Evaluating the Penetration Rate of Earth Pressure Balance Tunnel Boring Machines

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ABSTRACT

The penetration rate is a crucial parameter in the performance of Earth Pressure Balance (EPB) Tunnel Boring Machines (TBMs), which is used to assess the time and cost of completing a project. However, so far, no model has been presented to predict the penetration rate in soft soils, leading engineers to rely on approximate estimations based on similar projects. This results in significant inaccuracies in project completion time. In this article, statistical analysis has been conducted using performance data from EPB TBMs worldwide to examine the correlation between the penetration rate and its influencing factors. The parameters discussed include tunnel diameter, face pressure, undrained shear strength, unconfined compressive strength, head opening ratio, and standard penetration number. Based on the data analysis, three parameters, namely head opening ratio, unconfined compressive strength, and standard penetration number, have been identified as significant influencing factors. This article provides useful relationships for estimating the penetration rate with determination coefficients ranging from 68% to 72%. Considering the absence of an accurate performance prediction model for soft ground TBMs, the results of this study assist tunnel project engineers in the initial stages of the project by enabling better evaluation of performance parameters, time, and cost requirements.

KEYWORDS

EPB, Penetration rate, head opening ratio, unconfined compressive strength, standard penetration number.

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1. Introduction

The penetration rate (PR) is a vital performance metric for earth pressure balanced (EPB) tunneling machines, influencing both the timeline and cost of tunneling projects. Accurate estimation of PR is crucial for effective project management; however, existing predictive models for soft soils are often lacking. As a result, engineers frequently depend on rough estimates derived from analogous projects, which can lead to significant inaccuracies and unexpected delays in project timelines [1-3]. This study aims to systematically analyze the correlation between PR and various influential factors using a comprehensive dataset, thereby providing a more reliable framework for estimating project performance in the context of tunneling.

2. Methodology

Data were collected from 33 records concerning the operational performance of EPB tunneling machines from various projects worldwide. The key parameters analyzed include tunnel diameter, face pressure, consistency index, undrained shear strength, opening ratio of the cutter head, and standard penetration test (SPT) values. The analysis employed multiple linear regression techniques to identify significant relationships between penetration rates and the selected parameters.

The dataset was compiled from diverse geotechnical reports and research studies, ensuring a comprehensive representation of tunneling conditions. The methodology included the following steps:

- Data Collection: Gathering operational data from various geotechnical reports and scholarly articles related to tunneling projects.

- Parameter Selection: Identifying critical parameters that could impact the penetration rate, based on previous literature and expert recommendations (Table 1).

- Statistical Analysis: Utilizing multiple linear regression to analyze the relationships between penetration rates and selected parameters, determining the coefficients and significance of each factor.

Table 1: Summary of analyzed parameters

Parameter	Unit	Description
Tunnel Diameter	m	Diameter of the tunnel excavated
Face Pressure	kPa	Average pressure in the excavation chamber
Penetration Rate (PR)	mm/min	Rate of penetration of the cutter head per rotation
Standard Penetration Test (SPT)	-	Number of blows required to drive a sampler
Opening Ratio (OR)	%	Ratio of the total opening area to the cutter head area
Consistency Index	-	Measure of soil stiffness
Undrained Shear Strength	kPa	Shear strength of the soil in undrained conditions
Over Burden (OB)	m	Height above the tunnel crown to the ground surface

Fig. 1 shows the variation of penetration rate values in the database.

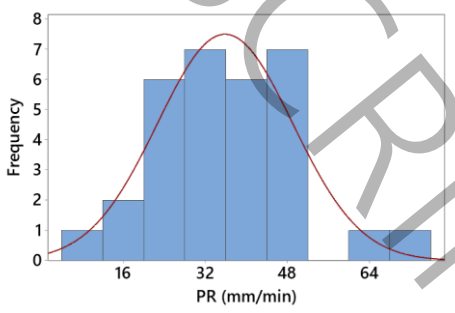

Figure 1. PR values distribution histogram

3. Results and Discussion

The results of regression analysis reveal several important trends:

- Opening Ratio (OR): A higher opening ratio is positively associated with increased penetration rates. This indicates that as the opening ratio increases, the machine's ability to transfer soil from the face to the chamber improves, facilitating a more efficient excavation process.

- Standard Penetration Test (SPT): Higher SPT values, indicative of stiffer soil, correlate with lower penetration rates. This finding aligns with the understanding that harder soils resist penetration, thus slowing down the excavation process.

- Consistency Index: Lower consistency indices, which indicate softer soils, are associated with increased penetration rates. This supports the notion that softer soils allow for easier movement of the cutter head, reducing the likelihood of clogging.

- Undrained Shear Strength: Higher undrained shear strength results in slower penetration rates. This finding is crucial for understanding the challenges posed by varying soil conditions.

The multiple linear regression analysis yielded significant insights into the factors influencing penetration rates. The regression equation derived from the analysis is as follows:

$$PR = e^{(2.780 \; - \; 0.01175 \; ABS(SPT-40) + \; 0.01940 \; OR \; + \; 0.01445 \; OB)} \qquad (1)$$

The overall model explained 72% of the variance in penetration rates (R^2 = 0.72), indicating a strong relationship between the predictors and the outcome variable.

4. Conclusions

This paper highlights key factors influencing penetration rates based on global project experiences, including geotechnical parameters, machine design specifications, and operational data.

A database of EPB machine performance was created from various projects, allowing for statistical analyses that identified relationships for predicting penetration rates. The results indicate that parameters such as the opening ratio of the cutter head, overburden height, undrained shear strength, and consistency index account for over half of the variance in penetration rates. Notably, optimal penetration rates occur with opening ratios of 40% to 45% and SPT values between 30 and 40.

Multiple linear regression analysis yielded relationships for estimating penetration rates, with determination coefficients ranging from 68% to 72%. These relationships are essential for engineers in the early stages of projects where accurate evaluations are critical. However, the proposed model may have limitations under specific conditions, necessitating further data collection and consideration of additional influencing factors.

References

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