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Muck discharge technology and application through slurry circulation system on the EPB TBM

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ABSTRACT: The earth pressure balance tunnel boring machine (EPB TBM) is mainly suitable to cohesive strata, sandy strata and gravel strata with a small amount of groundwater and small permeability coefficient. However, it faces many challenges when tunnelling through water-rich sandy strata with high water pressure, large boulders and high permeability coefficient. The Hamburg's district heating tunnel passes under the Elbe River and mainly goes through gravel, sand, clay, sedimentary limestone strata with local water-rich sandy strata, bringing high construction risks. Based on this project, this paper introduces an EPB TBM innovatively equipped with the slurry circulation system, which can successfully address the tunnelling and muck discharging challenges of the EPB TBM in water-rich sandy strata. It provides a valuable reference for the EPB TBM design in water-rich strata when passing under rivers.

1 INTRODUCTION

With the continuous innovation of the TBM technology, the TBM can be used to bore different types of tunnels, such as metro tunnels, railway tunnels, highway tunnels, municipal tunnels, water diversion tunnels and mine tunnels. Compared with the traditional tunnelling methods, the TBM method can greatly improve the construction efficiency.

In order to adapt to the complex and varied strata and the specific construction requirements, the TBM can be divided into various types including the EPB TBM, slurry TBM, hard rock TBM and multi-mode TBM. Given that the strata are complex and varied strata in China and abroad, a single-mode TBM has relatively higher construction risks while a multi-mode TBM is not cost-effective. For example, the EPB TBM has a major construction risk of muck and water inrush when tunnelling through water-rich sand layer with high water pressure, large boulders and high permeability. Therefore, there is an urgent need to explore a new muck discharge method.

2 PROJECT OVERVIEW

The Hamburg's district heating tunnel in Germany is highly symbolic. With the construction of the TBM method, the tunnel starts from Jachtweg on the south side of the Elbe River, passes beneath the Elbe and finally ends at the Hindenburgpark on the north side. The length is approximately 1,165m with the overburden ranging from 10m to 35m.

This project adopted an EPB TBM with an excavation diameter of 4570mm. The segment ring was 4300 mm in outer diameter, 3700mm in inner diameter and 1200mm in width, which could precisely meet the project requirements. During tunnelling, the EPB TBM went through gravel, sand, sandy soil, clay, sedimentary limestone and other strata. These strata had significant differences in permeability coefficients, ranging from 5×10^{-3}m/s to 1×10^{-12}m/s. The designed turning radius was 300m and the actual turning radius reached 1,000m during construction, demonstrating the excellent adaptability of the EPB TBM. The geological profile is shown in Figure 1.

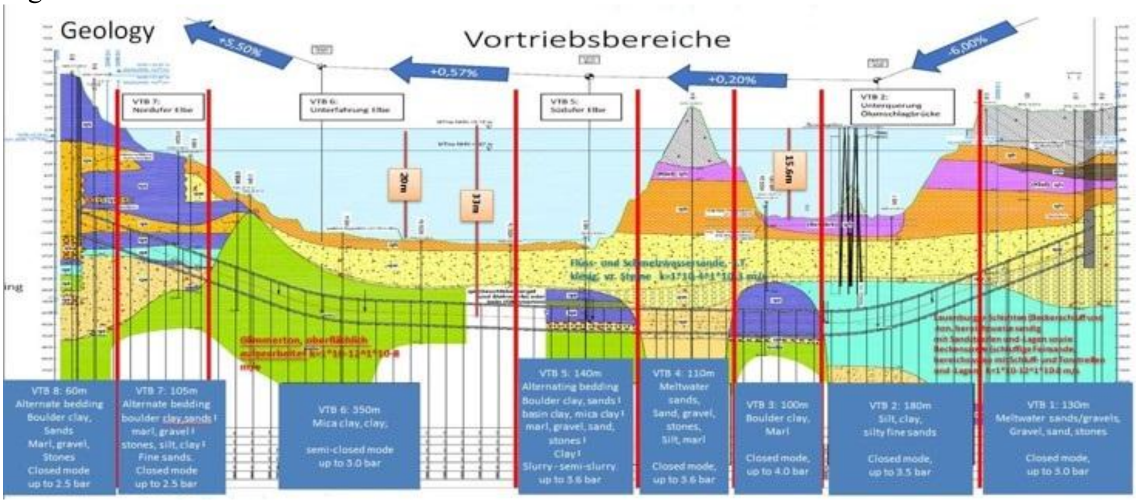

Figure 1. Geological profile of Hamburg's district heating tunnel

3 MUCK DISCHARGE DESIGN THROUGH SLURRY CIRCULATION SYSTEM ON THE EPB TBM

3.1 Principle design of slurry circulation system for muck discharge

The EPB TBM for this project adopts the slurry circulation system to discharge muck. The slurryfier box is connected behind the screw conveyor, followed by a slurry discharge pump. When the muck is discharged by the slurry circulation system, the discharge speed and excavation chamber pressure are controlled by the opening/closing of the discharge gate of the screw conveyor. But at this time, considering the unstable pressure control in the excavation chamber, the AFS system is connected with the slurry feeding pipe to inject the slurry into the excavation chamber by means of pressure compensation, which can realize the control of the excavation chamber pressure and the dilution of the muck in the excavation chamber. Moreover, the foam system and water system can also be used to inject the slurry to the excavation chamber and after the complete mixing with the cutter head, the muck in the excavation chamber is fully diluted. The design principle is shown in Figure 1. After conditioning in the excavation chamber, the muck density is stably maintained between 1.6 and 1.8 t/m³, significantly improving its flowability and transportability. Following further dilution in the slurryfier box, the muck density is reduced to 1.1–1.3 t/m³, making it more suitable for transportation by the slurry discharge pump to the slurry treatment plant. At the slurry treatment plant, the muck and slurry are separated, and the recovered feeding slurry maintains a density of 1.0–1.1 t/m³, which can also meet the requirements for reuse.

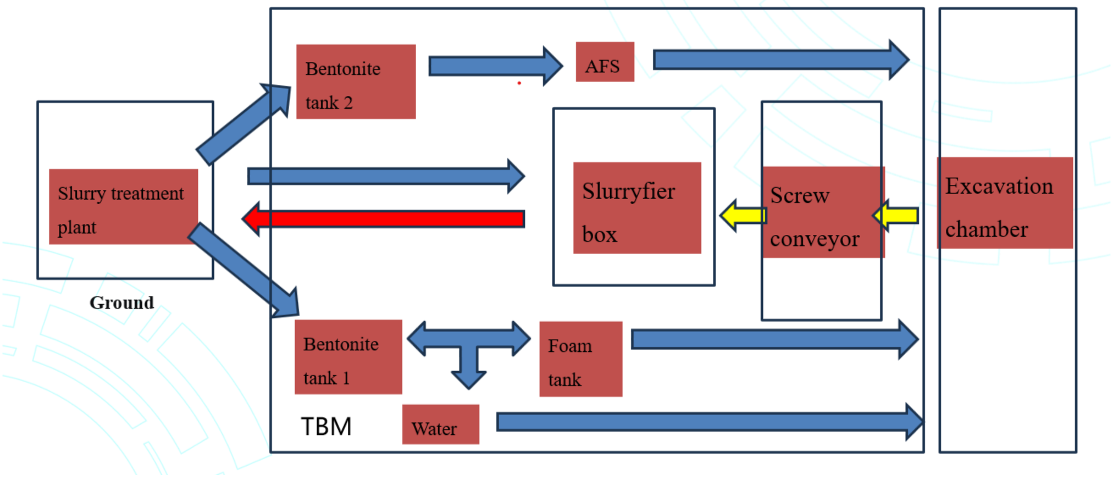

Figure 2. Design principle of the slurry circulation system for muck discharge

3.2 Parameter design of slurry circulation system for muck discharge

One feeding slurry pump is installed on the ground at the launch shaft, with a capacity of 400 m^3/h. It delivers the slurry, which has been treated at the slurry treatment plant, to the slurryfier box on the TBM, where it is used to condition and dilute the muck.One discharge slurry pump is installed on a temporary gantry at the rear of the main machine, with a capacity of 400 m^3/h. It pumps the muck from the slurryfier box out of the tunnel to the slurry treatment plant. The slurry feeding and discharge pumps are shown in Figure 3.

Figure 3. Slurry feeding and discharge pumps

The slurryfier box is equipped with a built-in jaw crusher and is installed on a temporary gantry at the rear of the main machine. Its front end is connected to the discharge gate of the screw conveyor, while the rear end is connected to the slurry discharge pump. The crusher has a crushing particle size of Φ250mm. The internal grid of the slurryfier box allows particles up to Φ70mm to pass through. The slurryfier box is fitted with four slurry inlet ports with a diameter of Φ100mm and one slurry outlet port with a diameter of Φ200mm. The overall dimensions of the slurryfier box are 2500 × 1300 × 1080 mm, as shown in Figure 4.

Figure 4. Slurryfier box

The slurry treatment plant adopts a three-stage filtration system and is installed on the ground at the launch shaft. Based on the capacity of the slurry circulation system, the treatment capacity of the plant is configured at 450 m^3/h, as shown in Figure 5.

Figure 5. Slurry treatment plant

4 PERFORMANCE

The EPB TBM was launched on November 2, 2023, as shown in Figure 6. The construction team adopted the umbilical launch method to start the excavation. During the second launch, the EPB TBM advanced with the cooperation of main machine and temporary gantry. At this time, the muck was excavated by the EPB TBM and discharged by the slurry circulation system.

Figure 6. Official launch

To significantly enhance the muck discharge efficiency during the umbilical launch, a series of effective technical measures were adopted. A crusher is equipped at the discharged gate of the screw conveyor to break down large soil lumps, making them easier for subsequent slurry transportation. Meanwhile, the slurry feeding pump was used to accurately transport slurry into the slurryfier box, where it was thoroughly mixed with the discharged muck to achieve efficient dilution. Afterwards, the slurry discharge pump continuously pumped the diluted slurry from the slurryfier box to the slurry treatment plant on the ground where the separation of soil and slurry was completed.

To maintain the stability of the tunnel face, a foam system and water system were used to inject bentonite into the tunnel face, improving the workability and fluidity of the muck. At the same time, the bentonite system was activated to work in conjunction with the AFS system to maintain stable pressure in the excavation chamber. With this pressure control system, the EPB TBM has achieved continuous tunnelling for 133m and steadily passed through the water-rich sand layers, thus successfully completing the second umbilical launch. The muck discharge process with the slurry circulation system is shown in Figure 7.

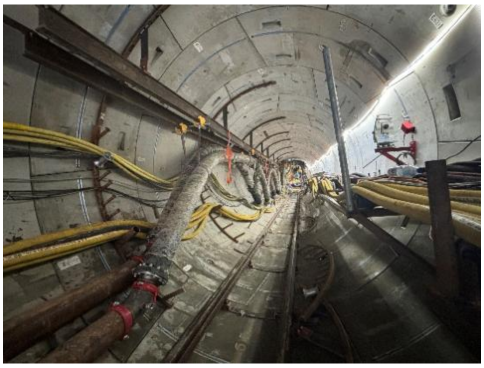

Figure 7. Muck discharge process with the slurry circulation system

During tunnelling through sandy gravel, gravel and water-rich sand strata, the slurry circulation system was adopted for muck discharge. When the TBM advanced by the 77th segment ring, the average thrust speed reached 21.3mm/min, with an average thrust force of 6474.69kN and an average torque of 518.85kN·m. The variations in torque and thrust force are shown in Figure 8.

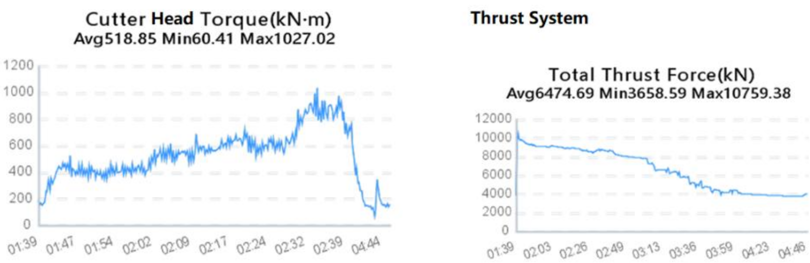

Figure 8. torque and thrust force when tunnelling in sandy gravel, gravel and water-rich sand strata

During tunnelling in clay strata, the belt conveyor of the EPB TBM was adopted for muck discharge. When the TBM advanced by the 717th segment ring, the average thrust speed reached 39.12 mm/min, with an average thrust force of 8012.28 kN and an average torque of 1275.61 kN·m. The variations in torque and thrust force are shown in Figure 9. Since the slurry circulation system was used for muck discharge in sandy gravel, gravel and water-rich sand strata, the friction coefficient of these strata was relatively low, resulting in significantly lower torque and thrust force compared to the clay strata. Moreover, due to the lower water content in clay, the belt conveyor for muck discharge was also relatively faster.

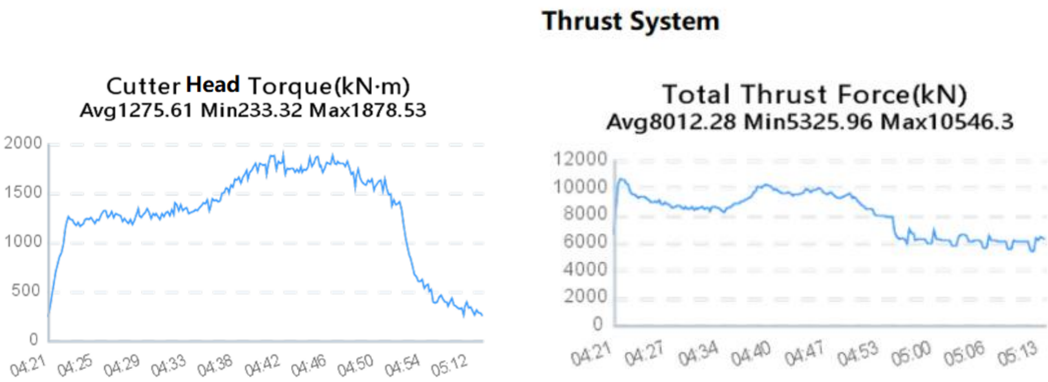

Figure 9. Torque and thrust force when tunnelling in clay strata

Throughout the entire construction process, the innovative EPB TBM with slurry circulation system for muck discharge demonstrated excellent operational performance and was successfully applied. It not only ensured the progress of construction but also showed its strong technical advantages under complex geological conditions, providing a highly valuable practical example for the construction of similar projects in the future.

5 CONCLUSION AND PROSPECT

On December 4, 2024, the Hamburg's district heating tunnel was successfully completed, marking the achievement of another significant engineering milestone. During the construction of this project, the EPB TBM is innovatively designed with a slurry circulation system for muck discharge, successfully overcoming the challenges of tunnelling and muck discharge in water-rich sand layers. This technological breakthrough not only ensured the smooth progress of the Hamburg's district heating tunnel but also provided valuable practical experience and innovative ideas for TBMs in complex geological conditions.

In response to the ongoing expansion of tunnel construction in China and abroad, as well as the increasingly complex construction environments, it is essential to relentlessly strengthen technological innovation. By continuously implementing innovative measures, the growing technological demands in the field of tunnel construction can be met, thus effectively driving the high-quality and sustainable development of the tunnel engineering area.