Research On the Design Process of Irregular-Shaped TBM Cutterhead

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Abstract. On the basis of a full analysis of the application market for the irregular-shaped TBM, this paper generally discusses the design features of the cutterhead of irregular-shaped TBM, i.e., the design principles of profiling cutterhead and combined cutterhead, and focuses on a series of key technologies such as overall structure design of cutterhead, geological adaptability design tool, cutting tools design and wear resistance improvement design, which have a guiding significance to cutterhead design of irregular-shaped TBM. The research provides an important reference for the design of cutterhead of more complex irregular-shaped TBM

Keywords: Irregular-shaped TBM; Combined cutterhead; Profiling cutterhead; Cutterhead design.

1. Introduction

Traditional urban subway tunnels mostly use circular cross-section, this is because circular tunnel lining structure has the advantages of uniform force, smaller internal force, simple manufacturing, easy control of advance axis, convenient construction, etc., and occupies a dominant position in the field of underground tunnel technology.

As underground space continues to be developed and utilized in-depth, new and diverse demands are being made on tunnel cross-sections and functions. However, it has been found that when using circular TBM to process rectangular, elliptical, horseshoe, double circular and other shaped sections, there are often disadvantages such as low section utilization and wasted space. The use of irregular-shaped TBM is much more reasonable, which can reduce the excavation area, cutting earth volume, residue disposal volume and backfill volume, thus improving tunnelling efficiency and space utilization, reducing cost and making the tunnel construction technology more advanced[1].

The cutterhead is one of the core components of TBM to realize the tunnelling function. During the tunneling process, the cutterhead has three major functions: Cutting earth under the joint action of cutterhead torque and propulsion force; supporting the tunneling surface during excavation and downtime; and improving earth by using stirring bar and improver during the tunneling process. It is essential to conduct an in-depth study on the key technology of irregular-shaped TBM cutterhead[2].Conventional cross-passage construction method.

2. Research on the design of irregular-shaped TBM cutterhead

The cutterhead design of irregular-shaped TBM should firstly ensure full section excavation, due to the irregularity of the tunnelling section, there is a certain blind area of excavation and mixing, the mobility of the soil is not good, the cutterhead mixing bar should have good mixing performance, and the earth improvement device should have good geological adaptability to meet the requirements of ground settlement.

Most of irregulr-shaped TBM adopt the form of multi- combined cutterhead, which can be divided into spoke-type combined cutterhead for soft ground, panel combined cutterhead for sand and pebble ground, panel combined cutterhead for hard rock ground, and moreover, multi-mechanical arm combined cutterhead for hard rock ground. according to different geological types, the different forms of tunnelling section, can be divided into multi-round cutterhead, rectangular cutterhead, horseshoe cutterhead and etc.

The profiling cutterhead uses the control theory to make the copy cutter extend a specific length in a specified area to achieve the excavating in irregular-area.

2.1. Profiling cutterhead

The profiling cutterhead uses the control theory to make the super-excavating cutter of the cutter extend a specific length in the specified area in order to excavate the designed shapes, as shown in Figure 1, whose structure mostly adopts the spoke structure of the circular cutterhead, with profiling cutters installed at the end of the spokes, hydraulic cylinders placed in the spoke structure, and stirring bars arranged on different radii at the rear of the spokes to agitate the cutting down soil.

The advantages of the profiling cutterhead are its symmetrical structure, uniform force, and small disturbance to the soil, which is conducive to the machine working and can achieve 100% excavation ratio. However, its transmission system is more complicated and the reliability of long-distance excavation is restricted by the harsh construction environment. In addition, due to the irreversibility of underground excavation works and the restricted operation space, The reliability requirements for TBMs are very high.

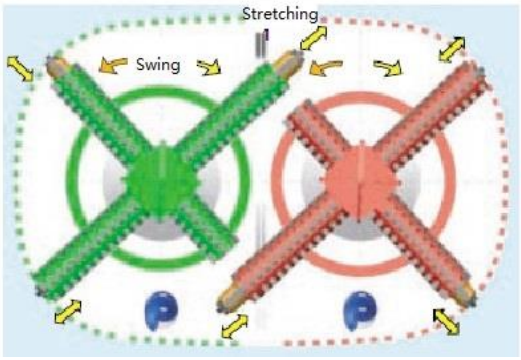


Fig. 1 Profiling cutterhead

2.2. Profiling cutterhead

Based on the different forms of combination, the multi-combined cutterhead can be divided into different forms such as multi-circular soft earth cutterhead, combined rotary cutterhead, combined horseshoe-shaped soft earth cutterhead and combined horseshoe-shaped hard rock cutterhead.

2.2.1 Multi-circular cutterhead

Multi-circular cutterhead are more frequently used in soft soil strata, and less in hard rock strata considering factors such as differences in surrounding rock layers and difficulty in designing of cutterhead combinations. Multi-circular soft earth cutter is a combination of circular cutterhead, and the essence of multi-circular tunneling machine is the combination of circular tunneling machine units, which performs simultaneous excavation on the palm face and individual discharge of muck when tunneling, and has been successfully applied in double-circular tunnel and multi-circular tunnel. The advantages of double-circle tunnels are that they occupy less width than single-line parallel circular tunnels and have shallower overburden than double-line circular sections. Applications are shown in Figures 1 and 2.

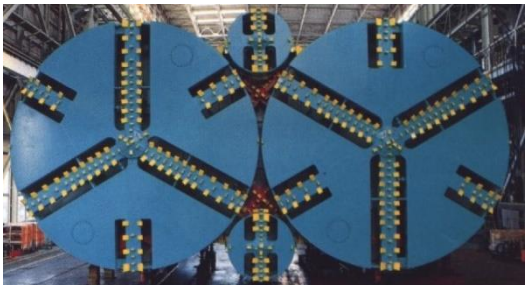


Fig. 2 Double circle TBM

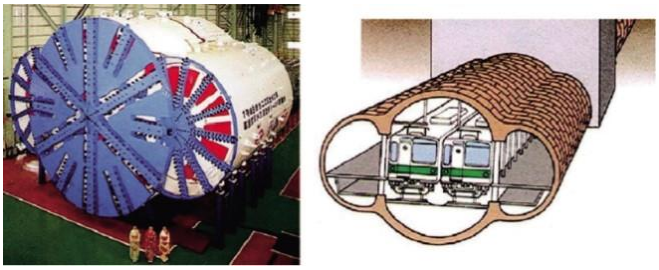


Fig. 3 Tri-circle TBM

2.2.2 Combined rotary cutterhead

A combined rotary cutterhead is devised on the basis of conventional circular cutterhead, and its structure usually has the following two forms: one relies on the mutual compensation of the excavation surface of the front and rear cutterheads to minimize the blind area of excavation in the rectangular area; the other arranges all the cutterheads in the same plane, which increases the mixing area of the cutterhead and makes the slag soil have good fluidity, plasticity and water resistance, and in addition to the above construction advantages, it also has significant advantages such as low cost and easy interchangeability[5].

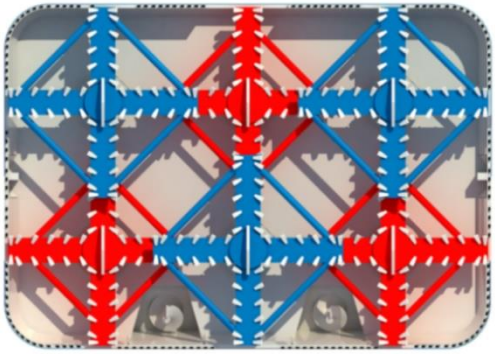


Fig. 4 Front and rear combined cutterhead

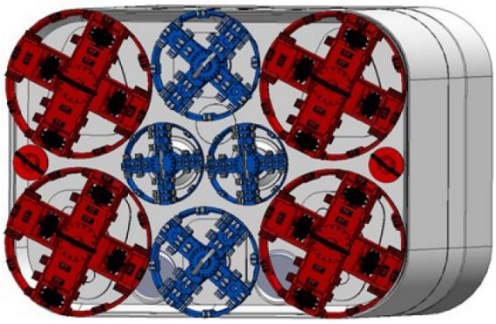


Fig. 5 Same plane combined cutterhead

2.2.3 Eccentric multi-shaft combined cutterhead

The eccentric multi-shaft cutterhead adopts the motion principle of parallel double crank mechanism[6], two eccentric crankshafts drive two profiling cutterheads with a certain crank length attached to achieve full section excavation, the advantage is that there is no cutting blind area, but because each point does rotational motion around its own circle center, the reaction force on the cutters arranged on it cannot be mutually eliminated, and the cutting reaction force is transferred to the shield body, which will easily cause the shield body to rolling or deflecting, thus causing earth disturbance, the specific form of which is shown in Figure 5.



Fig. 6 Eccentric multi-shaft combined cutterhead

In the design of irregular-shaped cutterhead, the cutterhead excavation section should be determined first, and after the cross section is confirmed, the cutterhead combination should be designed based on the ground conditions. In soft ground such as silt, clay, chalk and fine sand, the front and rear combined cutterhead should be used; in water-rich large grain size sand and pebble strata, the same plane cutterhead layout should be used; the cutterhead should be selected with ready-made specifications as far as possible to reduce repeated workload and make the cutterhead layout have sufficient excavation and mixing ratios.

3. The design of irregular-shaped cutterhead

Cutterhead is one of the core components of the TBM to realize the tunneling function. During the tunneling process of TBM, the cutterhead has three major functions, cutting the soil under the joint action of the torque of the cutterhead and the thrust force; supporting the tunneling surface; and improving the soil using stirring bars with improvers.

In the design of irregular-shaped cutterhead, the overall layout of multi-cutterhead should be confirmed first, and then the specific design should be carried out for single cutterhead, followed by the gradual development of geological adaptability design of cutterhead structure, tool design, opening ratio design, wear resistance design and auxiliary parts design, etc. The designing process is as shown in Figure 7.

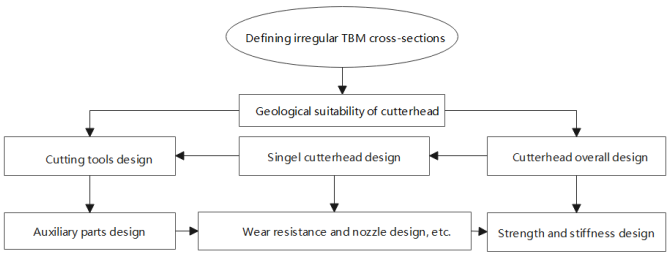


Fig. 7 Irregular-shaped TBM cutterhead designing process.

3.1. Geo-suitability desgin

As shown in Figure 8, the softness and hardness of the stratum is usually determined by the N value (standard penetration test hammering number N value). The main tunnel segment is divided into normal segment and particular segment. The particular segment is mainly applied at the connecting passage tunnel entrance, in the form of composite segment (steel pipe segment + concrete pipe segment), and the segments are connected by bolts to achieve the following purposes [5].

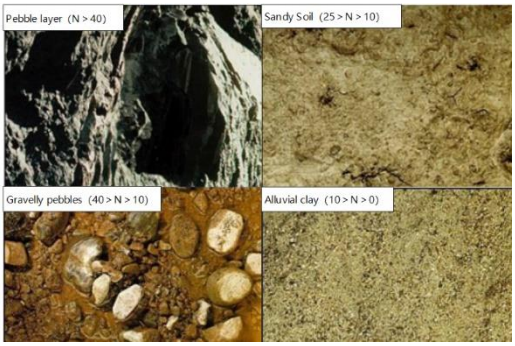


Fig. 8 N value of different stratum

In general, the softer sand and clay stratum should be used mainly for cutting and scrapers, while for the harder rock stratum, the matching disc cutter should be deployed. In case the tunneling stratum is highly abrasive and difficult to change the cutting tools, it is necessary to choose cutters with wear detecting.

The influence of the geological conditions of the tunneling on the design of the cutterhead can be referenced as shown in Figure 9 below.

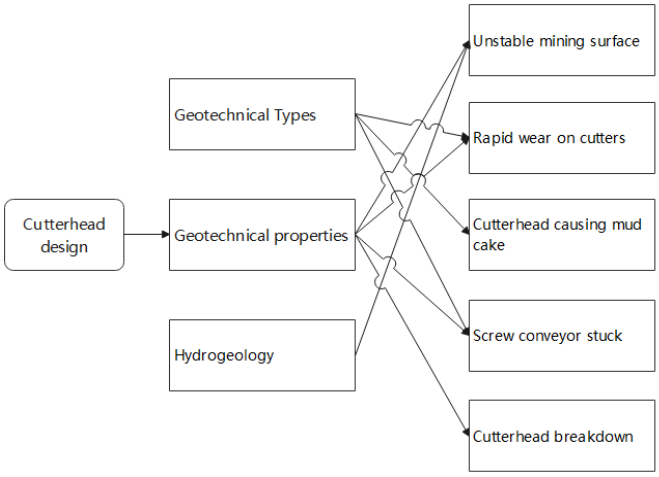


Fig. 9 N value of different stratum

3.2. Cutting tools design

The designed cutting tool must be compatible with the type of geology, otherwise, it will bring abnormal tool wear, difficulty in tunneling, etc.

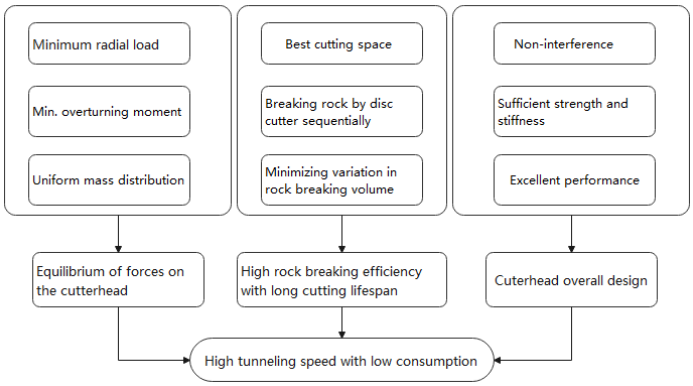


Fig. 10 Principles for cutterhead design

3.3. Opening ratio design

The cutter opening is mainly used for soil discharging in excavating surface, the cutter opening ratio has an important influence on the chamber pressure control, cutting torque and flowability, and also plays the role of limiting the size of the slag discharging. The opening ratio of spoke cutterhead is larger, generally around 65%~75%, which can avoid the problems of poor flow and large cutter torque, the opening ratio of the panel cutterhead is usually lower than 45% [4].



Fig. 11 Spoke cutterhead and panel cutterhead.

3.4. Wear-resistant design

The wear resistance of the cutting tool can be improved by adopting suitable materials and reasonable processes, such as welding wear-resistant alloy blocks, wear-resistant composite steel plates, wear-resistant grids or Hardox steel plates on the surface of the cutterhead, so as to improve the cutterhead lifespan, specifically the following measures.

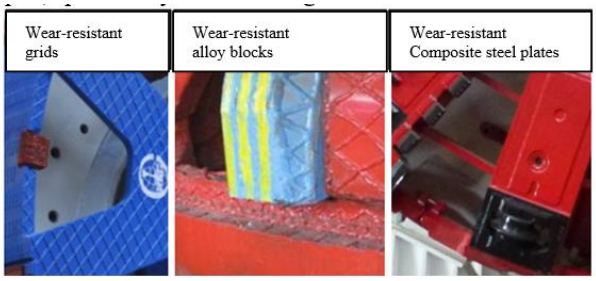


Fig. 12 Spoke cutterhead and panel cutterhead.

3.5. Strength and stiffness desgin

The strength and stiffness check of cutterhead is usually carried out by Ansys Workbench software. The purpose is to check whether the designed structure meets the requirements, if not, the structure optimization plan will be proposed basing on the calculation results. The geometric dimensions of the spoke-type cutter structure are taken from the drawing of the design scheme, and for the convenience of calculation, the cutterhead can be simplified in building the finite element model.

The cutterhead is mainly subjected to two kinds of loads in tunneling: axial thrust and torque, which are generally taken as earth pressure value of 50t/m² applied to the spoke panel as a uniform load; the cutterhead tunneling torque is taken as the rated torque of the main drive, which is acted on the whole spoke panel; all the degrees of freedom of the inner surface of the cutterhead cylinder ring are constrained. The specific boundary conditions are applied as shown in Figure 13-14.

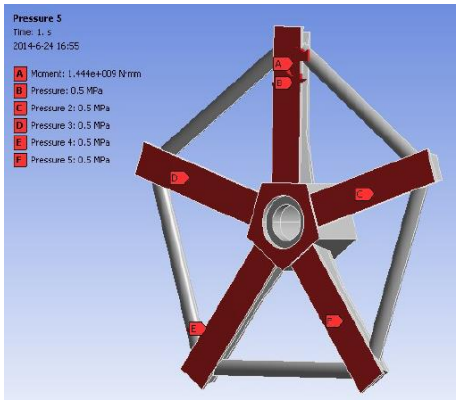


Fig. 13 Spoke cutterhead and panel cutterhead.

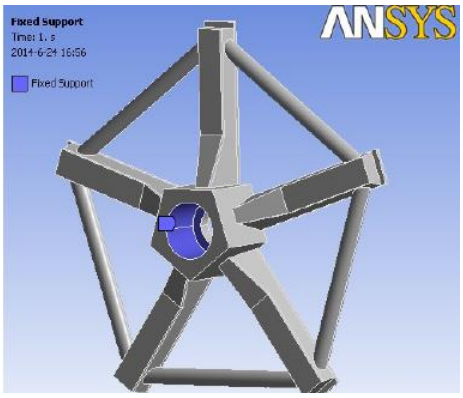


Fig. 14 Spoke cutterhead and panel cutterhead.

In this calculation case, the finite element model calculates that the maximum equivalent force of the cutter is 135Mpa, the maximum deformation is 2.5mm, the allowable stress of the material of the cutterhead is 295MPa, and the cutterhead design meets the requirements of strength and stiffness.

3.6. Auxiliary parts design

3.6.1 Supporting beam design.

The stirring bar is used for stirring the earth in the chamber when the cutterhead is rotating, so that the grouting material (slurry, water, foam) and the cutting earth can be fully mixed and the plasticity, fluidity and water resistance of the earth can be improved. Under the requirements of stirring torque, the mixing ratio should be as large as possible, meanwhile, the stirring bar should have strong enough impact resistance and wear resistance. The number of active and passive stirring bars, stirring elongation, stirring bar installation position and stirring bar type should be designed with the actual geology.

The support system can be widely used in various types of stratums such as silt, chalk, sand, pebbles, clay and rock formations.



Fig. 15 Supporting beam (Round pipe and square beam)

3.6.2 Stirring bar design

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3.6.3 Grouting nozzle design

A number of additive injection inlets should be arranged at the back of the cutterhead, and additive should be injected into the tunneling surface through the nozzle to ensure the mixing and improving effect of the muck, thereby reducing tool wear, and the design of the additive injection inlets should take into account the need for anti-blocking and pipeline cleaning.

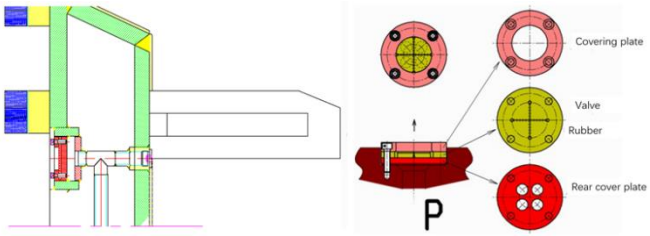


Fig. 16 Supporting beam (Round pipe and square beam)

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