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Evaluation of common TBM performance prediction models based on field data from the second lot of Zagros water conveyance tunnel (ZWCT2)

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ABSTRACT

Zagros water conveyance tunnel (ZWCT) is a 49 km tunnel designed for conveying 70 m^3/s water from Sirvan River southward to Dashte Zahab plain in western Iran. This long tunnel has been divided in 3 Lots namely 1A, 1B, 2. By November 2014, about 22 km of the Lot 2 (with a total length of 26 km) has been excavated by two double shield TBMs from two southern and northern portals. The bored section of tunnel passed through different geological units of 3 main formations of Zagros mountain ranges which mainly consist of weak to moderately strong argillaceous-carbonate sedimentary rocks. In this paper, the operating and as-built geological data collected during construction phase of the Lot 2 of ZWCT project was used to compare the calculated machine performance by empirical methods such as the Hassanpour et al. (2011), Q_{TBM}, NTNU, Palmstrom, and theoretical model of Colorado School of Mines or CSM. The predicted penetration rates were then compared with the observed field performance of the machine and the variations of predicted rates were examined by statistical analysis. The results showed that the site-specific model, which was based on TBM performance in similar formations can provide estimates closer to actual machine performance.

1. Introduction

In last two decades, many performance prediction models have been developed by various researchers to estimate penetration rate of hard rock tunnel boring machines (TBMs) in new tunneling projects. Some of the most important TBM prognosis models include CSM (Rostami, 1997), NTNU (Bruland, 1998), Q_{TBM} (Barton, 2000), and models proposed by Palmstrom (1995), Yagiz (2002), Gong and Zhao (2009), Hassanpour et al. (2009, 2010, 2011a,b), Hassanpour (2010), and Delisio and Zhao (2014). On the other hand due to observation of some shortcomings in existing prediction models and their application, it was necessary to continue research on the subject and for development of adjustments for the existing models and correction factors for special circumstances that would allow more accurate prediction of machine performance. Many researchers have conducted studies to modify and adjust common prediction models based on data collected from different projects. Bruland (1998) updated and improved NTNU model (originally introduced by Blindheim (1979)) based on field data collected from Norwegian tunnels. Yagiz (2002) has proposed new formulas involving additional rock parameters to modify CSM model by analyzing data from Queens's. Ramezanzadeh (2005) analyzed data from projects in Norway, Hong Kong and Switzerland and attempted to develop new equations for adjusting results of CSM model.

The current study is an attempt to compare the results of above mentioned prediction models, including Hassanpour et al., Palmstrom, NTNU, Q_{TBM} and CSM, with actual TBM performance, based on collected data from 9.5 km bored section of southern portal of ZWCT Lot2. This tunnel is under construction in geological zone of Zagros Mountains in western Iran. This paper will describe the tunneling project, geological conditions, estimated rates of penetration (ROP) obtained from these models, and compares the estimates with actual ROPs in different tunnel sections. Accuracy and reliability of each model in geological conditions of this project will be examined.

2. TBM performance prediction models

A wide variety of performance prediction methods and principles are used to estimate performance (penetration and advance

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rate) of a TBM in hard rock. Different models are used in different countries, contractors, engineers, and by various TBM manufacturers based on their experience and available information. Some of the methods are based mainly on one or two rock parameters (for instance uniaxial compressive strength and a rock abrasion parameter) while others are based on a combination of comprehensive laboratory, field and machine parameters. In general, methods for TBM performance prediction are classified in the following categories:

1. Theoretical/Experimental models (based on laboratory testing and cutting forces).
2. Empirical methods (based on field performance of TBMs and some rock properties).

In this research, CSM model from first category and NTNU, Q_{TBM}, Palmstrom and Hassanpour et al. models from second category were used to analyze field performance data related to the TBM application in Zagros tunnel. Table 1 presents an overview of the applied models in this paper.

Among the models presented in Table 1, Hassanpour et al. model has been developed based on data collected from some tunneling projects completed in Iran in recent years including first 5.3 km of ZWCT2 project. Actual machine performance and as-built geological data from three major hard rock mechanized tunneling projects in Iran (Karaj, Zagros and Ghomrood water conveyance tunnels) and Manapouri second tailrace tunnel in New Zealand have been collected and analyzed to develop relationships between machine performance and geological parameters. Table 2 lists empirical equations proposed in Hassanpour et al. model for estimating TBM performance in different geological conditions.

As can be seen in Table 2, among the machine performance parameters, field penetration index or FPI, which is a composite parameter based on penetration and cutter load, have been selected for developing empirical equations. Actually, this parameter showed the best correlations with geological parameters (Hassanpour et al. 2009, 2010, 2011a,b). This special parameter can be calculated from machine operating parameters using the following equation:

$$FPI = \frac{F_n}{P} = \frac{60F_nRPM}{1000ROP} \tag{6}$$

where F_n is average cutter load (kN/cutter), P is penetration (mm/revolution), ROP is rate of penetration (m/h) and RPM is cutterhead speed (revolution per minute). F_n is calculated by dividing operational thrust by number of disc cutters after subtracting the shield friction.

3. Project description

Zagros water conveyance tunnel with total length of 49 km and 6.73 m diameter has been designed for conveying 70 m^3/s water from the Sirvan River in South of Nowsood city to Dasht e Zahab plain in Kermanshah province in western Iran. The tunnel was divided into three sections including Lot 1A (14 km) as northeast section, Lot 1B (9 km) as middle section, and Lot 2 (26 km) as southwest section (Fig. 1). Currently, Lot 2 is under construction from two portals at south and north ends. Two other sections have been constructed from portals located in two deep valleys crossing the tunnel route.

At southern portal of Lot 2, a TBM was launched from a 200 m starter tunnel excavated by drill and blast method. The machine commenced excavation on March 2006 and at end of 2014, more than 19 km of tunnel was completed from southern portal. In July 2011, the TBM work was temporarily suspended to carry out a comprehensive overhaul and optional improvements on the machine. The overhaul was conducted in an excavated cavern at the intersection with an existing access tunnel at the chainage of 14,850 m of the main tunnel.

After encountering adverse geological conditions and dramatic reduction in TBM performance at beginning of the southern section, another TBM was mobilized and started to excavate the tunnel from northern portal in mid-2012. This machine has completed around 3 km of the tunnel in very difficult hydrogeological conditions. This tunnel is lined with pre-cast concrete segments with hexagonal arrangement and thickness of 25 cm.

4. Site geology

The area around the ZWCT2 project is located in Zagros zone, as one of the main geological and structural zones of Iran and in "simply folded" subzone. The main geological formations outcropped in the project area are Pabdeh, Gurpi and Ilam Formations. These are the major formations of the Zagros Mountain range which starts in northwest and extends to southeast of Iran. These formations are composed of a variety of carbonate and argillaceous rock units. Geological section in Fig. 2 shows the distribution of these stratigraphic units along the tunnel. Pictures (a) to (c) of Fig. 3 show different identified engineering geological units in outcrops and tunnel faces.

Due to considerable difference in engineering properties of the stratigraphic units, they can be considered as different engineering geological units. As shown in the geological section, due to folded structure of the formations, the geological units may be present through the tunnel alignment in different sections repetitively.

Table 1
Input parameters in applied prediction models.

Prediction model	Required input parameters		Output parameters	Limitations
	Rock mass parameters	Machine parameters		
CSM	Uniaxial compressive strength (UCS), Brazilian tensile strength (BTS) and Cerchar Abrasivity Index (CAI)	Cutter load capacity, cutter spacing, cutter diameter, cutter tip width, and TBM Thrust and Torque	Penetration	The original model is based only on intact rock properties
NTNU	Fracturing: frequency and orientation, Drilling Rate Index (DRI), Bit Wear Index (BWI) and Cutter Life Index (CLI), Porosity, and other parameters	Cutter thrust, cutter spacing, cutter diameter	Penetration rate, advance rate, utilization factor, tunnel cost	Determination of input parameters needs special tests
Q_{TBM}	RQD_0, Jn, Jr, Ja, Jw, SRF, rock mass strength, cutter life index (CLI), UCS, induced biaxial stress	Average cutter load, TBM diameter	Penetration rate, advance rate	The model Uses many parameters
Palmstrom	Elastic modulus, UCS, block size, roughness, length and direction of joints	Thrust, cutter distance, size and shape of the cutter, round the cutter head, cutterhead power	Penetration rate, advance rate	
Hassanpour et al.	UCS, RQD	Thrust, rotation speed of the cutter head, number of disc cutters	Penetration rate, boreability class	