost compared to other methods, it possesses unique advantages:

(1) It can be carried out concurrently with the shield tunneling process without affecting the overall construction schedule.

(2) It enhances the efficiency of maintenance personnel. Providing spacious construction space facilitates the operations of maintenance personnel.

(3) It offers higher safety levels. It ensures effective ventilation, reducing the risk of hot work construction and promoting the health of maintenance personnel. The tight integration of hollow piles and isolation piles with the shield tunneling machine not only guarantees the stability of the soil, but also provides a means to secure the cutterhead, reducing risks during in-chamber construction.

The use of hollow pile and isolation pile-assisted breakthrough technology in the conglomerate stone stratum demonstrates significant advantages. The combined effects of enhanced stratum stability, spacious construction space, and convenient operation for construction personnel after stratum reinforcement have led to a substantial increase in construction progress and a noticeable reduction in construction risks. In terms of safety and operability, this rapid maintenance space system holds strong potential for widespread application.

References

1. McLachlan, A., Turner, I. (1994). The interstitial environment of sandy beaches. Marine Ecology, 15(3-4), 177-212.
2. Chu, J., Lo, S.C.R., Lee, I.K. (1996). Strain softening and shear band formation of sand in multi-axial testing. Geotechnique, 46(1), 63-82.
3. Yamada, Y., Ishihara, K. (1979). Anisotropic deformation characteristics of sand under three dimensional stress conditions. Soils and Foundations, 19(2), 79-94.
4. Lee, C.J., Chiang, K.H., Kuo, C.M. (2004) Ground movement and tunnel stability when tunnelling in sandy ground. J. Chin.Inst. Eng., 27(7), 1021-1032.
5. Chungsik, Y., Lee, Y.J., Kim, S.H., Kim, H.T. (2012). Tunnelling-induced ground settlements in a groundwater drawdown environment – A case history. Tunn. Undergr. Space Technol, 29 (2012) 69-77.
6. Yu, B., & Ji, Y. (2018). Current Status and Risk Control of Shield Tunnel Breakthrough Technology in China. Tunnel Construction, 38(04), 683-693.
7. Zhang, W. (2022). Research on Prediction of Cutter Wear and Replacement Decision in Large Diameter Shield Tunneling through Composite Strata. Huazhong University of Science and Technology.

8. Ai, L. (2022). Research on Reinforcement Technology of Shield Tunnel Opening under Constant Pressure Based on Freezing Method. Guangdong Civil Engineering and Construction, 29(10), 95-98.
9. Lei, Z. (2021). Shield Tunnel Body Reinforcement Opening Technology in Soft Soil Stratum of Subway Tunnel. Engineering Machinery and Maintenance, 2021(05), 186-189.
10. Ma, J. (2022). Study on the Influence of Foundation Pit Excavation on Structural Stress and Deformation of Shield Tunnel Shaft. Anhui University of Science and Technology.
11. Wei, G., Mu, Z., Qi, Y., et al. (2023). Research on Deformation Protection of Adjacent Shield Tunnel in Deep Excavation Considering Ground Loss with Isolation Piles. Chinese Journal of Geotechnical Engineering, 1-11.
12. Zhang, H. (2021). Research on Opening and Large Opening Cutterhead Repair Technology under Constant Pressure with Hollow Pile Method. Engineering Construction and Design, 2021(07), 160-161+168.
13. Xu, Y., Yang, Z., & Lv, Z. (2022). Study on the Influence of Double-Row Pile Support Deep Excavation on the Adjacent Existing Subway Shield Tunnel Section. In Proceedings of the 2022 National Engineering Construction Industry Construction Technology Exchange Conference (Vol. 1, p. 5). Construction Technology (Bilingual) Magazine Press.
14. Lamont, D., Slocombe, R. (2019). Underground construction: working in high pressure compressed air. In Proceedings of the Institution of Civil Engineers-Civil Engineering (Vol. 173, No. 5, pp. 17-23). Thomas Telford Ltd.
15. Wang, Y., Zhou, Y., Hu, G., et al. (2019). Constant Pressure Cutter Replacement Technology for Shield Tunnel in Conglomerate Stratum with Abundant Water and Sand. Municipal Engineering Technology, 37(06), 155-158.