Research on the Key Technology of Large Diameter TBM in Soft Rock Formation

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Abstract—This paper discusses the key technology of large-diameter TBM applied to soft rock formation, and introduces in detail the optimized structure design of cutterhead, cutting tool configuration, soil conditioning and control system of large diameter TBM for soft rock.

1. Introduction
In recent years, large tunnels for highway, railway and sewage network purposes have been built one after another, and TBM, as the pillars of a great power for excavating tunnels, are favored by domestic and foreign customers because of their safe, efficient and economic use. In the process of advance, TBM will encounter various geological conditions, such as full-section hard rock, clay, sand and pebbles, weathered rock, etc. Targeted design of TBM is required for advance in different formation, which is critical to the success of the TBM construction, so it is especially important to study the key technology of TBM for advance in various formation. Taking the construction of Dubai sewage tunnel project as an example, this paper analyzes the design of cutterhead, soil conditioning and control mode, and researches and analyzes the key technology of TBM tunnelling in soft rock formation, so as to provide reference for the construction of large diameter TBM in similar formation.

2. Project Overview
The Dubai Deep Tunnel project is located near the World Expo 2020 pavilion and is an underground drainage system project in Dubai, which will undertake the task of collecting rainwater and draining flood from Dubai World Centre, the World Expo pavilion and the surrounding areas. The project was constructed by a joint venture between the famous European construction company PORR GROUP of Austria and BESIX GROUP of Belgium. The tunnel of this project is 10,269 m long, which is the main tunnel of the whole flood drainage system. The tunnel adopts two large diameter TBM of 11.05 m, with a total length of about 85 m and an overall weight of about 2,000 t. This is the largest diameter EPB TBM exported overseas by China at present. The TBM mainly traverses the Far and Barzaman formations. Both rock formations are weak, and the average strength UCS of the FAR formation is 6.1 MPa. The average strength UCS of the Barzaman formation is 3.6 MPa. The maximum rock strength of the two formations is less than 15MPA. The average is 4.8MPa. The average CAI wear index is as low as 0.23.
3. Cutting Tool Arrangement
Cutting tool design is the prerequisite and guarantee for the TBM to achieve underground excavation, and the correct configuration of the cutting tools largely affects the tunneling efficiency and service life of the cutting tools for TBM [1]. When the cutting tools are severely worn out, it will lead to lower performance and efficiency, and then the cutting tools severely worn must be replaced so as to maintain an efficient tunneling.

According to current design and construction experience, an eight main beams plus eight sub-beams structure is recommended for the TBM with a diameter of about 11m for the following reasons:

- Large excavation diameter for this project;
- Main geology: soft rock with low rock strength and low abrasiveness
- Based on the TBM manufacturing and construction experience, the design of eight main beams plus eight sub-beams structure is adopted for the cutterhead of this project.

The cutting tool arrangement of the cutterhead takes full consideration of the force performance of the cutterhead and strives to concentrate the combined force of the radial load of the cutterhead onto the center of the cutterhead. Considering the uniformity of the force to the cutterhead, the cutting tool
arrangement adopts the principle of cross intersection, symmetrical arrangement and less cutters inside while more cutters outside to achieve the symmetry about the center of the cutter as much as possible, in order to reduce the unbalance force onto the cutterhead, thus reducing the possibility of the main drive being subjected to overturning moment, and try to ensure that the wear of the cutting tools in each area is basically the same. The structural parts of the cutterhead are the basis to ensure the strength and stiffness of the whole cutterhead, and the finite element analysis of the structure of the eight main beams plus eight sub-beams of the cutter is carried out. According to the simulation and analysis of the load and torque for the cutterhead, it can be seen from the figure below that the deformation is within the normal range, the stress received is less than the allowable stress of the material, and the strength and rigidity of the cutterhead fully meet the requirements for excavation.

The cutterhead adopts 6 center twin rippers, 28 18-inch face disc cutters, 11 18-inch gauge disc cutters, 16 gauge scrapers, and 124 face scrapers. According to the existing project experience, the center twin disc cutters will often experience eccentric wear. Therefore, in combination with the soft rock geology of this project, the center twin rippers are used to greatly reduce the eccentric wear of the tool in the center area; In the other areas, single wedge double-edged disc cutters are used, the cutters height is 187.7mm, the cutters spacing is 250mm, the distance between the two blades of the double-edged disc cutters is 100mm, the front cutters arrangement adopts the serrated cutters spacing and the adjacent cutters spacing is different. The cutter height difference is 30mm, which is conducive to the flow of muck in front of the cutter head [2].

The outermost and second outer sides of the cutterhead are specially designed and arranged with three double-edged disc cutters, which effectively ensure the excavation diameter and rock breaking effect. Compared with single-edged disc cutters, double-edged disc cutters are more suitable for soft
rock geology. The cutters can increase the rotating torque and protect the cutter hub, and it is more economical to use less cutters. It can meet the requirements of tunneling and excavation at the same time.

Disc cutters are generally used in the cutterhead for mixed ground and the disc cutter spacing is closely related to the rock breaking efficiency. The Colorado School of Mines has conducted a long-term study on this. Roxbourogh, Sanio, Rostami, etc. [3~5] all made further improvement on CSM models and obtained a more practical and comprehensive model of disc cutter cutting force—CSM model:

\[
F_t = \frac{P_0 \phi R T}{1+\phi}
\]

In the formula, \(F_t\)—the resultant force of the disc cutter; \(R\)—the radius of the disc cutter; \(T\)—the width of the disc cutter blade; \(\phi\)—the pressure distribution coefficient of the disc cutter tip; \(\Theta\)—the contact angle between the blade of the disc cutter and the rock; \(P_0\)—the pressure in the crushing zone is related to the strength of the rock, disc cutter size and blade shape:

\[
P_0 = C \sqrt[3]{\frac{S}{\phi R T}} \sigma_c \sigma_t
\]

In the formula, \(\sigma_c\) is the uniaxial compressive strength of the rock; \(\sigma_t\) is the tensile strength of the rock; \(S\) is the cutters spacing; \(C\) is the dimensionless coefficient, \(C \approx 2.12\). Combining formulas (1) and (2), under the same conditions in other respects, the smaller the distance between the discs, the smaller the force on the disc cutter, that is to say, when the rock strength is low, the distance between the cutters can also be increased to ensure the efficiency of rock breaking.

4. Soil Conditioning

The mud cake reduces the penetration of the cutter head, slows the tunneling speed and increases the torque [6]. In order to ensure excavated soil consistency, low permeability and small frictional resistance, special device is configured to inject conditioning agents such as foam, bentonite and polymer to the soil during excavation. The rotation of cutterhead and screw conveyor accelerates the mix of soil and conditioning agents to modify properties of excavated soil and reduce the clogging on cutterhead.

Based on the geological condition of Dubai Project, soil conditioning is used to make tunneling process smoother. The water content of Dubai Project is as follows:

![Geological information](image-url)
Table 1. The geological condition of Dubai Project

| Dry muck density | Maximum plasticity index | Liquid limit water content WL | Average water content |
|------------------|---------------------------|-------------------------------|----------------------|
| 1.57 g/cm³       | 78                        | 139%                          | 21%                  |

The plasticity index is the percentage value of the difference between liquid limit and plastic limit (minus the percentage sign), which is expressed by IP and taken as an integer.

It means, plasticity index (IP) = [liquid limit water content (WL)-plastic limit water content (WP)] *100

That is, plastic limit water content (IP)=139-78=61%

While, volumetric water content =dry muck density * water content

So, water injection rate =1.57*(61%-21%)=62.8%

Table 2. The average advance speed and water injection rate

| Ring No. | Average advance speed (mm/min) | Water injection rate (%) |
|----------|--------------------------------|--------------------------|
| 108      | 23.53                          | 66.8                     |
| 135      | 34                             | 59.1                     |
| 137      | 30                             | 56.6                     |
| 140      | 36                             | 57.6                     |
| 156      | 32                             | 65.3                     |
| 158      | 32                             | 65.1                     |
| 159      | 32                             | 62.9                     |
| 160      | 32                             | 66.4                     |

The above table shows that the actual average water injection rate is 61.9%, which is close to the theoretical calculation of 62.8%, thus confirming the accuracy of the theoretical water injection rate.

In order to increase the tunneling speed of the large-diameter TBM to 60 mm/min, the required water injection flow rate shall be 3,611 L/min, calculated according to the above formula.

Table 3. The Parameters of the TBM excavation

| Excavation diameter | Excavation speed | Excavation volume per minute | Water injection rate | Muck conditioning water flow rate |
|---------------------|------------------|------------------------------|----------------------|----------------------------------|
| φ11,050 mm          | 60 mm/min        | 5750 L/min                   | 62.8%                | 3611 L/min                       |

TBM excavation volume calculation formula:

Q1-exavation volume per minute

D=excavation diameter of cutterhead

V-maximum thrust speed of the thrust cylinder

Q1=π/4×D²×V=5,750 L/min

Vp=Q1×τ

Vp-water flow rate for muck conditioning

τ-water injection rate

Vp=5,750×0.628=3,611 L/min

In order to meet the water injection requirements, the improved equipment is equipped with the foam system, bentonite system and water input system, so that the total amount of water input meets the actual requirements. Reasonably use foam, bentonite, polymer and other slag modifiers, and the super-large diameter earth pressure balance shield can be used in the construction of confined water-sand formation tunnels [7].

Considering the geological situation and excavation efficiency in Dubai Project, the TBM is equipped with foam injection system, and the calculated capacity of foam is as follows.
Table 4. Basic parameters table of TBM and its foam system

| Excavation diameter (D) | Segment width (L) | Tunnelling speed (Vmax) | CFR Foam additive | FER (expansion rate) | FIR (injection rate η) |
|------------------------|-------------------|-------------------------|-------------------|----------------------|-----------------------|
| φ11,050 mm             | 2 m               | 80 mm/min               | 5%                | 10                   | 60%                   |

With the above parameters, it can be calculated that:

- Excavation volume per minute
  \[Q_{\text{muck}} = \frac{\pi}{4} \times D^2 \times 1 \times V_{\text{max}}/1000 = 7.668 \text{ m}^3/\text{min}\]
- Foam amount per minute
  \[Q_{\text{foam}} = Q_{\text{soil}} \times η \approx 4.6 \text{ m}^3/\text{min}\]
- Foam amount per hour
  \[Q_{\text{foam}} = 4.6 \times 60 = 276 \text{ m}^3/\text{h}\]
- Foam mixture amount
  \[Q_{\text{mixture}} = 276/10 = 27.6 \text{ m}^3/\text{h}\]
- The shield is equipped with 12-line foam injection system in single-pipe and single-pump design, that is, the foam mixture amount per line
  \[Q_{\text{foam mixture amount per line}} = 27.6/12 = 2.3 \text{ m}^3/\text{h} = 38 \text{ l/min}\]

The 12 foam mixing pumps are frequency conversion screw pumps, and the flow rate is 60L/min, which meets the requirement for use. The parameters of the screw pump are as follows:

Table 5. The parameters of the screw pump

| Pump type  | Qty. | Flow rate | Power | Max pressure |
|------------|------|-----------|-------|--------------|
| Screw pump | 12 unit | 60 L/min | 2.2 Kw | 12 bar       |

5. Control mode

EPB TBM generally has three excavation modes: open mode, semi-open mode and earth pressure mode. Each excavation mode corresponds to different stabilization mechanism of the tunnel face and geological conditions, and all three excavation modes are available for the Dubai project according to the geological conditions there. In order to improve the excavation efficiency, the semi-open mode is recommended. The semi-open mode means the excavation chamber is filled with certain amount of muck, normally 1/3-2/3, and compressed air. The semi-open mode can reduce the secondary wear and torque of cutterhead, which makes the muck can be smoothly discharged through the screw conveyor, and stabilize the tunnel face together by the compressed air and muck in excavation chamber.

The first EPB TBM of Dubai project started to excavate in semi-open mode from the 135th ring, the muck level inside the excavation chamber is about 2/3 in semi-open mode, and the pressure in the upper part of the excavation chamber is 1.45bar; the rotation speed is 2.33rpm and the torque is 15000KNm, at this time the advancing speed of the shield machine is 34mm/min.
In order to reduce the torque and increase the rotation speed to improve the tunneling efficiency, the muck amount and pressure in the excavation chamber is reduced and the soil conditioning capacity is improved. The upper area pressure value is used as the control value to set the soil tank control pressure [8]. The muck takes up 1/3 of the excavation chamber in the 550th ring. Under this excavation mode, the upper pressure of the excavation chamber is 1.23 bar, the rotation speed is 2.62rpm, the torque is 10,800KNm, and the advancing speed is 60mm/min at this time.

6. Advance Rate
In the case of semi-open mode tunneling with good soil conditioning, the best performance is 45.1m per day, 222.9m per week and 927.2m per month.

7. Conclusion
After continuous design optimization, the large diameter shield TBMs applied to soft rock strata adopt the following design: the cutterhead adopts the form of eight main beams plus eight auxiliary beams, the cutting tools arrangement adopts cross intersection type, the cutter spacing adopts serrated arrangement, and thus the cutting tools match the cutterhead well to enhance the cutting effect and reduce the frequency of cutterhead intervention. The semi-open mode of tunneling is able to improve the tunneling efficiency and reduce the wear of cutting tools to meet the clients' requirement. However, the excellent performance is also attributed to reasonable structure of cutterhead and proper soil conditioning, so that the excavation and soil transportation is smooth.
With high geological adaptability, stability, excellent soil conditioning and control system, the Twins EPB TBM for DTSWS in Dubai have overcome the construction difficulty of cutterhead clogging in full-face mud sandstone and meets the requirements of long-distance tunneling, and thus win the unanimous recognition and high praise from the project owner and the contractor.

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