International Journal of Rock Mechanics & Mining Sciences 68 (2014) 55–65

Contents lists available at ScienceDirect

International Journal of Rock Mechanics & Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

A stochastic penetration rate model for rotary drilling in surface mines

Omid Saeidi [a,*], Seyed Rahman Torabi [a], Mohammad Ataei [a], Jamal Rostami [b]

[a] Department of Mining Engineering, Geophysics & Petroleum, Shahrood University of Technology, Shahrood, Iran
[b] Department of Energy & Mineral Engineering, Pennsylvania State University, University Park, PA 16802-5000, USA

ARTICLE INFO

Article history:
Received 10 June 2013
Received in revised form
31 January 2014
Accepted 9 February 2014
Available online 22 March 2014

Keywords:
Rock mass penetrability
Penetration rate
Rotary drill
Principal Component Analysis (PCA)
Monte Carlo simulation

ABSTRACT

Principal Component Analysis (PCA) is used to determine the most effective parameters on the rock mass penetrability by considering their variance ratio in the first principal component. A model is developed for the prediction of rotary drills penetration rate using non-linear multiple regression analysis. Distribution functions for the effective parameters are calculated using measured data from two case studies. Applying the developed penetration rate model, a stochastic analysis is carried out using the Monte Carlo simulation. The proposed method provides a simple and effective assessment of the variability of the penetration rate model and its dependent parameters. Results showed that the PCA and Monte Carlo are suitable techniques for modeling and assessing the variability of rock mass penetrability parameters. According to the developed distribution model, with 90% of confidence level the penetration rate values range 0.2–2.5 m/min, which shows the wide possible range of penetration rates for rotary drilling especially in sedimentary (limestone and sandstone bearing magnetite mineral of Golgohar mine) and Sarcheshmeh igneous porphyry rock masses.

1. Introduction

Rotary blast hole drills are extensively applied for overburden releasing throughout the world in surface mining. Prediction of penetration rate for rotary drill rigs is of great importance in the rock drilling process, especially in mining and petroleum engineering [1–6]. The prediction of penetration rate is essential in mine scheduling. Total drilling costs could be assessed by using prediction equations. In addition, one could use prediction equation to select the drilling rig type, which is best suited for given conditions [7]. In large surface mining operations, rotary tricone bits using tungsten carbide (WC) inserts are the most popular drilling tools for deep holes with large diameter. Their drilling rate has increased over the time due to higher powered drills and better control of the operational parameters, leading to increase in mining production and reduction in drilling costs.

2. Literature review

Yaşar et al. conducted experimental works on rock physico-mechanical properties in relation to its drilling penetration rate [8]. They found significant relationships between specific energy and penetration rate. Their results of the experimental work also demonstrate the significance of applied load and torque for both penetration rate and specific energy in drilling.

Howarth and Adamson considered the operational conditions of a diamond drilling machine, incorporating the effect of situation of cutting tools and UCS values on penetration rates. The results were valuable for the prediction of optimum cutting conditions for the diamond bits [9]. Experimental studies have been conducted on the cutting operation of a single diamond accepted to be the requirement of establishing design parameters for manufacturing the diamond bits. Specific energies and scaled particle size distributions were measured and torque and weight on bit measurements were performed. The relations between all these parameters were analyzed [10]. From the bit rotations, depth of specific cut could be calculated. For a given depth of cut, a particle size prediction could be established. The largest particle size together with the depth of cut will dictate the exposure and size of the diamond in the matrix. The depth and width of cut will also give indication about the optimum spacing of the diamonds. Pandey et al. found the relationship between penetration rate values obtained from micro-bit drilling test with compressive strength, tensile strength, shear strength and Protodyakonov index and establish logarithmic relationships [11]. Bilgin et al. presented a mathematical model of predicting the penetration rate of rotary blast hole drills using the drillability index obtained from the indentation tests [12]. Wijk used the stamp test strength index to derive a penetration rate model in the laboratory [13]. Kahraman determined different brittleness indices and also drillability and boreability from the experimental works of other researchers. He found that each

* Corresponding author. Tel.: +98 9149804239.
E-mail addresses: osaeidi914@gmail.com, o.saeidi@yahoo.com (O. Saeidi).

http://dx.doi.org/10.1016/j.ijrmms.2014.02.007
1365-1609/

brittleness index has its application depending on the mechanism of rock excavation that is one method of measuring brittleness based on impact strength that shows good correlation with the penetration rate of percussive drills, while the other methods does not [14]. Akun and Karpuz developed an empirical penetration rate model using RQD, discontinuity frequency, pressure loss, specific depth of cut and specific energy in a surface set diamond core drill. They concluded that drilling specific energy as the main drillability indicator is the most important parameter in drilling rate prediction. However, using RQD and discontinuity frequency simultaneously which are dependent variables could lead to the multicollinearity problem in the model [15].

Penetration rate models of rocks are among those practices with high uncertainties based upon rock mass and machine properties. When applying these models to rock drilling problems, most users consider only the “average” or mean properties. Rock properties, themselves, have uncertainties and exhibit a distribution about the mean, even under the ideal conditions, where these distributions can have a significant impact upon the design calculations [16]. Moreover, most of the previous developed models use exclusively intact rock properties or machine operational factors rather than comprising rock mass properties as joint characteristics (e.g. joint spacing, direction and aperture & fillings). Another drawback may go back to the deterministic values of the provided penetration rate by these models rather than their probabilistic values. Nevertheless, most of the involved rock parameters show wide range of values at the field. Accordingly, establishing a stochastic model might provide better estimation of the penetration rate of rotary drills.

PCA is a classical method that provides a sequence of the best linear approximations to a given high dimensional observation and it has received much more attentions in many literatures [17,18]. For multi-dimensional systems, factory analysis based on PCA is the most suitable technique to reduce system dimensions to the least effective one.

Probabilistic analysis has obtained significant attention in many engineering practices in relation to deterministic methodologies. Deterministic models apply single values for parameters to obtain the results. However it is well known that parameters are not reliable and are all associated with a level of uncertainty. The probabilistic method has also been used as an influential tool for representing uncertainty in the failure model and in the material characteristics.

According to the literature, the stochastic modeling by Monte Carlo method, which is the most common sampling technique, has gained many advocates among researchers [16,19–23]. In meaning, the Monte Carlo simulation technique is trying all valid combinations of the values of input variables to simulate all possible outcomes for output variable. Benardos and Kaliampakos defined a vulnerability index to identify risk-prone areas in TBM tunneling and finally they used the Monte Carlo technique to address the uncertainty in the parameters' values [24]. Ghasemi et al. developed an empirical model for predicting fly rock distance in a copper mine using regression analysis. They used the Monte Carlo method to simulate the distribution of fly rock distance at that mine and found that Monte Carlo simulation could predict fly rock distance relatively well near to the real data [25]. Park et al. used the fuzzy set theory together with the Monte Carlo technique to evaluate the probability of failure in rock slopes. They used the Monte Carlo simulation technique and reliability index approach with the fuzzy set theory in order to take into account the fuzzy uncertainties in the evaluation of the probability of failure. They found that the application of the fuzzy set theory shows consistent analysis results and can obtain reasonable results [26].

In this study, firstly, an attempt has been made to determine the most effective parameters on the rock mass penetration rate in rotary drilling by using the PCA technique. Finally, the Monte Carlo simulation was used to determine probabilistic distribution of rock mass penetration rate variables.

3. Effective parameters on the rock mass penetrability

3.1. Uniaxial compressive strength (UCS)

One of the most important properties in rock engineering and its related design parameters is the Uniaxial Compressive Strength (UCS). Rock material strength is used as an important parameter in many rock classification systems. UCS is influenced by many characteristics of rocks such as constitutive minerals and their spatial positions, weathering or alteration rate, micro cracks and internal fractures, density and porosity [6,27]. In addition, UCS of rocks can be considered as representative of rock strength, density, weathering and matrix type. It has been shown that rock drillability and penetrability will decrease when its UCS increases [4].

3.2. Rock hardness

Hardness is defined as a mineral or rock's resistance to tool penetration. Rock hardness is the first strength that has to overcome during drilling. Intuitively, the rock hardness depends on the hardness of the constitutive minerals, cohesion forces, homogeneity and the water content of rock [6]. Many different methods have been used to obtain rock hardness by using different testing machines [28,29]. It was shown that by increasing rock hardness, its drillability will decrease. Schmidt hammer rebound value, Shore hardness, Moh's scale and Vickers indentation hardness are among the most common methods to determine rock hardness [30]. In this study, Moh's scale was measured for different rock types at the case studies.

3.3. Rock abrasiveness

The term “abrasiveness” describes the resistance of a rock or soil to wear on a tool. Consequently, abrasivity is an important rock parameter to be determined and to be described in the course of any larger road, tunnel or mining project in order to allow the contractor to assess economic aspects of excavation methods [31].

Abrasivity investigation can be based on a wide variety of testing procedures and standards. Widely used geotechnical wear indices based on these systems included the Abrasive Mineral Content (AMC), also referred to as “Mean Hardness”, which uses Moh's hardness, the Equivalent Quartz Content (EQC), which uses Rosiwal grinding hardness and the “Vickers Hardness Number of the Rock” (VHNR), which is very common in Scandinavia and refers to Vickers indentation hardness [31]. Rock abrasivity tends to the bit wear and deformation of bit shape and causes significant decreasing of rock drillability. Rock Abrasivity Index (RAI) is the new geotechnical index defined to predict drill bit wear. Plinninger and Thuro found a good logarithmic relationship between the RAI and Cerchar Abrasivity Index (CAI) [32]. The index can be calculated as follows:

$$RH = \exp[(MH - 2.12)/1.05] \quad (1)$$

$$EQC = \sum_{i=1}^{n} RH_i A_i \quad (2)$$

$$RAI = UCS \times EQC \quad (3)$$

where RH is the Rosiwal grinding hardness (%), MH is the Moh's hardness, EQC is the equal quartz content, A_i is the mineral percentage (%), n is the number of minerals, which contribute in