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ORIGINAL ARTICLE

Effects of mixed-ground condition on tool life and cutterhead maintenance of tunnel boring machines

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Abstract This paper aims to investigate the impact of mixed ground conditions and the presence of groundwater, which are critical geotechnical variables during mechanized tunneling, on the tool life, reliability, and maintainability of the EPB-TBM cutterhead. To achieve this goal, field data from the Tabriz urban railway project were gathered and classified into two groups: failures occurring in the tunnel's upper section above the water level and failures in the lower section below the water level. A comprehensive analysis of this data was conducted. The examination of various cutting tool types' consumption in mixed ground conditions revealed that scrapers had the highest replacement rate, while other tool types experienced fewer replacements. In terms of maintainability, the analysis showed that under dry ground conditions, there is an 80% probability of completing cutterhead maintenance within less than four shifts. However, in saturated ground conditions, this figure rises to 18.5 shifts. The reliability analysis demonstrated that the mean time between failures in dry ground and below the water level stands at 49.8 and 107.4 h, respectively. The significant contrast between maintainability and reliability findings underscores the influence of ground conditions on machine downtime and operational efficiency. The outcomes of this study provide valuable operational benchmarks that can be applied in EPB mechanized tunneling, enabling better project scheduling and enhancing the reliability of construction contracts.

Keywords Maintainability · Reliability · Wear · Earth pressure balance (EPB)

1 Introduction

Replacing worn or damaged cutting tools poses a time-intensive challenge in mechanized tunneling, with potential impacts on TBM utilization, project costs, and timelines. To accurately assess TBM performance, project duration, and costs, a dependable evaluation of tool wear and cutterhead maintenance is essential (Hassanpour et al. 2014). The impact of ground conditions on tool life in tunneling machines has typically been explored through laboratory experiments, field observations, and numerical simulations. In early investigations, Köppl et al. (2015) introduced an empirical predictive model for wear of cutting tools in hydro-shield TBMs, utilizing the Soil Abrasivity Index (SAI). Rostami et al. (2012) devised a soil abrasivity test for soft ground shield machines, simulating tool working conditions in pressurized face shields' excavation chamber. Katushin et al. (2013) focused on lab-based wear tests for drag bit materials used in tunneling machines. Jakobsen et al. (2013) introduced the Soil Abrasion Tester (SGAT) device and showcased its ability to assess, quantify, and compare the effects of soil mineralogy, pressure, and water content on SGAT excavation tool wear. Mosleh et al. (2013) conducted an experimental study on cutting tool wear, simulating tool

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operation conditions in soil and examining the impacts of relative hardness and moisture on tool wear.

While multiple studies have explored cutting tool wear, the application of the aforementioned methods has been confined to homogeneous and uniform ground conditions. The complexity of constructing a tunnel in mixed-ground settings introduces notable limitations to their applicability. Mixed-ground conditions entail the simultaneous occurrence of two or more geological formations characterized by distinct geomechanical properties, hydrogeological conditions, or varying degrees of weathering at the tunnel face (Jakobsen 2014; Ma et al. 2015). Notably, the presence of boulders within the soil matrix poses a critical challenge to cutting tool lifespan reduction, a facet that has not received adequate attention in prior literature (Zhu and Ju 2005). In situations where tunneling occurs in grounds laden with cobblestones and boulders, cutting tools experience excessive wear, tears, failures, and even dislodgment (Thewes and Maidl 2013; Maidl et al. 2014).

This research paper aims to investigate the tool life and cutterhead maintainability of an earth pressure balance (EPB) TBM in the context of the Tabriz urban railway project. This project serves as a representative example of a tunnel located in complex and mixed-ground conditions. The paper also encompasses an analysis of failure modes for cutting tools, along with their classification within the case study tunnel.

2 Maintainability and reliability analysis

Maintainability refers to a trait inherent in an item or system, quantified by the likelihood that maintenance or repair activities are conducted within a specified timeframe using predetermined procedures and allocated resources (Birolini 2007). From a qualitative perspective, maintainability can be described as an item's capacity to either retain its intended condition or be reinstated to a predefined state (Dhillon 2008). Maintainability aspect can be mathematically expressed through Eq. 1:

$$m(t) = \int_{0}^{t} f_r(t).d(t) \tag{1}$$

where$f_r(t)$ represents the probability density function of repair downtime. Given that downtime data reflects the performance of maintenance practices and support systems, maintainability analysis plays a pivotal role in guiding the selection of appropriate corrective measures and enhancing operational effectiveness (Ben-Daya et al. 2009).

Reliability, on the other hand, refers to the likelihood that an item or system executes its intended function satisfactorily without experiencing failure within a specified time interval and under defined conditions (Ben-Daya et al. 2009). The reliability function can be mathematically defined as shown in Eq. 2:

$$R(t) = 1 - F(t) = 1 - \int_{0}^{t} f(t).d(t) \tag{2}$$

where R(t) represents the reliability at time t, f(t) denotes the failure density function (pdf) of the time between failures, and F(t) signifies the cumulative failure distribution function (CDF) (Hussin et al. 2013). Analyzing the time to repair (TTR) and time between failures (TBF) datasets enables the determination of the maintainability and reliability characteristics of repairable systems.

3 Tunnel boring machine's cutterhead maintenance

The role of the cutterhead is pivotal in ensuring the effective performance of Tunnel Boring Machines (TBMs) in mechanized tunneling projects (Zhang et al. 2016). In EPB-TBMs, worn-out or broken tools within the cutting chamber can be replaced to maintain operational efficiency. In urban settings, maintenance procedures for EPB-TBM cutterheads and associated tools often involve hyperbaric interventions (HI). However, in mixed-ground conditions, employing hyperbaric interventions becomes challenging due to the presence of obstacles like boulders, sand, and gravel in the tunnel face. These obstructions cause persistent pressure losses during air bubble creation and escalate water flow into the chamber. Consequently, maintenance duration and costs significantly increase. Typically, the time required for changing cutting tools during hyperbaric interventions can be calculated using Eq. 3:

$$T_{d.i} = T_{pre.i} + T_{cc.i} + T_{pos.i} \tag{3}$$

where $T_{d.i}$ is the total maintenance downtime or time to repair (TTR), $T_{pre.i}$ is the time for preparation, $T_{cc.i}$ is the time for cutting tool changing, and $T_{pos.i}$ is the time for post-processes activities.

The "preparation time" encompasses several shifts and involves the following tasks:

- Installing hyperbaric intervention equipment
- Emptying the chamber
- Injecting bentonite suspension into the chamber
- Awaiting the formation of a filter cake on the tunnel face

Subsequently, the maintenance team enters the chamber through a man lock to carry out repair and replacement of cutting tools under compressed-air conditions. Bentonite is reintroduced into the chamber at the end of each work shift.

After completion, post-process activities involve relocating all equipment outside the tunnel.

4 Cutting tools in soft and mixed-grounds

In soft ground tunneling, the standard cutting tools frequently employed include drag bits, teeth/picks, scrapers, rippers, peripheral bucket tools, and copy cutting tools. For cohesive ground, where clay and silt form the bulk of excavated materials, drag bits, teeth, and picks are utilized. In sandy grounds, scraper tools are commonly applied, designed to provide a cutting action that peels chips over the front edge of the blade. Ripper tools find use in coarse grain soil conditions like gravels (Li et al. 2017). Peripheral bucket tools and copy cutter tools are typically employed to safeguard the cutterhead rim and allow for overcutting. In mixed-ground conditions, a combination of various cutting tool types is often integrated into the cutterhead to address the diverse strength characteristics of different formations and face components.

5 Case study: Tabriz urban railway project

The Tabriz urban railway project involves the excavation of two parallel tunnels, each with a diameter of 6.9 m and a length of approximately 8 km, using two EPB-TBMs. The cutterhead is specifically designed to function effectively in both soft and mixed ground conditions. These tunnels traverse a diverse range of geological formations, including gravely-sand, sandy-silt, clay-sand, and silty-sand, which contain a notable volume of rock blocks and boulders. The excavation is carried out in two distinct sections, taking into consideration the groundwater level. Section one (S1) spans 2.5 km and is positioned above the water level, while section two (S2), with a total length of 5.5 km, lies below the groundwater level.

Comprising 46 rippers, 98 scrapers, 12 bucket knives, and 20 peripheral bits (as shown in Fig. 1a, b), the cutterhead is configured to address the challenges posed by the mixed-ground conditions. The careful arrangement of these cutting tools facilitates the cutterhead's passage through the formations, preventing issues such as TBM clogging and disc jamming (Bilgin et al. 2016). These problems can significantly impact critical performance factors including torque, thrust, energy consumption, and ultimately the tunneling advance rate.

5.1 Failure modes and life analysis of cutting tools

TBM cutting tools exhibit distinct failure modes that are closely associated with their types and positions within the cutterhead. Primarily, there are two primary failure modes observed in TBM cutting tools: wear and breakage. Wear refers to the surface deterioration or removal of material from one or both solid surfaces as a result of sliding, rolling, or impact motion relative to another surface (Sastri 2015). Wear occurs due to various mechanisms, including abrasion, adhesion, surface fatigue, erosion and percussion impact, chemical or corrosive action, and wear induced by electrical arcs. The dominant mechanism in a given application depends on the specific tribological system. Drucker (2011) conducted experimental studies and concluded that abrasion is the prevalent wear mechanism for cutting tools in mechanized tunneling employing a TBM.

Another failure mode encountered in cutting tools is breakage, which occurs due to significant impact loads, such as those resulting from encountering mixed-ground conditions with large boulders. In this scenario, when the cutter transitions from soft ground to hard rock, the cutting tools are subjected to high levels of stress. This type of damage occurrence can be effectively described through statistical methodologies that account for the likelihood of encountering substantial boulders or obstacles in the excavated ground along with the probability of cutting tool breakage (Felletti and Pietro 2009; Küpferle et al. 2017).

In the examined TBM case, the recorded failure data indicates that the predominant failure mode (approximately 90%) for cutting tools is breakage, while the remaining failures are attributed to normal wear. Specifically, scraper tools are prone to breakage when encountering boulders or coarse-grained soils, prior to experiencing wear. Unlike ripper tools that work in both rotational directions of the cutterhead, scraper tools operate in a single advance direction due to their distinct geometry. This one-directional movement contributes significantly to the damage incurred by scraper tools. The presence of broken scrapers on the cutterhead of the TBM under investigation is illustrated in Fig. 1, while examples of worn scraper samples are depicted in Fig. 2.

The longevity of cutting tools can be expressed in various manners, but the most common metric is the length of tunnel excavated per cutting tool (m/cutter). In the context of the studied project, the available data was segregated based on the designated sections (S1 and S2), and the lifespan of the cutting tools was examined across two distinct statistical groups (depicted in Figs. 3 and 4, along with Table 1). The analysis reveals that the lifespan of cutting tools in the dry ground condition is shorter compared to the section situated below the water level. Consequently, it can be inferred that scraper tools exhibit the shortest lifespan, averaging 5.45 m per cutter in Sect. 1 and extending to 9.14 m in Sect. 2.

In order to compare the performance of cutting tools under the two distinct ground conditions studied, a statistical analysis was conducted on the entire dataset of replaced scrapers' lifetimes. To achieve this, various

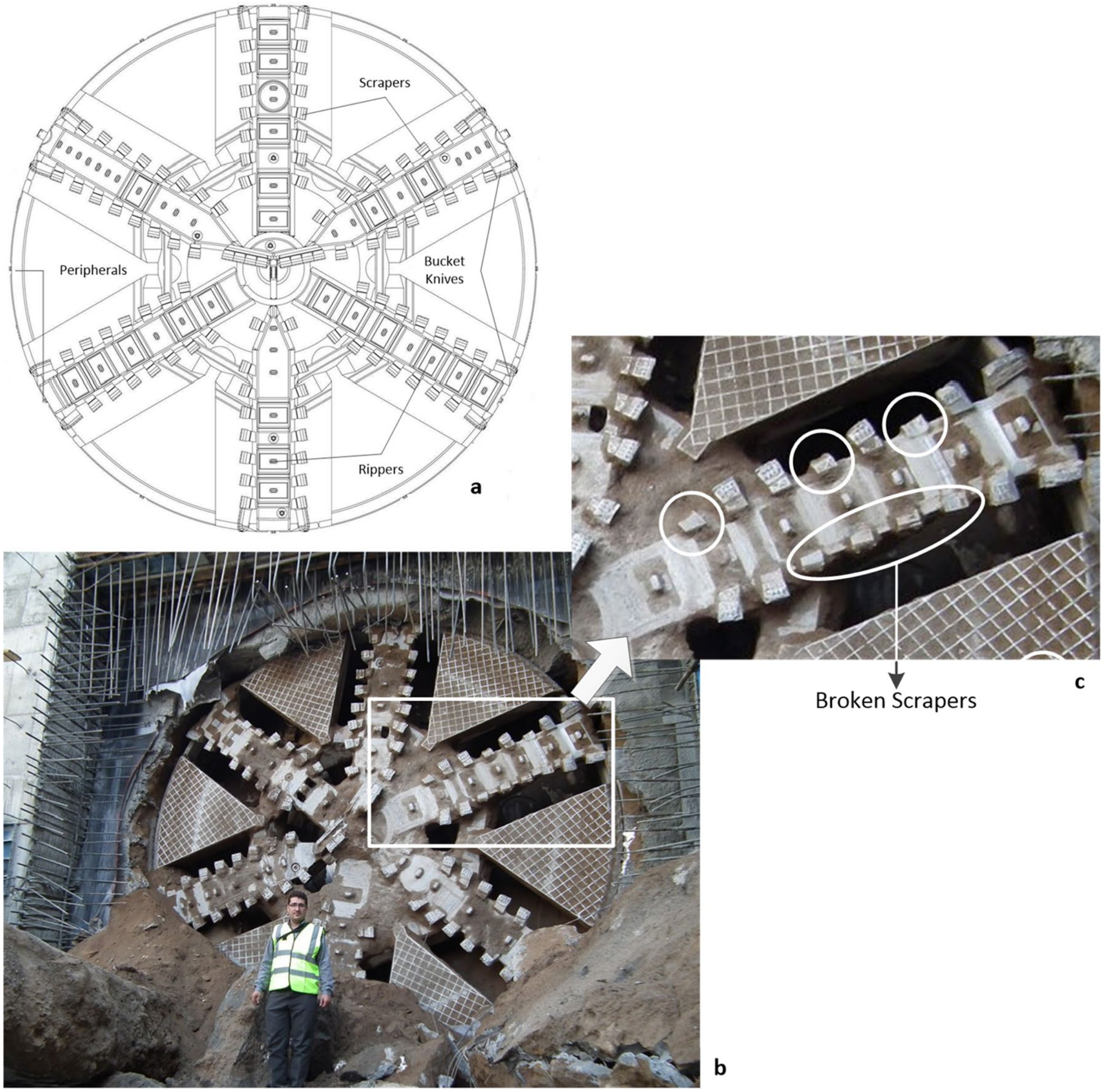


Fig. 1 TBM cutterhead in Tabriz urban railway project; **a** overall arrangement of cutting tools, **b** cutterhead after finalizing the tunnel excavation, **c** broken scrapers

Fig. 2 Samples of worn scrapers in the case study tunnel

probability distribution functions were examined with the available dataset, and the most suitable distribution functions were selected for each section. The findings indicate that the lifespan of scraper tools in Sect. 1 adheres to a log-logistic distribution, while in Sect. 2, it follows an exponential distribution. The histogram depicting the lifespan data, the chosen best-fitted functions, and their corresponding parameters are showcased in Fig. 5. The analysis unequivocally reveals that the consumption of cutting tools in section one is approximately twice as high as in section two. This discrepancy can be attributed to factors such as the ground condition, soil conditioning procedures, and the types of additive materials employed (such as foam, bentonite, and others).

Fig. 3 Cutter life (meter/cutter) in Sects. 1 (above the underground water level)

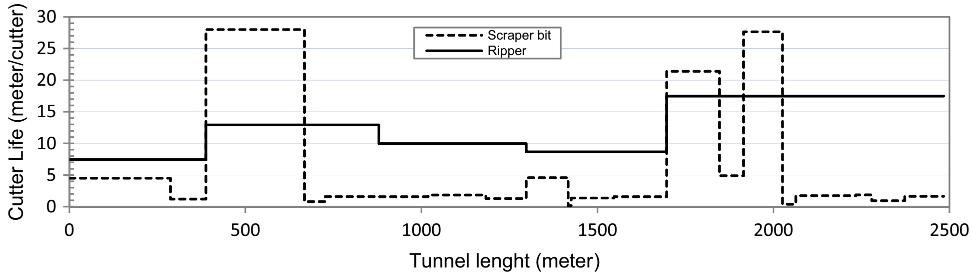


Fig. 4 Cutter life (*meter/cutter*) in Sects. 2 (below the underground water level)

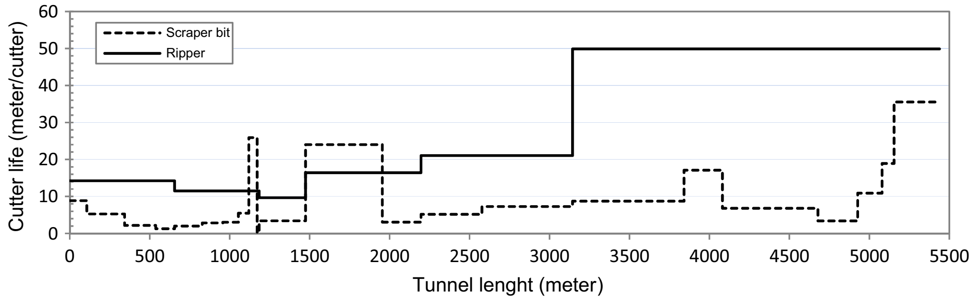
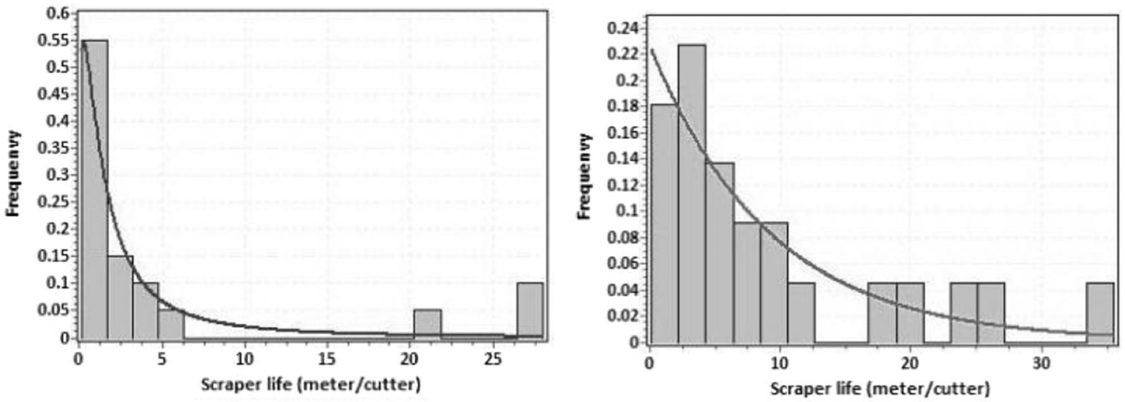


Table 1 Average cutting tool life in different ground conditions

	Scraper	Ripper	Bucket knives	Peripheral protection bit
Number of tools on the cutterhead	98	46	12	20
Cutter life in Sect. 1 (below the underground water level) (*meter/cutter*)	5.45	11.30	19.36	47.03
Cutter life in Sect. 2 (above the underground water level) (*meter/cutter*)	9.14	20.46	48.14	128.93



Section 1, life function of Log-Logistic with α=1.203, β=1.908and estimated mean(m/c)=5.25

Section 2, life function of exponential with λ=0.1093 and estimated mean(m/c)=9.15

Fig. 5 Best-fitted life probability density functions for scraper cutter life (m/c)

During the maintenance activities and cutting tool replacement procedures, data pertaining to the quantities of replaced tools during different stoppages in both sections were extracted from the database, as illustrated in Figs. 6 and 7. Notably, scrapers accounted for a significant portion of the replacements, whereas other types of tools underwent comparatively fewer replacements.

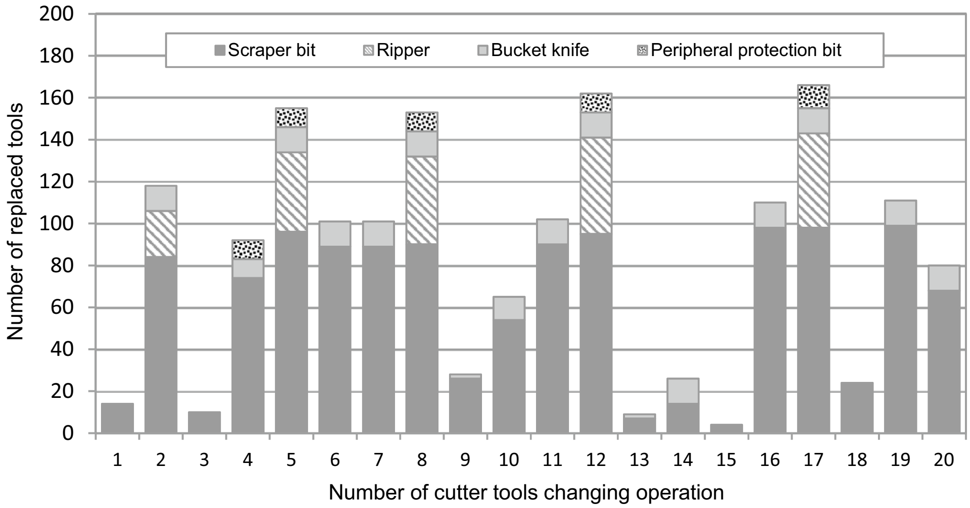


Fig. 6 Number of replaced cutting tools in various replacement and maintenance operations in S1

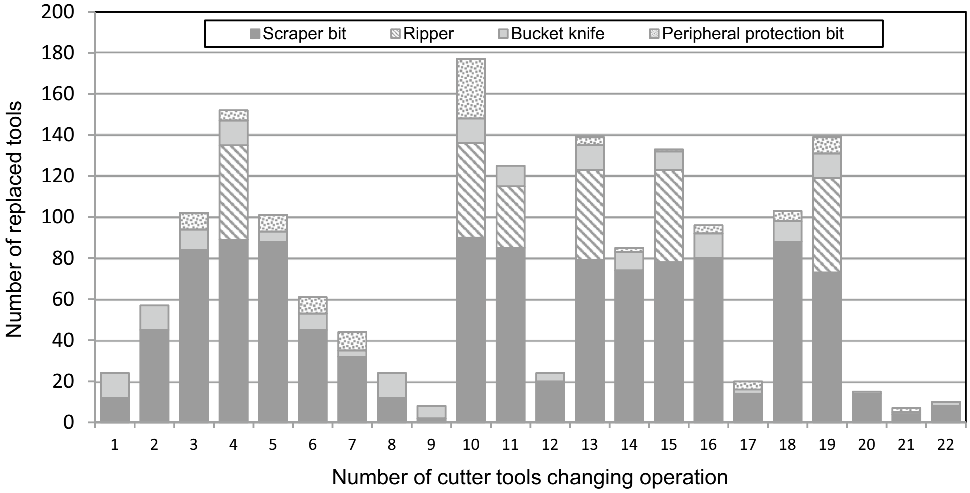


Fig. 7 Number of replaced cutting tools in various replacement and maintenance operations in S2

5.2 Maintainability and reliability analysis of the case study TBM cutterhead

The operational data collected from the case study tunnel indicates a TBM utilization rate of approximately 15%, with an average advance rate of 4.5 m per shift. This lower utilization rate can be attributed to significant mechanical downtimes, primarily linked to cutterhead backup and maintenance logistics systems. Notably, half of the total TBM repair downtimes are associated with cutterhead maintenance, particularly the replacement of cutting tools. Consequently, in-depth field studies and comprehensive statistical analyses are essential to address this issue and better understand the maintainability status of the examined TBM's cutterhead.

Initially, the time to repair (TTR) and time between failures (TBF) for all recorded maintenance operation data related to the cutterhead were extracted from the central database and computed. The subsequent analysis involved categorizing the aggregated data into two distinct statistical groups based on the time and location of operations: maintenance actions conducted below the groundwater level and above the groundwater level. A meticulous examination was performed to assess whether the data sets were independent and identically distributed (IID). This assessment included applying trend and serial correlation tests, which are established methods for evaluating the IID assumption. For this study, graphical tests were conducted following the procedures outlined by Kumar (1990) and Hoseinie et al. (2012). In the graphical approach, the trend test entails plotting the cumulative number of total downtimes against the cumulative total downtimes (CTTR) for Maintainability analysis. Similarly, the cumulative number of failures was plotted against cumulative operating time (CTBF) for reliability analysis. When the data shows no discernible trend, the fitted line on the graph remains straight (Lindqvist 2006). The results of the serial correlation and trend test for TTR in Sect. 2 are presented in Fig. 8.

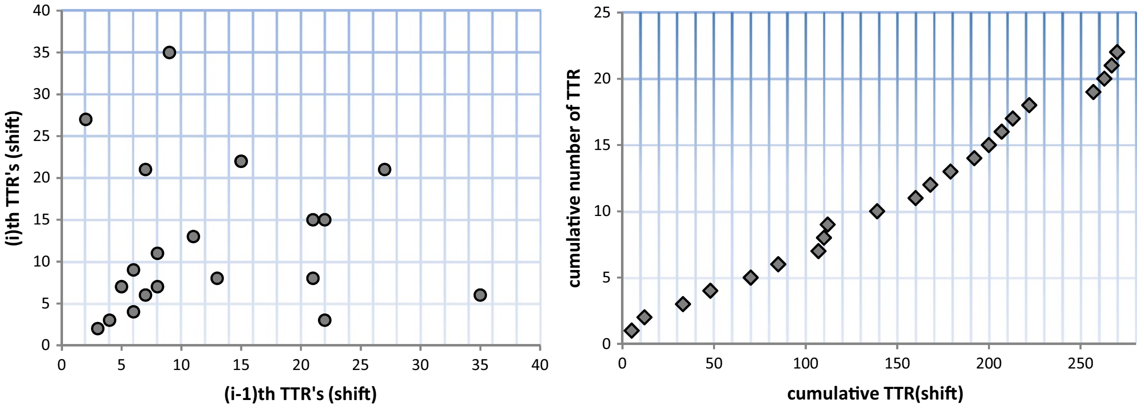


Fig. 8 The results of serial correlation and trend test (iid)—TTR: Sect. 2

The assessment for serial correlation was conducted by plotting the ith TBF or TTR against the (i-1)th TBF or TTR. If the plotted points are randomly distributed without any discernible pattern, it indicates a lack of correlation among the TBFs and TTRs data, thereby signifying data independence (Barabady and Kumar 2008). The outcomes of these tests for TTR and TBF data indicate that the failure data in both tunneling sections (S1 and S2) are independent and identically distributed. As a result, the renewal process can be applied for maintainability and reliability analysis. With the IID hypothesis confirmed, further statistical analysis was undertaken by fitting the most appropriate distribution function to the two data sets. The Kolmogorov–Smirnov (KS) test was employed to identify the best-fitting distributions, and their parameters were estimated using the maximum likelihood estimator (MLE). The analysis concludes that the log-logistic and three-parameter log-logistic distributions are the optimal fits for TTR data sets in sections one and two, respectively. Similarly, the logistic and Weibull distributions provide the best fit for TBF data sets in sections one and two, respectively. A comprehensive presentation of the detailed results of the statistical analysis can be found in Table 2.

he findings indicate that downtime in Sect. 1 ranges from one shift to eight shifts, with an average of 2.85 shifts. In contrast, in Sect. 2, it spans from two shifts to 35 shifts, averaging 12.27 shifts. The more extensive downtime in Sect. 2 can be attributed to challenging conditions such as water flow and an unstable tunnel face, leading to prolonged maintenance operations. The significant discrepancy is primarily attributed to the intensified preparation tasks, bolstering the resistance and permeability of the tunnel face, and maintaining consistent pressure in the chamber amidst demanding ground conditions.

The maintainability and reliability plots of the cutterhead in the two distinct ground conditions are visually depicted in Figs. 9 and 10.

As evident from the findings, in favorable ground conditions, there exists an 80% probability of completing cutterhead maintenance in less than four shifts. In contrast, this probability rises significantly to 18.5 shifts under mixed-ground conditions. These findings solidly demonstrate how ground conditions directly influence machine downtime and operational efficiency. It's crucial to note that maintenance is exclusively conducted during day shifts, while bentonite reinjection operations are carried out during night shifts. The maintenance tasks are executed by a crew of three members, with a maximum of three hours of work time allocated for each dive into the chamber.

Table 2 The results of Statistical analysis (TTR and TBF)

		Section 1	Section 2
Maintainability (TTR)	Best-fitted distribution	Log-Logistic	Log-Logistic (3P)
	Parameters	$\alpha = 2.205$	$\alpha = 1.819$
		$\beta = 2.09$	$\beta = 8.04$
			$\gamma = 1.188$
	Mean total downtime (shift)	3	15.25
Reliability (TBF)	Best-fitted distribution	Logistic	Weibull
	Parameters	$\alpha = 14.54$	$\alpha = 1.193$
		$\beta = 49.8$	$\beta = 113.98$
	Mean TBF (hr)	49.8	107.4

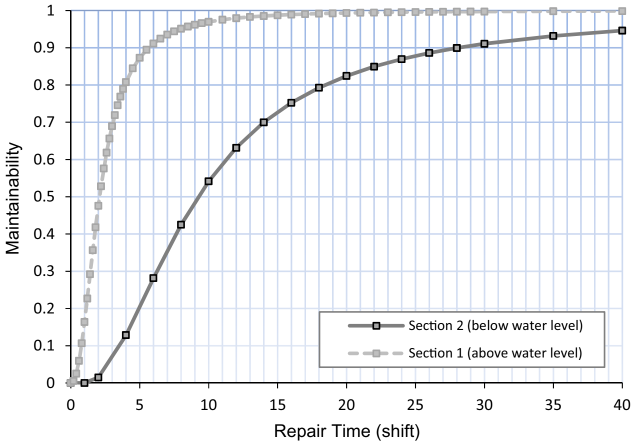


Fig. 9 Maintainability plots of cutterhead of case study EPB-TBM machine in different ground conditions

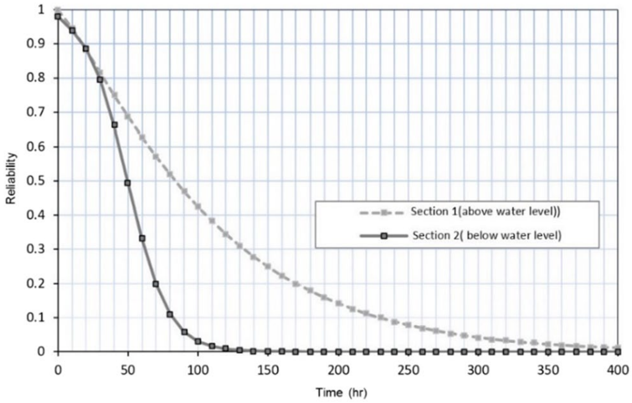


Fig. 10 Reliability plots of cutterhead of case study EPB-TBM machine in different ground conditions

Consequently, two working groups are required to operate during each shift.

6 Conclusion

This paper utilizes field data obtained from maintenance operations of EPB-TBM within the Tabriz urban railway project to conduct a comprehensive statistical analysis. The study focuses on analyzing the replacement frequency of cutting tools, along with examining the maintainability and reliability of the cutterhead, under varying ground conditions, particularly accounting for underground water presence.

The study's findings underscore the substantial impact of diverse operational and maintenance factors on TBM performance, especially when operating below the groundwater level and encountering mixed-ground conditions. The ground condition variation results in a significant reduction of tool life by 42% (from 9.15 to 5.25 m per cutter). The research also reveals that breakage constitutes the most common failure mode (90%) for scrapers on the studied cutterhead, while the remaining failures are attributed to normal wear. These findings underscore the pivotal role of factors like the strength, size, and frequency of coarse-grained soils and existing boulders in mixed-grounds. Addressing these factors becomes crucial, not just during excavation but also from the initial exploration phase, to ensure effective tunneling operations.

The conducted investigations and subsequent statistical analysis underscore the critical influence of underground water, a characteristic of challenging ground conditions, on EPB tunneling operations, leading to potential reductions in TBM utilization. From a different perspective, the maintainability analysis reveals notable differences in estimated downtime. Specifically, in dry ground conditions, the average downtime is around 3 shifts (1.5 days), while in conditions below the water level, it extends to approximately 15.25 shifts (7.6 days). Further analysis confirms that in favorable ground conditions, there is an 80 percent likelihood of completing cutterhead maintenance within fewer than four shifts. However, in demanding ground conditions, this probability increases significantly to 18.5 shifts. The reliability analysis also indicates variations, with the estimated mean time between failures (MTBF) being 49.8 h for dry ground and 107.4 h for conditions below the water level.

In conclusion, the outcomes of this study offer valuable operational benchmarks that can be effectively utilized in EPB mechanized tunneling projects to enhance project scheduling and bolster the reliability of construction contracts. This research underscores the importance of integrating explorational geotechnical studies not only for ground support and excavation design but also for optimizing maintenance and overhaul operations, thereby enhancing maintenance logistics and the overall support system.

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