Empirical relationship for drilling rate in hard rock underground mines

A C Adoko¹, D Moesi² and A S Sharipov¹

¹ School of Mining & Geosciences, Nazarbayev University, Nur-Sultan City, 010000, Republic of Kazakhstan
² School of Mines, China University of Mining and Technology, Xuzhou, Jiangsu 221116, China

amoussou.adoko@nu.edu.kz

Abstract. A reliable estimate of the drilling rate is essential in a successful drill and blast planning and mine production. Owing to this importance, numerous empirical equations of the drilling rate using the rock mass properties and the machine parameters have been proposed. However, these existing equations cannot be used in all site conditions. Hence, this paper aims to develop an empirical model for drilling rate estimation in hard rock mining. The data used for this study were collected from an underground mine located in Selibi-Phikwe, Botswana and included in-situ drilling rate, drilling machine specification and rock mass properties. Nonlinear regression model was used to derive the drill rate model. The result indicates high correlation between the estimated and the actual drill rates. In addition, it was found that the uniaxial compressive strength of the rock, the angle between the rock mass discontinuity planes and the drilling direction are the parameters impacting the drill rate the most. Also, the presence of quartz in the rock indicated good predictability of the drill rates.

1. Introduction

Drilling is a very critical operation in exploration and production processes [1]. Rock drilling is performed by a number of techniques ranging from rotary – percussive in very hard rock, rotary or crushing drilling in medium hard rock and soft rock types. For drilling blast-holes in hard rock, the rotary percussive drilling is a standard in underground mining and tunneling providing maximum performance under most circumstances [2, 3]. In underground mining context, if not optional, the drilling rate dictates the mine productivity rate as it affects all subsequent operational units [4]. Therefore, an accurate estimation of drilling rates is critical for proper planning of mine development and rock excavation projects.

The drilling rate is also one of the most important parameters in drilling economics due to its crucial role in minimizing drilling operational costs. Drilling rate can be defined as the depth of penetration achieved per unit time for a given type of rock, drill bit diameter and air or water pressure. In mining, the term drillability is used to describe the influence of a number of parameters on the drilling rate and wear of the drilling tool [5]. The drilling rate of rock varies with a number of factors, some of which are controllable and some uncontrollable including: rock type, physical and mechanical properties of rock,
orientation foliation, discontinuities, mineral composition, and type of drilling machine, thrust force, rotation, bit type, flushing, drilling method, experience of the operator and maintenance of the drilling machine.

Owing to this important, several methods have been developed to estimate the drilling rate. For example, Thuro [3] proposed a series of correlations between the drilling rates and the rock mechanical properties by developing the rock drillability charts. While these charts are very useful, their application is limited to rotary drilling. Kahraman, Bilgin and Feridunoglu [6] carried out a series of investigations correlating the drilling rate with rock properties and developing regression equations for percussion drilling. The results indicated that the strength of rock exhibits strong correlations with the drilling rate. A practical way of estimating the drilling rate is by using the use rock mass drillability, which relates the rock mass properties to the drilling rate [7-10]. However, some parameters used to formulate the rock drillability index may not show strong correlations with the drilling rate due to the characteristics of the excavations [11]. Therefore, to consider the most important parameters and to reflect the drilling process in a more practical way, a wide range of other methods have been proposed for different contexts including stochastic penetration rate model for rotary drilling [12]; machine learning based-model for drilling rate prediction [13, 14]; the use of energy dissipation and rock brittleness index to evaluate the performance of rock drilling [15]; and the weight-on-bit approach to assess the percussive drilling rate [16]. In essence, over the past few decades, several possible ways of optimizing the drilling and blasting operations have been achieved and different results have been obtained. While most of these studies suggested that the entire process should be modeled, some recommended a better understanding of the site specifications in modeling and designing the drilling and blasting operations. Hence, in this study, a new empirical equation for drilling rate estimation in hard rock mining is proposed on the basis of specific data obtained from an underground mine located in Selibi-Phikwe, Botswana.

2. Data source and data description
The Selebi-Phikwe nickel-copper deposit, owned by Bamangwato Concessions Limited (BCL) is located in Eastern Botswana, approximately 140 km from Francistown. BCL operates three mines in the area: Phikwe mine is the northern-most operation, while Selebi North and Selebi mines are located 8 km and 15 km to the south, respectively. The nickel-copper ore deposit in Selebi Phikwe occurs in an area dominated by the high-grade metamorphic gneiss units assigned to Phikwe complex rocks [17]. The orebody is basically a strata bound sulphide body occurring as amphibolite sill confined within the structurally complex biotite, quartz-biotite and hornblende rich gneisses. The orebody is mostly homogeneous and has a tabular geometry. Mineralization is hosted by amphibolite as massive, semi-massive and disseminated sulphides. The geological classification of rocks at Selebi North is presented in table 1.

The communication and availability of real time drilling data is highly critical to the exploration and production business of any company. In this study, the in-situ drilling data, rock type and rock properties, mineral composition and operating parameters were measured and recorded in two production blocks: block – N3 841/1700 and block – N3 856/1700. The drilling rates were consequently calculated after drilling of the long blast holes for stoping, using the length of the holes and net drilling times recorded during drilling according to Equation (1):

\[
\text{Drilling rate} = \frac{\text{Blast hole Depth (m)}}{\text{Net Drilling Time (h)}}
\]

Drilling was performed using Atlas Copco Simba H1257-130 and Atlas Copco Simba H1257-150 drill rigs, on rings with spacing of 0.5 m and burden of 1 m. The drilling data were recorded from more than 100 drill observations during a 10-hour day shifts over a period of 9 months. However, only 40 drill holes data were complete and, hence, used in this study. The data consist of the drill rate, the machine rotation
pressure, UCS of the rock, the angle between the rock mass discontinuity planes and the drilling direction, the rock density and the mineralogical composition. The rock density and the UCS were determined through the laboratory tests, whilst the rotation pressure was recorded from the drilling machine during the drilling operation. The rock type and mineralogical composition shown in table 1 were derived from geology reports and were consequently validated during the drilling operation. The corresponding drilling rates were calculated for all of these drilling parameters. A sample of the data is provided in table 2.

Table 1. Rock types and mineralogical composition.

| Rock type       | Description       | Mineralogical composition                  |
|-----------------|-------------------|--------------------------------------------|
| Amphibolite     | Weakly foliated   | Feldspar, Hornblende & Quartz              |
| Massive Sulphide| Medium-coarse grained | Pentlandite (Pyrrhotite & Chalcopyrite)  |
| Gneiss          | Medium-fine grained | Feldspar & Hornblende                     |

Table 2. Sample of the blast-hole drilling parameters of Selebi North (BCL Mine).

| Rock Type        | Discont. Orient. (º) | Density (kg/m³) | UCS (MPa) | Rotation Pressure (Bar) | Drill Rate (m/h) |
|------------------|----------------------|-----------------|-----------|-------------------------|-----------------|
| Amphibolite      | 45.80                | 2816            | 126.7     | 39                      | 49.10           |
| Amphibolite      | 43.22                | 2786            | 182.5     | 36                      | 50.20           |
| Amphibolite      | 69.52                | 2871            | 329.5     | 38                      | 31.00           |
| Amphibolite      | 45.26                | 2815            | 130       | 37                      | 45.00           |
| Amphibolite      | 43.66                | 2800            | 320.4     | 35                      | 35.20           |
| Gneiss           | 50.63                | 2710            | 169.6     | 36                      | 40.50           |
| Gneiss           | 69.52                | 2716            | 259       | 36                      | 36.20           |
| Gneiss           | 69.52                | 2758            | 247.7     | 36                      | 44.80           |
| Gneiss           | 50.63                | 2780            | 230       | 36                      | 45.00           |
| Gneiss           | 47.25                | 2716            | 239.7     | 36                      | 54.00           |
| Gneiss           | 43.22                | 2735            | 173       | 36                      | 53.00           |
| Massive Sulphide | 47.25                | 2689            | 219.5     | 35                      | 48.30           |
| Massive Sulphide | 57.32                | 2638            | 402.7     | 35                      | 30.10           |
| Massive Sulphide | 47.25                | 2667            | 206.7     | 35                      | 48.00           |
| Massive Sulphide | 45.80                | 2617            | 215.2     | 35                      | 46.30           |
| Massive Sulphide | 45.80                | 2657            | 264.6     | 37                      | 48.00           |
| Massive Sulphide | 50.56                | 2642            | 333.3     | 36                      | 33.30           |
| Massive Sulphide | 58.30                | 2643            | 301.5     | 35                      | 34.60           |
| Massive Sulphide | 58.30                | 2649            | 338.1     | 38                      | 31.70           |
3. Results and discussions
Firstly, a series of simple regressions were carried out and the obtained results show that the drill rate has a high linear correlation with the UCS of the rock mass (coefficient of correlation $R = 0.87$) (figure 1-A). The drill rate increases with a decrease of the UCS, which is in agreement with the drilling process and previous studies [3, 14]. On the other hand, the drill rate showed a nonlinear relationship with the angle between the rock mass discontinuity planes and the drilling direction (coefficient of correlation $R = 0.91$). As indicated in figure 1-B, when this angle of orientation is between $50^\circ$ and $70^\circ$, minimum drill rates are achieved while maximum drill rates are obtained for the orientation around $40^\circ$. This implies that there are certain orientations very favorable to drill rate. Small angles between discontinuity planes and drilling direction favor the drill rate. Similar observations are true for higher angle close to $80^\circ$. In figure 1-C the drill rate vs the rock density is provided showing poor correlations (coefficient of correlation $R = 0.57$).

![Figure 1. Correlations between Drill rates and: (A) UCS; (B) Discontinuity orientation; (C) Density.](image)

Figure 2 shows the relationship between the drill rate and the density of each rock type. In case of amphibolites (figure 2-A), very high coefficient of correlation is observed ($R = 0.93$). Amphibolites, unlike the other rock types, contain quartz minerals. This might indicate that mineralogical composition (presence of quartz) can also be a good predictor of the drill rates. However, the dataset contains only a few records of drill rate data corresponding to amphibolites, therefore, more data will be needed to validate this conclusion. Conversely, gneiss and massive sulphide rocks, which contain feldspar and hornblende as well as pentlandite minerals, do not show any meaningful correlations, implying that these minerals cannot be used as a reliable indicator of the drill rate (figures 2-B and 2-C).

![Figure 2. Correlations between drill rates and densities (A) Amphibolite; (B) Gneiss; (C) Massive sulphide.](image)
On the basis of these results, the UCS and the angle between the discontinuity plane and the drilling direction ($\beta$), were selected as the most important drill performance input parameters. A polynomial model of 2nd degree was used to fit the dataset. Excellent goodness-of-fit was obtained with the coefficient of determination ($R^2$) and the root mean square error (RMSE), with values of 0.92 and 2.48, respectively. The model expression is provided in Equation (2):

$$\text{Drill rate} = 177.1 - 0.05\text{UCS} - 4\beta + 1.6 \times 10^{-4}\text{UCS}\beta + 0.03\beta^2$$

(2)

Equation (2) was used to compute the predicted drill rates, which were compared to the actual drill rates (figure 3) showing high correlation ($R^2 = 0.83$), which could be further improved, if the outliner could be removed after further investigation.

![Figure 3](image_url)

**Figure 3.** Estimated vs actual drilling rates.

4. Conclusions

In this paper, an empirical drill rate model suitable for underground hard rock mining environment was proposed. A total of 40 blast-holes’ drilling data was compiled for this study. The data consisted of the drill rate, the machine rotation pressure, UCS of the rock, the angle between the rock mass discontinuity planes and the drilling direction, the rock density and the mineralogical composition. Initially, simple regression analysis was used to investigate the correlation between the drill rate and its influencing parameters. The results indicated that the UCS and the angle between the rock mass discontinuity planes and the drilling direction are the most correlated parameters with the drill rate. In addition, the presence of quartz minerals indicated high drill rate. Subsequently, a polynomial model for the estimation of the drill rate was developed as a function of the UCS, the angle between the rock mass discontinuity planes and the drilling direction. The prediction of drill rates using the polynomial model showed excellent agreement with the actual drill rates. It was concluded that these two parameters could be used to estimate the drill rates in BCL mines.

**Acknowledgment**

This study was supported by the Faculty Development Competitive Research Grant program of Nazarbayev University, Grants Nº 090118FD5338 and Nº 021220FD5051.
References

[1] Singhal R K 2014 Surface and underground excavations – methods, techniques and equipment *Int J Min Reclamat Environm* **28** 214-5

[2] Shaterpour-Mamaghani A and Copur H 2021 Empirical Performance Prediction for Raise Boring Machines Based on Rock Properties, Pilot Hole Drilling Data and Raise Inclination *Rock Mech Rock Eng*

[3] Thuro K 1997 Drillability prediction: geological influences in hard rock drill and blast tunnelling *Geologische Rundschau* **86** 426-38

[4] Poma M, Quispe G, Mamani-Macedo N, Zapata G, Raymundo-Ibañez C and Domínguez F 2020 Drilling-and-Blasting Mesh Design for Underground Mining Using the Holmberg Method. (Cham: Springer International Publishing) pp 683-9

[5] Thuro K and Spaun G 1996 Introducing the 'destruction Work' As a New Rock Property of Toughness Referring to Drillability In Conventional Drill- And Blast Tunnelling. In: *ISRM International Symposium - EUROCK 96* (Turin, Italy: ISRM)

[6] Kahraman S, Bilgin N and Feridunoglu C 2003 Dominant rock properties affecting the penetration rate of percussive drills *Int J Rock Mech Min Sci* **40** 711-23

[7] Hoseine H, Aghababaie H and Pourrahimian Y 2008 Development of a new classification system for assessing of rock mass drillability index (RDi) *Int J Rock Mech Min Sci* **45** 1-10

[8] He M, Li N, Zhang Z, Yao X, Chen Y and Zhu C 2019 An empirical method for determining the mechanical properties of jointed rock mass using drilling energy *Int J Rock Mech Min Sci* **116** 64-74

[9] Cheniany A, Hasan K S, Shahriar K and Khademi Hadimi J 2012 An estimation of the penetration rate of rotary drills using the Specific Rock Mass Drillability index *Int J Min Sci Tech* **22** 187-93

[10] Ataei M, KaKate R, Ghavidel M and Saeidi O 2015 Drilling rate prediction of an open pit mine using the rock mass drillability index *Int J Rock Mech Min Sci* **73** 130-8

[11] Yarali O and Soyer E 2013 Assessment of relationships between drilling rate index and mechanical properties of rocks *Tunnel Undergr Space Tech* **33** 46-53

[12] Saeidi O, Torabi S R, Ataei M and Rostami J 2014 A stochastic penetration rate model for rotary drilling in surface mines *Int J Rock Mech Min Sci* **68** 55-65

[13] Mehrad M, Bajolvand M, Ramezanzadeh A and Neycharan J G 2020 Developing a new rigorous drilling rate prediction model using a machine learning technique *J Petrol Sci Eng* **183** 106332

[14] Munoz H, Taheri A and Chanda E K 2016 Rock Drilling Performance Evaluation by an Energy Dissipation Based Rock Brittleness Index *Rock Mech Rock Eng* **49** 3343-55

[15] Song X, Aamo O M, Kane P-A and Detournay E 2020 Influence of Weight-on-Bit on Percussive Drilling Performance *Rock Mech Rock Eng*

[16] Brown P J 1988 Petrogenesis of Ni-Cu ore bodies, their host rocks and country rocks at Selebi-Phikwe, Eastern Bostswana. (Southampton: University of Southampton, UK) p 333