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Predicting performance of impact hammers from rock quality designation and compressive strength properties in various rock masses

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ABSTRACT

Predicting the performance of the impact hammers is one of the major subjects in determining the economics of the underground excavation projects in which they are utilized. Therefore, researchers have been attracted to developing performance prediction models for these machines. Physical and mechanical properties of rocks have been used to estimate the performance of impact hammers over the last few decades. In this study, the instantaneous breaking rate (*IBR*, m^3/h) of an impact hammer used in construction of Levent-Hisarüstü metro tunnel (Istanbul) is recorded in detail. Sixty rock samples are obtained from tunnel route during the excavation of which the machine is employed. Physical and mechanical property tests are performed on the obtained samples. A data set including uniaxial compressive strength (*UCS*), rock quality designation index (*RQD*), Brazilian tensile strength (*BTS*), density (ρ), Schmidt hammer hardness (*SHH*), Shore scleroscope hardness (*SSH*), Cerchar abrasivity index (*CAI*), and *IBR* is formed. Regression analysis techniques are applied to the created data set in order to develop a performance prediction model. The investigation results in a model that can predict *IBR* based on *UCS*, *RQD*, and the output power of the impact hammer. The proposed model passes both F-test and *t*-test at 0.95 confidence level. The soundness of the model is successfully tested against two formerly developed models. Covering a wide range of application and requiring only two of the most common and versatile rock properties as input parameters are the other advantages of the suggested model.

1. Introduction

Impact hammer can serve as a sufficiently fast excavation equipment that requires low capital cost. Furthermore, compared to drilling and blasting method, mechanical excavations can offer more control on strata and a safer working environment (Robbins, 2000). On the other hand, although there are some limitations in urban area, drilling and blasting becomes a necessity when the length of operation is short or the rock is so abrasive and hard that mechanical excavation cannot be economically utilized. To choose the best method of excavation, one should consider feasibility, installation problems, ability of negotiation with adverse geological conditions, total cost and advance rate (Terezopoulos, 1987). Therefore, determining the advance rate (performance) of an excavator is a decisive factor from the very early phase of feasibility studies (Aksoy et al., 2013).

From 1960s, impact hammers have been extensively exploited in mining and in the field of construction (Pelizza et al., 1995; Rodford, 1974). Lower capital cost compared to Tunnel Boring Machines (*TBM*) and roadheaders, makes impact hammer a desirable choice when the conditions are favorable. Being able to operate flexibly is another advantage of impact hammer, which makes it irreplaceable in terms of mining engineering. The flexibility makes the operator able to either follow irregular ore bodies through bulk material or use foliations or beddings to facilitate excavation process (Tuncdemir, 2008). Previous studies noted that hydraulic impact hammers gained a wide acceptance in Italian construction industry (Pelizza et al., 1995). This is thought to be rooted in strict Italian rules on application and transportation of explosives. Bilgin et al. (2013) stated that impact hammers excavated almost 20 km of metro tunnels in Istanbul with *RQD* values of 0–80.

A few methods have been developed to predict the performance of impact hammers. Bilgin et al. (1996) suggested a model (Eqs. (1) and (2)) based on the data collected from tunnel construction operations in Istanbul metro.

$$IBR = 4.24 \times P \times (RMCI)^{(-0.567)} \tag{1}$$

$$RMCI = \sigma_C \times (RQD/100)^{(2/3)} \tag{2}$$

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where *IBR* is the instantaneous or net breaking rate in m^3/h, *P* is the input power of hydraulic hammer in Hp, *RMCI* is the rock mass cuttability index in MPa, σ_C is the uniaxial compressive strength (*UCS*) of the intact rock in MPa, and *RQD* is the rock quality designation. The correlation coefficient (r) and coefficient of determination (R^2) for this model are 0.7 and 0.49 respectively. The model covers *RQD* values ranging from 18% to 85%. However, the investigated data set to does not include points with *RQD* values between 38% and 78%.

Bilgin et al. (2002) investigated the relationships between the performance of impact hammer, *RQD* and Schmidt hammer rebound values. Their study yielded a relatively high correlation ($R^2 = 0.83$) between Schmidt hammer rebound values (*SHRV*) and the *IBR* of impact hammer for rocks having *RQD* values between 25% and 49% (Eq. (3)).

$$IBR = (-1.05 \times SHRV) + 70.1 \tag{3}$$

where *IBR* is the net breaking rate in m^3/h and *SHRV* is the Schmidt hammer rebound values associated with the excavated section of tunnel.

Aksoy (2009) investigated the relations between performance of impact hammer and factors such as block punch index, excavator power, geological strength index, and weak rock breakability index. Eqs. (4) and (5) were suggested to predict the *IBR* of impact hammer.

$$IBR = 15.423 \times P^{(0.057)} \times WRBI^{(-0.229)} \tag{4}$$

$$WRBI = \frac{265 \times BPI^{(0.25)} \times GSI^{(0.2)}}{20} \tag{5}$$

where *IBR* is the net excavation in m^3/h, *P* is the excavator power in Hp, *WRBI* is the weak rock breakability index, *BPI* is the block punch strength index in MPa, and *GSI* is the geological strength index. Eqs. (4) and (5) are applicable to rocks with *RQD* values of less than 20%.

Kucuk et al. (2011) developed an artificial neuro-fuzzy inference system (*ANFIS*) and a multiple regression model for performance prediction of impact hammer by taking account of rock and machine properties such as block punch strength index, geological strength index, and impact hammer power. Although they achieved very high accuracy levels, the range of application for the proposed models was limited to rocks with *RQD* values between 0% and 20%. Aksoy et al. (2011) investigated the excavability of various weak rocks ($0\% < RQD < 20\%$) with impact hammer using geological strength index, power of impact hammer, and block punch strength index. Eqs. (6)–(8) were developed to predict the *IBR* of impact hammer in slope excavation, tunnel excavation and all excavations, respectively. The value of R^2 for Eqs. (6)–(8) are 0.7, 0.87, and 0.77 in turn.

$$IBR = 289.28 \times P^{(0.036)} \times GSI^{(-0.73)} \times BPI^{(-0.17)} \tag{6}$$

$$IBR = 1596.71 \times P^{(-0.25)} \times GSI^{(-1.025)} \times BPI^{(-0.11)} \tag{7}$$

$$IBR = 406.87 \times P^{(-0.064)} \times GSI^{(-0.76)} \times BPI^{(-0.15)} \tag{8}$$

where *IBR* is the instantaneous breaking rate in m^3/h, *P* is the power of the machine in kW, and *GSI* is the geological strength index.

Iphar (2012) compared the potential of artificial neural networks, *ANFIS*, and multiple linear regression (*MLR*) for predicting the *IBR* of impact hammers based on Schmidt hammer rebound values and *RQD*. The data set used to develop the models was the same as the one used by Bilgin et al. (2002) with 22 samples. Aksoy et al. (2013) defined rock structural index (*RSI*) to be used for performance prediction of the impact hammer. *RSI* is defined as the summation of the ratings associated with structure rating (Sonmez and Ulusay, 2002), discontinuity surface condition rating (Sonmez and Ulusay, 2002), rock strength (*UCS*), and minimum breaking energy, which is a new parameter defined by Aksoy et al. (2013). They studied 44 different fields, different rock conditions, and hammers with different specifications. Aksoy et al. (2013) suggested Eq. (9) for prediction of *IBR*.

$$IBR = 202.13 \times RSI^{(-1.04)} \times P_{out}^{(0.47)} \tag{9}$$

where *IBR* is the net breaking ratio in m^3/h, *RSI* is the rock structure index, and P_{out} is the output power of impact hammer in kW. R^2 for Eq. (9) equals 0.71.

Although a number of *IBR* prediction models have already been developed, they suffer from either limited range of application, shortage of accuracy and reliability, or dependency on less commonly used rock properties that are involved in judgment or special equipment to be determined. The objective of this study is to assess multiple regression analysis (*MRA*) using a new and ample set of data (60 rock samples) collected from Levent-Hisarüstü metro project in Istanbul, to suggest more accurate and reliable performance prediction models for impact hammer using a simple combination of the most commonly used physical and mechanical properties of rocks. The most favorable prediction model will be the one that provides the highest reliability and accuracy compared to the other models developed during this study and previously developed *IBR* prediction models while comparatively requiring the most few, common, and easy to access set of predictors. Data transformation is applied on the potential predictors in order to improve increase the chance of finding the desired prediction model and as well as the accuracy of the *MLR* model.

2. Field observations and laboratory studies

2.1. The geology

European part of Istanbul hosts Strandja metamorphics and the Carboniferous Trakya Formation covered by Cenozoic sediments. Palaeozoic sedimentary rocks and Upper Cretaceous volcano-sedimentary sequences, separated by the Sile thrust, crop out over large areas on both sides of the Bosporus and on the Asian side of Istanbul (Ozgul, 2012).

Trakya Formation of the Carboniferous age is found in the studied area. The formation consists of fine- to coarse-grained and eminently fractured mudstone, laminated fractured siltstone, shale, sandstone, and conglomerate. Some diabase and andesite dykes have also been encountered while driving the tunnel.

2.2. Construction method and field studies

The New Austrian Tunneling Method (*NATM*), also known as Sequential Excavation Method (*SEM*), is a method of tunnel design and construction that was first introduced in the 1960s. The flexibility of the *NATM* allows the engineers to design support elements based on observations made during the excavation process. This tunneling method makes the construction less costly while maintaining the safety at a sufficient level.

Mini-metro having length of 3104 m is a part of underground transportation project that connects Levent region to Hisarüstü in the European side of Istanbul. The project has been finished in two years. It connects the Aşiyan neighborhood, along the Bosphorus, to the Yenikapı-Hacıosman metro line via a 730 m funicular that reaches to the end of the mini-metro line at Hisarüstü, outside Boğaziçi University. The mini-metro is set to have five stations. The new metro line is capable of transporting up to 10,000 passengers per hour. The route of the metro line is depicted in Fig. 1. As seen in Fig. 2, single-track tunnel (type-A) excavated in Levent-Hisarüstü metro project has 34.72 m^2 of vertical cross sectional area and is excavated in two steps. The upper bench of 27.3 m^2 was excavated first and was followed by the 7.42 m^2 lower bench with a 25–30 m