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Study of various models for estimation of penetration rate of hard rock TBMs

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ABSTRACT

Various approaches for predicting penetration rate of hard rock tunnel boring machines (TBMs) have been studied by researchers since the early stages of TBM application in the 1950s. These studies resulted in the development of several penetration prediction models. For evaluation and validation of a model, it is important to test its predictive capability on new projects. A model should include parameters for machine specifications and ground conditions. The model validation process can reveal problems that an existing model may have in providing an accurate estimate for a given combination of specifications and conditions.

This paper offers a brief review and discusses the capabilities of some of the more commonly used TBM performance prediction models. To evaluate the accuracy of these models, the predicted rates are compared with recorded TBM penetration rates in a database of recently completed tunnels. Comparison between predicted and recorded rates indicates that most of the existing models tend to overestimate TBM performance. This comparison highlights the on-going difficulties the industry continues to experience in estimating penetration rate. Even the use of normalized penetration rate indices has not been able to provide higher accuracy expected in related predictions.

This paper discusses the development of new models to support an improved level of predictive accuracy in penetration rate estimating. These models are based on the analysis of a comprehensive database of more than 300 TBM projects records. Analyses of performance information within this database provided for the development of simpler models that are focused on quantifying the influence of primary factors, such as tunnel diameter, UCS, RPM, and rock type. These new models are introduced to provide alternative ways of penetration prediction. These models are especially useful at the planning stage of a tunneling project where TBMs can be used. These models also serve to provide secondary checks for other more in-depth analyses of TBM performance for an initial assessment of required boring time (inverse of penetration rate), and an estimate of utilization rate in an activity-based TBM model.

1. Introduction

TBM performance has a dominant impact on tunnel completion time and cost. A key component in the successful planning of TBM tunneling is the accurate prediction of TBM performance parameters, notably the penetration rate (PR, the rate of TBM penetration during boring times) and the advance rate (AR, the rate of TBM progress during a work time period). Over the past few decades, several studies have been carried out to develop more accurate and comprehensive TBM performance prediction models. Early applications of TBMs were mainly undertaken in relatively massive rocks. In such rock masses research modelers focused primarily on evaluating the influence of intact rock properties on PR for a given set of TBM parameters. As the use of TBMs and related manufacturing technology has evolved, the range of application of the TBM has expanded. TBMs are now frequently used in a wider range of rock mass conditions. Since joints and discontinuities within a rock mass may impact TBM performance, a need for an improved penetration rate predictive model for TBMs operating in fractured rock units became evident. Many of the earlier models could not address the impact of discontinuities on TBM PR. Consequently, attempts were made to either modify existing models or develop new models that included rock mass parameters. These modified and new models can be categorized into four classes as shown in Table 1. In developing a practical model, researchers focused on including the rock mass parameters that were known to have the strongest influence on TBM performance.

One of the main challenges in developing predictive methods for TBM performance is accounting for the interaction between TBM and rock mass. To better model the complexity of this interaction, some researchers developed new tests and indices that were specifically devised for TBM tunneling prognosis. Special testing to derive parameters for boreability, drillability, and

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Table 1
Empirical or field-based TBM performance prediction models and their advantages and disadvantages.

	Example	Typical advantages	Typical disadvantages
Simple models	Graham (1976)	• Easy to apply	• Might underestimate due to lack of joint parameters • Limited range of application
Multiple parameters models	CSM (Rostami, 1993, 1997), NTNU (Bruland, 1998), Q_{TBM} (Barton, 1999)	• Accounting for both rock mass and TBM parameters • Relying on good database	• Several parameters • Complex relationships • Using uncommon tests
Probabilistic models	Laughton (1998)	• Accounting for randomness and approximation	• Lack of detailed information from a like-case tunnel
Computer-aided models	Neural network models (e.g. Alvarez et al., 2000, Alvarez, 2000)	• Relying on good database	• Complex underlying structure • Over fitting • Usually not available in public domain

indentation were all developed to provide for an improved prediction of cutter penetration under a given set of TBM–rock interaction conditions, such as the one described for NTNU modeling by Bruland (1998). Other researchers have gone one step further and have attempted to recreate the process of rock fragmentation in a laboratory setting through the use of disc cutters. The use of full scale linear cutting tests, such as those described by Rostami and Ozdemir (1993), Rostami (1997, 2008), Sato et al. (1991), Sanio (1985), and Ozdemir et al. (1978) provide researchers with an enhanced ability to match field parameters to deliver more accurate TBM performance predictions. Only a few laboratories around the world are equipped to perform such tests. Where such testing is not possible, TBM performance predictions may need to be based on an adjustment of performance data taken from sites where a rock with similar strength properties was bored. These adjustments may introduce significant errors into the estimating process. The amount and likelihood of errors being introduced depend on accuracy of the underlying model assumptions, and the quality and quantity of TBM related and ground conditions data.

Simple models are easy to use since they include only a few basic parameters (e.g. rock compressive and tensile strength), but they can only offer a limited range of application; many of the parameters that influence TBM performance in more variable ground conditions, such as rock mass properties (e.g. RQD and rock type), are unaccounted for in the modeling process. Probabilistic models offer a more complex methodology for estimating performance. These models should only be used when it can be demonstrated that the detailed information (e.g. probability distribution functions for various parameters) of a similar tunnel is available to support the prediction of TBM performance on a new project. These models use performance data collected from similar case histories. If there are significant differences in ground conditions or technology choices between the new drive and case histories within the database, substantial errors are likely in using the model. Another potential problem, which is also common for computer-aided models, is that in practice, these models are rarely used for TBM performance prediction purposes, even though they offer several advantages over the other methods (e.g. having a higher correlation coefficient and taking complex formula structures wherever needed).

Multiple parameters models use more project specific data (compared to simple models), and they are easier to apply (compared to probabilistic and computer-aided models). Therefore, these models are among the most-favored models used in TBM performance prediction. This paper compares the results of common TBM performance prediction models through the evaluation of their predictive abilities. For this purpose, a testing database of 17 recent tunnel projects was used to represent the new projects. This database includes information on key performance parameters for various geological zones encountered along the tunnel. The paper also discusses the development of a new model that can be used for the estimation of penetration rate. The new model is generated on the basis of the analysis of data from more than 300 TBM projects records (named as general database) from around the world. In other words, the TBM performance records in the general database are used to generate the new formulae and the testing database projects are treated as new projects where an estimate is needed (i.e. the results of predictions are compared with the actual field performance to evaluate the validity and accuracy of the predictions and to objectively assess the predictive capabilities of a proposed set of new formulas).

2. Description of the TBM field performance databases

Two separate databases were compiled from the review of various technical sources. The first database (general database) was assembled with the objective of developing a new performance model. The second database was developed to support model validation work.

2.1. General database

The database on TBM field performance contains different levels of information which defines the tunnel, rock mass conditions, and TBM performance parameters over the full length of a tunnel drive, within discrete geological zones, or short tunnel reaches. The general database contains data on more than 260 tunnel projects and includes over 300 data sets. This database is the continuation of an existing database developed at the University of Texas at Austin (UTA) (Nelson et al., 1994). Additional projects were added to the original sets from other available sources found in the literature. This database contains diameter from 1.63 to 11.74 m. TBM projects compiled in the database were completed between 1966 and 2004. An effort was also made to complete missing data fields within the database by checking many sources and published literature. In comparison to the original UTA databases, the updated database contains more detailed information and several new, more recently completed tunnel projects. This new database includes bored tunnel records with a total length of over 1500 km. Table 2 lists main parameters included in this database.

The original database of Nelson et al. (1994), included data on 640 TBM projects. Data from the UTA database was compiled from diverse sources, including literature survey, manufacture records, and detail project records. Parameters for the database were recorded either as directly reported in documents or as estimated based on references (Laughton, 1998). The original database contained four levels of information. The first three levels contain progressively more detailed information for a tunnel project over shorter spatial increments. Each zone is categorized based on a general geological structure and similar rock material characteristics. This increased level of detail continues down to a mining cell, which