STATE OF THE ART REVIEW: MONITORING-WHILE-DRILLING FOR MINING APPLICATIONS

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ABSTRACT

Monitoring-While-Drilling (MWD) is a proven technique that records instantaneous on-drill parameters which can be used to supply contextual information for in-situ, down hole conditions, such as: changes in geology, the presence of pre-existing fractures and dynamic alterations, down hole conditions including bit bailing, bit blockages and bit wear, and improper drill operation. This technique has been widely used in the oil and gas industry and, eventually, it was transferred to the mining industry. A challenge when analyzing and interpreting MWD data is in utilizing proper filtering which enables one to properly eliminate any 'noise' from the signals of interest. Overall the importance of MWD data is that, through the collection of operational field-based data, a dataset can be acquired which allows experimentation and analysis to be carried out. Such a dataset is often impossible to replicate in a laboratory setting. If successful, and through iterative refinement, any promising method can eventually be implemented on-machine and using real-time monitoring techniques. This paper will provide a state of the art review of presently used MWD techniques and applications in industry. The paper's primary focus will be on shallow, mining-style, blast hole drilling but will also take into account techniques and applications utilized in oil and gas drilling which have not been adopted in the mining industry. In the cases where MWD techniques and applications exist solely in oil and gas drilling the paper will examine and comment on the potential utility of technology transfer to mining applications.

KEYWORDS

Drilling, Surface mining, Monitoring-while-drilling (MWD), Geology

INTRODUCTION

Monitoring-While-Drilling (MWD) is a proven technique which has been widely used in mining for the better part of two decades. The technique allows for the recording of instantaneous on-drill parameters while the drill is operating. In the mining industry, such information is currently used in a variety of ways, the most common of which is for modeling of in-situ geological conditions. This is of value as it can supplement and improve the existing mine models and decrease the need for costly and labour intensive exploration drill core sampling and geophysical logging. Exactly how this is done will be examined and discussed.

A robust MWD dataset can only be acquired if the necessary signal sensors are in place onboard the drill unit. A good understanding of MWD requires a good understanding of the supporting sensors required. These sensors will be discussed and examined. Also of importance is the signal analysis that must be conducted on the data output by the onboard sensors. This includes required frequency of data collection, required segmentation of MWD data and the data filtering methods employed.

In addition, this paper will explore the potential for new technology and applications based upon the MWD data. This will be based upon ongoing academic research which is not yet available commercially. Technologies used in oil and gas for MWD that are not used in mining will also briefly be examined for potential utilization. However, it is expected that there will be little potential for transfer from oil and gas drilling to mining industry drilling. This is due to the nature of the blasthole drilling application which encompasses shallow, single directional holes of a mostly vertical nature. Since mining is the field of interest the application of MWD for blasthole drilling will be the primary focus of this paper.

MONITORING-WHILE-DRILLING

MWD, also sometimes referred to as Logging-While-Drilling (LWD), involves the recording of select drill variables of interest while the drill unit is in the process of drilling. These data can then be used to obtain useful information about the down-hole drilling environment and further analyzed for the use in ore boundary zone determination, in-situ rock strength estimation, drill and operator performance evaluations, blast design optimization, drill automation, and bit wear monitoring (Beattie, 2009). The most commonly monitored variables (and their most commonly used units) are listed below (Gonzalez, 2007).

- Depth (m)
- Time (s)
- Penetration Rate (m/s)
- Rotary Speed (RPM)
- Pull-down Force (N)
- Torque (Nm)
- Flushing Medium Pressure (kPa)

Following convention the units above were presented in SI units however, due to some of the industry being located within the United States, the data can occasionally be presented in Imperial Units. In addition to the above listed variables, it is also of use to monitor the operator (or computer controlled) machine set-points for each variable. This allows for the understanding and, if necessary, elimination of operator or control logic influence over the monitored variables (Lucifora, 2012).

MWD originally was developed by research funded for the petroleum industry in the 1970s (Smith, 2002). It was eventually adapted for use in the mining industry (Peck, 1986). While MWD is not a new concept and its method of employ has not changed it is now considered an industry standard practice. While the onboard data collection aspect has remained static, the supporting technology has greatly advanced, as have the analysis tools available. This has led to MWD data having greater potential value than ever before. The most important benefits of MWD data to industry are seen to be the following (Smith, 2002):

- Less geological and geophysical investigation
- Optimization of drilling by choosing the best parameters
- Better definition of coal seams
- Identification of weak and strong zones
- Optimization of blast design
- Improved data reports
- Less resources required for log interpretation and data handling

A recently completed MWD-based study concluded that penetration rate provided an accurate indicator of rock strength (Phelps Dodge Mining Company et al., 2002). This reinforced the findings of a similar previously completed McGill University-led study (Scoble et al., 1989). The study, done by Phelps Dodge, also pointed out that penetration rate can be measured without the use of MWD and its required supporting technology. This is because one can simply calculate the penetration rate for each hole if the hole's depth and total drilling time are known. Indeed, it is because of the simplicity of measurement and no need to purchase costly technology that many mines attempt to determine in-situ geology using this penetration based method. Unfortunately, this method can be quite unreliable and incredibly misleading if done without supporting MWD data. It is not the absolute values of penetration rate that distinguish particular rock strength and types because penetration rates vary depending on machine set-points such as pull-down force, flushing pressure and rotary speed. Therefore, if the aforementioned machine set-points vary over the depth of the hole drilled, the absolute value of the penetration rate may not accurately reflect the true nature of the rock (Scoble et al., 1989). It is for this reason that penetration rate cannot accurately predict in-situ rock hardness without supporting MWD data. This highlights the value of the MWD technique.

All of the above mentioned MWD approaches have focused exclusively on mining. Since the petroleum industry is where the MWD technique originated it was thought to be of use to explore current technologies available for MWD in petroleum and oil and gas fields. While there are some new developments with advanced technology for down-hole data acquisition in real-time, unfortunately these sensors all focus on real-time drill bit positioning and not rock recognition or drill bit wear (Noureldin, 2002). Due to the shallow-hole nature of the drilling application in mining, drill bit advancement is not steerable and therefore not as dynamic as in oil and gas. For these reasons real-time drill bit positioning would be redundant in the mining industry so long as the drill unit is leveled and in position over the desired blasthole location.

MONITORING SIGNALS AND SIGNAL PROCESSING

Roller-cone bits are widely used in mining applications as well a soil well drilling applications because of their cost effectiveness. However, it can prove to be problematic to gather information about in-situ, down hole conditions, including: changes in geology, bit bailing, bit blockages, bit wear, and improper drill operation. A lack of this information can result in drilling inefficiency and can lead to more serious problems.

Naganawa (2012) has studied the feasibility of roller-cone bit wear detection using axial bit vibration. Researchers have found that the peaks in the vibration frequency spectrum of a drill bit will gradually shift to higher frequencies as the bit wears, shown in Figure 1. This is a phenomenon that can be examined using monitoring techniques.

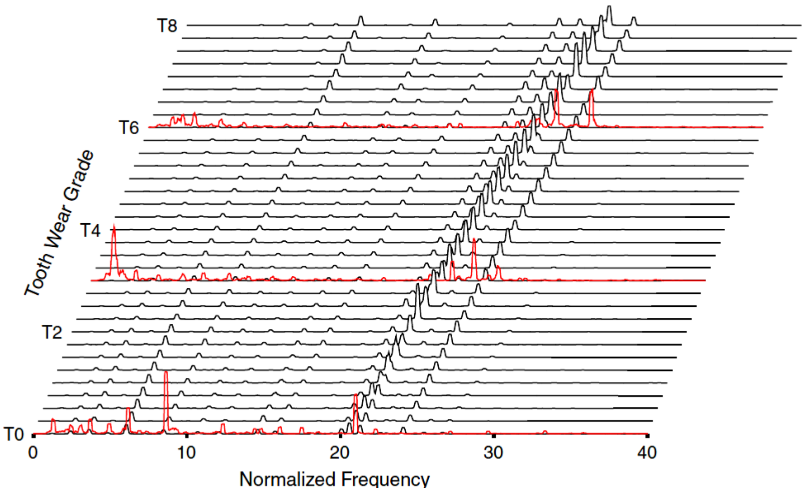

Figure 1 – Effect of bit wear on vibration frequency spectrum (Naganawa, 2012)

During the study by Naganawa (2012), the researchers modeled the dynamics of roller-cone bit axial vibration to evaluate bit tooth wear quantitatively. The model produced included the kinematics of the bit motion and also a model for bit-rock interaction. The model was validated by comparing the power spectral densities for simulated time histories of axial bit vibration with the experimental results of full-scale drilling tests.

Sensors used to collect vibration data are known as accelerometers. “An accelerometer is a transducer whose output is proportional to acceleration. For example, a mass-spring system acts as an accelerometer when it operates below its natural frequency.” (Poletto et al., 2004). In industrial applications, usually piezoelectric accelerometers are implemented.

A piezoelectric accelerometer is made with material that generates voltage in response to strain. Due to advantages in their sensory parameters piezoelectric accelerometers are widely used in industry. The most important parameters associated with the accelerometers are listed below (Poletto et al., 2004):

- Sensitivity – the ratio of sensor output to mechanical input
- Resolution – the smallest change in input acceleration for which a change in electrical output can be generated
- Amplitude linearity – consistency of the ratio of voltage output to acceleration input
- Frequency range – the range in which the sensitivity of the transducer varies less than a certain percentage from a given reference sensitivity

Cooper (2002) proposed a method to estimate the degree of tooth wear of a drill bit by comparing its actual drilling performance with the theoretical performance of the same bit, calculated using the properties of the bit, the knowledge of the operating conditions and the strength of the rock being drilled. The author proposed that if an onboard system had access to real-time MWD data, as well as an independent estimate of the rock strength then the log-derived rock strength could be compared with the estimate derived from the drilling record. This is illustrated in Figure 2.

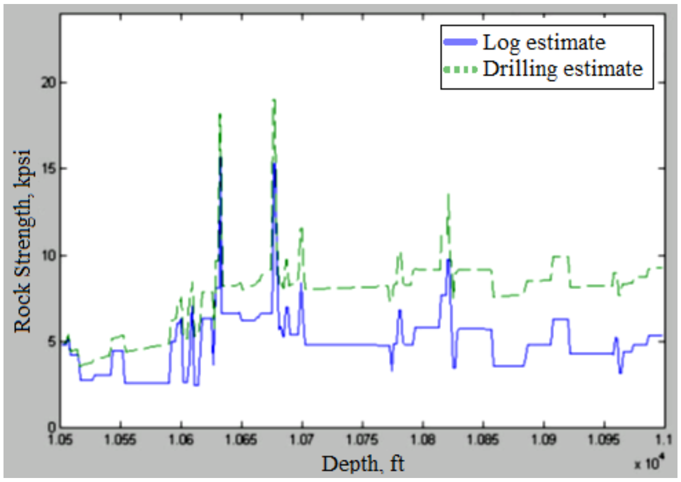

Figure 2 – Comparison of estimated and measured rock strength (Cooper, 2002)

“This clearly shows the steadily increasing distortion introduced into the estimate derived from the drilling data by bit wear. We see that substantial wear occurs in the sands in the upper portion of the interval, and that more wear occurs in the section with the strong limestone stringers, and that relatively little additional wear occurs in penetrating the shales from 10,700 ft downward.” (Cooper, 2002).

Vardhan et al. (2009) investigated the estimation of rock properties like compressive strength and abrasiveness using sound signals produced during drilling. Their investigation included laboratory scale tests using a small portable pneumatic vertical drill. “The noise measurement for the same type of drill machine varies from strata to strata. Thus, the variations in the sound level can indicate the type of rock, which can be used to select suitable explosives and blast designs.” (Vardhan et al., 2009). The study concluded that the sound level in the low frequency range is due to the impact between the piston and the drill steel and also between the drill steel and the rock. The exhaust of the drill machine produces sound levels in the frequency range of 125 Hz–2 kHz. The sound level from 2.5–20 kHz is due to the resonance frequency of the drill string steel. They found a direct relationship between the thrust and the sound level at higher mid-band frequencies within the noise spectrum.

Another signal which has been investigated to obtain information from the geology, rock and drilling process is the bailing air pressure signal (Gonzalez, 2007). A common sensing principle for pressure sensors is piezoresistivity. A strain deformation induced by pressure within the piezoresistive material alters the resistance of the material. Aschematic cross-section of a piezoresistive pressure sensor, using a silicon wafer, is illustrated in Figure 3.

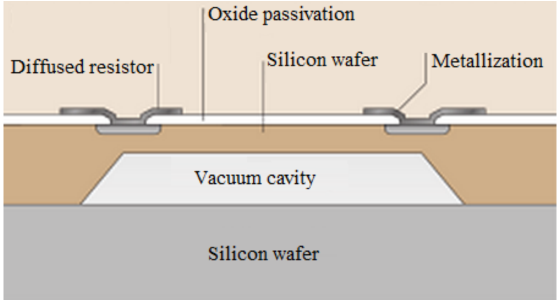

Figure 3 – Schematic cross-section view of a piezoresistive pressure sensor (Bhushan, 2007)

A challenge in the processing of real, while-drilling signals is the noise contained within them. Before any analysis on signals can occur, they must be pre-processed to remove the unwanted noise. In the literature, several methodologies are proposed for the separation of the noise from the valuable signal data. The most common methods are listed below. These methods are extensively discussed in work done by Poletto et al. (2004).

- Entropy and repeatability of the drill-bit source
- Common-level stack of correlations with noise
- Selective stack by drilling parameters
- Noise cancellation by orthogonal pilot traces
- Noise separation by independent pilot traces
- Analysis of torsional pilot waves

GEOLOGY

While there are many potential uses for MWD data, the most common motivation for implementing MWD techniques is to better define in-situ geology. The allure of the MWD technique has to do with the fact that MWD data have been shown to accurately determine some of the geological properties of the in-situ material being drilled and does so in a non-invasive, relatively cheap manner with no extra resources required. The opposite is true of the two other potential sources of in-situ geological information: exploration drilling core logs and geophysical logging. Both of these methods are expensive and require extra, non-production related resources to be hired.

Exploration drill core logs are typically acquired very early in the life of a mine – during the mineral exploration phase. During this phase one of the most important tasks is that of resource evaluation which is undertaken to quantify the grade and quality of a mineral occurrence to determine if the deposit is commercially viable to mine (Amirbekyan, 2010). This resource evaluation is conducted through exploration drilling during which holes are drilled through the rock mass containing the suspected ore body (and future potential mine site) with core samples extracted and removed from these holes. A geologist is on hand and examines the core samples taken. Records are then created which include spatial coordinates of the sample, rock type, ore grade, pre-existing fractures, and other parameters of interest (Amirbekyan, 2010). These borehole core records are eventually used to create a 3D model of the ore body which includes ore zones, rock type distributions and grades. The more drill hole data acquired, the more accurate the created model will be. However, the more core logs acquired the higher the cost for the company, therefore, advanced computer models are used to approximate the ore body as best as possible with the least amount of core logs being drilled and sampled. The actual amount of drill core required is dictated by the economic and statutory standards attached to each project (Amirbekyan, 2010). Typically, the bigger the project, the more debt equity loans are required, and the more drilling core logs are required.

Geophysical logging can be done at any stage of the mine's life. Due to the cost associated with conducting these activities, typically a mine will attempt to minimize the amount of geophysical logging done. Geophysical logging is generally only done when incredibly dynamic geology is encountered that is not explained by the existing mine model. These logging data are then fed back and used to update the mine model to more accurately reflect the physical reality of the deposit. There are many different technologies that can be used for geophysical logging but some of the most common include gamma logs and neutron logging. Typically a combined analysis of both neutron and gamma logs is undertaken as that method provides a better and more reliable interpretation of the geology (Scoble et al., 1989).

The most common form of using MWD data to find the in-situ properties of the rock being drilled is through the use of Teale's Specific Fracture Energy (SFE) equation however there are some other similar equations that can also be employed (Gokhale, 2011). Teale calculated energy consumption during drilling as a function of the measured mechanical variables of the drill and defined SFE as the work done per unit volume of excavated rock (Teale, 1965). Since the power transmitted by the drill is done so in two ways (rotary and pull-down) the equation for work done by the drill can be written as:

$$W = FR + \pi NT/30 \tag{1}$$

The two forms of power transmission can be clearly seen in Equation 1. The pull-down component is given by pull-down force (F) in Newtons multiplied by penetration rate (R) in metres per second. The rotary component is given by rotary speed (N) in rotations per minute multiplied by torque (T) in Newton-metres multiplied by pi (π) and divided by 30. The sum of the two forms of power transmission is the work per unit time (W) in Joules per second.

It was then observed that the volume drilled per unit time (V) in cubic metres per second can be expressed as a function of the area of the drill hole (A) in metres squared multiplied by penetration rate (R) in metres per second. This relationship is given in Equation 2.

$$V = AR \tag{2}$$

Teale then derived specific fracture energy (SFE) in Joules per cubic metre by dividing the work done by the drill unit by the volume drilled per unit time. This can be seen in Equation 3.

$$SFE = F/A + \pi NT/30AR \tag{3}$$

Teale concluded his study by stating that minimum SFE is constant in all rock types and that it correlated well with compressive strength; however he noted that there was evidence that other factors influence SFE such as bit geometry (Teale, 1965). This evidence was substantiated by a later study by Rabia which concluded that factors such as hole size, mode of rock breakage and bit type can all affect SFE (Rabia, 1982). The study by Rabia is of particular interest as most MWD-based rock recognition products on the market (CAT Terrain, Leica Geosystems) use Teale's SFE equation or some variation to provide an estimate of rock drillability or Blastability Index (Caterpillar Inc., 2012). This could indicate that the proprietary algorithms used by industry are incomplete and/or lacking and should be investigated further.

Typically mines will compare the Blastability Index (or other) output from the rock recognition software with the expected stratigraphy from their existing mine model (derived from the two methods described above). If the mine model and the Blastability Index match then the mine will assign the rock types to the corresponding layer. If they do not match, the mine model will be updated to reflect the monitored in-situ conditions. In this manner the MWD-based rock recognition data can act as a substitute for expensive and highly involved geophysical logging. Since the data can be captured in the background, as the drill is performing its regular tasks, MWD-based rock recognition products are an easy and popular sell.

CONCLUSIONS

MWD techniques are widely employed in the mining industry and, in particular, are used in parallel with required blasthole drilling for open pit mining. They are easily applicable for basic performance monitoring, consumables tracking and maintenance planning. The most advanced and widely accepted use for MWD is for in-situ geological estimation (rock recognition) for use in mine model validation and/or tuning. This reduces the need for costly geophysical logging and core drilling. MWD accomplishes this through the utilization of the SFE equation developed by Teale and later refined by Bauer and Calder (Vardhan et al., 2009). However it was noted that work done by Rabia showed that the SFE equations commonly used by rock recognition products may not take into account key variables in the drilling process and, therefore, may be incomplete and/or lacking. Future work should attempt to explore and quantify this suggestion.

MWD data are captured through the use of onboard sensors which record signals of interest from the drill rig while drilling is occurring. The signals of interest and the sensors required to capture them have both been explored in detail and commented upon.

Additionally, potential applications for MWD data have been reviewed and discussed. The potential applications discussed were identified during preliminary academic research but have not yet been fully explored or commercialized.

Although MWD is already widely accepted and utilized by industry one could argue that commercially available MWD products are actually underdeveloped. This is due to the existence of many new applications for MWD techniques that have the potential to be of significant benefit to the mining industry. These applications deserve to be further explored and developed through extensive research programs. MWD data continue to be a rich source of contextual operation data, which can be used to optimize mine site production, reduce maintenance costs and aid in the advancement of autonomous mining toward the mine of the future.

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