International Journal of Rock Mechanics & Mining Sciences 73 (2015) 130–138

Contents lists available at ScienceDirect

International Journal of Rock Mechanics & Mining Sciences

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

Drilling rate prediction of an open pit mine using the rock mass drillability index

Mohammad Ataei*, Reza KaKaie, Mehdi Ghavidel, Omid Saeidi

Mining, Petroleum and Geophysics Department, Shahrood University, Shahrood, Iran

A R T I C L E I N F O

Article history:
Received 21 February 2014
Received in revised form
7 August 2014
Accepted 18 August 2014
Available online 27 November 2014

Keywords:
Rock drillability
Structural parameters
Open pit mine
Drilling rate
RDi
UCS

A B S T R A C T

Besides intact rock properties, structural parameters of rock mass have strong effect on drilling rate. In this research, 11 different zones of an open pit iron mine were studied precisely to classify the area based on rock drillability point of view. Laboratory tests were conducted on the rock samples to determine strength parameters. Geological mapping of the rock facies was carried out and rock mass structural parameters as joint inclination, spacing, aperture and filling were recorded along with net drilling times of drill holes. Using these data, an empirical relation was developed to predict drilling rate (*DR*) using the rock mass drillability index (*RDi*) and also a relation that can predict uniaxial compressive strength (*UCS*) of rocks in terms of Schmidt hammer rebound values at this mine. In conclusion, all 66 zones of the mine area were classified according to the *RDi*. It was observed that *RDi* can reasonably predict drilling rate of rock masses. A new penetration rate model is defined based on the measured data and then compared with previous model of penetration rate from literature. Since the new model which involves not only intact rock mechanical properties but also structural properties of rock masses could attain better predictions in relation to the previous model.

1. Introduction

Drilling and blasting play vital roles in open pit mining. These operations do not only affect the cost of production directly but as well the overall operational costs [1]. The penetration rate prediction is a necessary value for the cost estimation and the planning of the project. For instance, the knowledge of penetration rate equation in a mine and classification of all the zones based on the equation someone could calculate the time required to drill mine i.e. (total net time = total drilling length/penetration rate). According to the calculated time project planning could be adopted in an exact manner at the mine site.

Drillability and penetration rate can be defined as similar terms. While drillability indicates whether penetration is easy or hard, penetration rate indicates whether it is fast or slow. Rock drillability cannot be measured by a single index or a single test. It is influenced by many parameters. Various rock parameters have been used to predict the performance of drilling rigs. Drilling, like the other exploitation stages in open pit mining, has a direct and close relation with the rock mass, and thus would be affected by the geomechanical characteristics of the rock material as well as the rock mass. Therefore, recognition of the drilling environment and the in situ rock mass properties would be of great help in choosing the appropriate type of drilling system, number of drills, and the mine production rate [2].

In recent years, many researchers have attempted to define a rock drillability classification. Teale proposed the concept of specific energy as a simple means of assessing rock drillability [3]. Selim and Bruce, using stepwise linear regression analysis, developed a penetration rate model that is a function of the drill power and the physical properties of the rock being drilled [4]. Wilbur emphasized the Mohs hardness, texture, fracture and structure of the rock mass as important parameters affected drilling [5]. Howarth et al. carried out percussion drilling tests on 10 sedimentary and crystalline rocks [6]. They correlated penetration rate with rock properties and found that bulk density, compressive strength, apparent porosity, P-wave velocity and Schmidt hammer value exhibit strong relationships with the penetration rate. Jimeno et al. [7] introduced hardness, origin of rocks, *UCS*, elasticity, plasticity, abrasion, and texture and rock mass structure as the parameters involved in drilling. Osanloo [8] investigated the rock cohesion force, porosity, density, texture, uniaxial compressive strength (*UCS*), *RQD*, elasticity, plasticity, rigidity, hardness and structure of rock mass effects on drilling. Recently, Kahraman [9] has developed a penetration rate model using multiple regression for rotary drilling in surface mines. The

* Corresponding author. Tel.: +98 9125732469.
E-mail address: ataei@shahroodut.ac.ir (M. Ataei).

http://dx.doi.org/10.1016/j.ijrmms.2014.08.006
1365-1609/

model is expressed as follows:

$$ROP = 1.05\frac{WOB^{0.824}\ RPM^{1.69}}{D^{2.32}\ UCS^{0.61}} \quad (1)$$

where *ROP* is the penetration rate of rotary drill in m/min, *WOB* is the weight on bit in kg, *RPM* is the rotation speed, *D* is the bit diameter, and *UCS* is the uniaxial compressive strength in MPa. The results of our study are compared with Eq. (1) to test the significant of the new model with previous models.

Kahraman et al. [10], in addition to present a new drillability index, studied the various parameters such as *UCS*, tensile strength, point load index, Schmidt hammer hardness, P-wave velocity, elastic modulus and density. Hoseinie et al. [2] developed a rock mass classification index for assessing of rock mass drillability as *RDi*. Nonetheless, previous drillability classifications which mainly have discussed on the intact rock properties; this index considers filed geological data including rock joint parameters of the rock mass along with physico-mechanical properties of rocks.

In the present study, *RDi* raw data including intact rock properties and structural parameters were obtained in Gole Gohar Sirjan, an Iron mine in south of Iran. Extraction of 11.5 million tons of iron ore and 10.4 million tons of waste material by drill and blast in a year declares the importance of presenting a rock mass drillability classification in the mine. Finally, 66 different zones were categorized according to the *RDi* classification system. The range of drilling rate of the mine formations was classified from slow to slow-medium. A new penetration rate model based on the observed data is defined and is compared to the previous model.

2. Rock mass drillability index, *RDi*

Many investigators have focused on the rock drillability classification systems [11–14]. According to the literature, maybe the most applicable classification system, the drilling rate index (*DRI*), was developed by Selmer-Olsen and Blindheim [15]. They found a good correlation between penetration rate and the drilling rate index (*DRI*) and expressed the rock properties that are important in drilling as hardness, strength, brittleness and abrasivity. However, as mentioned rock drillability depends on many rock parameters rather than limited properties.

Hoseinie et al. [2] developed a new classification system for rock mass drillability. The advantage of the proposed index in addition to its simple method of surveying data it takes into account the effective rock mass structural parameters on rock drilling rate. Table 1 represents the *RDi* classification, rating and its effective parameters.

Based on the parameters rating in Table 1 by summation all rates the authors proposed a qualitative prediction of drilling rate of rock mass drilling given that $7 < RDi < 20$ equivalent to Slow rate for drilling, $20 < RDi < 40$ equivalent to Slow-medium rate for drilling, $40 < RDi < 60$ equivalent to Medium rate for drilling, $60 < RDi < 80$ equivalent to Medium-fast rate for drilling, $80 < RDi < 100$ equivalent to Fast rate for drilling.

3. Description of the case study

Data for the *RDi* classification have been obtained from Gole Gohar Sirjan Magnetite mine located near Sirjan city in south of Iran. Gole Gohar mine was located on the edge of Sanandaj-Sirjan zone and massive salt anticline of Kheir-Abad between Sanadaj-Sirjan and Urumie dokhtar zones. Geological formations contain Paleozoic metamorphic rocks in the south, Mesozoic and Cenozoic sedimentary rocks in east of the mine. Paleozoic metamorphic rocks comprise Gole Gohar complex which is the oldest metamorphic setting and also provided iron ore deposits in the area. Bottom division of the complex includes intermittent of gneiss, mica schist, amphibolite and quartz-schist [16]. Ultimate pit limit of the mine is an ellipsoidal shape with dimensions of $2250 \times 750\ m^2$, 21 benches of 15 m height and 25 m width. Drill rigs that measured their properties were DMH-Ingersoll-Rand with Tricone bits.

4. Laboratory tests and geological surveying

Net drilling rates were measured on rotary drill rig in 11 different zones of Gole Gohar Sirjan mine. According to the drill hole pattern in practice, for each zone nearly 25 net drill times were recorded and averaged as drilling rate of the zone. Therefore, with 11 zones in the mine site and 25 drill holes in each zone the number of 275 net drilling times were recorded during the research due. Logical relations between drilling rates, experimental data and the *RDi* values were obtained to classify the mine area divided into 66 zones. In Fig. 1 location of the zones and recorded drilling times is shown on the mine contour map. It should be noticed that, zoning of the mine site was based on geological condition and observation of outcrops. A sample sheet used in the mine site for recording the *RDi* parameters, geological parameters and drilling times is shown in Table 2.

To obtain rock physico-mechanical properties, 5–10 representative cube rock samples with dimensions of $20 \times 30 \times 20\ cm^3$ from 11 sites were transported to the laboratory. Uniaxial compression tests were performed on trimmed core samples, which had a diameter of NX size (54 mm) and $L/D \sim 2–2.5$. The stress rate was applied within the limits of 0.5–1.0 MPa/s. In addition, indirect tensile strength, density and porosity determination tests were carried out according to [17].

Non-destructive tests as sound velocity tests to determine dynamic elastic of rocks are acceptable methods in today's rock engineering works [18–22]. P and S waves velocities were measured on the rock samples and dynamic Young's modulus were obtained for each rock sample. N-type Schmidt hammer tests were conducted in the field. The Schmidt hammer was held on downward position and 20 rebound values recorded from single impacts separated by at least a plunger diameter, and the upper 10 values averaged as final rebound value [17]. Results of the laboratory and filed data are recorded in Table 3.

5. The rock masses classification in the Gole Gohar mine

The main purpose of the research was classifying the rock mass of Gole Gohar Sirjan open pit mine by the rock mass drillability index, *RDi*. This classification is intended to improve the blasting operation, drilling time determination and production planning of the mine.

In situ rock mass data were gathered along with average net drilling times for 11 sites. Rock samples were collected and transported to the laboratory for physico-mechanical and strength tests (Table 3). At this step, obtained results were correlated with the *RDi* values and drilling rate (DR) to determine reasonable relations. Determining the relation between *RDi* and average net drilling rates and also *UCS* from laboratory tests and Schmidt hammer rebound values were very crucial to follow up our research all over the mine site. Using these relations one can predict *RDi* and *UCS* values for all 66 zones. Fig. 2(a–i) displays the correlations between laboratory test results of rock samples obtained from 11 sites and net drilling rates.

As can be seen in Fig. 2(a), by increasing Schmidt hammer rebound value, R_n, the drilling rate decreases linearly. By increasing the dynamic Young's modulus E_{dyn}, *UCS* and tensile strength in