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Rock characterization while drilling and application of roof bolter drilling data for evaluation of ground conditions

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ABSTRACT

Despite recent advances in mine health and safety, roof collapse and instabilities are still the leading causes of injury and fatality in underground mining operations. Improving safety and optimum design of ground support requires good and reliable ground characterization. While many geophysical methods have been developed for ground characterizations, their accuracy is insufficient for customized ground support design of underground workings. The actual measurements on the samples of the roof and wall strata from the exploration boring are reliable but the related holes are far apart, thus unsuitable for design purposes. The best source of information could be the geological back mapping of the roof and walls, but this is disruptive to mining operations, and provided information is only from rock surface. Interpretation of the data obtained from roof bolt drilling can offer a good and reliable source of information that can be used for ground characterization and ground support design and evaluations. This paper offers a brief review of the mine roof characterization methods, followed by introduction and discussion of the roof characterization methods by instrumented roof bolters. A brief overview of the results of the preliminary study and initial testing on an instrumented drill and summary of the suggested improvements are also discussed.

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1. Introduction

A review of the statistics of fatalities and injuries in various industrial settings in US between 1988 and 1997 (NIOSH, 2000) showed that the “Fall of Ground” is the second leading cause of 6% of the total fatalities reported in underground mining. Brief screening of similar data in 2006 and 2010 (CDC, 2013) indicated the same trend and proportions. A quick review of published literature from other countries also showed that the same trend is true elsewhere in the world (Mark, 2014), despite some improvements in the overall statistics and a reduction in total number of injuries in underground mining and tunneling operations. This reveals that roof falls and resulting injuries are fairly persistent, if the conditions relative to health and safety performance of underground mines are not to be improved. The situations are perhaps more serious in smaller mines with less automation and mechanization. A comparative study of mines in China, with the largest amount of coal production in the world for the time being, could prove a similar trend.

Roof characterization is essential for design of safety and cost of effective ground supports in underground space. The typical geological features used for roof mapping include rock type, rock strength, voids, cracks, discontinuities, shear zones, beddings, and similar geotechnical features. Ground characterization in underground environment can be performed by various methods such as visual observation and geophysical loggings, bore scoping, rock mass rating of the roof and walls, and instrumented roof bolters or jumbo drills. Using the borehole logs from the original exploration borings to identify geological features is usually insufficient to provide detailed information on the roof conditions. Although the bore scoping is very useful for the identification of the rock types, voids, fractures and formation boundaries, it is a time-consuming method for the stability analysis and ultimately, just a complementary measure to standard geological back mapping procedures. On the other hand, rock mass rating cannot usually be determined in advance of mining, since it requires some on site geological measurements and observations. Therefore, these methods seem to fall short of providing sufficient information on roof conditions within the desired time frame to allow for real time evaluation of the ground support.

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Roof bolting is a practical method employed in most coal mines. Recent advances in ground control technology and development and site deployment of instrumented roof bolters have provided a large number of drilling data for roof bolting available for analysis. The data are obtained during normal roof bolt installation with little or no interruption in mining operations (Peng et al., 2003). This information can be used for roof characterization by instrumented drills to provide an instant mapping of the roof ahead of mining, which is more advantageous than other roof mapping methods that have a time lag. The same concept can also be used in tunneling and underground construction for geological mapping of the structure (Rostami et al., 2014). The system utilizes the data including roof bolter's drilling parameters to instantly evaluate the ground conditions and ground support required, and thus helps miners to mitigate potentials for failure and roof collapse on a real time basis.

This paper includes a brief review of the history of ground characterization by instrumented drill and some of the preliminary results of testing on an instrumented roof bolter in laboratory and field conditions.

2. Ground characterization by instrumented drills

The idea of using drilling parameters to characterize the rock either at the working face while drilling the blast round at the heading or when drilling into the roof and walls for support installation has been around for a long time. It is just that the accuracy and reliability of various sensors have been improved drastically in recent years and the required computational power of the computers has reached to the point that onboard data processing for ground characterization could be a reality at present. The early work on this subject includes Frizzell et al. (1992) who presented the initial results of a research program at the Spokane Research Center of the US Bureau of Mines, directed toward investigating drilling parameters (thrust, torque, penetration rate, and drill revolutions) during the drilling of roof bolt holes. Signer and King (1992) and King et al. (1993) explained the unsupervised learning technique and the expert system which had an interface with the instrumented roof bolter to determine geological features, select the significant roof features in relation to the support parameters, and suggest improvements to the support design. The system was successfully tested in an underground coal mine (Frizzell et al., 1992). It was stated that the obtained results led to improvements in sensory instruments for measuring the drilling parameters of torque, thrust, penetration rate, and rotation rate, as well as improving ways to display and record data for operators and mine engineers. Hoffman (1994) introduced the development of a computer monitored and controlled mast-type model roof drill. The project was an extension of both the smart drill and the parvNET-controlled model drill which were previously developed. The system combined the monitoring and control features of the earlier drills and added vibration analysis, and could use off-the-shelf controllers and data acquisition systems.

Utt (1999) and Utt et al. (2002) applied neural network technology to the classification of mine roof strata in terms of relative strength. They presented the results of the above-mentioned project as a whole report and stated that it was expected that a remote-control system could allow a drill operator to be positioned in a safer location and be less likely to be under a roof fall. LaBelle et al. (2000) and LaBelle (2001) instrumented a portable hydraulic powered coal mine roof bolter drill to classify rock strata in coal mines. They used a neural network to classify material lithology where the inputs to the neural network were sensed drill parameters such as thrust, torque, rotary speed and penetration rate, as well as information derived from these sensors over time (Fig. 1). A research team of West Virginia University performed a study on the characterization of mine roof using the drilling parameters of an instrumented roof bolter drill which started in 1999. A series of manufactured roof rock blocks was tested in the laboratory. Some underground tests were also conducted. Several graduate thesis studies (Finfinger, 2003; Gu, 2003; Mirabile, 2003; Tang, 2006) and papers (Finfinger et al., 2000, 2002) have been published on this project. Finfinger (2003) conducted a series of experiments to determine the relations between the drilling parameters and the geomechanical roof rock properties including the presence of fractures, joints and voids, the locations of rock layer boundaries, and the strength of the rocks. Finfinger (2003) also stated that it was impossible to determine the location of boundaries between rock layers of different physical characteristics using the four primary drilling parameters (thrust, torque, revolution per minute (RPM), and penetration rate).

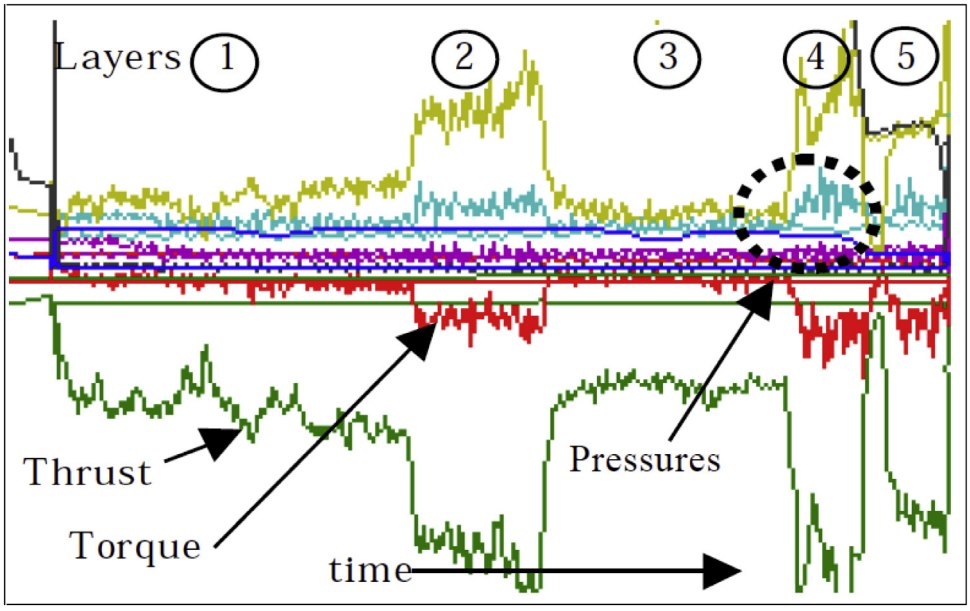

Fig. 1. Concrete drill hole sensor recordings for one drill hole (LaBelle, 2001).

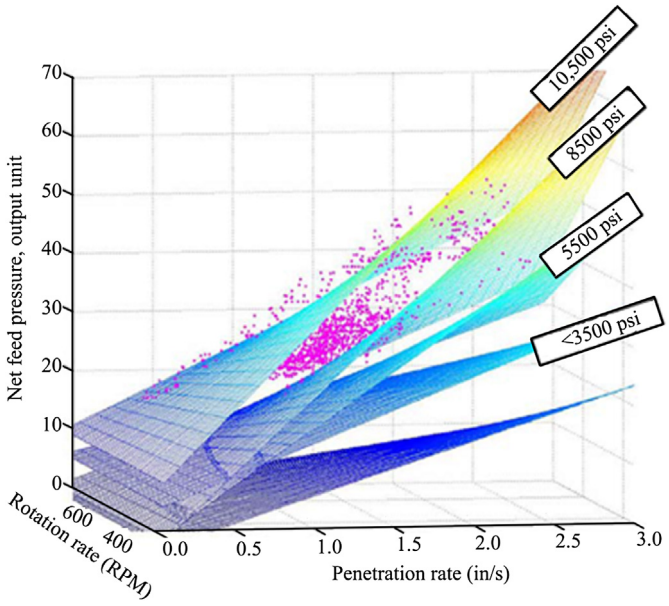

Fig. 2. Distribution of drilling data points and boundary planes for estimating rock strength (Tang, 2006). One psi is approximately 6.895 kPa.

(1) The feed pressure tends to drop to the level of drilling in the air when a void/fracture in rock is encountered. This parameter can be used to detect the voids/fractures. The laboratory and field tests showed that a very high prediction percentage has been achieved for the 3.2 mm (1/8 inch) or larger voids.
(2) The strength of roof rock can be determined/classified based on the magnitude of feed pressure.
(3) A new software package called mine roof geology information system (MRGIS) was developed to allow mine engineers to make use of the large number of roof drilling parameters for roof support design.

A real time drilling display system (DDS) for the J.H. Fletcher & Co. HDDR dual head roof bolter for rotary roof bolting was developed and tested in the field (Collins et al., 2004). The study showed that a fairly accurate representation of void or separation locations in the mine roof can be determined from sensor data recorded during production bolting cycle. This information can be presented to the machine operator in a usable concise real time format. In a recent project of the West Virginia University, the software was modified to communicate in real time with the DCU and display the information as the holes were being drilled (Anderson and Prosser, 2007).

Table 1
Instrumented systems for roof bolt drills.

System	Parameters monitored	Specification	Remarks
System by Parvus Corporation	Thrust, torque, RPM and penetration rate	The real time specific energy of drilling is calculated by the expert system.	The system is not currently used
System by Muroran Institute of Technology	Thrust, torque, RPM and penetration rate	The system is able to estimate 3D geostructure of roof rock.	–
System by Robotics Institute of Carnegie Mellon University	Thrust, torque, RPM and penetration rate	A neural network is used to classify lithology of geomaterial.	There is no update on the system
Feedback Control System by J.H. Fletcher & Co.	Thrust, torque, RPM and penetration rate	Real time detection of roof geology is performed. Drilling parameters can be preset.	The system has been developed and is commercially available

Gu (2003) and Gu et al. (2005) attempted to map the roof geology in real time by developing a new drilling parameter called the drilling hardness to detect the locations of interfaces between rock layers and discontinuities, and to classify the rock types. Luo et al. (2002) proposed a systematic approach to estimate the rock strengths using the drilling parameters. The mathematical model developed based on this approach was able to take into consideration many important factors, such as bit geometry, bit wear, and driller operating parameters that have rarely been considered previously. Mirabile (2003) and Mirabile et al. (2004) aimed to develop a methodology capable of displaying the nature of a mine roof using drilling parameters sampled from a roof bolter during routine drilling operations. A real time roof geology detection system and a mine roof geology information system were developed by the research team of West Virginia University using drilling parameters during roof bolting operation (Tang et al., 2004; Peng et al., 2005; Tang, 2006). The study included a series of laboratory and underground tests to develop the theoretical methodology for predicting roof geology based on the drilling parameters of roof bolter. An example of the results is given in Fig. 2, where the strength of rock is estimated from penetration rate and feed pressure. A drill control unit (DCU) installed in the J.H. Fletcher & Co. HDDR dual head roof bolter was used to control drilling and collect the drilling parameters for all experiments. The main results of this study are summarized as follows:

Itakura et al. (1997) presented the laboratory and field test results of a pneumatic rock bolt drill equipped with a data-logging system which monitors the torque, thrust, rotational speed and stroke. A new data acquisition system was developed for the

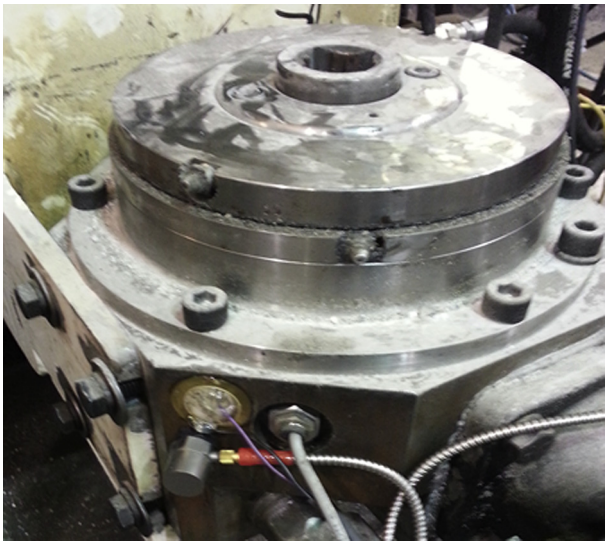

Fig. 3. Installation of the vibration and acoustic sensors on Fletcher drill unit.

Table 2
Summary of new void detection algorithm based on CUSUM logic.

Concrete combination	Number of holes	Detection rate (%)	False alarms
S–H	17	82.3	1
H–S	17	88.2	1
M–H	17	100	0
H–H	18	94.4	1
H–M	21	100	0
M–S	18	100	2
S–M	18	83.3	2
M–M	18	88.8	1
S–S	17	100	2

hydraulic roof bolters and the system was improved for the estimation of three-dimensional (3D) geostructure of strata and the design of rock bolting pattern, and tested in some coal mines (Itakura, 1998; Itakura et al., 2001). Field experiments using the instrumented roof bolter showed that the software could analyze the mechanical data log and display locations of discontinuities using the neural network techniques (Itakura et al., 2008). Li and Itakura (2011a,b) proposed an analytical model to describe rock drilling processes using drag bits and rotary drills, and to introduce relationships among rock properties, bit shapes, and drilling parameters (rotary speed, thrust, torque, and stroke). Li and Itakura (2012) proposed an in-situ method of evaluating uniaxial compressive strength (UCS) of rocks using specific energy, based on an analytical model of drilling processes. It should be mentioned that Atlas Copco has a drilling system that can monitor rock properties while drilling face holes for blast round. The instrumented roof bolter drills that were developed for rock characterization and their status are summarized in Table 1.

3. Ongoing research of instrumented roof bolt drilling void detection

The research team at the Pennsylvania State University has been working on improving the accuracy of DDS void detection system of the J.H. Fletcher & Co., as well as enhancing the machines ability to identify the rock strength as an attempt to complement the MRGIS and develop a 3D visualization of the ground conditions in the mine roof. Testing of roof bolter drills has been underway for two years. One of the initial steps in improving the system was to add additional sensors to complement the existing instruments and also take a closer look at the data collection rate as well as the feature detection algorithm.

The additional instrumentation of the drilling units includes a vibration sensor (3D accelerometer) and an acoustic sensor (flat microphone) to monitor the drilling parameters (Fig. 3). Sixteen concrete blocks with different strengths were poured and cured for more than 28 days. The blocks were approximately 0.5 m × 0.5 m × 0.75 m (~20 in × 20 in × 30 in) in size, and the concrete mix was designed for various strengths: low (~20 MPa), medium (50 MPa), and high (70 MPa). In this setup, a hard (high-strength) concrete block was placed on top of a soft (low-strength) concrete block. There was a small gap, less than a couple of millimeters, between the two concrete blocks that was considered to simulate a "void". The preliminary drilling test results show that the void detection algorithms could be improved to increase accuracy and precision of the detection and to reduce the false detection. This has been accomplished by using a higher data rate and also a new detection routine using cumulative sum (CUSUM) algorithm. The details of the CUSUM method can be found in Basseville and Nikiforov (1993). Meanwhile the use of the data from the

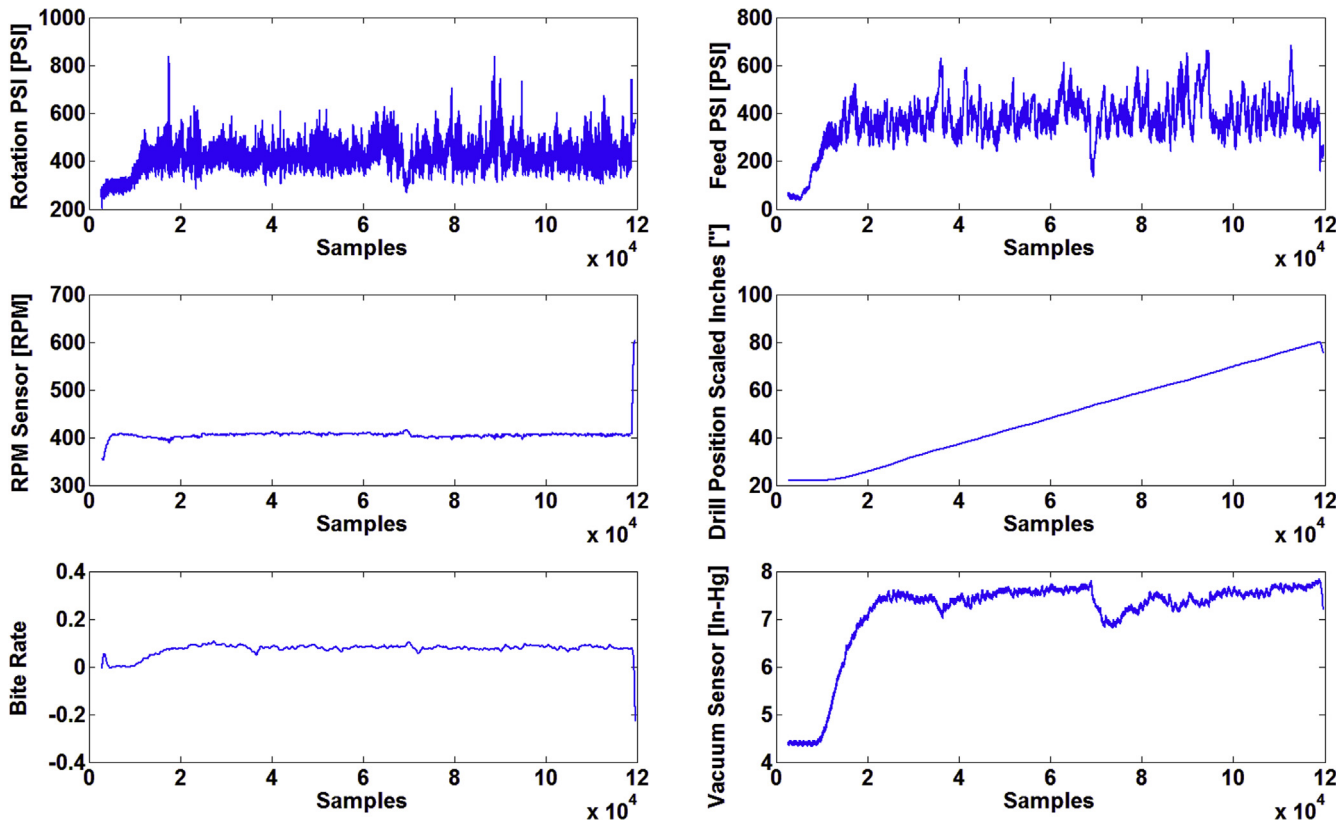

Fig. 4. Example of data collected by the drill with a void/joint between the blocks. Recorded data include rotational pressure, rotational speed, bite or penetration rate, feed pressure, bit position, and vacuum pressure used for flushing.

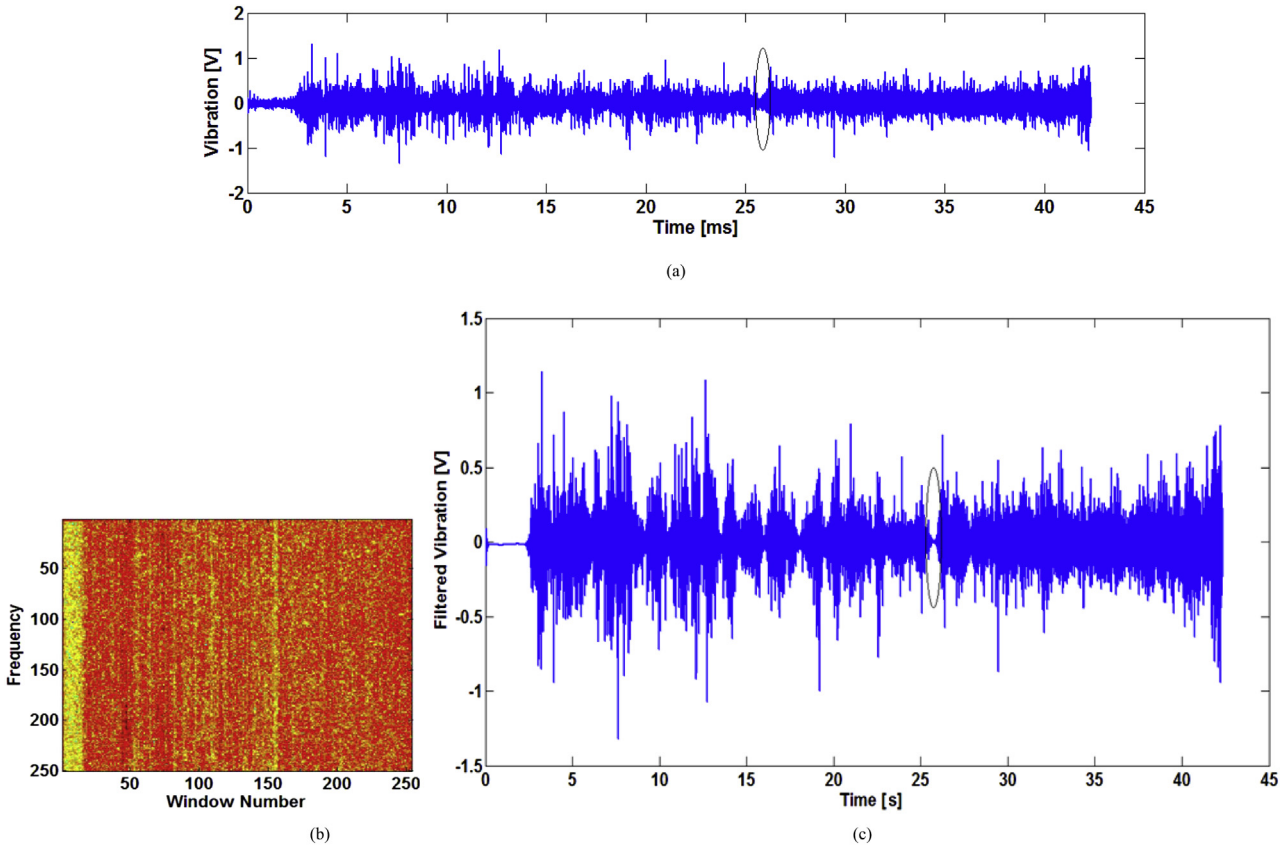

Fig. 5. Plots of (a) vibration signal data, (b) frequency analysis, and (c) reconstruction of signal after digital filtering.

accelerometer and acoustic sensor has been proven to be able to detect the voids, even smaller apertures independent of the other sensory data (Bahrampour et al., 2013). Obviously, combination of the two systems can significantly improve the ability of the roof bolters in locating various discontinuities and bed separation.

Two sets of analyses have been done based on the data. One is to use the normal drilling parameters shown in Fig. 1 based on the sensors currently installed on the roof bolters, and the other is to use the data obtained by the accelerometer and microphone. The new algorithm for void detection based on current machine configuration has been fairly successful in identifying the voids with 93% accuracy and less than 7% in false alarms when tried in various combinations of hard (H), soft (S), and medium (M) blocks as can be seen in Table 2. The main incentive in using the vibration signal for void detection, rather than using a process-dependent signal such as feed pressure is that accelerometer readings are independent of the feedback control of the system and thus not affected by drilling rate and other parameters in a retroactive manner. An example of recorded data in a full scale drilling test and variation of parameters such as feed rate, feed pressure, torque, RPM, etc., is shown in Fig. 4. A drop of the feed pressure is usually observed at the location of the voids. But in some tests, the feed pressure did increase when reaching a void.

As for the analysis of data from the acoustic source and accelerometer, Fig. 5a shows the plot of position and vibration signal obtained while drilling a hole along a set of block with a void in between the blocks. The vibration signal is not a uniform periodic signal because the concrete block is not a homogeneous material. However, at 26 s of the test, where the drill bit reaches the void located 1 m (39 in) into the block, the amplitude of the vibration signals decreases. It is logical to anticipate a reduction in the vibration signal when no rock/concrete is being drilled, and the bit runs through the void. However, this happens rather quickly and in split seconds.

Having additional sensory information to make a collective decision would potentially increase and improve the detection rate and reduce the false alarm rate. Moreover, the drop in feed pressure is not necessarily due to the voids, but could be caused, for example, by the control unit forcing the drill to operate at optimal range or for a given designed operating point. This is related to the feedback control that is implemented in the drill control system for optimized drilling, but it interferes with the void detection algorithm.

The results of the short windowed Fourier transformation of the vibration signal is shown in Fig. 5b to better illustrate the suitability of the vibration measurement for void detection. To make the void more visible in the time domain, these two narrow bands are filtered from the vibration signal, and the resulting signal is shown in Fig. 5c. This figure clearly demonstrates the suitability of vibration signal for void detection.

In addition to analyses of the data from vibration sensor and accelerometer, Fig. 6a shows the acoustic signal during the same experiment where the vibration signal was studied. It might seem that the acoustic signal cannot be utilized for the purpose of void detection. However, with proper filtering the signal could be used for void detection. Fig. 6b shows the frequency response of the signal, which illustrates that the acoustic signal is, indeed, periodic with important components at a frequency close to 6.6 Hz. This is justified by the fact that the rotational speed of the drill machine was set to 400 RPM during the drilling of the hole, equivalent to almost 6.6 turns per second. This periodic signal existed for the whole time when the drill bit was rotating, and its amplitude was very big, masking other important information embedded in the signal, including the void information. Therefore, to utilize the

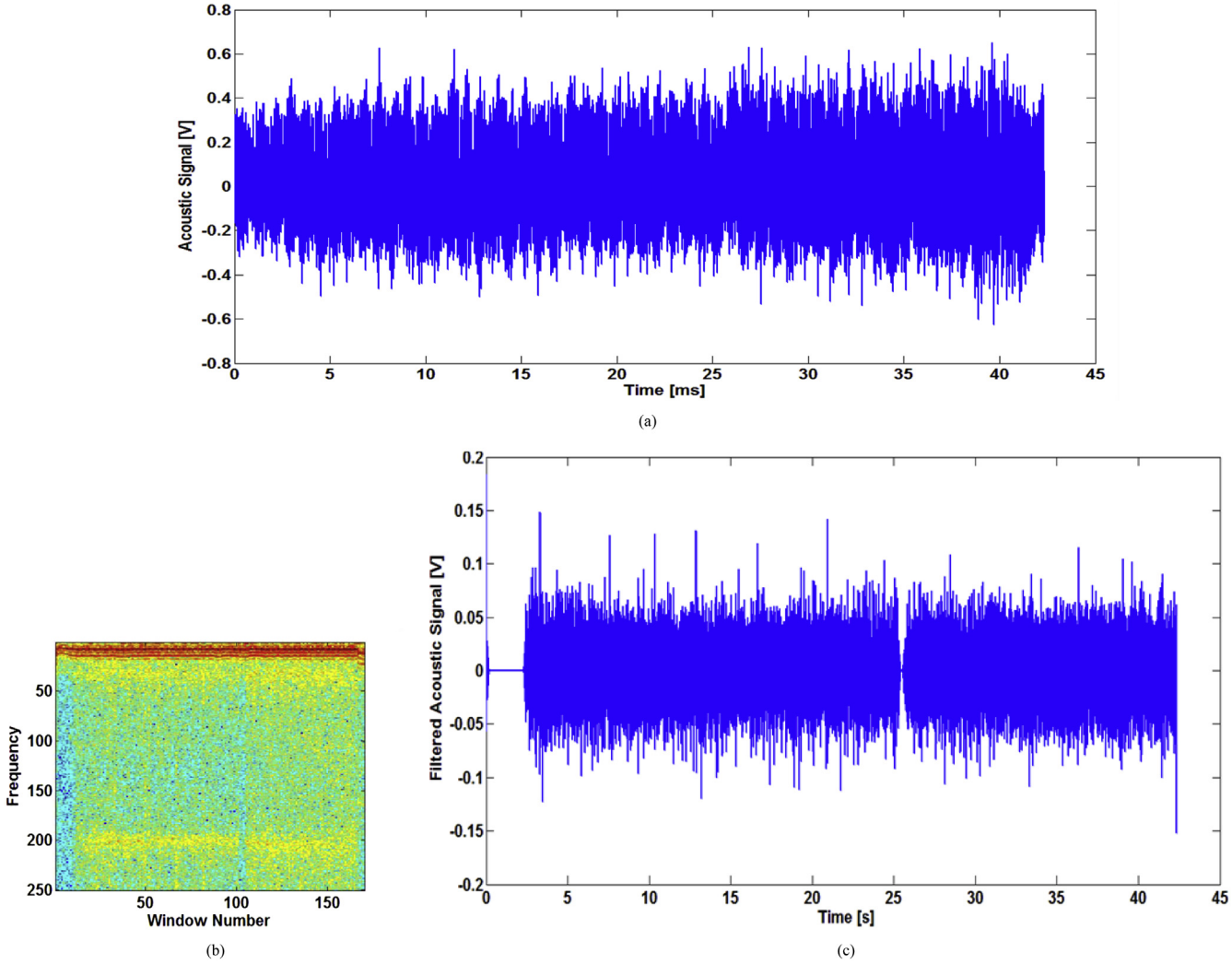

Fig. 6. Plot of (a) acoustic signal data, (b) frequency analysis, and (c) reconstruction of signal after digital filtering.

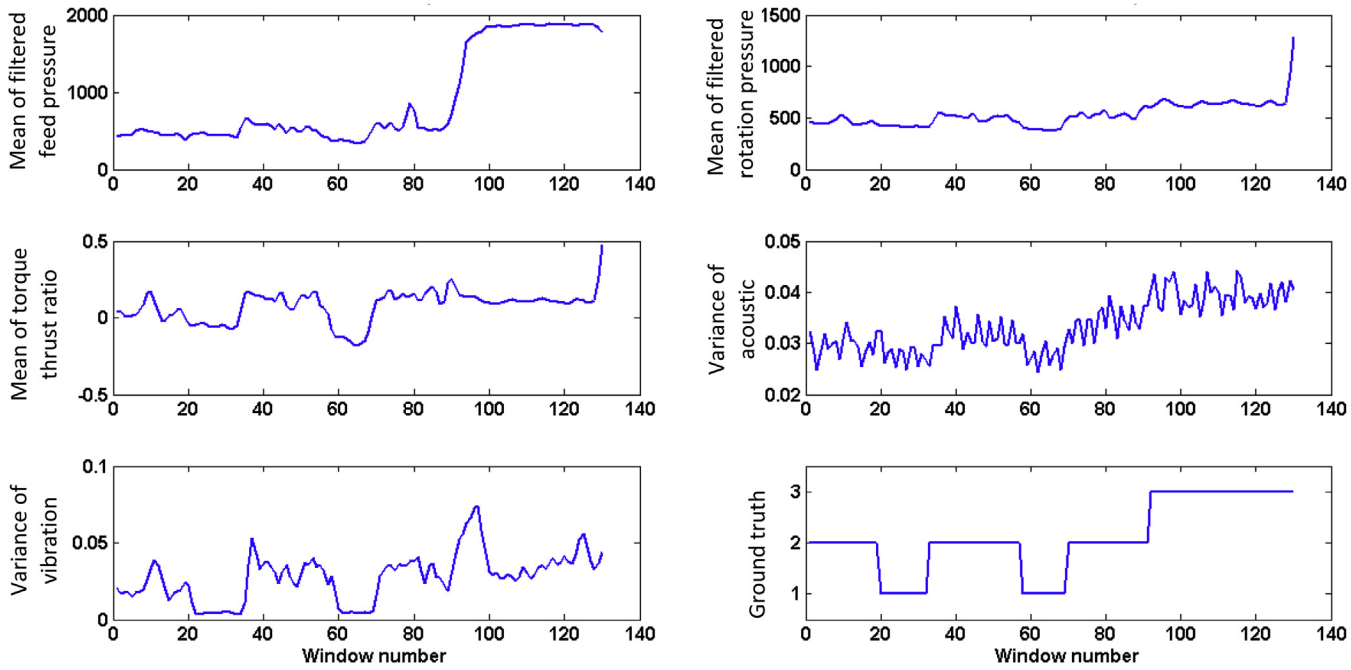

Fig. 7. Example of data collected from the instrumented drill in various rock types and the strength of rock as indicated by ground truth log.

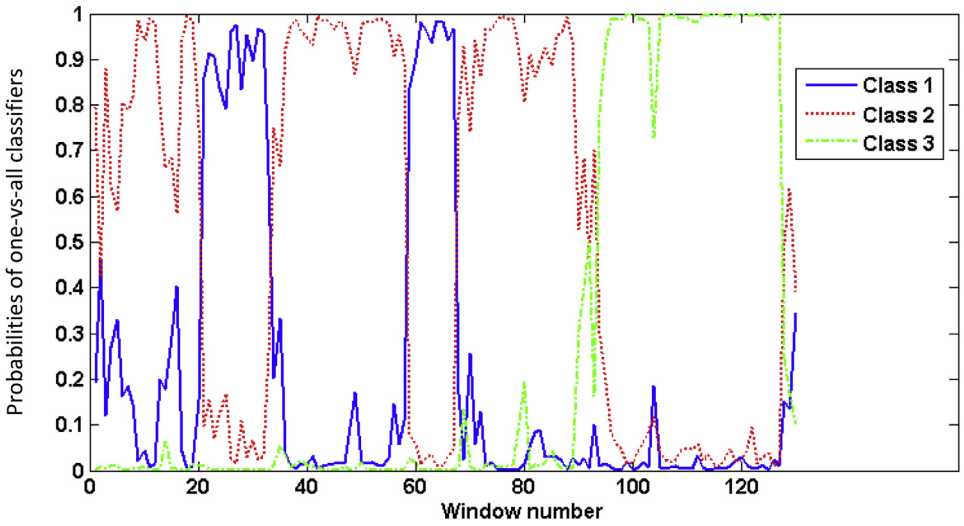

Fig. 8. Probabilities of a given window of the data belonging to different types/classes of rocks as calculated by the artificial intelligent classifiers, based on drilling parameters.

acoustic signal for void detection, the signal should be treated with a high pass filter. If the low frequency component is removed, the rest of the spectrogram clearly shows the same two bands observed on the vibration signal. After having a nonlinear filter to further isolate these two bands and reconstructing the signal results, the filtered acoustic signal is shown in Fig. 6c. This clearly demonstrates the success in the application of the acoustic signal for void detection. Additional testing is underway to improve the void

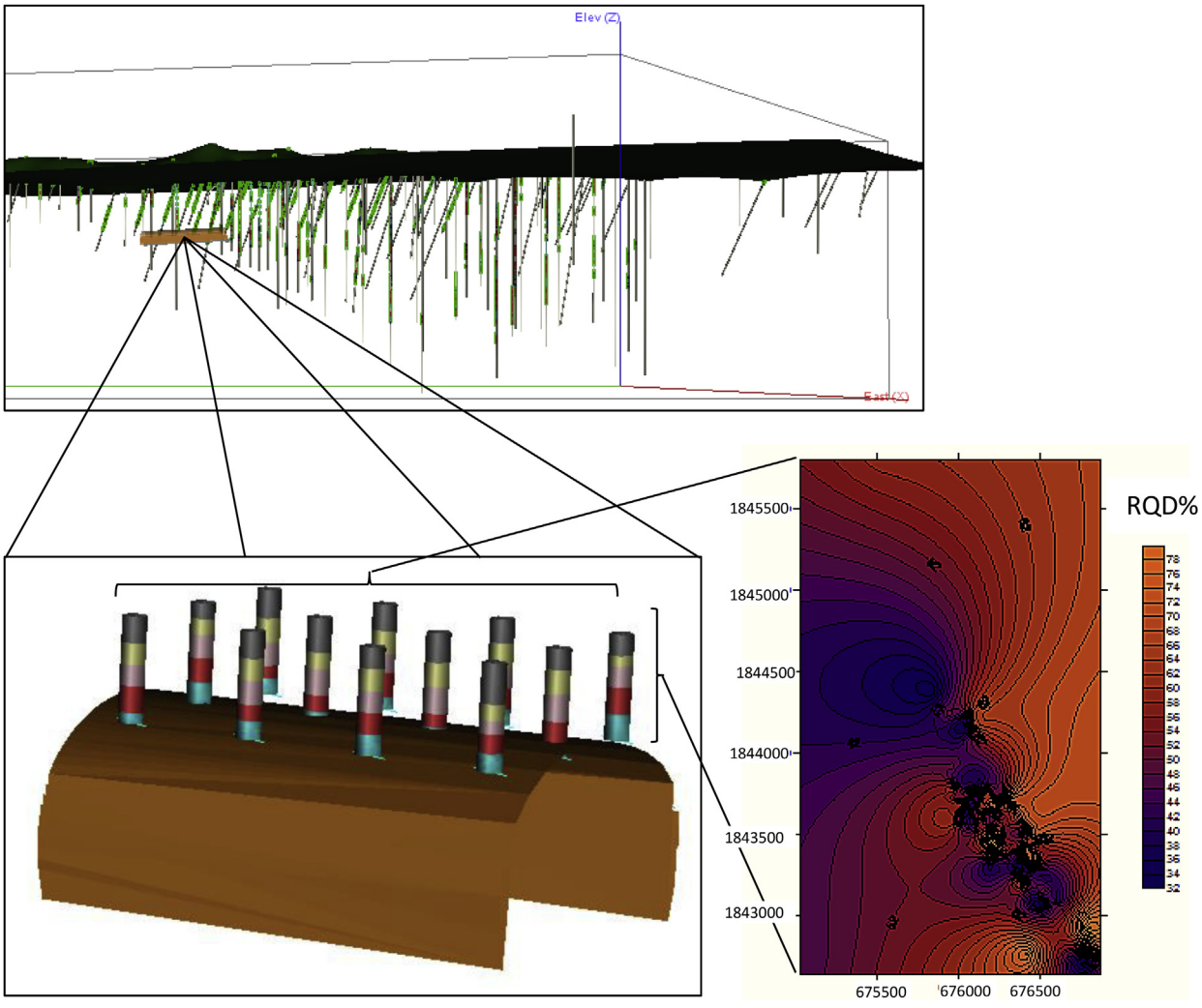

Fig. 9. 3D visualization of hypothetical set of boreholes drilled in a tunnel and contour map for rock quality designation or roof stability index.

detection system on roof bolter of the J.H. Fletcher & Co. Moreover, the analysis of data to correlate the measured parameters to rock strength is also being performed as can be seen in Fig. 7 (Bahrampour et al., 2014).

3.1. Rock strength evaluations

Fig. 7 shows that various parameters can be monitored and combined to identify the rock and assign a strength to each rock being drilled. This is done through an analysis of probability of being in a certain rock based on the registered distinctions which allows the rock to be placed in a certain class, as shown in Fig. 8 (classes 1, 2 and 3 based on rock strength).

3.2. Field testing and 3D visualization

Testing the system in the field is the best proof of functionality of the system and its ability to detect the voids and to identify the rock types based on their respective strength. This is the subject of parallel testing and development of relevant borehole probes that allow for identification of various rock types and locations of fractures and joints so that the data obtained from the drill can be used for training the system to characterize the ground as the drilling proceeds in the field. Borehole probing system includes the optical televiewer to generate a 360° image of the borehole for structural analysis and a borehole scratch test that allows for evaluation of rock strength (Rostami et al., 2014). The ultimate goal of this study is to develop a 3D view of ground conditions as well as contour line of roof/wall hazards by combining the information obtained from various sources, including the routine bolting of the underground working as part of ground support installation as shown in Fig. 9.

In addition to the borehole televiewer that can characterize the joints, probes are needed to easily and quickly offer a measurement of rock strength. For the time that no equipment or device is available, which can evaluate rock strength within a small diameter, short borehole is drilled upward which is typical of roof bolting boreholes. For this reason, initial testing is underway to develop a borehole scratcher probe that can scribe a small grove in the side of the hole and estimate rock strength based on the forces acting on the scribe. Combination of rock joint and strength information obtained from these probes, along with the drilling information and parameters, are used to train the related program or algorithm on the equipment to identify the rock types, strength and joint locations in field trials. This allows for generating the essential information needed for rock mass classification (i.e. roof rating) and ultimately for assessment of ground support requirements.

4. Conclusions

Many improvements have been made on the roof characterization by instrumented roof bolter. However, there are still several issues that must be solved to improve the accuracy and precision of the void detection system to locate joints with smaller aperture. The improvement in characterizing the rock and rock mass features will allow for improving the understanding of the ground conditions and rock mass classifications, in addition to the effectiveness of systems used for ground support. These capabilities will lead simultaneous analysis of the information for developing 3D visualization of the data and establishing hazard map of the underground structure that will help in mine safety and reducing related injuries and fatalities. The initial full scale drilling tests on instrumented roof bolter at the J.H. Fletcher & Co. facility and subsequent analyses of recorded data show that high levels of accuracy can be achieved in detecting the joints, identifying various rock types and estimating their strengths. Also, additional instrumentations can be provided for a level of redundancy that is needed for functionality of the equipment under peculiar operational circumstances.

Conflict of interest

The authors wish to confirm that there are no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

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