The 2025 World Congress on
Advances in Structural Engineering and Mechanics (ASEM25)
BEXCO, Busan, Korea, August 11-14, 2025

Statistical investigation of mechanisms contributing to abnormal wear in TBM disc cutters

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ABSTRACT

While numerous studies have investigated the occurrence of disc cutter wear, the majority have focused on normal wear conditions. This study employs statistical analysis to explore the mechanisms contributing to abnormal wear in TBM disc cutters. The Wasserstein distance was utilized to identify features with significant differences in their distributions between normal and abnormal wear. Four features, including chamber pressure, elastic modulus, thrust force, and screw conveyor RPM, were found to exhibit significant differences. Additionally, the cumulative distribution functions (CDFs) of these features indicated that chamber pressure and thrust force were positively correlated with the occurrence of abnormal wear, while elastic modulus and screw conveyor RPM exhibited negative correlations.

1. INTRODUCTION

With the increasing importance of underground space development, Tunnel Boring Machines (TBMs) have been widely adopted in tunnel excavation. Among their key components, disc cutters are subject to continuous wear, which is inevitable during operation. Disc cutter wear can be classified into two types: normal wear, characterized by uniform abrasion, and abnormal wear, which includes partial wear and fractures. Abnormal wear causes stress concentration and may lead to brittle fracture of cutter ring (Ge et al., 2022). Furthermore, abnormally worn cutters can disrupt the rotation of adjacent cutters and potentially damage the cutterhead itself (Li et al., 2024). Disc cutters exhibiting abnormal wear should be promptly replaced upon detection, as delays in replacement can significantly increase both construction time and cost. Accordingly, it is essential to predict and manage abnormal disc cutter wear.

Although several studies have been conducted to predict cutter wear (Gehring, 1995; Rostami, 1997; Bruland, 1998), most rely on theoretical or empirical approaches that do not fully account for diverse geological conditions and TBM operational parameters. To address these limitations, machine learning-based approaches have recently been introduced (Zhang et al., 2023; Kim et al., 2024; Shin et al., 2024; Kwon et al., 2025; Yeom et al., 2025). However, since abnormal wear occurs far less frequently than normal wear, machine learning models are often biased toward predicting normal wear. Moreover, the limited availability of abnormal wear data makes it challenging to identify the underlying mechanisms. As a result, research on abnormal disc cutter wear remains limited.

In this study, the mechanisms underlying abnormal wear were investigated through statistical analysis. Using a dataset collected from a TBM tunneling site, the Wasserstein distance was applied to identify features that significantly influence abnormal wear. Furthermore, the cumulative distribution functions (CDFs) of the identified features were analyzed to examine their correlations with the occurrence of abnormal wear.

2. Statistical analysis

The dataset used in this study was collected from an Earth Pressure Balance (EPB) Tunnel Boring Machine (TBM) tunneling site. The geological conditions at the site comprised weathered, soft, and hard rock layers, along with gravelly sedimentary deposits interspersed with cohesive soils. The TBM was equipped with 50 disc cutters mounted on the cutterhead. For this analysis, center and gauge cutters were excluded, with a focus placed on 32 face cutters.

2.1 Difference in data distribution

A total of 13 features potentially influencing disc cutters wear were selected. Box plots illustrating the data distributions of each feature are presented in Fig. 1, where blue and red boxes represent normal and abnormal wear, respectively. Among these features, GWL refers to the groundwater level measured from the tunnel crown, while CF (Concentration of Foam), FIR (Foam Injection Ratio), and FER (Foan Expansion Ratio) are related to foam injection parameters. The plots indicate that several features, such as elastic modulus, thrust force, chamber pressure, and screw conveyor RPM, exhibit clear differences in distribution between normal and abnormal wear.

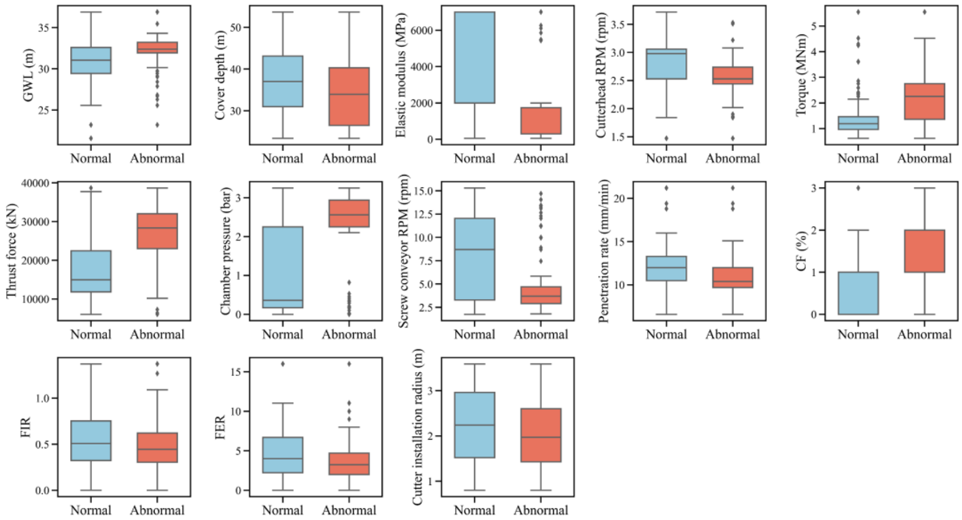


Fig. 1 Box plot of each feature

2.2 Quantification of distributional difference

To quantitatively assess the differences in feature distributions between normal and abnormal wear, the Wasserstein distance was employed. This metric measures the dissimilarity between two probability distributions by calculating the minimal cost required to transform one distribution into the other (Panaretos and Zemel, 2019). In this study, the Wasserstein distance was computed for each feature and subsequently normalized by the corresponding data range to derive the Wasserstein-distance ratio. This ratio facilitates a comparative analysis of the relative distributional differences across features. As shown in Fig. 2, elastic modulus, chamber pressure, thrust force, and screw conveyor RPM exhibit relatively high Wasserstein-distance ratios, suggesting that these four features are particularly influential in distinguishing between normal and abnormal wear.

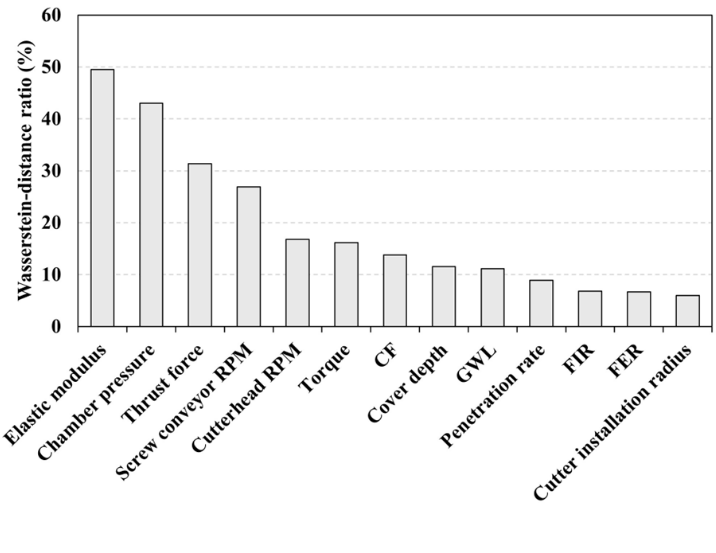
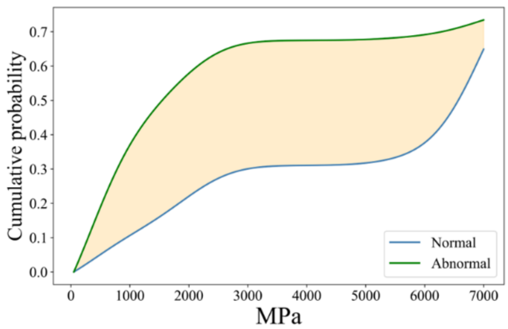


Fig. 2 Wasserstein distance ratio of each feature

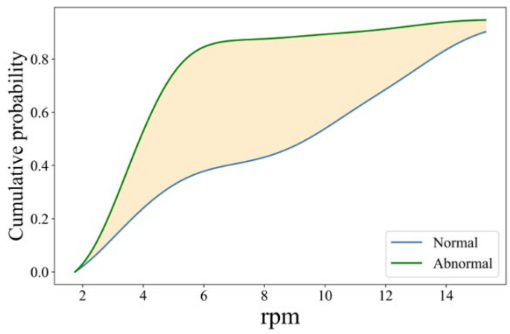
2.3 Correlation with abnormal wear

To further examine the relationship between each influential feature and abnormal wear, cumulative distribution functions (CDFs) are presented in Fig. 3. In Fig. 3(a), the CDF for abnormal wear exhibits a steep increase up to an elastic modulus of approximately 2,500 MPa, indicating that abnormal wear predominantly occurs under ground conditions with low elastic modulus, such as soft or mixed ground with lower stiffness. Similarly, Fig. 3(b) shows a rapid rise in the CDF for abnormal wear up to a screw conveyor RPM of 6 rpm, suggesting that abnormal wear is more likely to occur at relatively low screw conveyor speeds. Fig. 3(c) demonstrates that the CDF for abnormal wear remains nearly constant up to a chamber pressure of 2.0 bar, after which it increases sharply. This implies that abnormal wear tends to occur more frequently under higher chamber pressures. In Fig. 3(d), a noticeable rise in the CDF for abnormal wear is observed beyond a thrust force of 20,000 kN. Excessive chamber pressure used to stabilize the tunnel face or elevated thrust force can increase friction between the disc cutter and the muck, impeding smooth cutter rotation and contributing to abnormal wear.

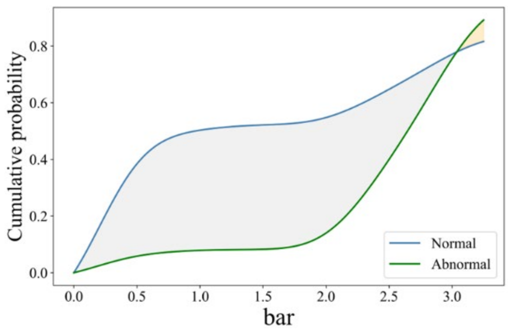
The CDFs for elastic modulus and screw conveyor RPM rise earlier than those for normal wear, indicating a negative correlation with the likelihood of abnormal wear. In contrast, the CDFs of chamber pressure and thrust force increase later than those for normal wear, suggesting a positive correlation with the occurrence of abnormal wear.



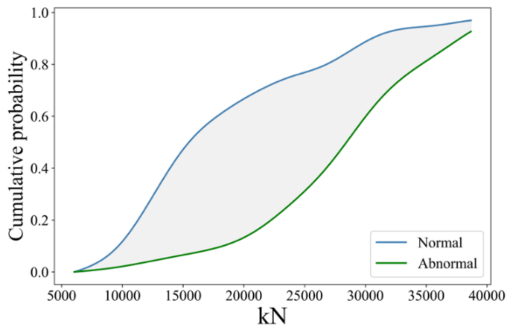
(a) Elastic modulus



(b) Screw conveyor RPM



(c) Chamber pressure



(d) Thrust force

Fig. 3 CDF of each influential feature

3. CONCLUSIONS

This study investigated the mechanisms underlying abnormal wear of disc cutters using three statistical analysis approaches. This analysis identified four key features showing distinct trends following abnormal wear: elastic modulus, chamber pressure, thrust force, and screw conveyor RPM. Specifically, abnormal wear was associated with higher chamber pressure and thrust force, as well as lower elastic modulus and screw conveyor RPM.

ACKNOWLEDGEMENT

This research was supported by the Korea Agency for Infrastructure Technology Advancement under the Ministry of Land, Infrastructure and Transport (No. RS-2024-00410248).

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