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A Closer Look at the Design of Cutterheads for Hard Rock Tunnel-Boring Machines

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ABSTRACT

The success of a tunnel-boring machine (TBM) in a given project depends on the functionality of all components of the system, from the cutters to the backup system, and on the entire rolling stock. However, no part of the machine plays a more crucial role in the efficient operation of the machine than its cutterhead. The design of the cutterhead impacts the efficiency of cutting, the balance of the head, the life of the cutters, the maintenance of the main bearing/gearbox, and the effectiveness of the mucking along with its effects on the wear of the face and gage cutters/muck buckets. Overall, cutterhead design heavily impacts the rate of penetration (ROP), rate of machine utilization (U), and daily advance rate (AR). Although there has been some discussion in commonly available publications regarding disk cutters, cutting forces, and some design features of the head, there is limited literature on this subject because the design of cutterheads is mainly handled by machine manufacturers. Most of the design process involves proprietary algorithms by the manufacturers, and despite recent attention on the subject, the design of rock TBMs has been somewhat of a mystery to most end-users. This paper is an attempt to demystify the basic concepts in design. Although it may not be sufficient for a full-fledged design by the readers, this paper allows engineers and contractors to understand the thought process in the design steps, what to look for in a proper design, and the implications of the head design on machine operation and life cycle.

1. Introduction

A tunnel-boring machine (TBM) is a "tunnel-production factory"; as such, all parts of the production line should be functional in order to make the final product, which is the next meter of excavated tunnel. TBMs have existed since the mid-19th century, both in concept and in reality, and have been an integral part of the tunneling industry since the 1950s. The continuous improvement of TBMs and their capabilities since their introduction, especially in the past two decades, has made them the method of choice in many tunneling projects longer than ~1.5 km. Of course, other issues related to the tunnel application or ground conditions may change this choice, and may require the use of competing systems such as drill and blast and/or the use of the sequential excavation method (SEM), also known as the new Austrian tunneling method (NATM), which primarily uses roadheaders.

Although the selection and choice of TBM specifications appear to be straightforward, this seemingly simple task has proven to be challenging in several projects [1]. Problematic situations include deep tunnels, where shield machines can be used but risk getting trapped, and mixed ground conditions, where the choice of open-type machines for higher cutting speed has resulted in dramatic setbacks. In any case, the choice of machine type and specifications overshadows the operation of the machine and its performance during tunnel construction. Thus, it is critical to understand the implications of the choice of various machine types and related specifications when estimating the potential performance of tunneling machines. Although the choice of machine type is very important to the success of an operation, the design of the cutterhead is the single most critical part of the TBM operation, irrespective of the type of machine. This is because the TBM cutterhead is the "business end" of the machine—the place where the cutting tools meet the rock for the first time.

Designing the cutterhead involves the following factors: the choice of the cutter type, spacing of the cutters for the given geology along the tunnel, cutterhead shape and profile, balance of the

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head, efficient mucking, position and design of the muck buckets, access to the face and allotted space for letting miners reach the face, consideration for the structural joints and assembly of the head, and cutting clearance for the cutters and the body of the TBM. Each of these design parameters has some implication for the efficiency of the cutting process as well as the maintenance of the cutters, cutterhead, and cutterhead support. Another issue with the design of the head is the smooth operation and balance of the head, which allows for better steering of the machine, especially in mixed face conditions.

Despite the importance of the cutterhead design of a TBM, the amount of published literature on this subject is very limited [2]. This is because cutterhead design is mainly performed by the machine manufacturers, and the end-users often do not get involved with this level of detail. There has been limited academic interest on this topic due to a lack of opportunity to perform tests or follow normal procedures to validate hypotheses or obtain results. As a result, it is difficult to design different cutterheads and try them on an equal basis in order to assess their field performance or compare their design implications. Miniaturization of the head to assess its performance is not very attractive because rock excavation is widely viewed as not being scalable. On a large and full scale, it is very rare for a project to allow significant changes or modifications to the cutterhead design, unless something drastic happens. This is because it is very expensive and time-consuming to change the cutterhead in the field, so alterations are often limited to structural repairs and minor modifications of the mucking system.

Some activity on this topic has taken place in recent years, as the TBM market seems to be growing in Asia. Research on this topic has mainly taken place in the state key laboratories in China, and has also been done by researchers in Turkey and Korea [1,3–6]. The focus of these activities has been to make the machines more effective, primarily to address the dire need and pressure to improve the speed of tunneling and increase efficiency. However, some of the work in the past has focused on modeling without a discussion of design steps [7,8], while other work has looked at the design from a purely mechanical engineering point of view, without an in-depth discussion of rock behavior as it pertains to cutterhead design and machine operation [9]. This paper is intended to shed some light on the topic and to cover some basic principles of the cutterhead design procedure for hard rock TBMs. The content is not intended to be a discussion of a specific research project; rather, it is a reflection on the experiences of the primary author in cutterhead design during the past two decades.

2. Cutterhead design in simple steps

This section offers an overview of cutterhead design in terms of simple steps to allow the reader to understand the process and be able to evaluate the critical design issues when dealing with the acquisition of a new rock TBM or the refurbishment of an existing machine for a given tunnel geology.

2.1. Cutter selection

The first step in the process of cutterhead design and in the evaluation of a TBM for a project with a given geology is cutter selection. More information and a general guide on cutter selection for rock-cutting applications can be found in a paper by Rostami [10]. In addition, a discussion on various disk cutters and general trends in the application of disk cutters can be found in other publications [11,12]. The trend in the industry has been to use 432 mm (17 in) diameter constant cross-section (CCS) disk cutters as the base choice in various applications, especially on hard rock TBMs. An exception has been the use of larger 483 mm (19 in) disk cutters on TBMs working on very hard and abrasive rock, in order to minimize the need for cutter replacement. Another exception has been the use of >500 mm (20 in) disk cutters on TBMs larger than 10.5 m in diameter [12,13]. Smaller cutters, such as 150 mm, 300 mm, and 365 mm cutters, are used for smaller cutterheads. The implications of the disk cutter size are as follows:

(1) **Cutter load capacity.** This determines the depth of penetration. The typical load capacities of the 432 mm and 483 mm cutters are 250 kN and 310 kN, respectively.

(2) **Required cutting forces.** These increase with the size of the cutter for the same rock type.

(3) **Cutter velocity limit.** This is imposed by the maximum allowed rotational speed of the bearings. The typical velocity limits are 165 $m \cdot min^{-1}$ and 200 $m \cdot min^{-1}$ for 432 mm and 483 mm disk cutters, respectively.

Note that the cutterhead rotational speed (measured in revolutions per minute) on hard rock TBMs is a function of the disk cutter size and velocity limit, and the diameter of the TBM, as follows:

$$V_R = V_L / (\pi D_{TBM}) \quad (1)$$

where V_R or RPM is the rotational speed of the cutterhead in $r \cdot min^{-1}$, V_L is the velocity limit in $m \cdot min^{-1}$ (based on the cutter diameter, as noted above), and D_{TBM} is the machine diameter in m. Larger cutters typically have higher velocity limits and are suitable for larger TBMs. A higher cutterhead rotational speed means a higher rate of penetration (ROP), assuming that the machine power is sufficient.

The cutter tip width, T, is another parameter to be selected; this controls the cutting forces, F, in an almost linear fashion ($F \sim T$). The typical tip width varies from 12.5 mm to 25 mm. The higher the capacity of the cutter and the higher the strength and abrasivity of the rock, the higher tip width is needed.

2.2. Cut spacing

The second step in cutterhead design involves the selection of the cutting geometry, including the spacing and location of the cutters on the profile. Selection of the spacing and penetration is a function of the cutting forces. Although the allowable cutter load is the first parameter to check when selecting the cutting geometry, it is necessary to keep in mind that an overall check of the TBM thrust, torque, and power may be needed in order to verify the assumption of the penetration at the end of the design cycle.

Optimum spacing is a concept that has been discussed in the literature; it refers to the spacing at which the required energy of rock cutting/excavation is minimized for a given depth of penetration [14]. The most common measure of optimization is the use of specific energy (SE), which is the amount of energy required to excavate a unit volume of rock. SE is typically expressed in $hp \cdot h \cdot cyd^{-1}$ (1 hp = 745.700 W), $hp \cdot h \cdot ton^{-1}$, $kW \cdot h \cdot m^{-3}$, or in similar units that express energy per volume or weight of excavated rock. It has been proven that the magnitude of SE is minimized when plotted against the spacing-to-penetration (S/P) ratio. The range of S/P ratios that require a minimum SE, or a so-called optimum S/P ratio for disk cutters, is typically within 10–20, although it has been reported to be as low as 6 and as high as 40. The optimum range of S/P ratio is a function of rock type; it increases with rock brittleness and can change slightly with varying penetration. However, for the most part and for practical design, an S/P ratio of 10–20 is often used in order to select the optimum spacing for a given range of penetration. For example, if the anticipated penetration is about 5 $mm \cdot r^{-1}$, which is typical for granitic rock, the range of optimum spacing is between 50 mm and 100 mm. In general, however, in order to avoid ridge buildup in high-strength and tough rocks, a spacing of 75–100 mm is selected for most cutterhead