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A support vector regression model for predicting tunnel boring machine penetration rates

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ABSTRACT

With widespread increasing applications of mechanized tunneling in almost all ground conditions, prediction of tunnel boring machine (TBM) performance is required for time planning, cost control and choice of excavation method in order to make tunneling economical. Penetration rate is a principal measure of full-face TBM performance and is used to evaluate the feasibility of the machine and predict advance rate of excavation. This research aims at developing a regression model to predict penetration rate of TBM in hard rock conditions based on a new artificial intelligence (AI) algorithm namely support vector regression (SVR). For this purpose, the Queens Water Tunnel, in New York City, was selected as a case study to test the proposed model. In order to find out the optimum values of the parameters and prevent over-fitting, 80% of the total data were selected randomly for training set and the rest were kept for testing the model. According to the results, it can be said that the proposed model is a useful and reliable means to predict TBM penetration rate provided that a suitable dataset exists. From the prediction results of training and testing samples, the squared correlation coefficient (R^2) between the observed and predicted values of the proposed model was obtained 0.99 and 0.95, respectively, which shows a high conformity between predicted and actual penetration rate.

1. Introduction

Tunnels play an essential role for urban transportation, water conveyance, storage, defense and underground mining operations. Mechanized tunneling technique has found extensive applications in tunnel constructions in recent decades. Tools for excavation range from excavators equipped with ripper teeth, hydraulic rams and roadheaders to tunnel boring machines (TBMs) of various designs. TBM refers to a machine for driving tunnels in hard or soft rock with a circular full-face cutterhead, generally equipped with disc cutters. The rock or soil is cut using these excavation tools by the rotation of the cutterhead and the blade pressure on the face.

Nowadays, many underground excavations are performed by mechanical means. By far, TBMs are the most popular method of tunnel excavation and have been widely applied to subways, railways, water conveyance projects, mines etc. In this respect, application of TBMs for excavation of long tunnels and mine galleries is generally the fastest and the most economical method.

At present, different TBM types, such as gripper, open face, earth pressure balance (EPB), slurry, single and double shield, mixed shield and convertible shield are designed to suit for the different ground conditions [1]. However, TBMs are very sensitive to adverse geotechnical conditions, such as spalling, rock bursting, squeezing, swelling and high water inflows [2]. In addition, tunneling is a high-risk industry covering geological, operational, physical and financial risks which are growing with the increase use of mechanized tunneling.

From the beginning of a tunnel excavation and during the tendering of a tunnel project, the performance of a TBM has to be estimated to achieve an accurate time schedule of the whole project. A reliable estimation of TBM performance is required for time planning, cost control and choice of excavation method in order to make tunnel boring economical rationalization.

TBM performance is measured in terms of penetration rate (PR), utilization index (UI) and advance rate (AR), which rely mainly on the geological conditions, geomechanical properties, hydrological conditions, machine design parameters, engineering and operational factors etc.

Optimal design of machine and project planning are essentially based on site geological conditions, which are fundamental factors. Due to the natural variation of geological conditions along the tunnel alignment, it is often difficult to predict exact rock mass behavior along the tunnel on the basis of site investigation [1]. With varying geotechnical conditions, TBM design is difficult to

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deal with all the possible scenarios in an optimum mode, and it has to compromise to suit the dominating geotechnical conditions, properties of rock mass and mechanical properties of material to strive an overall performance. Such difficult conditions have influences on TBM performance, and affect the overall advance of the project and the total costs.

The three main parameters affecting the TBM performance are machine design related factors, geological conditions and geomechanical properties of rocks along the tunnel axis [3–6].

The machine related factors are such as: thrust, torque, disk geometry, disk wear, disk diameter, cutter arrangement and cutterhead revolutions per minute (RPM). Further, rock properties include strength, brittleness, abrasiveness, fracture frequency, hardness, orientation of joints, faults, and bedding related to tunnel axis. These rock properties are the basis for various prediction models and are usually available from the geomechanical tests to site investigations.

Over the years, many researchers suggested a wide variety of performance prediction methods to predict and improve the TBM performance in different projects with various rock masses. However, due to the complexity of ground nature, mechanized tunneling still faces many challenges.

Due to various geotechnical conditions encountured along the tunel alignment, prediction of the performance of a TBM is a nonlinear and complex problem [7,8]. Many researches had been done to correlate TBM performance in terms of PR and AR with rock mass and machine parameters through either empirical or experimental approaches. Recently artificial intelligence (AI) based models are successfully employed by some researchers to solve this difficult non-linear problem in geotechnical projects.

Alvarez Grima et al. [4] applied a neuro-fuzzy method to predict TBM performance. Kim [9] applied fuzzy logic to establish a TBM performance model with respect to the geological and geotechnical site conditions. Acaroglu et al. [7] developed a fuzzy logic model to predict specific energy requirement for TBM performance prediction. Artificial neural networks (ANNs) are also employed to estimate the performance of TBMs in the literature [8,10,11]. Recently, particle swarm optimization (PSO) technique was applied on rock properties data in order to predict TBM penetration rates [12].

In this research, the main problem to be solved is the approximation of an unknown function from the observation of a number of known input–output datasets to predict the rate of penetration and subsequently predict TBM performance. In this regard a new model is developed to estimate the rate of penetration with both rock mass and material properties and also machine parameters.

In order to predict PR, a SVR analysis as a new machine learning (ML) algorithm is used to develop our predictive model. ML is considered as a subfield of AI and is concerned with the development of techniques and algorithms, which enable the computer to learn and perform tasks and activities. SVR is a supervised ML method based on the statistical learning theory and is capable to give good performance for a wide variety of non-linear regression problems.

2. Literature review

Many prediction models were introduced to estimate the TBM performance, which are commonly categorized as two methods, theoretical/experimental models and empirical methods [3]. The former are based on full-scale laboratory cutting tests and the latter are based on field performance of the machine and encountered rock mass properties.

One of the famous experimental models is a method developed in the Earth Mechanics Institute of Colorado School of Mines (CSM). The CSM model which is mainly based on full-scale laboratory cutting tests and database accumulated during past experiences, was developed at first by Ozdemir [13] then was updated by Rostami et al. [3] and afterward Cheema [14] suggested some modifications on it. Further, Yagiz [15] introduced the Modified CSM model, giving more precise estimation result in fractured rock mass condition by inserting rock brittleness and rock mass properties including distance between plane of weakness (DPW) and orientation of discontinuities like faults and fractures into the previous CSM model.

NTNU/NTH (Norwegian University of Science and Technology) model is one of the famous empirical TBM performance prediction methods [16], which is based on data collected from Norwegian terrains. This method was based on multiple laboratory tests and a vast amount of field experience. It takes into account intact rock as well as rock mass properties. It also utilized various machine variables to predict PR and cutter wear [17].

A wide range of empirical tests has been used to predict machine performance with varying degrees of success. These empirical predictive models have been developed based on the historical field data of TBM performance in various ground conditions. Protodyakonov [18] introduced coefficient of rock strength in order to predict PR. Punch penetration test is also used for predicting TBM performance in the literature [19–21]. More, Schmidt hammer and Shore hardness tests are together utilized for performance prediction of TBM [22,23].

With regard to the TBM penetration rate, Rostami and Ozdemir [24] developed a model for performance prediction of hard rock TBM. Barton [25] also reviewed a wide range of TBM tunnels to establish the database for estimating PR, UI and AR. Yagiz [26] utilized rock mass and material properties to construct a new empirical equation for predicting TBM performance in fractured hard rock conditions. Farrokh et al. [27] estimated PR of hard rock TBMs by studying various predictive models and application of combined models was recommended to ensure a higher degree of confidence in final estimation relative to the ground conditions and TBM types.

Influence of rock mass characteristics on TBM performance, mainly from the point of view of PR, has been investigated by some researchers. In this regard, performance of TBM has been estimated by using the empirical approaches, which two such approaches are rock mass quality for TBM (Q_{TBM}) developed by Barton [28,29] based on expanded Q system [30], and also rock mass excavability (RME) index proposed by Bieniawski et al. [31].

Rock Mass Rating (RMR) system is also used for estimating TBM performance by researchers [5,31–33]. In addition, Rock Structure Rating (RSR) [34] is used together with uniaxial compressive strength of rock for estimating the rate of penetration [35,36].

Howarth et al. [37] investigated correlation of performance of three types of drilling tool namely percussion drilling, diamond drilling and TBM with physical rock properties. Their findings show significant trends between several physical rock properties and PR for the range of rock types and drilling tools.

Gong and Zhao [38] investigated the influence of rock brittleness on TBM penetration rate using non-linear regression analysis and numerical simulation simultaneously. According to their findings the PR almost increases linearly with increasing rock brittleness index. Further, they developed a rock mass characteristics model for prediction of PR of TBM [6].

3. TBM performance parameters

A TBM is a complex set of equipment assembled to excavate a tunnel. TBM system performance is evaluated using several parameters that must be defined clearly and used consistently for