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Prediction of roadheader performance by artificial neural network

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ABSTRACT

Performance prediction of the roadheaders is one of the main subjects in determining the economics of the underground excavation projects. During the last decades, researchers have focused on developing performance prediction models for roadheaders. In the first stage of this study, the performance of a roadheader used in Kucuksu sewage tunnel (Istanbul) was recorded in detail and the instantaneous cutting rate (ICR) of the machine was determined. The uniaxial compressive strength (UCS) and rock quality designation (RQD) are used as input parameters in previously developed empirical models in order to point out the efficiency of these models, and the relationships between measured and predicted ICR for different encountered formations. In the second stage of the study, Artificial Neural Network (ANN) technique is used for predicting of the ICR of the roadheader. A data set including UCS, RQD, and measured ICR are established. It is traced that a neural network with two inputs (RQD and UCS) and one hidden layer can be sufficient for the estimation of ICR. In addition, it is determined that increase in number of neurons in hidden layer has positive optimizing on the performance of the ANN and a hidden layer larger than 10 neurons does not have a significant effect on optimizing the performance of the neural network. Furthermore, probability of memorizing is being recognized in this situation. Based on this study, it is concluded that the prediction capacity of ANN is better than the empirical models developed previously.

1. Introduction

Performance prediction is one of the major parameters for the success of roadheader applications and generally deals with machine selection, production rate, and bit consumption. Instantaneous cutting rate (ICR) is defined as the production rate during a continuous excavation phase in m^3/h. ICR of the roadheader is controlled by several parameters such as rock parameters, ground conditions, machine specifications, and operational parameters (Rostami et al., 1994). Many roadheader performance prediction models have been published in the literature using a combination of these parameters; however, these models generally provide weak or moderate correlation with actual field performance of roadheaders.

Artificial Neural Networks (ANNs) have emerged as a new tool for analyzing the geotechnical problems. This technique allows generalizing from a training pattern, presented initially, to the solution of the problem. Once the network has been trained with a sufficient number of sample data sets a new input having a relatively similar pattern will be predicted on the basis of the previous learning pattern (Javad and Narges, 2010). ANN has been used to analyze the rock properties in recent years. Yang and Zhang (1997), Shahin et al. (2001), Singh et al. (2001), Khandelwal et al. (2004), Sonmez et al. (2006), Yilmaz and Yuksek (2008), Dehghan et al. (2010), Manouchehrian et al. (2012), Ceryan et al. (2012), Enayatollahi et al. (2013) are among the researchers who studied ANN approach for this purpose.

Research studies for mining and tunneling projects have been carried out to analyze the performance of mechanical excavators by using ANN. Alvarez Grima et al. (2000), and Benardos and Kaliampakos (2004) modeled TBM performance by using ANN. Bilgin et al. (2006) used ANN for predicting rock cuttability from rock properties. Kahraman et al. (2006) estimated the sawability of carbonate rocks from shear strength parameters by using ANN. Tiryaki (2008) used ANN to predict the cuttability of rocks by drag tools. Tiryaki (2009) developed new predictive models for rock cutting by using ANN. Javad and Narges (2010) estimated the penetration rate of tunnel boring machine (TBM) by using ANN. Jain and Rathore (2011) used ANN approach to predict cutting performance of diamond wire saw machines in quarrying of marble. Salsani et al. (2013) studied ANN modeling for roadheader performance prediction.

This study presents the application of an ANN modeling technique to predict roadheader performance. Four empirical models using the same predictors (UCS and RQD) have also been tested

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in this study. A data set obtained from Kucuksu sewage tunnel project is first used to analyze the efficiency of previously developed empirical performance prediction models. The main parameters used to predict the ICR of roadheader are uniaxial compressive strength (UCS) and rock quality designation (RQD), which are used as input parameters in these models. This original data set, taking into account these input parameters, is then subjected to ANN to build a predictive model for roadheader performance. The efficiency of the previous empirical models and suggested ANN model are discussed in detail.

2. Previous studies on roadheader performance prediction

In the literature, two methods have been suggested for the performance prediction of roadheaders. The first method concerns on small scale and full scale laboratory rock cutting tests. The second method depends on the empirical models developed by using a large amount of in-situ data, and ICR of roadheaders correlated with rock parameters, ground conditions, and machine specifications. The most widely used experimental and empirical prediction methods suggested for roadheader performance prediction and their input parameters can be summarized as follows:

The first method of estimating ICR of roadheader is to use specific energy (SE), described as amount of energy required for cutting unit volume of rock. The investigations made by McFeat-Smith and Fowell (1977, 1979), Fowell and Johnson (1982) and Fowell et al. (1994) present good relationship between SE obtained from core cutting test (small scale) and in-situ ICR values for medium and heavy weight roadheaders of earlier versions. In the literature, one of the most accepted laboratory predictive methods to estimate machine excavation performance is to use cutting power of roadheader, optimum SE value obtained from full scale rock cutting test, and energy transfer ratio (k). Rostami et al. (1994) developed Eq. (1) for ICR prediction and strongly recommend using optimum SE values obtained from full scale cutting test in order to have a precise estimation.

$$\mathrm{ICR} = k \times \frac{P}{\mathrm{SE}_{\mathrm{opt}}} \tag{1}$$

where ICR is the instantaneous cutting rate in m^3/h, P is the installed power in kW, $\mathrm{SE}_{\mathrm{opt}}$ is the optimum specific energy in kW h/m^3, and k is the energy transfer ratio, which is suggested as between 0.45 and 0.55 for roadheaders, without mentioning the type of roadheader cutterhead. Copur et al. (2001) indicated that SE obtained from full scale linear cutting tests in optimum cutting conditions was highly correlated to multiplication of UCS and Brazilian tensile strength (BTS) of rocks. They also emphasized that laboratory rock cutting tests are more precise compared to other methods for performance prediction of mechanical excavators.

Empirical performance prediction models are mainly based on past experience and the statistical interpretation of previously recorded case histories. Therefore, the collection of field data is very important for the development of empirical performance prediction models. The accuracy and reliability of these models depend on the quality and extent of the available data (Copur et al. 2001). Bilgin et al. (1988, 1990, 2004) studied the effect of machine specification in addition to rock characteristics on ICR of a roadheader and suggested Eqs. (2) and (3) for empirical performance prediction:

$$\mathrm{ICR} = 0.28 \times P \times (0.974)^{\mathrm{RMCI}} \tag{2}$$

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

where ICR is the instantaneous cutting rate in m^3/h, P is the installed cutterhead power in HP, RMCI is the rock mass cuttability index in MPa, UCS is the uniaxial compressive strength in MPa, and RQD is the rock quality designation in percentage. Gehring (1989) developed empirical relationship between UCS and ICR for an axial type roadheader (230 kW cutterhead power) and transverse type roadheader (250 kW cutterhead power) and developed Eq. (4) for transverse and Eq. (5) for axial type roadheaders:

$$\mathrm{ICR} = \frac{719}{\mathrm{UCS}^{0.78}} \tag{4}$$

$$\mathrm{ICR} = \frac{1739}{\mathrm{UCS}^{1.13}} \tag{5}$$

where ICR is the instantaneous cutting rate of roadheader in m^3/h and UCS is the uniaxial compressive strength in MPa. Sandbak (1985) and Douglas (1985) investigated the advance rate changes of roadheaders by using rock classification system at San Manuel Copper Mine. Copur et al. (1997, 1998) investigated the performance data of different roadheaders at various geological conditions. They indicated that, if machine weight and installed cutterhead power (P) considered together in addition to UCS, the cutting rate estimation would be more accurate. They suggested Eqs. (6) and (7) for predicting the cutting rate of transverse type roadheaders excavating evaporitic rocks up to 60 MPa:

$$\mathrm{ICR} = 27.511e^{0.0023(\mathrm{RPI})} \tag{6}$$

$$\mathrm{RPI} = P \times W/\mathrm{UCS} \tag{7}$$

where ICR is the instantaneous cutting rate in m^3/h, RPI is the roadheader penetration index, P is the installed cutterhead power in kW, W is the weight of the roadheader in tones and UCS is the uniaxial compressive strength in MPa. Thuro and Plinninger (1999) developed empirical relationship between UCS and ICR and Eq. (8) was suggested based on their study:

$$\mathrm{ICR} = 75.7 - 14.3 \times \ln(\mathrm{UCS}) \tag{8}$$

where ICR is the instantaneous cutting rate in m^3/h and UCS is the uniaxial compressive strength in MPa. Balci et al. (2004) suggested a performance prediction model considering the energy transfer ratio of roadheader cutterhead in addition to UCS and P given in Eq. (9) for transverse and Eq. (10) for axial type roadheaders:

$$\mathrm{ICR} = k \times \frac{P}{0.37 \times \mathrm{UCS}^{0.86}} \tag{9}$$

$$\mathrm{ICR} = k \times \frac{P}{0.41 \times \mathrm{UCS}^{0.67}} \tag{10}$$

where ICR is the instantaneous cutting rate in m^3/h, P is the installed cutterhead power in kW, UCS is the uniaxial compressive strength in MPa, and k is the energy transfer ratio. Bilgin et al. (2005) applied linear cutting tests in single scroll pattern and indicated that k value is around 0.40 for an axial type roadheader used in Kucuksu Tunnel. If double scroll cutting pattern is used in linear cutting experiments, specific energy values decrease around 20% (Avunduk et al., 2013), which generate k value of around 0.50. Bilgin et al. (2014) revised the k value given in Balci et al. (2004) as being between 0.45 and 0.55 as suggested by Rostami et al. (1994), and may be 0.45 for axial and 0.55 for transverse types of roadheaders. Since Eqs. (9) and (10) are especially given for axial and transverse types of roadheaders, it might be correct to use an average k value of 0.50 in Eqs. (9) and (10) as suggested by Copur et al. (in press).