Design Study for Key Components of Slurry TBM in Tunnel with High Pressure Water

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Abstract. Taking an Italian tunnel project with high pressure water as an example, this paper analyses and researches the sslurry TBM's key components such as cutterhead, main drive and thrust system for large overburden tunnel and high hydrostatic stratum by combining the probability analysis of geological data, and by this way derives its theoretical design basis, aiming to provide some theoretical basis on the tunnel projects and reference for the design of subsequent projects.

Keywords: Slurry TBM · Cutterhead · Main Drive · Thrust System · Over-excavation

1 Project Overview

A highway tunnel project in Italy consists of three sections: BGN, AMA, and MNT, with a total length of 14.4 kms. Two mix-shield slurry TBM with diameter of 14.69m are required for construction.

The geological conditions for the tunnel mainly include clay layers, basalt, limestone, and schist, with a maximum uniaxial compressive strength of 130MPa. The project's maximum overburden is 370m, with a maximum hydrostatic pressure of 16bar. The high-pressure water, large burial depth, and geological convergence faced in this project are important aspects of tunnel construction [1] [5].

This article will focus on a detailed analysis of the design of the slurry TBM from the aspects of cutter head design, main drive design, propulsion system, and over-excavation cutter (copy cutter) design, aiming to provide a certain theoretical reference for similar projects.

2 Analysis of Cutterhead Design

According to the diameter of the tunnel segment and relevant design requirements, the excavation diameter of the cutterhead in this project is Φ 14.69m, designed with an accessible cutterhead and a telescopic and swinging main drive. In order to adapt to the high-pressure water presenting in the tunnel route, the disc cutters are equipped with pressure compensation devices. Based on the above geological conditions and the spatial

S. H. B. D. M. Zailani et al. (Eds.): ICMSEM 2023, 259, pp. 1122–1129, 2024.
https://doi.org/10.2991/978-94-6463-256-9_112

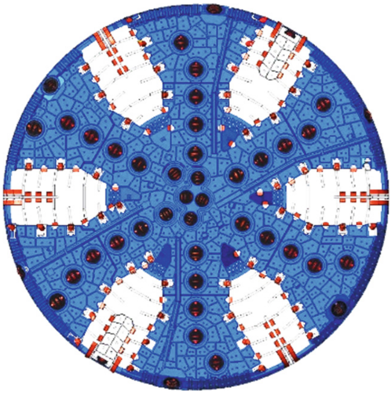


Fig. 1. Cutterhead Layout

structure of the accessible cutterhead, the cutterhead spacing is designed to vary between 100mm and 85mm (with a cutterhead spacing of 120mm in the central area). In total, 12 pcs 17 "single disc cutters and 67 pcs 19" single disc cutters are arranged. Therefore, the maximum thrust applied to the cutterhead is calculated as follows:

$$F_{CH} = \sum_{i=1}^{n} N_{c,i} \bullet F_{max,i} = 250 \times 12 + 315 \times 67 \approx 24MN$$

The cutter head design considering the structure and tool layout is shown in the Fig. 1.

At the same time, the cutter head is equipped with online real-time disc rotation, temperature detection and wear detection devices to accurately judge the tool usage during the excavation process, reducing the cutting tool inspections during the hyperbaric intervention.

3 Main Drive Design Analysis

For slurry TBM tunnelling under high water pressure, the pressure-bearing capacity of the main drive seal is the key link. The drive of this project adopts the special design of 3 VD + 1 finger seal, which can withstand the maximum high-pressure water of 20 bar and meet the high hydrostatic pressure requirement of 12–16 bar of this project.

According to the geological situation and soil and water pressure of the project, and referring to GB/T 34651–2017, it shall be considered comprehensively disc cutter's cutting torque T1, friction torque of cutterhead face T2, friction torque of cutterhead backside T3, friction torque of outer ring T4, main bearing rotating reaction torque generated by self-weight T5 and main bearing rotating reaction torque generated by cutterhead thrust load T6. In this way, required total main drive torque Tc can be calculated as 33604kNm [2] [4] [6] shown in Table 1.

For this purpose, a Φ7600mm main bearing and supporting pinions, 350kW motors, and gear reducers with reduction ratio of 64.46 are used. Where the motor parameters:

Table 1. Main drive component forces

T1/kNm	T2/kNm	T3/kNm	T4/kNm	T5/kNm	T6/kNm	T_C/kNm
5392	19642.4	1964.2	5529.2	82.4	993.9	33604

rated torque 2249Nm, rated speed 1487r/min, maximum speed 2970r/min, then the main drive parameters are shown in the following calculation, rated torque $M > T_c$, to meet the project requirements.

$$M = T \times i \times A \times \eta \times i_1 = 2249 \times 64.46 \times 16 \times 0.95 \times 16.25 \approx 35808kN \bullet m$$

In the formula,

M-Main drive rated torque, kN-m;
T-Motor rated torque, N-m;
A-Number of drive groups, 16;
i-Reduction ratio of the gearbox, 64.46;
i1-Ring reduction ratio,16.25;
η-Drive efficiency, taken as 0.95.

The maximum torque of this drive configuration can be reached $T_{max} = 1.3 \cdot M = 1.3 \times 35808 = 46550kN \bullet m$, and the decoupling torque $T_{breakout} = 1.35 \cdot M = 1.35 \times 35808 = 48341kN \bullet m$.

Comprehensive geological conditions and relevant standards of the tunnelling industry, the force on the cutter in the boring process is mainly as follows in Table 2 [2]:

Based on the ITAtech design standard, the force model of the cutterhead and main drive in the tunneling process is established as shown below in Fig. 2, while L1 and L2 will change accordingly in the cutter telescopic swing.

Where T1 is the thrust component due to the cutter torque, T2 is the thrust component on the drive ring due to the support pressure, and F_{CH} is the cutter thrust as in the Table 3:

$$T_1 = 10 \bullet \frac{T_C}{D}$$

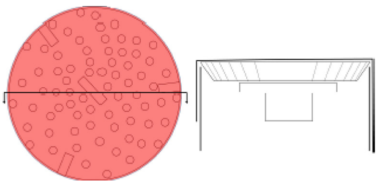
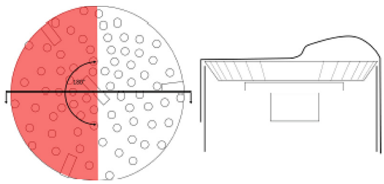
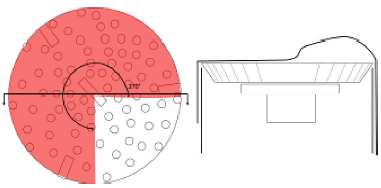
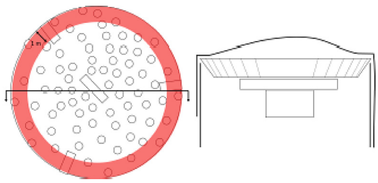
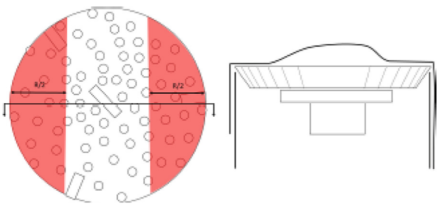
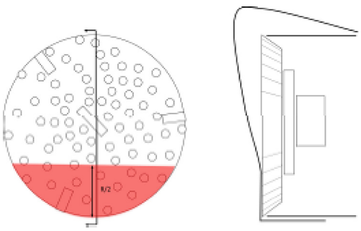
$$T_2 = F_{FP} \bullet \frac{\pi(d_1^2 - d_2^2)}{4}$$

Combined with ISO DIN 281, the life of the main drive bearing can reach 16700 h, which meets the requirements of use.

4 Thrust System Design

The total thrust of tunnelling boring machine is determined by the sum of various propulsion resistances and the required margin. For slurry TBM, the commonly considered propulsion resistances include shield body friction force F1, tunnel surface horizontal

Table 2. Cutterhead load case analysis

	
LC1: Full face contact	LC2: Partial face contact (180°)
	
LC3: Partial face contact (270°)	LC4: Routine over-excavation due to shield jamming
	
LC5: Local contact due to vertical fracture layer	LC6: Local contact due to collapse/cavern

pressure F2, cutterhead tools thrust F3, friction force F4 between the TBM tail skin and the outer surface of segment, and towing force for backup F5 [3], which are shown in Fig. 3.

$$F_{max} = F_1 + F_2 + F_3 + F_4 + F_5$$

From the geological analysis calculations it can be seen that in the MNT tunnel a larger shield thrust force is required due to the presence of a larger stratigraphic convergence, as shown in the Fig. 4 below, demonstrating the shield thrust requirements in this tunnel line (with minimum, maximum and median values, 5th and 95th percentile), it can be seen that there are 4 different zones (divided into two areas), where the characteristic value of the maximum required thrust (95%) exceeds the exceptional value, as shown in the Table 4.

To better understand the impact of these results on the TBM advance, we calculated the number of times the nominal thrusts and exceptional thrusts which were exceeded in all areas of the tunnel. In only 8 m of the entire tunnel is greater than the maximum thrust

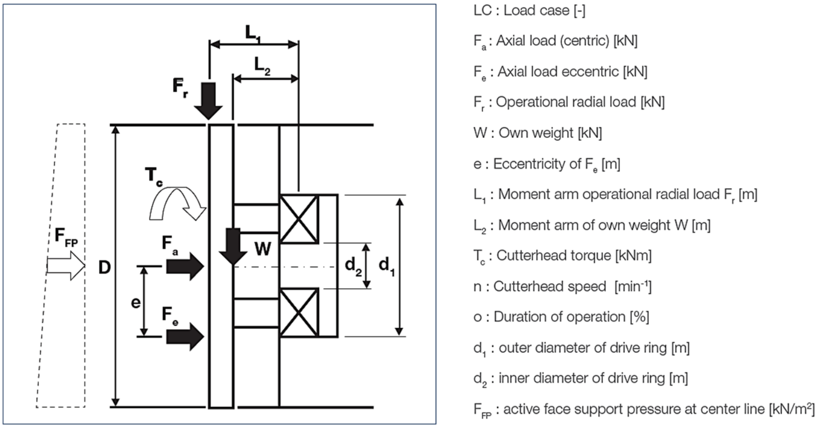


Fig. 2. Force model of the cutterhead and main drive

Table 3. Load cases

LC	Fa (kN)	Fe (kN)	F_{FP} (kPa)	Fr (kN)	W (kN)	e (m)	Tc (kNm)	n (rpm)
LC 1	F_{CH} + T1 + T2	0	1200	$2T_C/D$	W	0	T_C	n_{max}
LC 2	T1 + T2	0.5 F_{CH}	1200	$2T_C/D$	W	0.2 D	T_C	n_{max}
LC 3	T1 + T2	0.75 F_{CH}	1200	$2T_C/D$	W	0.1 D	T_C	n_{max}
LC 4	0.35 F_{CH} + T1 + T2	0	1200	$2T_C/D$	W	0	T_C	n_{max}
LC 5	0.4 F_{CH} + T1 + T2	0	1200	$2T_C/D$	W	0	T_C	n_{max}
LC 6	T1 + T2	0.2 F_{CH}	1200	$2T_C/D$	W	0.35 D	T_C	n_{max}

required (only 0.13%), especially considering the worst-case scenario (area #32, Ch13 + 432.00 to 13 + 440), less than half of the cases (about 42.7%) require thrusts higher than the maximum thrust. The frequency distribution of the accumulated and required thrusts along the whole tunnel route is shown in the following Fig. 5:

Consider over-excavation measures for areas with excessive thrust. Taking the MNT tunnel (PK13 + 430) as an example, the calculation results show that the effect of over-excavation for the local area is much greater than the effect of shortening the shield length, as shown in the results below, a 5% reduction in shield length (15m) reduces the thrust by only 2–3%; while using a large stroke over-excavation will reduce the thrust by 20–25%, which is an obvious effect as shown in Fig. 6.

Therefore, synthesizing the above analysis results and the space limitation of shield structure design, this shield propulsion system adopts 27 sets of double-cylinder design (φ460/φ360). With this configuration, the rated thrust reaches 403,842kN@350bar, and the maximum thrust reaches 565,379kN@630bar. In the worst-case scenario, the TBM

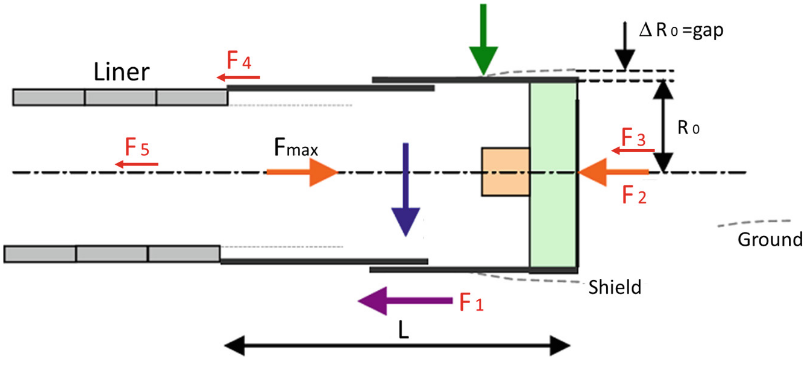


Fig. 3. Thrust analysis schematic diagram

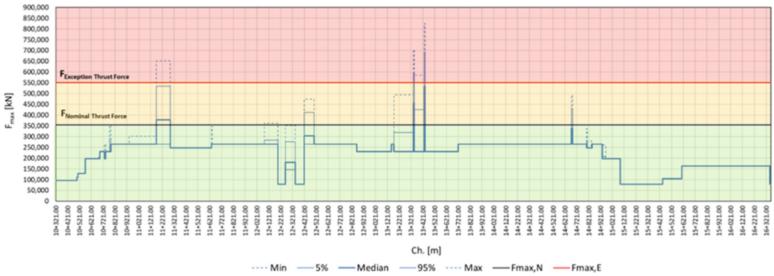


Fig. 4. Thrust trends required for MNT tunnel

Table 4. Required Thrusts - Worst Case Scenario along the MNT Tunnel

Section	Length of interval [m]		Length	Required thrust[kN]					Max thrust
[#]	Start	End	[m]	min	5th percentile	Median	95th percentile	max	[kN]
14	11 + 171.70	11 + 288.00	116	264941	264941	377268	534284	651811	565000
30	13 + 341.00	13 + 349.00	8	301841	351813	455814	592763	704214	
31	13 + 349.00	13 + 432.00	83	231044	231044	231044	425522	585849	
32	13 + 432.00	13 + 440.00	8	359556	414704	533200	693154	824147	

can use the large-stroke over-excavation cutter to increase the excavation diameter to reduce the friction force between TBM shield and ground. Above all, the thrust system configuration meets the requirements of project use.

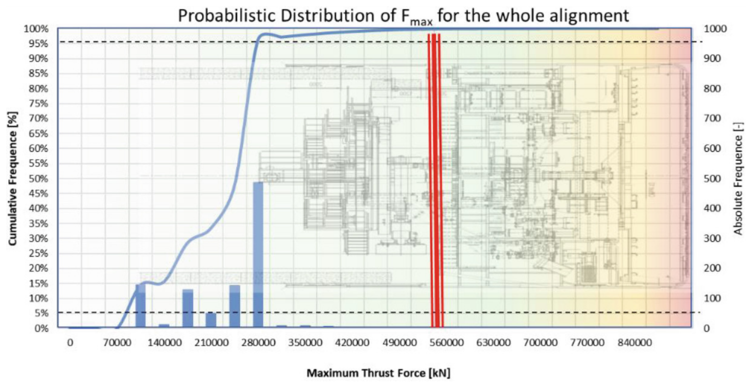


Fig. 5. Probability distribution of the requested thrusts along the MNT tunnel

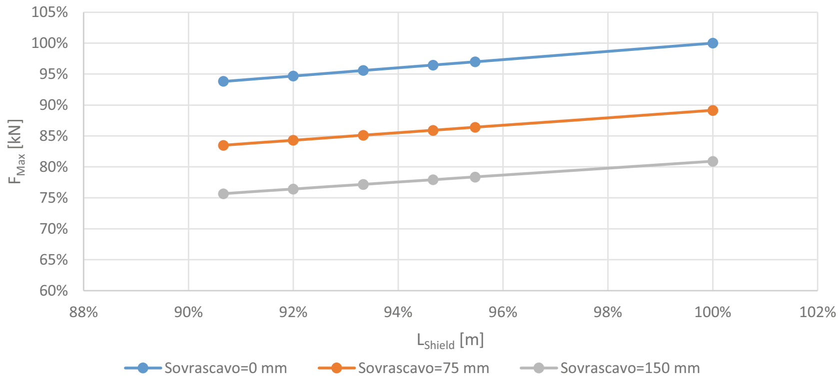


Fig. 6. Analysis of the reduction in thrust value (y-axis) versus shield length (x-axis) in the critical section of the MNT tunnel (pk13 + 430)

5 Over-Excavation Cutter (Copy Cutter) Design

As mentioned in the previous section, in order to avoid the occurrence of shield jamming during excavation and to reduce the maximum thrust demand, the cutterhead is equipped with two 150mm-stroke multi-blade over-excavation cutters with large stroke, as shown in the figure below, to alleviate the shield jamming problem and the problems of thrust and torque system faced by slurry TBM during excavation.

6 Conclusion

[1] This project is located in the Alpine region, and the tunnel projects along Alpine are more likely to face the risk of large overburden and high-pressure water. At the same time, the rock strength is very high, so the cutter design needs to consider reasonable cutter spacing and structural strength [5] [6].

[2] Most of the construction projects in this region need high torque and large thrust, it is recommended that the main drive should be configured with sufficient power and the propulsion system should be designed with high thrust and have high pressure decoupling function.

[3] For large overburden strata, by analysing the geological loading effect on the shield body, the configuration of large-stroke over-excavation cutter in the special interval can greatly reduce the demand for the maximum propulsion capacity of the shield to a certain extent and can solve the problem of space limitation in the design of the shield structure.

[4] This project provides an in-depth analysis of the design of the key components of the shield and the countermeasures of the stratigraphic risk in combination with the relevant European design standards, which also provides a reference basis for the subsequent related projects.

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