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 m³/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), QTBM, 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.

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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), QTBM (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 Queen’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, QTBM 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
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_{TBMS} 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:

\[
FPI = \frac{F_n}{P} = \frac{600F_nRPM}{1000ROP}
\]

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 m³/s water from the Sirvan River in South of Nowood 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.

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**Table 1**

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

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## Table 2
Empirical equations developed by the first author and his colleagues for different geological conditions.

<table>
<thead>
<tr>
<th>No.</th>
<th>Equation</th>
<th>Eq. no</th>
<th>Project</th>
<th>Application range</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$FPI = \exp(0.005\text{UCS} + 0.002\text{RQD} + 2.129)$</td>
<td>(1)</td>
<td>KWCT1</td>
<td>Pyroclastic rocks</td>
<td>Hassanpour et al. (2010)</td>
</tr>
<tr>
<td>2</td>
<td>$FPI = \exp(0.004\text{UCS} + 0.008\text{RQD} + 2.077)$</td>
<td>(2)</td>
<td>ZWCT2</td>
<td>Carbonate-argillaceous rocks</td>
<td>Hassanpour et al. (2009)</td>
</tr>
<tr>
<td>3</td>
<td>$FPI = \exp(0.004\text{UCS} + 0.023\text{RQD} + 1.003)$</td>
<td>(3)</td>
<td>GWCT</td>
<td>Low grade metamorphic rocks</td>
<td>Hassanpour (2010)</td>
</tr>
<tr>
<td>4</td>
<td>$FPI = \exp(0.005\text{UCS} + 0.020\text{RQD} + 1.644)$</td>
<td>(4)</td>
<td>MSTT</td>
<td>Igneous and metamorphic rocks</td>
<td>Hassanpour et al. (2011b)</td>
</tr>
<tr>
<td>5</td>
<td>$FPI = \exp(0.008\text{UCS} + 0.015\text{RQD} + 1.384)$</td>
<td>(5)</td>
<td>All projects</td>
<td>General</td>
<td>Hassanpour et al. (2011a)</td>
</tr>
</tbody>
</table>

**Fig. 1.** Details of Zagros water conveyance tunnel scheme, west of Iran.

**Fig. 2.** Geological cross section along the tunnel.
Structurally, the area around the tunnel is moderately folded and gently faulted. As shown in Fig. 2, the tunnel in the bored section has passed through some minor synclines and anticlines. There are no important faults in the bored section of the tunnel route, but some minor faults and shear zones have been identified as crossing the tunnel line. The thickness of these fault zones is estimated through back mapping of the tunnel and it is recognized that generally ranges between 10 and 25 m.

Results of petrographic analyses show that considering mineralogy and texture, there are four main lithotypes in the tunnel alignment. These lithotypes include (1) Limestone, (2) Shaly limestone, (3) Limy Shale, and (4) Shale. The first two lithotypes are competent and more brittle rocks with developed joint systems and two others are incompetent rocks with plastic behavior and weathered features at outcrops. Main petrographic, physical, and mechanical characteristics of these lithotypes are summarized in Table 3.

In this study, to determine drillability indices, 12 sets of Norwegian tests were performed by SINTEF laboratory on samples taken from different boreholes along the tunnel alignment. Also, a series of tests were performed using devices in a local laboratory. To investigate the relationship between drillability indices and mechanical parameters of rock, some common rock mechanic tests (such as UCS, BTS...) were conducted on same samples used for drillability tests and results have been analyzed separately. Using these analyses drillability indices for each lithotype were estimated and summarized in Table 3.

In the course of tunneling, the machine encountered many extraordinary situations related to intrusion of hydrogen sulfide (H₂S) and some methane gases released in the tunnel as they evolved from groundwater. These events resulted in significant downtimes for mitigation of the toxic and hazardous gases and modification of the equipment, reduction in TBM utilization rate, and increase in construction delays.

Groundwater conditions along the tunnel vary from dry to continued flow of water in carbonate aquifers. During construction wherever tunnel passed through Pabdeh and Gurpi formations, no major water inflow was observed. Groundwater condition along this part of the tunnel was “damp to wet” and infrequently “dripping”. In contrast, while entering the Ilam limestone, water inflow increased immediately and exceeded 100 l/s in some sections. As shown in Fig. 4, the H₂S gas was first encountered at chainage 3700 m and reoccurred at several geological zones. The main hazards of the gasses were toxicity to humans and corrosive effects on mechanical and electrical equipment. Presence of hydrogen cyanide (HCN) was also detected by field and laboratory tests at chainage 4446 m which resulted in a 3 week TBM shutdown. At chainage 4157 m, a first significant water ingress was encountered \( Q = 110 \text{ l/s} \), which gradually accumulated to \( Q = 730 \text{ l/s} \) with further advancement to chainage 8256 m. At chainage 13,846 m, 155 l/s of gas rich water intruded into the tunnel, totaling the tunnel accumulative discharge flow at the portal to 900 l/s. This amount of water released 700 ppm H₂S gas into the atmosphere (Jalilian Khaveh, 2013).

5. TBMs specifications

As mentioned before, a double shield machine was selected for excavating the tunnel from the southern portal. Main technical specifications of this machine are summarized in Table 4. Fig. 5 shows two pictures of the machine which excavated the tunnel from the southern portal. The TBM mining the tunnel from the northern portal is a different double shield machine with specifications similar to the machine in Fig. 5.

6. Actual machine performance

This study is focused on TBM performance for the first 14.8 km of the southern section of the ZWCT Lot 2 project. This part of the tunnel was completed in July 2011, before machine overhauling at an excavated cavern in chainage 14,850 m. According to Fig. 6, excavated length of this section of the tunnel was completed in 285 full working weeks at an average advance of 50 m/week and best week advance of more than 180 m. As shown in Fig. 6, occurrence of geo-
logical problems (gas and water inflow toward the tunnel) caused many long delays in TBM operation and considerable reduction in average advance rate and utilization factor (Fig. 7).

Fig. 7 shows the utilization factor for TBM operation in this project and while rates higher than 25% have been realized in many individual weeks, due to long TBM stoppages, average utilization rate for the whole tunnel was less than 14%.

Fig. 8 shows recorded rate of penetration, averaged on a weekly basis. As shown in this figure, the normal range of ROP was 1.5–3 m/h with an average of 2.5 m/h for the total length of bored section.

7. Development of TBM performance database

As mentioned earlier, the main objective of this study was evaluation of accuracy of most common TBM performance prediction models in a given geological condition encountered at this site (Foliated, jointed and blocky argillaceous and carbonate rocks). As the first step to achieve this goal, a database has been developed to record and organize collected geological and machine performance data. This database includes three main sections as follows:

1: Operational and machine performance data measured or calculated in tunnel;
2: As-built geological and geomechanical data;
3: Results of performance prediction by different models.

Each row in the database is related to an engineering geological unit identified along the tunnel and recorded and calculated parameters have been averaged for each unit. It should be noted that the data from first 5.3 km of tunnel has been previously used
for development of Eq. (2) in Table 2 (Hassanpour et al., 2009), therefore it was excluded from this analysis. The database for current paper includes only the remaining 9.5 km of the available TBM field performance data from chainage 5300–14,800 m.

7.1. TBM performance data

First section of database includes parameters such as net boring time, length of the unit, and average of machine operational
parameters (thrust, RPM, power and applied torque) through the unit. These parameters were obtained from daily operating sheets and TBM data logger. Also the most important performance parameters including average penetration per revolution, rate of penetration (ROP), field penetration index (FPI), and specific energy have been calculated and are recorded in Section 1 of database.

Graphs presented in Fig. 9(a–d) show the variations of the FPI, P or penetration (mm/rev), total TBM thrust and cutterhead RPM at different identified geological units along the bored section of tunnel used in this study. As can be seen in the graphs, the minimum and maximum FPI and ROP in different geological units are 11 and 22 kN/cutter/mm/rev and 2 and 12 mm/rev, respectively.

### 7.2. Ground characteristics

In Section 2 of the database, results of ground characterization (laboratory and field measured parameters) are compiled. To characterize the ground along the tunnel, two sets of parameters including intact rock properties and rock mass parameters were considered. Using these two sets of parameters, rock masses identified along the bored section of tunnel were subdivided into 41 units with uniform characteristics related to TBM performance, tunnel stability and groundwater inflow (engineering geological units).

**Intact rock properties:** In general, the TBM performance is controlled by intact rock properties such as petrographic characteristics, physical and mechanical properties and drillability. Each of these parameters have been evaluated in the laboratory using a variety of testing methods. In addition to tests performed on pre-construction phase, many samples were obtained and tested during construction phase. Average values of intact rock properties for each tunnel section (engineering geological units) from different phases of testing were calculated and recorded in the database.

**Rock mass parameters:** Fractures, joints and discontinuities influence boreability of rock mass depending on their spacing, surface condition and orientation with respect to the direction of machine advance. In this study, these parameters for each engineering geological unit have been evaluated using measurements and observations within the tunnel as well as surface outcrops. Average values of rock mass parameters (and intact rock properties) have been used to determine geomechanical conditions of the identified engineering geological units by some empirical rock mass classification systems including RQD (Deer, 1964), RMR (Bieniawski, 1989), GSI (Hoek et al., 2002) and Q-system (Barton et al., 1974). The variations of rock mass parameters in identified engineering geological units in the database are plotted against respective unit name in Fig. 10.

### 7.3. Estimation of TBM performance using common prediction models

Based on data arranged in Sections 1 and 2, and using selected TBM performance prediction models, rate of penetration at each tunnel section has been calculated and recorded in Section 3 of the database. In this research, recorded machine parameters and as-built geological and geomechanical data are used as input data for usual prognosis models introduced in Table 1. Main output parameter from these models is rate of penetration (ROP) at each tunnel section (or engineering geological unit). Calculation procedure for each model has been explained in related references presented in Table 1.

![Fig. 9. Variations of average TBM performance parameters along the tunnel; (a) RPM; (b) Total TBM thrust; (c) Field penetration index (FPI); (d) Disc cutter penetration (P).](image-url)
8. Comparison between the results of different TBM performance models

Fig. 11 shows estimated ROP (m/h) for the TBM in each unit using above mentioned prediction models. Also, variations of absolute errors or $E(\%)$ for each model in each tunnel section, are shown in the graphs of Fig. 12. Absolute errors were calculated according to following formulae:

$$E(\%) = 100 \left( \frac{Actual \ ROP - Estimated \ ROP}{Actual \ ROP} \right)$$

A summary of the statistical analysis performed on calculated rates and respective errors are presented in Table 5. Following conclusions can be made by reviewing Figs. 11 and 12 and Table 5:

1. There are significant differences in the ROPs estimated using different prediction models. The NTNU and Palmstrom models show lower values than measured ones, while two models of CSM and particularly $Q_{TM}$ show very higher values.

2. The results obtained from $Q_{TM}$ model are very far from actual values. The main reason is consideration of some parameters (like in-situ stress) in the model which their influence on TBM performance in this project have not been proved yet. The highest values of $E(\%)$ are related to this model (Table 5 and Fig. 12).

3. The results obtained from the original CSM model do not match the measured values, because this model has been basically developed for massive rocks with no significant fracturing. This study shows that this model needs modification by adding correction factors for jointing condition. In recent years, some researchers (Yagiz, 2002; Ramezanzadeh, 2005) have proposed the correction factors to update the model for jointed rock masses.

4. The results obtained from Palmstrom and NTNU models indicate relatively good matches with the actual results. These two empirical models apply rock mass parameters which are very important in boring process. Difference in geology of projects used in the original database of the models which was subsequently used for development of this method and the case study for this paper seem to be the weakness point of these models.

5. As expected, among the studied models the best results obtained from Eq. (2) which has been developed based on data collected from first 5.3 km of this project. As shown in Table 5 and Fig. 12, the lowest values of $E(\%)$ are related to this model.
6. To calculate the performance parameters of the machine using Hassanpour et al. (2011) model, the general equation (Eq. (5), Table 2) was also applied. As shown in Fig. 12, although trend of variations matches the actual values, there are significant errors in some tunnel sections.

7. As an important conclusion, it must be emphasized that site specific prediction models are the best models for estimating TBM performance in a given project. This requires real time analysis of the machine performance and establishing a relevant site specific database to capture the ranges of variation.
and relationship between machine performance and geological units. This is due to the fact that machine related parameters are constant and as such, the variation in geological conditions along the tunnel can be singled out as the input parameter for the modeling. The downside of this approach is that the models developed in this manner cannot be used elsewhere.

8. Using more comprehensive and established models should be considered when there is no track record of site-specific machine performance and for project design purposes. In such cases, it is recommended to use various models to observe the range of variations and sensitivity of these models to input parameters for the specific project under study.

9. Conclusion

In this study, accuracy and validity of some common TBM performance prediction models were examined based on recorded machine performance from a long tunnel under construction in western Iran. Reliable data was available for 9.5 km of this tunnel and was used for this study. The geological units along the tunnel were subdivided into 41 engineering geological units and rock and rock mass properties were measured and compiled in a TBM performance database along with actual TBM performance and operational parameters for each tunnel section. This information was subsequently used to calculate TBM performance using common prediction models.

The main conclusion of this study is that, for selection of an empirical model to predict TBM performance in any case one should pay attention to the application range of the model and geological conditions that the original model is based on. This study indicated that the site specific models with similar geological parameters and machine specification, show best matches with actual TBM performance. In this case, as expected, the results of performance predictions by empirical equation developed from first 5.3 km of the ZWCT2 project showed the best match with TBM performance in continuation of the project. So, it is recommended that engineers and contractors establish a TBM field performance database early in the project and use it to develop a site specific model and predict the anticipated machine performance for the rest of the project to minimize the errors of general TBM performance models and to provide a more accurate projection of the project completion time.

References


