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The Use of Specific Energy in Rotary Drilling: The Effect of Operational Parameters

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ABSTRACT: In rotary drilling, specific energy is considered to be an important parameter for defining mechanical efficiency of the rock destruction process. Specific Energy is defined as the energy required to remove one unit of rock. Specific energy is the function of the size of the borehole and various operational parameters including feed force, rotation speed, rotation torque and penetration rate. The harder the material, the higher the specific energy. The traditional method to calculate the specific energy is based on the parameters penetration rate, feed force, torque and rotation speed, that can be provided by Measurement While Drilling (MWD) data from the drill process. In this study, MWD data from an open pit mine in Sweden are used to evaluate data trends among logged parameters and calculated average specific energy. The results show that there is a significant hole length dependency for penetration rate and feed force that affects the predicted specific energy. This may be explained by that the hole cleaning efficiency is reduced with increasing hole length. The analysis shows that the specific energy is over-estimated by 45% in the bottom of an 18 m hole compared to the collaring point. The suggested solution is to use hole average or complement the specific energy calculation with a hole length related component.

INTRODUCTION

Measurement While Drilling (MWD) is a drill monitoring technique providing information about the mechanical characteristics of the subsurface. In the mining industry, MWD is used for rock mass characterization, short and long term planning, optimization of fragmentation, equipment planning to achieve cost effective production (Ghosh et al., 2014). It is also important for throughput prediction of the comminution process (Segui and Higgins, 2002; Schunnesson and Mozaffari, 2009). In underground mining, MWD has been considered capable of providing ore grades and ore delineation for production planning (Schunnesson and Holme, 1997) with the potential for selecting rock support (Turtola, 2001).

Initially, Measurement While Drilling (MWD) was used in the petroleum industry; then in 1911, Schlumberger began electrical logging in the oil industry (Segui and Higgins, 2002). In the oil and gas industry, MWD has been used to determine the direction of the well path, the bottom hole temperature, pressure, drilling dynamic parameters and, in some cases, gamma logging meanwhile Logging While Drilling (LWD) system can provide information about formation and formation fluid properties such as water, oil and gas (Rogtec website, 2013). In the 1970s, drill monitoring systems was introduced in open pit mining operations (Segui and Higgins, 2002). MWD has also been useful in tunnel construction (Schunnesson, 2011). During recent decades, the technology has been tremendously updated.

It has always been challenging to get detailed, high resolution information on the geo-mechanical properties of rock masses. For example, it is time consuming and expensive to use core sampling to fully understand the behaviour and details of a large rock mass. MWD can therefore be considered as a robust technique for detailed characterizing of large rock masses provided that the raw data is treated properly and effective analysis is applied. Considerable research has been done in this area. For example, the MWD technique has been used for improving blast design and fragmentation (Smith, 2002). Drill performance parameter can be related with rock compressive and shear strength and further, the possibility of estimating rock strength properties (Peck, 1989). In percussive drilling, monitored data have been used to evaluate the hardness, fracturing and weathering of the rock mass as well as localization of ore and rock type boundary (Schunnesson, 1998). Average penetration rate and average specific energy were used in order to characterize relative hardness of the rock mass along the bench and how it can be statistically similar along the bench was illustrated by Ghosh et al., 2014.

According to Thuro (1997), the concept of drillability was proposed to classify rock mass by drilling parameters and the idea of excavatability was also introduced to find the relationship between destruction work and the specific consumption of explosive by using drilling rate. In another study, drillability index was also used to predict penetration rate from rock mass characteristics (Kahraman et al., 2000). Teale (1965) defined specific energy by correlating drill performance parameters in rotary drilling. For percussive drilling, Rock Quality Designation (RQD) was also predicted in a tunnelling operation by using drill monitored data rather than more common optical, mechanical and geophysical methods (Schunnesson, 1996). Drilling monitoring data together with image analysis was used to get information required for the optimization of blasting (Schunnesson and Mozaffari, 2009). Drill monitoring data can also provide information about bench geology and structure influencing blastability. This was used for modification of blast design in time and thus further affecting on production and mineral processing (Yin and Liu, 2001). Another example has been reported by Turtola, (2001) that used MWD data to interpret the geology in Aitik Mine, Sweden.

In this paper, the concept of specific energy has been analysed based on real drilling data from Aitik Mine, Sweden.

MEASUREMENT WHILE DRILLING (MWD)

Two types of drilling parameter are normally measured during drilling: independent and dependent parameters. Independent parameters are controlled by the operator or by the drilling system itself while dependent parameters are the responses to the changes in the geo-mechanical properties of the rock mass (Peck, 1989). Table 1 shows the most commonly used parameters with their respective definitions and units.

THE CONCEPT OF SPECIFIC ENERGY

According to Teale (1965), rotary drilling consists of two actions; Indentation and Cutting. Indentation means the bit is pushed continuously into the rock. Cutting occurs when the bit is given a lateral movement to fragment the rock.

Table 1. MWD parameters (Peck, 1989)

Types	Parameters	Definition	Units
Independent	Depth	It is necessary to record the MWD data with respect to depth along the borehole and hence better prediction about the alteration of geo-mechanical properties of the rock mass along the depth (Schunnesson and Mozaffari, 2009).	m
	Time	Monitored data should be recorded with specific dates and times to allow the productivity evaluation (Schunnesson and Mozaffari, 2009).	yyyy-mm-dd and hh:mm:ss
	Feed force	Feed force influences penetration rate. The drilling rate increases as the feed force increases up to the limit where the bit is stalled in the rock material and cannot complete penetration (Teale, 1965; Segui and Higgins, 2002).	N
	Rotation Speed	It is defined as the number of rotation per minute.	rpm
	Air pressure	This is used to remove cuttings from the borehole.	bar
Dependent	Penetration rate	It is the rate of penetrating of the drill bit through the rock mass and is influenced by geo-mechanical response of the rock mass (Schunnesson and Kristoffersson, 2009).	m /min
	Torque	This is the force multiplied by the radius to maintain the required rotation. It depends on rock type, weight on the bit and the bit design (Peck, 1989).	N-m
	Vibration	There is significant vibration of the drill rig during drilling through the rock mass (Schunnesson and Kristoffersson, 2009).	N-m/s

Specific energy is defined as the energy required to break one unit volume of rock. It is a measure of the amount of work done per unit of volume. In rotary drilling, specific energy consists of two parts: (1) work done by the axial feed force; (2) work done by the rotational torque. It is formulated by Teale (1965) in the following equation.

Specific energy = Specific energy due to the axial force + Specific energy due to the rotation
= Work done per unit volume by feed force
+ Work done per unit volume by rotation torque

$$= \left(\frac{F}{A}\right) + \left(\frac{2\pi}{A}\right)\left(\frac{NT}{P}\right) \text{in} - \text{lb/in}^3 \quad \textbf{(1)}$$

where F = Feed force (lb), A = Cross-sectional area of the drill hole (in^2), N = Rotation speed (rpm), T = Torque (lb-in), and P = Penetration rate (in/min)

Despite the advantages of being able to describe the rock mass properties with a defined physical measure, the calculation of specific energy also normalises monitored data so that variations in feed force and rotation speed, that are influenced by the operator, the drilling process or drill control system, will not affect the specific energy value. Therefore it is argued that the specific energy value represent the conditions of the true rock mass and will not be affected by the conditions and operation of the drill system.

Based on measurements made on an actual drilling machine, Teale (1965) however showed that specific energy can reach high values at low thrust and this does not follow the proposed equation. A minimum amount of feed force has to be used to overcome friction between bit and rock surface; thus the bit will penetrate the rock after doing a finite amount of work. Therefore, due to the friction, the total amount of work will decrease. As the feed increases, the size of the fragments increases. Combining those effects, specific energy increases while feed force decreases and thus specific energy becomes infinite at zero feed force (Teale, 1965).

Again, according to Teale (1965), the work done by feed force is negligible compared to that of the rotation. Experiment was done for Pennant Sandstone and Darley Dale Sandstone by using a tri-cone roller bit. Rotation speed was kept constant while the correlation was made between feed force and rotary component of specific energy. In this correlation, the rotary component of specific energy decreases with the increase of feed force. After that, the minimum specific energy was compared to the crushing strength of those samples. In this experiment, the curve drawn between torque and penetration per revolution for rotary drilling followed a straight line through the origin. Specific energy was assumed constant over a wide range of work where torque and penetration per revolution followed straight line. In addition, minimum specific energy was considered to be the order of the quoted compressive strength of the material drilled. Finally, excess specific energy was considered as the degree of wear (scuffing action) of the bit (Teale, 1965).

Specific surface energy in rotary rock drilling was introduced by Liu and Karen (2001). They defined it as the energy required for creating a new surface of unit area. For the same rock type, the specific surface energy will only depend on its crystalline structure. As, it is only material related and can be considered as a rock property, they took it as a rock drillability indicator and specified the following relationship between specific energy and specific surface energy (Liu and Karen, 2001).

$$E_a A_s = E_v = \frac{F}{A_e} + \frac{2\pi NT}{A_e u} - \frac{V_{vib}}{A_e u} \quad N/m^2 \tag{2}$$

where, E_a = Specific surface energy (N/m), A_s = Specific surface area (m^2/m^3), E_v = Specific energy (N/m^2), F=Pull down force (N), A_e = Excavation area (m^2), N = Rotation speed (rps), T = Torque (N-m), u = Penetration rate (m/s), and V_{vib}= Total vibration (N-m/s)

The first term of the equation (2) is the pull down component of the work done in rotary drilling. It represents mean compressive pressure exerted by the pull down over the cross-section of the hole. The second term represents the rotary component and has a dimension of stress. The third term represents the contribution from vibration which is normally neglected due to the small magnitude as compared to the first two terms. Therefore, the above equation can be written as:

$$E_a = \frac{1}{A_s A_e}\left(F + \frac{2\pi NT}{u}\right) N/m \tag{3}$$

Specific energy and vibration were used to describe the rock mass for a real drilling operation at the Earnest Henry gold and copper mine in Queensland, Australia (Smith, 2002). The result from this study shows that specific energy and vibration are inversely proportional. This conclusion was based on field data and should further be tested using laboratory equipment which can take higher sampling rate with better sensitivity and fewer outside influences (Smith, 2002).

Specific energy has been used as a local drillability index to characterize the rock mass at a specific site (Peck, 1989). In another case, it proved helpful in identifying the boundaries between different rock formations (Izquierdo and Chiang, 2004).

One important argument for the use of specific energy is that it is independent of the drill system even if Teale (1965) pointed some specific conditions that are not completely explained by the formula. One parameter that is not included in Teale (1965) and Liu and Karen formulas (2001) is the drill depth. Schunnesson (1998) showed that not only penetration rate but also feed force and rotary torque have a significant trend versus hole depth for percussive drilling. He also pointed out the impact of flushing, where increasing hole depth will affect the hole cleaning efficiency. Even if the percussive drilling and rotary drilling are significantly different, the flushing efficiency is equally important in both cases.

CASE STUDY

Aitik Mine

Aitik Mine is the largest open pit copper mine of Europe and is owned by the Swedish mining company Boliden Minerals AB. The mine is located about 60 km north of the Arctic Circle and 20 km from the city of Gällivare, in Northern part of Sweden, see Figure 1. The production of crude ore was in 2013, 37.07 million tons (Boliden website, 2013), and the stripping ratio is about 1:1 (Mining technology website, 2013). The length and width of the ore body are about 3 km and 1 km respectively (Sammelin et al., 2011). The ore body is divided into two zones: Northern and Southern. The planned final depth is 460 m in the southern zone and 630 m in the northern zone, while the current mining depth is about 430 m in the deepest part. The mineralisation continues below the final depth, but is presently not economical to extract.

In 2013 the mine produced 70.86 kilo tonnes of copper, 53.612 tonnes of silver and 1.765 tonnes of gold ([1]Boliden website, 2014). The average grade in the proven reserve of the ore (691 million tons estimated by 2013-12-31) contains 0.22 percent copper, 0.15 g/t gold and 1.6 g/t silver ([2]Boliden website, 2014).

Drilling System

MWD data were collected from the four rotary blast hole drilling rigs, Atlas Copco Pit Viper (PV351) using a tricone bit. The diameter of the production hole is 12¼" (311 mm). The average bench height is 15 m and the depth of the borehole varies from 15 m to 20 m with a sub drilling length 2 m. The burden and spacing of the production holes are 7.75 m and 9.75 m respectively (Bergman, 2005). Drill monitoring system has been assembled with the drill rig to collect Measurement While Drilling (MWD) Data. The recorded data consists of log time (YYYY-MM-DDThh:mm:ss), depth (m), penetration rate (m/min), rotation speed (rpm), air pressure (bar), feed force (kN) and rotation torque (kN-m). Measurements have been recorded at about 0.1 m intervals along the borehole. A total of 16881 boreholes have been considered for this study.

SELECTION OF FILTER CRITERIA

Monitored data from a real production environment will normally include some incorrect or faulty data. These failure data can be generated by measurement error, abnormal operational conditions

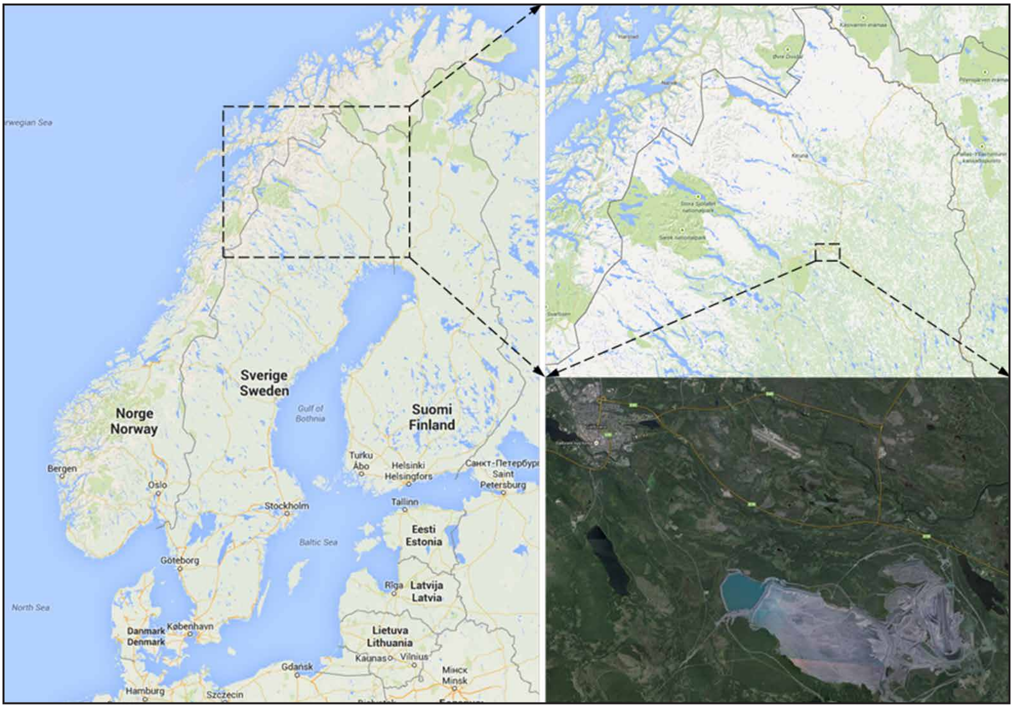

Figure 1. Geographical location of Aitik Mine

or operator's error. To handle this, faulty or unrealistic values must be removed from the data set before further analysis can be done.

The criteria for filtering raw data have, in this case, been based on both frequency analysis and practical experience. The ranges of recorded parameters have been observed by frequency analysis, as shown in Figure 2. Empirical distribution function has been determined to define the limit of the recorded parameters. Practical experience has also been used to define some filter limits. For example, the recorded penetration rate varies from 0 to 20 m/min. A penetration rate of 20 m/min is unrealistic for real drilling. Even to move the bit forward in free space at a speed of 20 m/min is not possible for the drill rig in question; therefore the data are clearly faulty. 0 values of any operational parameters are also unrealistic for a real drilling operation and are considered as a measurement failure in this study.

The upper part of each hole has also been removed from the data set since it may be fragmented and affected by the bottom charge of the blasting of the previous bench. Consequently the first 4 m of the holes have been removed.

The used filter limits for the study are presented in Table 2. For penetration rate this limit corresponds to 97.24% empirical distribution function. For the other operational parameters feed force, rotation speed, rotation torque and air pressure the used limits corresponds to 99.99% empirical distribution function. For the filtering of data it means that data sets which do not satisfy all filter conditions, are considered as incorrect and will not be considered in the continued analysis.

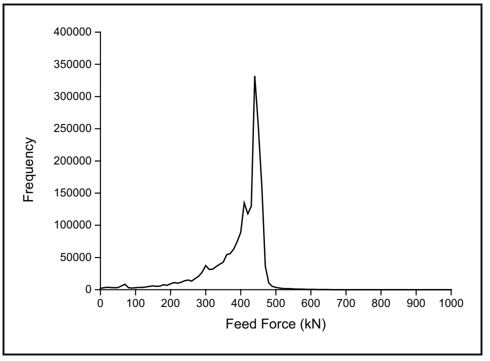

Figure 2a. Frequency for measured feed force (kN)

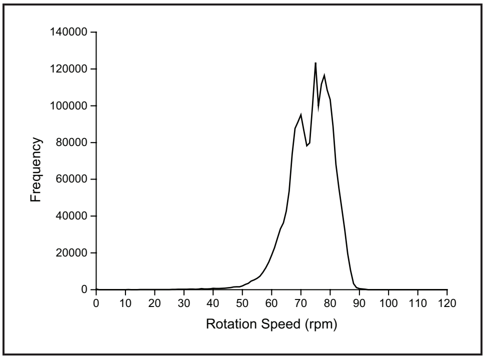

Figure 2b. Frequency for measured rotation speed (rpm)

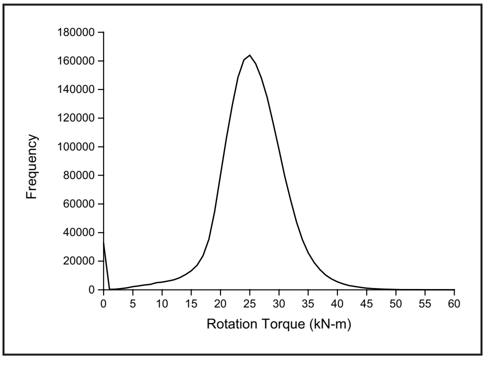

Figure 2c. Frequency for measured rotation torque (kN-m)

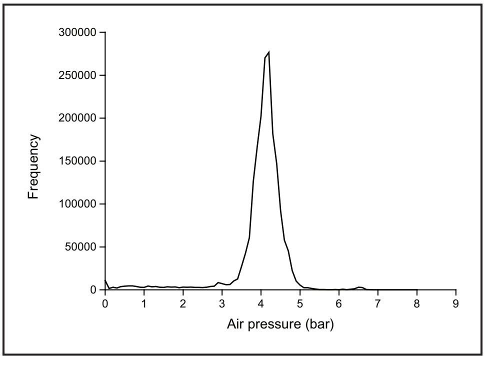

Figure 2d. Frequency for air pressure (bar)

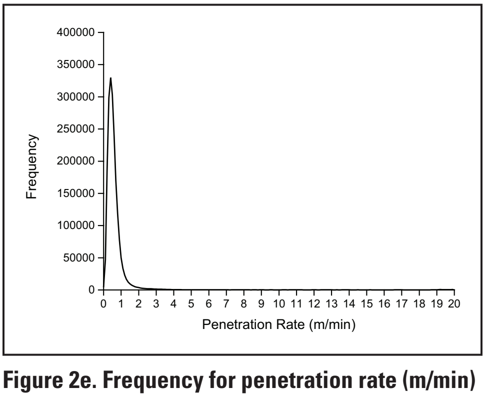

Figure 2e. Frequency for penetration rate (m/min)

RESULTS

To analyse trends in the raw data the filtered data on feed force, rotation speed, rotation torque, penetration rate and specific energy, have been, averaged at each depths for all the boreholes, see Figure 3. Findings show that the average feed force increases with increasing hole depth, as depicted in Figure 3(a). The average feed force ranges from 360 kN up to 415 kN at the end of the hole. Average rotation speed and average rotation torque were almost constant at about 74 rpm and 25 kN-m as shown in Figure 3(b) and Figure 3(c) respectively. Also the air pressure did not vary significantly and was in average about 4 bar independent of hole depth, see Figure 3(d). The average penetration rate on the other hand, decreases with increasing hole depth as seen in Figure 3(e). The average penetration rate varies from about 0.65 m/min down to 0.5 m/min at the end of the hole. The calculated parameter, specific energy, that depends on both

Table 2. Selection of intervals for filtering raw data

Recorded Parameters	Ranges of the Measured Parameters in Raw Data	Selected Intervals of the Measured Parameters Based on Filter Criteria
Feed force (kN)	0–980	>0 and ≤730
Rotation speed (rpm)	0–95	>0 and ≤93
Rotation torque (kN-m)	0–57	>0 and ≤56
Penetration rate (m/min)	0–20	>0 and ≤2
Air pressure (bar)	0–8	>0 and ≤7.8

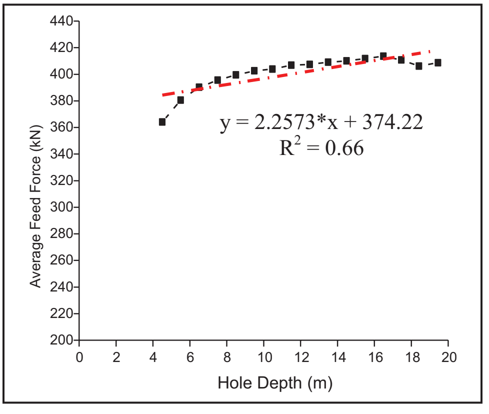

Figure 3a. Feed force (kN) versus depth

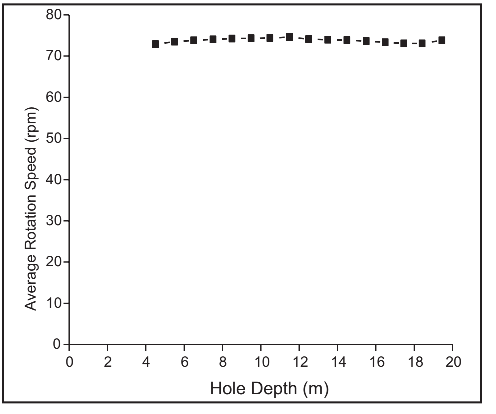

Figure 3b. Rotation speed (rpm) versus depth

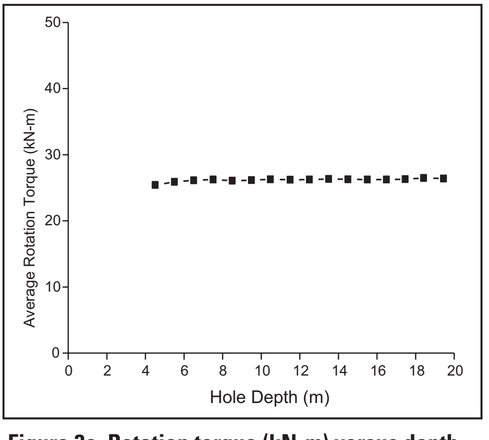

Figure 3c. Rotation torque (kN-m) versus depth

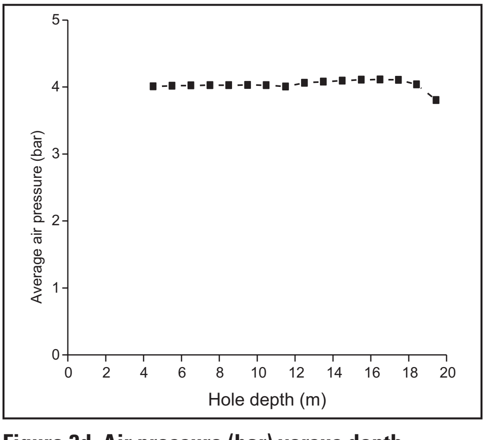

Figure 3d. Air pressure (bar) versus depth

penetration rate and feed force, see equation (1), increases significantly along the hole depth from about 29×10^7 N-m/m^3 to about 42×10^7 N-m/m^3 as shown in Figure 3(f). This means there is an increase of specific energy of almost 45% from the collaring point down to a depth of 18 m.

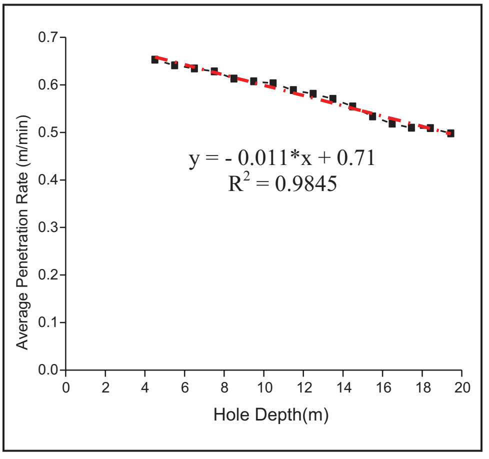

Figure 3e. Penetration rate (m/min) versus depth

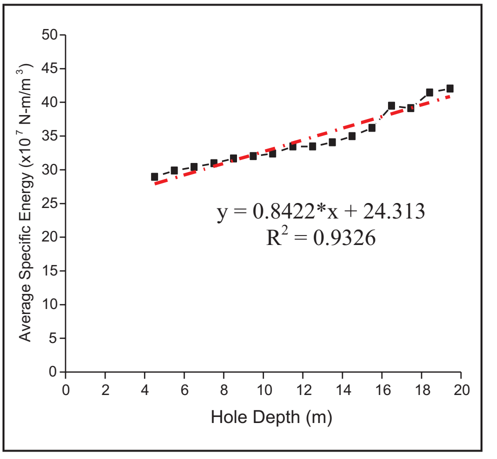

Figure 3f. Specific energy (N-m/m^3) versus depth

DISCUSSION

The monitored drilling data display a systematic variations over hole depth. Specifically, the feed force increases with increasing hole depth while the penetration rate decreases. According to equation (1), both increasing feed force and decreasing penetration rate will result in higher specific energy, as shown in Figure 3f. The other monitored parameters, rotation speed, rotation torque and air pressure do not show any systematic variation with drill depth.

According to Teale (1965), specific energy is defined as the work/volume ratio and is treated as mechanical efficiency for the study of rock working process. This means that for a specific drill set-up the specific energy describes the rock mass characteristics. In the tested mine there are no geo-mechanical rock mass variations versus hole depth that could explain the recorded trends. Instead it is more likely that it is the drill system and operational behaviour and drill control that causes the recorded data trends.

The drill control system is not known to the authors at the case study mine; however it is not unlikely that the drill control will respond to the decreasing penetration rate with an increasing feed force in order to try to restore the drill productivity. The reason for the decreasing penetration rate is not equally obvious but one likely reason is related to the flushing conditions. The monitored flushing parameter, air pressure (bar) is however constant versus hole depth, as seen in Figure 3d.

Even if the air pressure are low (4 bars) the air volume capacity of the used rigs are large which would secure efficient hole cleaning capacity. In this case however only the air pressure is monitored and not the air flow, which reduces the possibility to analyse the hole cleaning efficiency. Only knowing the air pressure also limit the knowledge of the flushing efficiency at the bit position of the drill string as the hole gradually gets deeper. With a constant air pressure there is a significant difference in flushing efficiency between the collaring point where the annulus area outside the drill string has limited depth compared to an 18 m long annulus area where air and cuttings are mixed and where additional pressure drops caused by water inflow regularly occurs. This means that even if the recorded air pressure is constant the cleaning efficiency at the bit position may deteriorate as the hole gets longer. Additionally this would reduce penetration rate and increase the specific energy. As seen in Figure 3 the hole depth dependent trends, will significantly influence the usefulness of specific energy defined by Teale (1965). With an identical geomechanical material, seen in the case study mine, the specific energy still drops to 45% between the collaring point and the end point at 18 m.

In order to use specific energy as a measure of rock mass characteristics, the presented problems must be removed or handled in the analysis phase. One way of neutralising the effects is to use hole averages to generate horizontal maps. This has been done by Ghosh et al (2014) in an attempt to characterize larger areas of an open pit. However it is important to distinguish that this calculated specific energy over estimates the actual specific energy and are also effected by bit wear. Another way to treat the data is to modify the penetration rate value in equation (1) with a compensated penetration rate value based on the regression line in Figure 3a. A more direct solution is to modify the flushing system/control to achieve a more constant hole cleaning efficiency. This is however a challenge to implement as all mining companies and equipment supplier has been working with this to improve drilling efficiency.

CONCLUSIONS

Following are conclusions from the performed study:

- The data from the site study show that several of the monitored parameters contains significant variation versus hole depth which are not related to geo-mechanical properties in the rock mass.
- The influence of hole depth on recorded parameters have a significant impact on the calculated specific energy. In this case a 45% increase in specific energy was recorded from the collaring point down to 18 m depth.
- With the constant air pressure, the overall hole cleaning efficiency may deteriorate with increasing hole depth and may explain the negative trend for the penetration rate that also influences the trend for the calculated specific energy.
- The indicated problems i.e., hole depth dependency and flushing condition can be solved by using hole average or normalisation based on depth trends.

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