Empirical Models for Estimating Performance and Operational Parameters of Raise Boring Machine in Mining Applications

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Abstract. Raise boring machines (RBMs) are commonly utilized for drilling of shaft and other inclined structures in mining and civil applications. This paper aims to introduce several empirical equations to estimate the performance and operational parameters of RBMs. For the aim, datasets having rock properties including uniaxial compressive strength (UCS), Brazilian tensile strength (BTS), brittleness (BI), rock quality designation (RQD), elastic modulus (E) and Poisson ratio (ν); and also RBMs operational parameters including instantaneous penetration rate (IPR), specific energy (SE), reamerhead power (Pw) and rotational speed (RPM), were established from published case studies. After that, re-established dataset was utilized to develop multiple regression models to predict the performance and operational parameters of RBM. It is found that IPR, SE, Fpush, Pw and RPM could be estimated using several alternative rock properties with coefficients of determination ranging from 0.77 to 0.95. Based on utilized dataset, it is also concluded that RQD and BI are the most common rock properties for estimating the performance and operational parameters of RBMs.

1. Introduction
In present, mechanical excavation takes a key role in the mining and tunnelling industry as an alternative to conventional drill and blast method. Many mechanical excavation machines have been historically designed to be utilized in different mining and civil construction projects. Mechanized excavation offers safer, faster, more efficient, and more environment friendly operations in excavation projects; However, the initial and capital cost of these machines are high and unable to cut very hard and very abrasive rocks [1]. Raise Boring Machines (RBMs) is an effective means of shaft construction where bottom access is available for removal of cuttings. Raise Boring Machines are one of the excavation machines for excavating vertical and/or inclined shafts and drifts such as ore passes, ventilation shafts and drifts, surge in hydropower plants, switching lines between underground subway tunnels (horizontal) and
stairs tunnels (inclined) [2]. Access to both top and bottom locations of the hole is a prerequisite for conventional raise boring method. Application of RBMs to excavate the shaft can be found in the literature [2]. The performance and operational parameters of the mechanical excavators such as RBMs, roadheaders, and impact hammer should be estimated prior to starting the excavation operation to fulfill the economic requirements of the project.

Two main factors in performance of mechanical excavators are machine specifications including Specific energy, thrust, torque, power and speed rate and also rock properties such as strength, brittleness, orientation and frequency of discontinuities that could be measured via rock quality designation (RQD) in the field. Several researchers have been examined the interaction between the specification of RBMs and rock properties for estimating the RBMs performance. Morris [3] developed a semi-empirical method for assessment of machine penetration rate and cutter consumption. Wilson and Graham [4] reported their experience during raise boring machine operation in gold mines of South Africa. Dollinger et al [5] stated that the machine advance rate and cutter consumption rate had to be balanced to obtain optimum performance in RBMs. Several researchers [1, 5, 6, 7] stated that the index obtained from indentation tests could be used to estimate the performance of machines such as Tunnel boring machine (TBM), Raise boring machines (RBMs), roadheaders (RH). It should be noted that indentation tests have been used in different way to measure several rock properties including rock toughness, hardness, and brittleness indices based on evaluation of test output. Yagiz [8] stated that the indentation test could be used for estimating the rock brittleness. Later on he developed rock brittleness classification based on indentation test which is also so called punch penetration test in the USA [7-9]. Some research outputs was published to introduce the relations between rock properties and operational parameters of RBMs [4, 9-11]; however none of them was used rock brittleness together with some rock properties to estimate the performance and operational parameters of RBMs.

The aim of this study is an attempt to examine the effects of intact rock properties (uniaxial compressive strength and indirect tensile strength), dynamic and states elastic modules (E_{stat}, E_{dyn}) and Poison ratios (\nu_{stat}, \nu_{dyn}), brittleness (BI) and RQD (rock quality designation) on the operational and performance parameters of a RBMs including specific energy (SE), instantaneous penetration rate, (IPR), speed rate (RPM), Power (P_s) and Cutter Load (F_{push}). For this aim several alternative multiple regressing models are developed and then the most precise of them have been reported herein to be used in practice.

2. Description of case study and data development

Balya mine is located 50 km North-West of Balikesir province in Turkey have been used as a case which data obtained for this study (figure 1). The sublevel stoping method is used for extraction. An incline ramp with a slope of 14.5% is used as the mine main gallery to minimize the transportation distance from the ore production area to the surface. This mine is the deepest lead-zinc mine in Turkey [2]. The RMBs for excavation of ventilation shafts was used in 2013. They successfully developed five shafts which lengths varies from 197 to 335m. The pilot and final diameters of the all shafts were 0.31 and 2.44 m, respectively. Sandvik Rhino 1088 DC raise boring machine was used to excavate these shafts as specifications of the RBM given in table 1.

A series of laboratory tests were carried out on rock specimens obtained during site investigation to measure intact rock properties for the aim [2]. The rock samples were selected from the closest exploration borehole to the shaft. Uniaxial compressive strength (UCS) and Brazilian tensile strength (BTS) tests were performed according to the suggested methods by International Society of Rock Mechanics [12]. The UCS tests were performed on the ground core samples with a length to diameter ratio of around 2.5 and the loading rate was 0.5 kN/s. Brazilian tensile strength (BTS) tests were performed on core samples at 0.25 kN/s loading rate and the ratio of length to diameter of around 0.5. Elastic properties of rock samples for both static and dynamic condition is also measured using the ISRM standards [12]. During the tests, rock specimens were observed carefully to examine the failure type of the samples under constant loading condition as suggested [12].
Figure 1. Case study used for this research (Balya mine-Turkey) [13].

| Table 1. Main specifications of Rhino 1088 DC RBMs. |
|----------------|----------------|
| Parameters     | Value          |
| Excavation length: | 610m          |
| Excavation diameter: | 0.66-2.44m    |
| Thrust:         | 4000kN         |
| Break out torque: | 300kNm        |
| Reaming torque: | 160kNm         |
| Rotational speed of pilot drilling: | 0-60rpm |
| Rotational speed of reaming: | 0-21rpm |
| Power demand:  | 400kW          |
| Mass (without crawler): | 16,500kg |

Besides rock properties including density, strength and elasticity parameters of rocks, Rock Quality Designation (RQD) is obtained for rock mass characterization as given in table 2. Based on the suggested method by Deere and Miller [14] strength classification of intact rocks ranges from moderately hard rock (53 MPa) to very hard rock (211 MPa). Rock brittleness ranging from extremely low (23.0) to very high (40.3) according to the Yagiz’ classification method [9] in table 3.

| Table 2. Rock brittleness classification for excavatability [9]. |
|----------------|---------------|
| BI            | Description  | Excavatability |
| >45           | Extremely High| Extremely Difficult |
| 40-45         | Very High     | Very Difficult   |
| 35-39         | High          | Difficult        |
| 30-34         | Medium        | Medium           |
| 25-29         | Low           | Easy             |
| 20-24         | Very Low      | Very Easy        |
| <20           | Extremely Low | Extremely Easy   |

In this study, dataset published by [2] have been used for examining the relations between relevant
Mechanics and Rock Engineering, from Theory to Practice
IOP Conf. Series: Earth and Environmental Science 833 (2021) 012129
doi:10.1088/1755-1315/833/1/012129

rock properties and operational parameters of RBMs. Further, rock brittleness index is computed using Yagiz’ method [7] as a function of UCS, BTS and density of rocks to be used for input for performance analysis of the RBMs herein. The main rock properties either measured in the laboratory or computed using the formulae in the literature are given in table 3. Further, the mean measured operational and performance parameters of the RBMs for the reaming drilling operation is summarized in table 4 based on rock types.

| Rock Types       | Origin of rocks | RQD | UCS (MPa) | BI (kN/mm) | $E_a$ (GPa) | $v_a$ (%) | $E_d$ (GPa) | $v_d$ (%) | Excavatability |
|------------------|-----------------|-----|-----------|------------|-------------|-----------|------------|-----------|----------------|
| Dacite           | Igneous         | 93.0| 74        | 16.6       | 32.1        | 0.23      | 38.3       | 0.0       | Extremely Easy |
| Hornfels         | Metamorphic     | 52.0| 86        | 31.7       | 16.4        | 0.14      | 28.4       | 0.19      | Medium         |
| Fault zone       | Igneous         | 51.0| 211       | 32.2       | 34.1        | 0.18      | 37.7       | 0.23      | Medium         |
| Pyrite ore       | Igneous         | 92.0| 127       | 40.3       | 23.6        | 0.27      | 32.5       | 0.31      | Very Difficult |
| Limestone-1      | Sedimentary     | 53.0| 75        | 19.8       | 21.4        | 0.15      | 24.2       | 0.18      | Extremely Easy |
| Meta-limestone   | Sedimentary     | 91.0| 133       | 23.0       | 19.4        | 0.13      | 31.6       | 0.16      | Very Easy      |
| Limestone-2      | Sedimentary     | 89.0| 116       | 31.8       | 28.3        | 0.19      | 38.9       | 0.22      | Medium         |

Table 3. Summary of physical-mechanical properties of the rock samples and RQD values.

3. Data Analyses
Several statistical analysis including simple and multiple, linear and non-linear regressions are conducted to obtain the best relations among the obtained rock properties and both operational and performance parameters of RBMs. It is known that even though several rock properties have relations with operational and performance parameters of RBMs, none of them could be reliable enough for estimating the RBM performance by itself, since performance of RBMs is depend on more than one rock property. Due to that, two main methods is used herein to obtain the aim via statistical approaches [15] as follow.

3.1. Simple regression analysis
As mentioned above, there are no single rock property that could help to estimate operational and performance parameters of RBMs itself. The UCS, BTS and RQD that is the way to measure frequency of discontinuities have relations with operational and performance of RBMs as reported previously [2]; however, statistical analysis is performed to find out best relationships among the variables in dataset. Simple regression analysis is used in the case of measuring the linear or non-linear relationship between an input and output. The coefficient of correlation (R) is used to examine the accuracy of the relations as shown in table 5.

| Rock Types       | Origin of rocks | RPM (rev/min) | $F_{push}$ (kN) | $P_w$ (kW) | SE (kWh/m$^3$) | IPR (m/h) |
|------------------|-----------------|---------------|-----------------|-----------|----------------|-----------|
| Dacite           | Igneous         | 3.6           | 395.0           | 11.34     | 15.68          | 0.18      |
| Hornfels         | Metamorphic     | 3.9           | 507.0           | 16.28     | 4.73           | 0.95      |
| Fault zone       | Igneous         | 3.1           | 326.0           | 12.85     | 5.26           | 1.54      |
| Pyrite ore       | Igneous         | 3.9           | 768.0           | 20.11     | 9.13           | 0.50      |
| Limestone-1      | Sedimentary     | 3.4           | 607.0           | 19.00     | 5.83           | 1.10      |
| Meta-limestone   | Sedimentary     | 4.0           | 841.0           | 20.95     | 12.41          | 0.55      |
| Limestone-2      | Sedimentary     | 3.8           | 813.0           | 21.99     | 10.23          | 0.68      |
Instead of given the figure for each simple relations, given coefficient of determination between the operational and performance parameters of RBMs with simple rock properties were preferred since the simple regression itself is not valuable for estimating the unknowns. As seen in table 6, each rock properties shows different relations with RBMs parameters but it is not efficient to be used by it; however, it is seen that RQD value have good relations with several parameters of RBMs such as RPM, SE and IPR. So, the one of the main rock parameters for multiple linear regression is RQD together with other variables in next section. Also, it should be mentioned that one of the aim of the paper is to examine the BI of rock for estimating the operational and performance parameters of RBMs.

### 3.2. Multiple regression analysis

One of the most common method to estimate unknown from known parameters in engineering research is multiple linear or non-linear regression analysis. Several rock properties including RQD, UCS, BI, Elastic properties of rock were examined to find their effect on operational and performance parameters of RBMs performing multiple regression analysis method. Several alternative models including different rock properties as inputs were constructed via alternative methods using SPSS software. Every rock properties measured is considered to examine their influence on the aim of paper. Consequently it is found that the each rock properties have influence on different parameters of RBMs with different weight. As a result of multiple linear and nonlinear regression analysis, it is found that RQD and BI together with elastic properties have great effect on the parameters of RBMs. Even it is know that the UCS of rock is significant variables for almost any type of projects, BI values was the superior to the UCS when using the multiple linear regression for the aim. Following equations are chosen among the developed models due to the highest $R^2$ ranging from 0.77 to 0.95 as below:

\[
RPM = 0.011 \cdot RQD + 0.006 \cdot BI - 0.036 \cdot E_{st} + 3.6
\]
\[
F_{push} = 8.34 \cdot RQD + 9.72 \cdot BI - 11.7 \cdot E_{st} + 331
\]
\[
P_w = 0.38 \cdot BI + 0.162 \cdot RQD - 0.369 \cdot E_{dy} - 56.3 \cdot v_{dy} + 19.5
\]
\[
SE = 0.168 \cdot RQD - 0.209 \cdot BI + 2.36
\]
\[
IPR = 0.012 \cdot BI - 0.019 \cdot RQD + 1.85
\]
\[
IPR = 0.004 \cdot UCS - 0.017 \cdot RQD + 1.61
\]

From Equations 1 to 6, the best relations are given to estimate the unknowns; however, it is seen that Equations 5 and 6 belongs to estimate IPR of the RBMs using UCS and BI of rocks. It is found that the UCS of rock is significant parameters for estimating IPR; however the BI also very important for that since the BI combination of rock properties rather than one parameter. The obtained multiple correlations between the measured IPR, $F_{push}$, RPM, $P_w$, SE and that predicted is shown in figures 2.

### Table 5. Simple relations between the rock properties and parameters of RBMs.

| R     | RPM (Rev/min) | $F_{push}$ (kN) | $P_w$ (kW) | SE (kWh/m³) | IPR (m/h) |
|-------|---------------|-----------------|------------|-------------|------------|
| RQD   | 0.59          | 0.56            | 0.30       | **0.88**    | **0.88**   |
| UCS   | 0.41          | 0.15            | 0.10       | 0.27        | **0.56**   |
| BI    | 0.19          | 0.24            | 0.32       | **0.46**    | 0.24       |
| $E_{st}$ | **0.66**      | 0.49            | 0.54       | 0.28        | 0.24       |
| $V_s$  | 0.05          | 0.09            | 0.16       | 0.36        | **0.45**   |
| $E_{dy}$ | 0.14          | 0.17            | 0.30       | **0.49**    | 0.22       |
| $v_{dy}$ | 0.03          | 0.09            | 0.18       | 0.18        | **0.29**   |

a Function of UCS, BTS and D of rock herein as suggested [7].
Figure 2. Relations between rock properties and operational and performance parameters of RBMs.

4. Conclusions
In this paper, several alternative simple and multiple linear non-linear regression analysis are examined to estimate the operational and performance parameters of RBMs as a function of rock properties including strength, brittleness, dynamic and static elasticity parameters of rocks together with RQD that sued to measure frequency of discontinuities in rock mass. It is found that RQD, BI and elasticity properties of rock are the main variables to estimate the relevant RBM parameters. RQD and BI have a
great influence on all RBMs parameters that estimated herein. Even though BI itself does not have any relations with machine parameters, it is one of the significant rock properties to be used in multiple regression equations, since it is combination of rock properties rather than one parameters. So, the BI can be replaced with rock strength to estimate the parameters of RBMs. The developed equations can be used for similar rock type with care since the database is not enough to use outputs in general.

Acknowledgments
This study was supported by the Faculty Development Competitive Research Grant program of Nazarbayev University, Grant No: 021220FD5151.

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