Experimental Study on Partial Wear of TBM Disc Cutter

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2024 Prognostics and System Health Management Conference (PHM) | 979-8-3503-6058-5/24/$31.00 ©2024 IEEE | DOI: 10.1109/PHM61473.2024.00054

***Abstract*—In tunnel construction with Tunnel boring machines (TBMs), accurate knowledge of disc cutter failure states is crucial for ensuring efficient operation and preventing delays and cost overruns. This study investigates the influence of partial wear on disc cutter excavation parameters in shield tunneling operations. Meticulously designed experimental setups and procedures were employed to obtain precise excavation parameters, enabling faithful replication of the excavation process. The experimental apparatus, including a scaled-down shield test rig, adhered closely to similarity criteria with an actual shield. Careful designs of the cutterhead and disc cutters allowed for the simulation of various wear scenarios. Comprehensive data collection facilitated real-time analysis of excavation parameters, enhancing the scholarly robustness of the study. The investigation focused on the impact of failure states of disc cutters on torque and thrust, critical metrics for assessing shield tunneling efficiency. Results indicated that increasing partial-wear rates of disc cutters led to distinctive trends in mean and standard deviation of torque and thrust, revealing the complex interplay between partial wear and excavation parameters.**

Keywords—Tunnel boring machine (TBM), Disc cutter, Partial wear, Excavation parameters

I. Introduction

Disc cutters constitute critical components within tunnel boring machines (TBMs) and are pivotal to the success of tunneling operations. Although disc cutters are designed to endure harsh and unpredictable underground conditions [1], they often experience elevated failure rates due to the substantial stresses and abrasion encountered during operation [2-3]. Considering the significant consequences of cutter failures, it is imperative to assess the health status of these components and promptly replace any damaged units [4]. However, the existing maintenance approach for disc cutters relies heavily on periodic manual inspections. This methodology necessitates TBM shutdowns and the deployment of maintenance personnel into the TBM cutterhead. Consequently, it poses considerable safety hazards, reduces TBM utilization, escalates construction costs, and ultimately proves highly inefficient [5]. Routine maintenance efforts often yield either inadequate or excessive interventions. Statistical data emphasize that cutter consumption contributes to one-third of the total tunnel construction costs. Additionally, the time allocated to cutter inspection and replacement comprises approximately one-third of the overall project duration [6-7]. In light of these challenges, the development of disc cutter failure detection and early warning technologies has garnered substantial research interest.

The state-of-the-art of disc cutter fault detection methods can be broadly categorized into two distinct approaches: sensor-based real-time monitoring and data-driven prediction. The development and application of sensor-based technologies encounter significant challenges due to the harsh operating conditions and limited installation space inherent in tunneling environments. Moreover, the high costs associated with sensors and challenges in signal transmission present additional hurdles to the practical implementation of these technologies on construction sites, confining their utility largely to laboratory settings [8]. In contrast, data-driven approaches aim to predict disc cutter status by leveraging excavation data [9]. For instance, Karami [10] conducted research aimed at estimating the cumulative volumetric mass loss of disc cutters using metrics such as the compressive strength index (CAI) and rock quality designation (RQD). Through this investigation, Karami provided a chart to determine disc cutter wear. Notably, these data-driven models, founded upon statistical analyses of extensive datasets, underscore the valuable insights embedded within excavation parameters concerning the interaction dynamics between worn disc cutters and rocks, thus enabling effective wear prediction. However, these studies mainly focus on prediction normal wear, leaving a significant gap in research on abnormal damage, which is quite common in engineering.

Abnormal damage in disc cutters manifests in various forms, including partial wear, fracture, and edge curling, distinct from the gradual material removal observed in normal wear [11-13]. Notably, partial wear emerges as the most prevalent type of abnormal damage encountered in tunneling operations [14]. For instance, in the Gaoligong Mountain tunneling project in China, partial-worn cutters constituted 58.3% of the total number of abnormally damaged cutters and 18.2% of the overall worn cutters [15], as depicted in Fig. 1(a). Fig. 1(b) provides a visual representation of the partial wear state observed in the cutterhead of a decommissioned TBM. The implications of such damage surpass those of normal wear [16]. During the partial-wear process, the cutter ring undergoes rapid and partial deterioration, often attributed to cutter bearing failure or obstructions hindering rotation around the cutter shaft, thereby

2166-5656/24/$31.00 ©2024 IEEE

DOI 10.1109/PHM61473.2024.00054

limiting contact between the cutter and the rock surface [17]. The transition from rolling to sliding motion exacerbates wear at the contact interface between the cutter ring and the rock, thereby accelerating the wear rate of adjacent disc cutters and precipitating premature failure [18]. Failure to promptly replace partially worn cutters can compromise the integrity of the entire cutter head and drive system, posing significant safety hazards and entailing substantial economic losses.

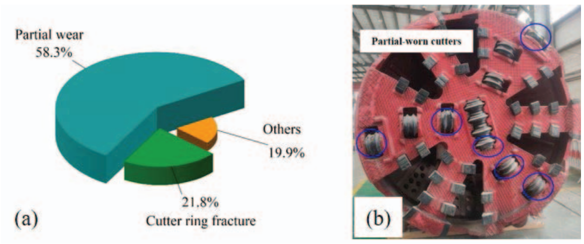

Fig. 1. The partial wear: (a) Proportion of partial-worn cutters in total damaged cutters; (b) Partial-worn cutters in cutterhead.

To assess the impact of partial wear, Sun et al. [19] conducted rock-cutting experiments to analyze the changes in cutting forces, rock fragmentation, and energy consumption. However, their investigation primarily centered on individual disc cutters, overlooking the broader implications of partial wear in terms of its quantity and extent on the overall loading of the TBM. There is a notable deficiency in systematic research on partial wear. Knowledge gaps persist regarding the alterations in tunneling parameters following partial wear, efficient real-time detection of partial wear occurrence, and evaluation of the degree of partial wear.

To address these knowledge gaps, this study investigates the differences in tunneling parameters between partially worn and normal disc cutters. This investigation aims to facilitate the development of models capable of evaluating partial wear rates, thereby enhancing construction operations and maintenance practices.

The remainder of this paper is organized as follows: a series of experiments on both normal and partial-worn cutters are carried out based on a reduced-scale shield test rig. The torque and thrust in tunneling parameters under different failure modes are acquired and analyzed, and some conclusions are drawn.

II. Experimental Methodology

This section delineates the experimental setup and procedure devised to investigate partial wear of disc cutters. Attaining precise and dependable excavation parameters necessitated a meticulously designed experimental framework capable of faithfully reproducing the excavation process. The procedural methodology adhered to a systematic approach, enabling the conduct of experiments and the systematic documentation of observed wear patterns in the disc cutters.

A. Experimental Set-up

In the context of tunneling operations, the TBM encompasses a multitude of operational parameters that pose challenges for complete replication in scaled-down experiments. This study centers on investigations pertaining to partial wear, employing a shield test rig at a reduced scale. The principal parameters under scrutiny encompass the size and material composition of the cutterhead and disc cutters, as well as thrust force, advance speed, cutterhead rotation speed, and cutterhead torque. The established similarity ratio between the test rig and the operational TBM deployed at the Zhengzhou Metro construction site stands at 10:1. The criteria for scaling are as follows: (1) Ensuring conformity of the cutterhead and disc cutter materials with those utilized in the actual TBM, alongside proportional diameters and specifications. (2) Aligning the thrust force exerted by the test rig with the actual thrust force of the TBM. (3) Synchronizing the advance speed of the test rig with the TBM's operational advance speed. (4) Maintaining proportionality between the cutterhead torque in the test rig and the actual cutterhead torque of the TBM. (5) Ensuring parity between the cutterhead rotation speed in the test rig and the actual rotation speed of the TBM.

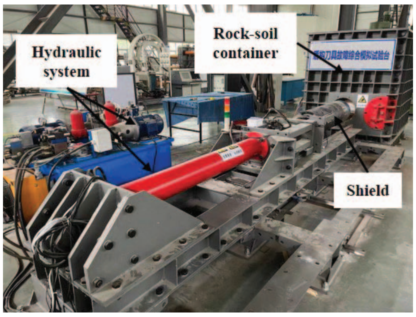

Fig. 2. The reduced-scale shield test rig for experiments on partial wear.

TABLE I. Primary Technical Specifications

Technical parameter	Design value
Overall dimensions (mm)	4300×866×1300
Maximum stroke (mm)	1300
Cutterhead Rotation Speed (r/min)	0-10
Maximum allowable torque (N·m)	1000
Advancing speed (mm/min)	0-50
Size of rock-soil container (mm)	1200×1500×1500

Fig. 2 depicts the test rig configuration, comprising a hydraulic system, shield, and rock-soil container. Table I provides a comprehensive overview of the primary technical specifications associated with the test rig. Control over the horizontal displacement of the shield is facilitated by the hydraulic system, whereas rotation is propelled by a servo motor. Positioned at the forefront of the shield machine, the cutterhead accommodates both normal and partially worn disc cutters, secured in place using bolts.

The compound cutterhead utilized in this study is purposefully engineered to primarily drive the rotation of disc cutters for rock-breaking applications, as depicted in Fig. 3(a). The illustration depicts a configuration comprising 15 cutter seats distributed across the cutterhead. Among these, 12 seats host positive disc cutters, evenly spaced at 60-degree intervals along the circumference, while the outer circle accommodates 3 seats housing edge disc cutters. These are positioned at intervals of 120 degrees and inclined at an angle of 10 degrees. For clarity, the 15 disc cutters are labeled numerically, and their respective installation radii are specified in Fig. 3(a) and Table II. It is worth noting that disc cutters numbered 1 to 12 correspond to positive disc cutters, while numbers 13 to 15 denote edge disc cutters. Moreover, scrapers are divided into three groups, each spanning 120 degrees, with 8 units per group. These scrapers are affixed to the opening edge of the cutterhead. The dimensions of the scrapers have been proportionally downscaled at a ratio of 1:10, following established engineering conventions.

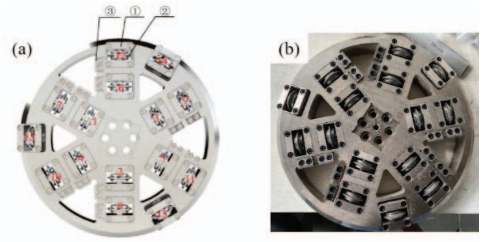

Fig. 3. Cutterhead: (a) schematic structure and disc cutter numbering diagram: ①-cutter seat; ②-disc cutter; ③-scraper, (b) Assembly of the cutterhead

TABLE II. INSTALLATION RADIUS OF DISC CUTTERS

Number	Installation radius (mm)	Number	Installation radius (mm)
1	65	2	70
3	75	4	80
5	85	6	90
7	120	8	125
9	130	10	135
11	140	12	145
13	147	14	149
15	151		

In engineering applications, partial wear of disc cutters typically stems from bearing failures or impediments hindering their rotation around the cutter shaft, leading to a transition from rolling to pure sliding motion between the cutters and the rock [20]. To accurately replicate the significant differences between normal and partially worn cutters, effective structural modifications were implemented for both the cutter seat and the disc cutter during the experimental phase. As depicted in Fig. 4, the cylindrical ends of the normal cutter were replaced with a square structure, and corresponding adjustments were made to the cutter seat, facilitating the occurrence of cutter jamming during shield tunneling—a condition referred to as a trapped cutter. Under such circumstances, the cutter ring remains unworn. Moreover, when the outer contour of the cutter no longer maintains a complete circular shape, it is classified as a partially worn cutter, as exemplified in Fig. 5. The geometric configuration of the contact area can be partitioned into two distinct regions: the arc surface and the plane. The depth of partial wear is defined as the disparity between the radius and the perpendicular distance from the disc cutter's center to the contact plane. To faithfully simulate this scenario, the designed cutters underwent linear incisions, progressively experiencing depths of partial wear wherein 0.5mm, 1.0mm, 1.5mm, and 2.0mm of material were successively removed from the cutting ring. Correspondingly, the actual partial wear depths amount to 5mm, 10mm, 15mm, and 20mm, respectively.

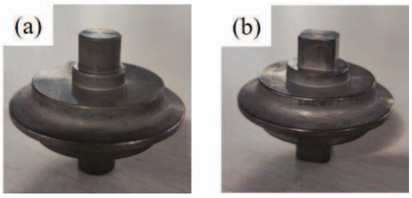

Fig. 4. Structural design of disc cutters: (a) Normal cutter, (b) Trapped cutter.

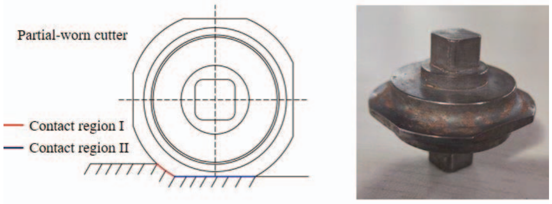

Fig. 5. Partial-worn cutter.

A composite stratum comprising soft soil overlying sandstone was chosen for the shield tunneling experiments, and it was positioned within the rock-soil container. All materials utilized in the experiments were sourced from the same construction site of the Zhengzhou Metro to ensure uniformity in composition and strength. The rock-soil container's dimensions were 1200×1500×1500, significantly larger than the shield's excavation diameter, thus reducing the impact of constrained boundaries during the experiments. To facilitate real-time data collection during excavation, a comprehensive data acquisition and monitoring system was deployed. This system records a variety of parameters, including cutterhead speed, advance speed, cutterhead torque, and thrust, at a sampling frequency of 1 Hz. High-precision torque sensors (0-1000 Nm) and wheel-type pressure sensors (0-80 tons) were employed to measure cutterhead torque and thrust, respectively. Cutterhead speed and advance speed were derived from the signal output ports of a servo motor driver.

B. Experimental Procedure

The experimental procedure comprises several sequential steps. Initially, the shield is adjusted to the appropriate excavation position. Subsequently, the rock-soil container is filled with the composite strata. During the assembly process, the disc cutters are arranged according to varying failure ratios. Following these preparatory stages, the full-face excavation mode is selected on the control console, with the cutterhead speed set to 6 r/min and the advance speed set to 6 mm/min. To explore the influence of partial wear on excavation parameters, seven distinct test groups were established, each characterized by different proportions of failed cutters and varying depths of partial wear. The specific parameters for each test group are outlined in Table III. In practical engineering scenarios, it has been observed that disc cutters positioned farther from the center of the cutterhead are more susceptible to failure [21]. Consequently, the arrangement of failed cutters progresses from the outer periphery towards the inner ring of the cutterhead, with an escalating proportion of failures. Each test group underwent three repetitions, with an excavation distance of 10 mm per repetition. The resulting average values were computed and presented as the conclusive findings of this study.

TABLE III. PROPERTIES OF THE EXPERIMENTAL MATERIALS

Index	Proportion	Numbers	Types of cutters	Partial-wear depth (mm)
1#	0	/	Normal	0
2#	25%	10, 11, 12	Trapped	0
3#-1			Partial-worn	0.5
3#-2				1.0
3#-3				1.5
3#-4				2.0
4#	50%	7, 8, 9, 10, 11, 12	Trapped	0
5#-1			Partial-worn	0.5
5#-2				1.0
5#-3				1.5
5#-4				2.0
6#	75%	4, 5, 6, 7, 8, 9, 10, 11, 12	Trapped	0
7#-1			Partial-worn	0.5
7#-2				1.0
7#-3				1.5
7#-4				2.0

III. RESULTS AND ANALYSIS

Excavation parameters play a pivotal role in numerous models aimed at investigating the interaction mechanisms between disc cutters and rock [22]. Specifically, the thrust along the tunnel axis and the cutterhead torque around the tunnel axis are widely recognized as the excavation loads of cutter groups and serve as crucial metrics for assessing the tunneling efficiency of a shield. The former denotes the aggregate of normal forces exerted on all disc cutters, while the latter signifies the cumulative total of the rolling forces acting on the disc cutters multiplied by their respective installation radii. Consequently, fluctuations in these parameters reflect alterations in the cutting forces exerted by the disc cutters, thereby serving as indicators of disc cutter health status.

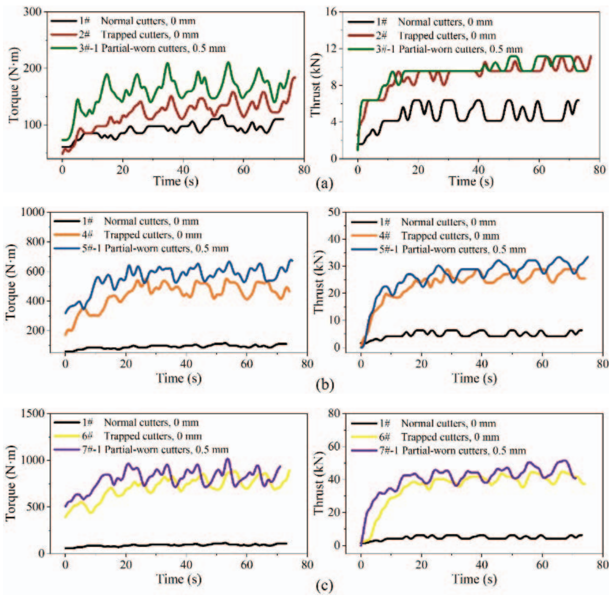

Fig. 6. Torque and thrust of different proportions of failed cutters: (a) 25%, (b) 50%, (c) 75%.

Fig. 6 illustrates the torque and thrust curves associated with different types of disc cutters. Initially, during the stage of shield tunneling, both torque and thrust experience rapid increases before stabilizing, marked by periodic fluctuations. This trend arises due to elastic deformation of the disc cutters upon initial contact with the rock, resulting in a swift escalation of cutting forces. Subsequently, as the rock approaches its strength limit, fractures begin to propagate, leading to a sharp decline in cutting forces. Consequently, the rock-breaking load exhibits a periodic fluctuation pattern during excavation. In cases where normal cutters become trapped and cease rotation, torque and thrust experience notable increases (1#, 2#, 4#, 6#), thus diminishing the rock-breaking efficiency of the cutters. The alteration in motion pattern elevates sliding friction forces, outweighing rolling friction forces, thereby significantly amplifying the rolling forces exerted by the cutters, and subsequently increasing torque. Changes in the geometric shape of the cutter's contact area influence rock fragmentation patterns, promoting the accumulation of rock powder in the contact region II plane, consequently augmenting normal force and thrust. As contact areas develop wear on trapped cutters, the plane length increases proportionally with the depth of partial wear, intensifying sliding friction between cutters and rock. This results in slight increases in thrust and torque for the affected cutters (2# and 3#-1, 4# and 5#-1, 6# and 7#-1). However, compared to normal cutter failures, these alterations are relatively minor.

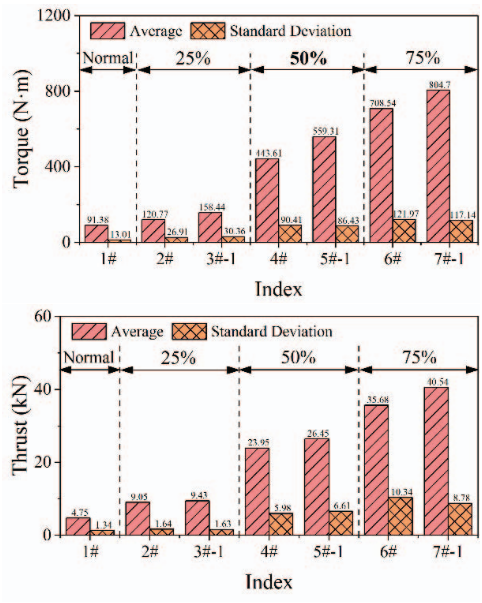

Fig. 7. Torque and Thrust data statistics.

Fig. 7 presents the average values and standard deviations of torque and thrust obtained from each test group, serving as statistical features of the data signals in the time domain. Among instances where the cutters remained in normal condition, both torque and thrust exhibited the smallest values. Correspondingly, standard deviations were also minimal, indicating relatively low fluctuations experienced by the normal cutters, with minor disparities between maximum and minimum cutting forces (1#). This stability may be attributed to the intact circular contact area, which maintained consistent contact with the rock. As the number of partially worn cutters increased, reflecting a higher failure rate (25%, 50%, 75%), noticeable elevations in torque and thrust, accompanied by larger standard deviations, were observed (1#, 2#, 4#, 6#). However, the impact of partial wear, with identical partial-wear rates, on the standard deviation was found to be insignificant. In certain cases, partial wear even led to a reduction in standard deviation (4# and 5#-1, 6# and 7#-1). This observation suggests that enlarging the plane area has minimal effect on the contact stability between cutters and rock, thus exerting minor influence on load fluctuation magnitude.

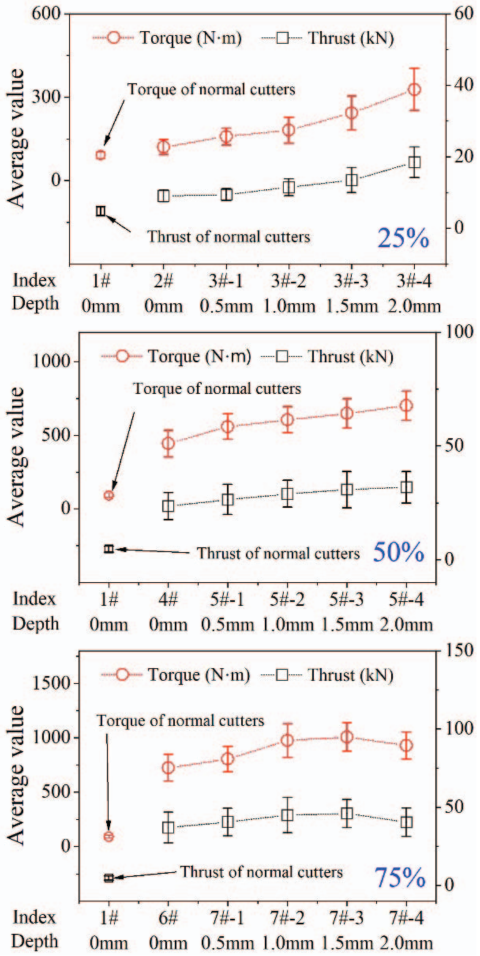

Fig. 8. Average torque and thrust of different partial-wear depth.

Fig. 8 provides a comparative analysis of torque and thrust at varying partial-wear depths, offering a visual depiction of the substantial impact of partial-wear rates on shield tunneling parameters. At a partial-wear rate of 25% (2#, 3#-1, 3#-2, 3#-3, 3#-4), both the mean and standard deviation of torque and thrust exhibit an upward trend. This trend can be attributed to the increased contact area resulting from partial wear, consequently augmenting normal forces and sliding friction forces on the cutters. As the partial-wear rate reaches 50% (4#, 5#-1, 5#-2, 5#-3, 5#-4), the rate of increase in mean values decelerates, with standard deviation tending to stabilize. Ultimately, at a partial-wear rate of 75% (6#, 7#-1, 7#-2, 7#-3, 7#-4), fluctuations in torque and thrust are observed at a partial-wear depth of 1mm. This observation likely stems from a critical level of cutter failures, wherein the shield's rock-breaking capacity approaches its limit. At this stage, the front face of the cutterhead becomes enveloped by soil and rock, necessitating heavy reliance on scrapers and edge cutters positioned along the outer edge of the cutterhead for excavation advancement.

IV. Conclusion

This study aimed to investigate the impact of partial wear on disc cutter excavation parameters through systematic experimental setups and procedures. Careful designs of the cutterhead and disc cutters were employed to simulate various wear scenarios, while comprehensive data collection facilitated real-time analysis of excavation parameters. The following conclusions are drawn from the current study:

1) During stable excavation phases, torque and thrust in excavation parameters often exhibit periodic fluctuations. These fluctuations stem from the force exerted on the cutter reaching the ultimate strength of the rock, causing the cutter to penetrate the rock and form cracks, ultimately leading to the spalling of rock chips, triggering a decrease in torque and thrust.

2) Instances where normal cutters become trapped and cease rotation result in a sharp increase in torque and thrust. This phenomenon arises due to the transition in movement pattern between the cutter and rock from rolling friction to sliding friction, altering the geometry of their contact area. As the wear depth increases, the flat area expands. Compared to normal cutter failure, this condition has a much smaller impact on excavation parameters.

3) Statistical analysis results indicate that an increase in the partial-wear rate leads to an increase in torque and thrust. Meanwhile, the standard deviation shows that the flat contact area between partially worn cutters and the rock tends to stabilize the amplitude of data fluctuations.

4) With the partial-wear rate remaining constant, torque and thrust increase with the increase in wear depth. However, when partial-wear rate increases to 75%, torque and thrust remain stable or even decrease. This indicates that the surface of partially worn cutters is covered by rock and soil, which may pose serious dangers to the entire cutterhead system and even the entire TBM.

Acknowledgment

This work was partially supported by the Natural Science Basic Research Program of Shaanxi (ProgramNo. 2019JLZ-13), the National Key R&D Program of China (Grant No. 2022YFC3802305), the National Natural Science Foundation of China (No. 52105074), the Open Project of State Key Laboratory of Shield Machine and Boring Technology (No. SKLST-2021-K02).

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