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

Enhanced Prediction of Disc Cutter Wear and Failure in Complex Ground Conditions using XGBoost

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ABSTRACT

Accurately predicting disc cutter wear and ensuring timely replacement are critical for improving excavation efficiency and minimizing operational downtime in tunnel boring machine projects. Existing disc cutter life prediction models are typically developed under the assumption of homogeneous ground conditions and are only designed to estimate normal wear of the disc cutter. In complex grounds, unpredictable wear types can occur, accelerating cutter failure and inducing excessive loads on adjacent cutters, negatively impacting excavation efficiency. The study proposes a machine learning-based prediction model that enhances the accuracy of disc cutter wear forecasting in complex ground conditions. A predictive model utilizing the XGBoost classification algorithm was developed to determine cutter replacement needs and classify the corresponding wear patterns. The positions of cutters on the cutterhead were incorporated as a key correction factor to enhance predictive accuracy. The model demonstrated enhanced performance in capturing the variability of wear mechanisms in challenging geological settings. This research contributes to a better understanding of disc cutter wear behavior and provides practical insights for optimizing tunneling operation strategies.

1. INTRODUCTION

Shield Tunnel Boring Machine (TBM) is being increasingly adopted for tunnel construction projects with the growing demand for tunnel construction in urban areas. Accordingly, predicting disc cutter wear and the optimal timing for replacement have become essential for tunneling efficiency and minimizing costs. Existing disc cutter life prediction models, such as CSM (Colorado School of Mines)(Roastami, 1997), NTNU (Norwegian University of Science and Technology)(Bruland, 1998 and Macias, 2016), and Gehring (Gehring, 1995) models are primarily based on experience based formulas and laboratory tests conducted under homogeneous ground conditions. As a result, their

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predictive accuracy diminishes in complex ground conditions, and they are incapable of identifying abnormal wear states that may arise in heterogeneous or mixed ground layers. Jung et al. (2010) analyzed disc cutter consumption at domestic subway construction sites and found that the actual total consumption was more than twice the amount predicted by existing models. These limitations of conventional prediction models emphasize the necessity for developing a model capable of accurately predicting disc cutter wear patterns and lifespan under complex ground conditions.

Disc cutter wear during excavation in heterogeneous ground conditions is governed by multiple factors. This study proposes a disc cutter replacement decision model based on the eXtreme Gradient Boosting (XGBoost) classification algorithm, which employs the continuously recorded TBM machine data and wear measurements obtained throughout the excavation process. By incorporating real-time excavation data, the proposed model not only predicts normal wear patterns but also detects abnormal wear phenomena arising from ground strength variability, face irregularities, and impact loads. The development of such a model aims to enhance operational efficiency and reliability of TBM tunneling.

In this study, the performance of the XGBoost model was compared with those of conventional machine learning models, including k-Nearest Neighbors (KNN), Support Vector Machine (SVM), and model stacking techniques employed in previous studies (Kim et al.,2024). The results demonstrated that the XGBoost model achieved improved performance in predicting disc cutter replacement decisions. Furthermore, the model was able to identify major influencing factors associated with abnormal wear occurrences.

2. Site Overview

2.1 Geological and tunneling condition

The tunnel project in this study has a total length of 3,930 m, of which only the section beneath the river was excavated using a slurry shield TBM. The geological strata are distributed from the surface to the landfill layer, including sedimentary layers, weathered soil, weathered rock, and bedrock (which encompasses both soft rock and hard rock). The tunnel passage section consists of a composite stratum, and a large number of boulders were found in it, posing significant challenges to excavation efficiency. The geological profile at the site is shown in Fig.1, and the data were collected and utilized for the study from the red dotted box (length 490m with 327 rings). Fig.2 shows the selected mechanical data such as thrust, torque, cutter head rotation per minute (RPM), and penetration rate (PR) were analyzed based on their relevance to disc cutter wear among the hundreds of types of data generated during tunneling. These parameters, averaged by ring from second-by-second data, varied with ground conditions and machine operational states. In mixed ground conditions, thrust and torque tend to increase while RPM and PR decrease, indicating higher loads on the disc cutters and reduced excavation efficiency. Furthermore, it was observed that when disc cutters reached their wear limits, torque increased significantly and both RPM and PR declined, suggesting that changes in mechanical data can effectively reflect cutter wear conditions.

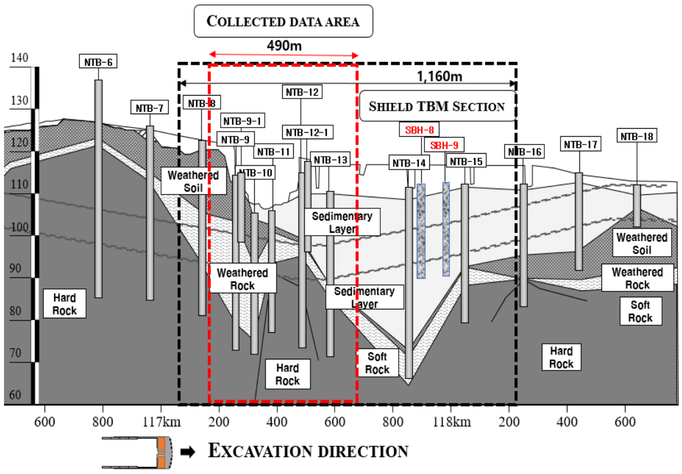

Fig.1 Geological profile at tunneling site (Kim et al., 2024)

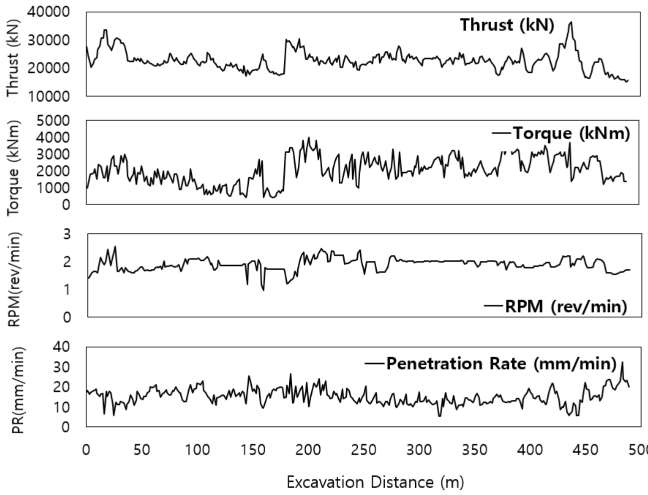

Fig. 2 Shield TBM operational data in excavation distance

2.2 Disc cutter wear patterns

As the TBM excavates through the ground, disc cutters mounted on the cutter head serve as a cutting tool for rock and naturally undergo wear during the excavation process. Disc cutter wear can be categorized into normal and abnormal wear, depending on ground and tunneling operation conditions. Normal wear refers to uniform abrasion formed along the cutter ring and typically occurs under homogeneous rock conditions. In contrast, abnormal wear of disc cutters is prone to occur in heterogeneous or mixed ground conditions, which often induce asymmetric loading and impact with hard rock or lithological boundaries, potentially leading to cutter ring breakage. Abnormal wear typically occurs in forms such as uneven wear, ring breakage or detachment, and mushrooming. Mushrooming, a form of the cutter profile deformation, can also develop when the cutter material is softer than the surrounding rock. Unlike normal wear, which is generally predictable in the wear limit of the cutter, abnormal wear is irregular and difficult to forecast due to the complex interplay between ground variability and mechanical response. Fig.3

illustrates the observed wear patterns of disc cutters at the time of replacement. A total of 188-disc cutters were replaced during excavation in the study site, and most disc cutters were replaced due to normal wear, but 22.9% of the disc cutters were replaced due to abnormal wear.

Normal wear	Uneven wear	Ring breakage
	Abnormal wear	

Fig. 3 Site-observed disc cutter wear at replacement

3. Disc cutter life prediction models with XGBoost Algorithm

3.1 XGBoost algorithms

XGBoost is a supervised machine learning algorithm and operates by building a parallel of decision trees, where each new tree is trained to correct the errors made by the previous trees, which solves many data problems in a fast and accurate, as shown in Fig.4. In addition, it is widely used for both classification and regression problems. The algorithm operates by constructing multiple decision trees, which are updated iteratively to minimize residual errors, thereby improving model performance. The final prediction is obtained by aggregating the outputs of all individual trees using a weighted approach. In a classification problem, the model combines the outputs to determine the most probable class label, whereas in a regression problem, it computes the weighted average of the predicted values.

3.2 Disc cutter wear prediction model with XGBClassifier

In this study, a disc cutter wear prediction model was developed using the XGBoost classification algorithm in this study. Input features were selected based on their correlation with cutter wear, which included key TBM operational parameters, such as thrust, torque, RPM, penetration rate, and excavation distance, along with the cutter position on the cutterhead (radius). Additionally, both ring-based rotation distance and accumulated rotation distance for each disc cutter were considered. The output feature was categorized into three classes: no replacement required (class 0), replacement due to normal wear (class 1), and replacement due to abnormal wear (class 2).

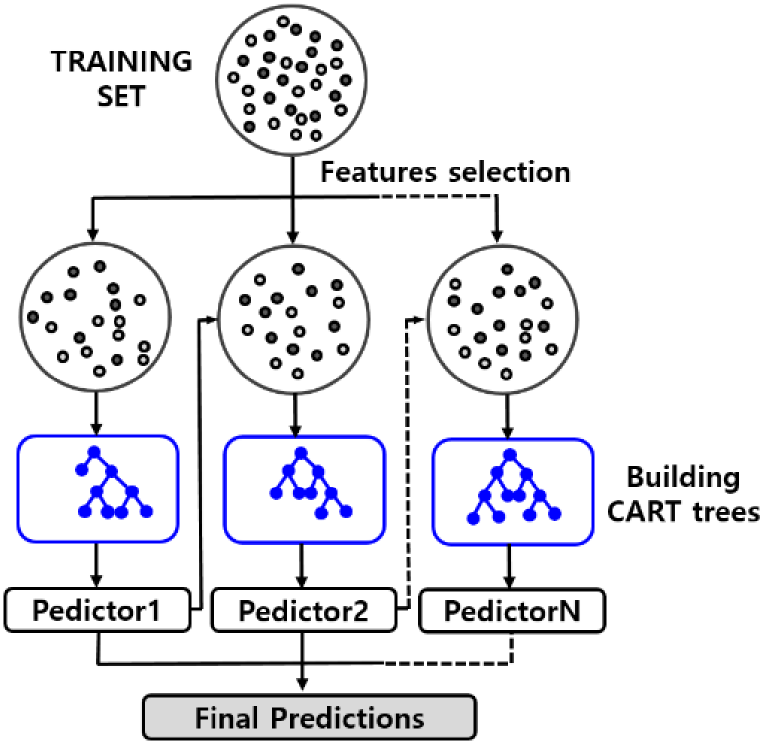

Fig.4 Flow chart of the XGBoost algorithm

The dataset used for model training is summarized in Table 1. To ensure reliable model performance, data preprocessing was conducted before training. This included outlier removal, normalization, and balancing class distributions using the Synthetic Minority Over-sampling Technique (SMOTE). After preprocessing, the dataset was applied to the XGBClassifier model within the XGBoost framework. Hyperparameter was tuned to optimize the model, which was then used to classify the necessity of cutter replacement and determine the type of wear condition at the time of replacement.

Table 1. Data configuration for binary and multi-class classification model

Input features	**Output feature (Multi-class classification)**
Excavation distance Disc cutter location (radius) Thrust RPM Torque Penetration rate Rotation distance Accumulated rotation distance	No replacement **(class 0)** Replacement for normal wear **(class 1)** Replacement for abnormal wear **(class 2)**

3.3 Model performance evaluation

The evaluation of the classification model is based on a confusion matrix, as shown in Table 2, which displays the confusion matrix for a three-class classification model. In a confusion matrix, the actual and predicted classes from the test output data can be counted, and evaluation indices such as accuracy, precision, recall, and F1-score can be calculated based on the matrix values (Grandini et al., 2020). Each class 2, 1, and 0 represents the replacement for abnormal wear, normal wear, or no requirement for replacement, respectively. The numbers in the matrix represent the number of predicted classes classified by the model for each actual class. Accuracy, Precision, Recall, and F1-score are the evaluation indices for evaluating the model performance, and these values in each class can be calculated from Eqs. (1) to (4), respectively.

Table 2. Confusion matrix for three-classes classification model

Confusion matrix for multiclass(3x3) classification		Predicted classes		
		Replacement for abnormal wear (2)	Replacement for normal wear (1)	No replacement (0)
Actual classes	Replacement for abnormal wear (2)	TP_2	FN_{21}	E_{20}
	Replacement for normal wear (1)	E_{12}	TP_1	E_{10}
	No replacement (0)	E_{02}	E_{01}	TP_0

$$\text{Accuracy} = \frac{\text{TP} + \text{TN}}{\text{TP} + \text{FP} + \text{FN} + \text{TN}} \times 100\ (\%) \tag{1}$$

$$\text{Precision} = \frac{\text{TP}}{\text{TP} + \text{FP}} \times 100\ (\%) \tag{2}$$

$$\text{Recall} = \frac{\text{TP}}{\text{TP} + \text{FN}} \times 100\ (\%) \tag{3}$$

$$\text{F1} - \text{score} = 2 \times \frac{\text{precision} \times \text{recall}}{\text{precision} + \text{recall}} \tag{4}$$

4. Results and Discussion

The cutter replacement decision model aims to determine the appropriate timing for disc cutter replacement, distinguishing among cutters that do not require replacement, those that require replacement due to normal wear, and those needing replacement due to abnormal wear. In this study, the performance of the proposed XGBoost model was compared with previously applied algorithms such as KNN, SVM, and a stacking ensemble model in a previous study by Kim et al. (2024). Fig. 5 presents a comparative evaluation of performance metrics across the different models.

The analysis was conducted in three categories: all cutters, cutters requiring replacement due to normal wear, and those requiring replacement due to abnormal wear. The XGBoost model demonstrated higher reliability than the single classifiers (KNN and SVM), and a performance comparable to that of the stacking ensemble model. Although the stacking model showed slightly better performance in classifying cutters with abnormal wear, the XGBoost model outperformed others in identifying cutters that needed replacement due to normal wear. These results indicate that XGBoost is a practical algorithm for making cutter replacement decisions.

Moreover, the XGBoost algorithm offers the advantage of quantifying the contribution of each input variable to the model predictions. As shown in Fig. 6, feature 'torque' was identified as the most influential feature, 22% in model training, whereas variables such as radius (representing cutter position on the head) and excavation distance were found to have relatively low importance. This suggests that mechanical parameters exert a greater influence than positional or cumulative data in determining whether a cutter should be replaced due to wear, particularly for distinguishing between normal and abnormal wear cases.

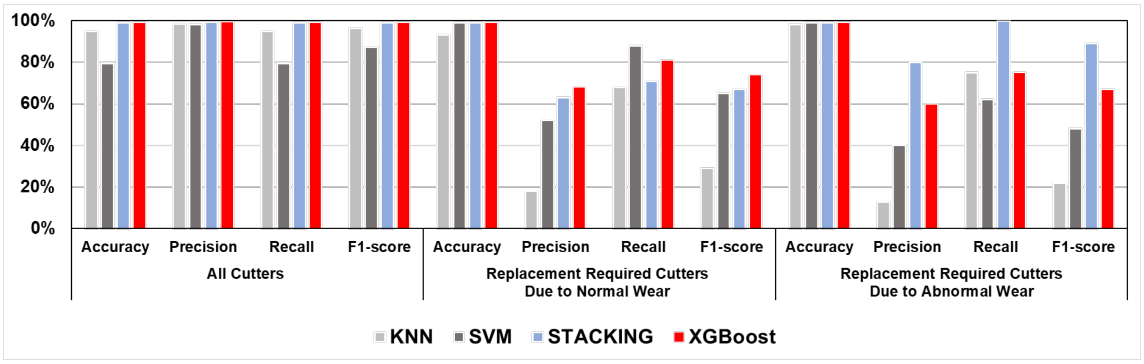

Fig.5 Comparison of performance evaluation indices for the disc cutter replacement decision model using XGBoost and other algorithms (KNN, SVM, STACKING)

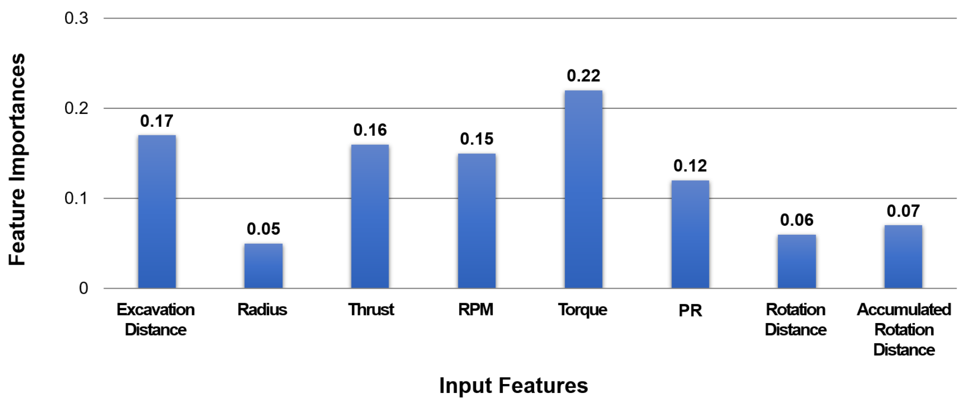

Fig.6 Feature importance of input variables in the XGBoost-based disc cutter replacement decision model

5. Conclusion

This study proposes a disc cutter wear prediction model based on the eXtreme Gradient Boosting (XGBoost) algorithm, aimed at improving the performance of cutter replacement decision models in shield TBM operations. By utilizing continuously recorded machine operation data alongside cutter position information, the model was able to classify the cutter wear condition with a high level of accuracy, including the identification of abnormal wear cases.

When compared with existing machine learning techniques such as KNN, SVM, and Stacking algorithms, the XGBoost model demonstrated enhanced performance in both predicting normal and abnormal wear. In particular, the model developed for predicting abnormal wear revealed that mechanical variables, such as torque, thrust, and RPM, had a significant influence on the prediction, as determined through feature importance analysis. Due to the significant loads imposed by thrust and torque on each disc cutter, especially in mixed ground conditions, these operational parameters have a pronounced impact on the progression of cutter wear.

The results of this study indicate that the proposed model can serve as a valuable decision-support tool for TBM operation, enabling timely cutter replacements and reducing unexpected downtime. Ultimately, the application of this approaches in tunnel projects contributes to improving the overall efficiency and reliability of mechanized tunneling projects.

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