Rock Mechanics and Rock Engineering
https://doi.org/10.1007/s00603-017-1359-z

ORIGINAL PAPER

Application of Composite Indices for Improving Joint Detection Capabilities of Instrumented Roof Bolt Drills in Underground Mining and Construction

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Received: 9 April 2017 / Accepted: 2 November 2017

Abstract

Roof bolts are the dominant method of ground support in mining and tunneling applications, and the concept of using drilling parameters from the bolter for ground characterization has been studied for a few decades. This refers to the use of drilling data to identify geological features in the ground including joints and voids, as well as rock classification. Rock mass properties, including distribution of joints/voids and strengths of rock layers, are critical factors for proper design of ground support to avoid instability. The goal of this research was to improve the capability and sensitivity of joint detection programs based on the updated pattern recognition algorithms in sensing joints with smaller than 3.175 mm (0.125 in.) aperture while reducing the number of false alarms, and discriminating rock layers with different strengths. A set of concrete blocks with different strengths were used to simulate various rock layers, where the gap between the blocks would represent the joints in laboratory tests. Data obtained from drilling through these blocks were analyzed to improve the reliability and precision of joint detection systems. While drilling parameters can be used to detect the gaps, due to low accuracy of the results, new composite indices have been introduced and used in the analysis to improve the detection rates. This paper briefly discusses ongoing research on joint detection by using drilling parameters collected from a roof bolter in a controlled environment. The performances of the new algorithms for joint detection are also examined by comparing their ability to identify existing joints and reducing false alarms.

Keywords Ground control · Roof bolts · Joint detection · Composite indices · Drilling parameters · Roof bolter · Ground support optimization · Mining health and safety

1 Introduction

One of the most serious and frequent health and safety issues in underground mining, tunneling, and underground construction is ground instability such as roof/rib failures. These incidents cause many injuries, and in some cases, fatalities every year and despite much advancement in mining techniques, it has been a fairly persistent safety risk. A key component in optimizing the ground support design is accurate characterization of the ground and developing a good understanding of the rock mass properties, including joints, discontinuities, weak/shear zones, and strengths of rock layers.

To address this issue, many geophysical methods have been introduced for ground characterization. These systems offer capabilities to locate voids, joints, discontinuities as well as recognize information about different rock strengths with limited degree of success. In addition, various probing systems have been introduced to log the rock mass properties in the boreholes. This includes bore-scopes, borehole optical, sonic, and other types of televiewers. These methods all have limited capabilities, but more importantly, they are disruptive to operations, and require high degrees of specialization to offer reliable interpretation of ground conditions. However, the analysis of data from drilling for roof

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Published online: 18 November 2017

bolters or blast holes can provide sufficient information to allow for detection of the joints and strength of various rock strata that are needed for evaluation of rock mass. This information can be used to optimize the ground support design, while the method is neither disruptive nor adds any cost to the operation, since drilling these boreholes are a part of the operational cycle.

This paper reviews the past studies in this area and will discuss ongoing research by the authors on joint/void detection through analyzing composite indices, which are various combinations of several recorded roof-bolter drilling parameters. These indices have shown better overall results compared to using individual parameters.

2 Background

The concept of using drilling parameter for ground characterization has been studied for a while. The system relies on drilling into the roof or ribs, which is a routine part of the operation for support installation, to generate required data that can be used for identification of the target features in the ground. For this purpose, various drilling parameters, including thrust, torque, penetration rate, RPM, etc., are recorded during typical roof bolt installation cycle in mining operations (Peng et al. 2003) and simultaneously analyzed to identify joints or evaluate rock strength. Rostami et al. (2014) suggested that similar systems could also be utilized in tunnel and underground construction applications.

Many studies have focused on identifying voids and joints using instrumented drilling units. Parvus Corp. designed and promoted a drill monitoring system and applied it on a roof-bolting drill (Takach et al. 1992; Hill et al. 1993). The United States Bureau of Mines (USBM) developed a computer monitored and controlled mast-type model roof drill which was a natural extension of the smart drill and the parvNET-controlled model drill (Hoffman 1994). Itakura et al. (1997), Itakura (1998) and Li and Itakura (2012) conducted some tests both in the laboratory and in field to monitor torque, thrust, rotational speed and stroke by instrumenting a pneumatic rock bolt drill. Some discontinuities, which were pre-designed as cracks, boundary layers, boundary separations in rock, could be identified by this system in laboratory tests. Figure 1 shows typical patterns corresponding to various discontinuities. To offer in situ evaluation of roof rock in field, Itakura et al. (2001) developed a Measurement While Drilling (MWD) system that could locate discontinuities by analyzing torque, thrust, RPM, and stroke data collected during drilling process. However, this smart system could not discriminate cracks with small aperture. Itakura concluded that it was hard to identify hairline cracks from drilling data.

The research team at West Virginia University (WVU) also performed many studies on the characterization of mine roof by analyzing drilling parameters of an instrumented roof bolter. They conducted many laboratory and field tests by applying a J.H. Fletcher dual head roof bolter with intelligent drilling systems to locate voids, joints, bed separations and fractures. In their research, drilling parameters, including rotational speed, thrust, torque, and penetration rate were recorded while drilling. As shown in Fig. 2, they mentioned a phenomenon of "thrust valley" appeared in recorded thrust data at the moment of the drill bit encountered a fracture, while they also proved the feasibility of using the specific

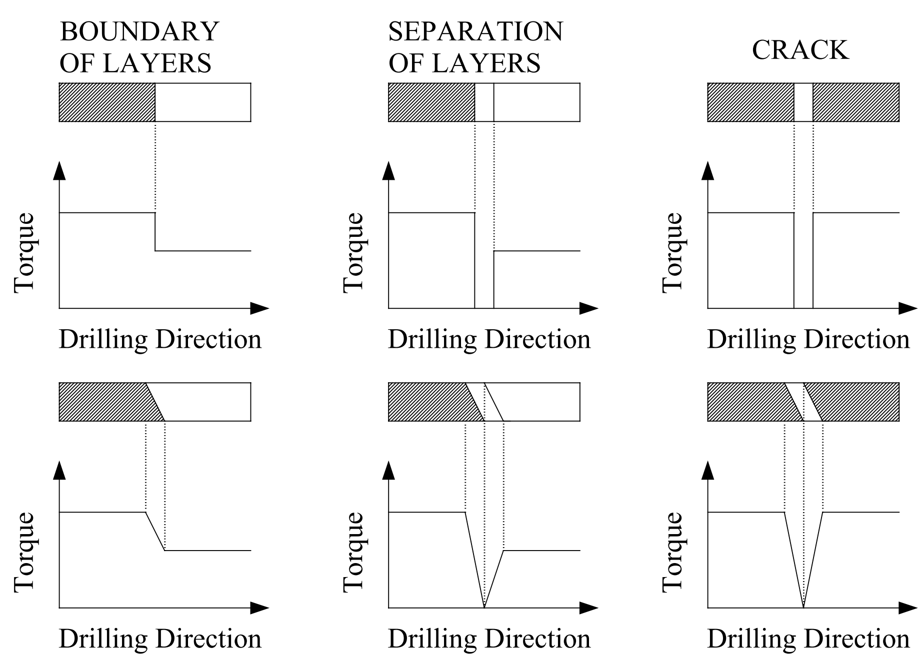

Fig. 1 Typical patterns corresponding to various discontinuities. (Reproduced with permission from Itakura et al. 1997)

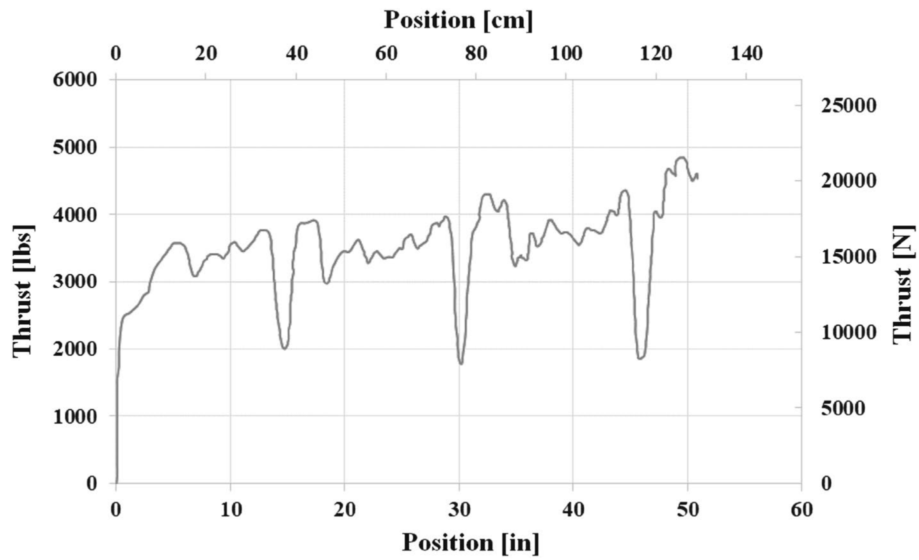

Fig. 2 "Thrust valleys" associated with fractures in concrete block. (Reproduced with permission from Finfinger et al. 2000)

energy of drilling (SED) for identification of anomalies. The concept of SED was introduced by Teale at 1965 and could be calculated from drilling parameters. However, the WVU team noticed that SED showed significant variations in same rock material, and their research could not locate joints with the aperture less than 3.175 mm (0.125 in.) (Finfinger et al. 2000).

A Real-Time Drilling Display System was developed and equipped on a J.H. Fletcher & Co.'s HDDR dual head roof bolter to detect voids and/or fractures by analyzing drilling parameters in the field. This system could show the detected void information with a usable concise real-time format. The sensitivity of this system needed to be improved to identify voids with smaller apertures and/or distinct fractures (Peng et al. 2003; Collins et al. 2004). In following research, they improved the Real-Time Assessment of Roof Conditions system to detect voids and/or bed separations in real-time while drilling was in process. This updated system could display feature information in four separate drill holes as four side-by-side graphs, and the developing trend of the void and/or separation could be clearly explained to the operators. Yet the updated system was unable to identify hairline and vertical cracks which were identified in bore-scoping videos in field tests (Anderson and Prosser 2007).

Bahrampour et al. (2013) at the Pennsylvania State University applied a J.H. Fletcher drill unit for void detection. In their research, vibration sensors and acoustic sensors were added to the Fletcher drill unit to record vibration and acoustic signals during the drilling process. By analyzing vibration and acoustic signals collected from laboratory tests, geological features such as voids and/or joints could be identified, but void and/or joint with the opening size smaller than 3.175 mm (0.125 in.) could not be successfully detected. Many false alarms were also generated in the detection process.

Kahraman et al. (2015) offered a brief review of mine roof characterization methods which was based on instrumented roof bolters. Table 1 offers a brief overview of

Table 1 Summary of past studies on instrumented roof bolt drills used for joint detection. (Reproduced with permission from Kahraman et al. 2015)

System	Parameters monitored	Specification	Remarks
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
Muroran Institute of Technology	Thrust, torque, RPM and penetration rate	The system is able to estimate roof rock 3-D geostructure	No updates is available
Robotics Institute of Carnegie Mellon University	Thrust, torque, RPM and penetration rate	A neural network is used to classify lithology of geomaterial	No updates is available
Feedback Control J. H. Fletcher & Company	Thrust, torque, RPM and penetration rate	Real-time detection roof geology is performed Drilling parameters can be preset	The system has been fully developed and is commercially available

various instrumented systems for roof bolt drills discussed in their study.

3 Test Setups for Joints Detection by Instrumented Roof Bolt Drilling

Ongoing research on the ground characterization while drilling for bolts involves improving the accuracy and sensitivity of a real-time drilling display system (DDS) of the J.H. Fletcher & Co. HDDR dual head roof bolter. As shown in Fig. 3, a drill control unit (DCU), which was developed by J.H. Fletcher & Co., was applied for laboratory tests at a Fletcher testing facility in Huntington, WV. Moreover, DCU could monitor drilling parameters, including feed pressure (thrust), rotation pressure (torque), RPM, penetration rate, drill bit position, and flushing air pressure, while drilling in process. Additional instrumentation for the current study includes vibration sensors (3D accelerometer) and acoustic sensors (flat microphone). These sensors were installed on the Fletcher drill unit to record vibration and acoustic data for further analysis (Rostami et al. 2015).

Fig. 3 J.H. Fletcher & Co. drill control unit. (Reproduced with permission from Bahrampour et al. 2015)

The preliminary laboratory tests were conducted in a set of concrete blocks with three different pre-designed strengths. These blocks were poured and cured for more than 28 days. The physical dimensions of each concrete block were about 0.9 m × 0.9 m × 0.75 m (or ~ 36 in. × 36 in. × 30 in.). A margin of around 0.2 m (or ~ 8 in.) from the edges was designated not drilled to avoid drilling out of the sample and to hold the sample together. Therefore, the available dimensions of each block were approximate 0.5 m × 0.5 m (~ 20 in. × 20 in.). The concrete used for casting the blocks had three pre-designed strengths of soft (S, ~ 20 MPa), medium (M, ~ 50 MPa) and high (H, ~ 70 MPa). To simulate a pre-existing joint, one concrete block was placed on top of another block, and shims with certain thickness were used between two blocks to create a small gap with the clearance of about 2 mm. This gap was considered to be the simulated joint for detection. With this arrangement, the pre-determined joint was located at the depth of approximate 76.2 cm (30 in.) in each test sample, comprised a set of two blocks. With various combinations of block strength, there were a total of nine test setups, including soft–soft (S-S), S-M, S-H, M-M, M-S, M-H, H-H, H-S, and H-M. These combinations were made for joint detection purposes to mimic various scenarios of drilling from rock with certain hardness to another layer (Liu et al. 2016, 2017). Figure 4 shows the process of pouring concrete blocks and cured test samples.

Fig. 4 Pictures of pouring concrete blocks and cured testing samples

4 Preliminary Analysis of Test Results

The preliminary analysis of the data from testing allowed the research team to develop new joint detection algorithms with increased accuracy and precision of joint detection and reduce the number of false alarms (Rostami et al. 2015, Bahrampour et al. 2013, 2014). The algorithms used for joint detection were pattern recognition systems based on cumulative sum (CUSUM) analysis. CUSUM algorithm is a sequential analysis technique, which was initially developed by E.S. Page at the University of Cambridge, and is typically used for change detection in streaming data (Page 1954; Basseville and Nikiforov 1993). Monitoring drilling parameters indicated a notable change in the data once the drill bit encountered a joint or a void. For instance, Fig. 5 shows the variation in feed pressure (thrust) where a brief drop in feed pressure (thrust) can be noticed at the location where drill bit encountered the artificial joint. The feed pressure rapidly recovers after the drill passes through the discontinuity.

Various drilling parameters included thrust, torque, as well as vibration and acoustic data have been individually used to identify the joints with some degree of success (Bahrampour et al. 2015; Liu et al. 2016, 2017). Table 2 is the summary of the joint detection rate for each individual

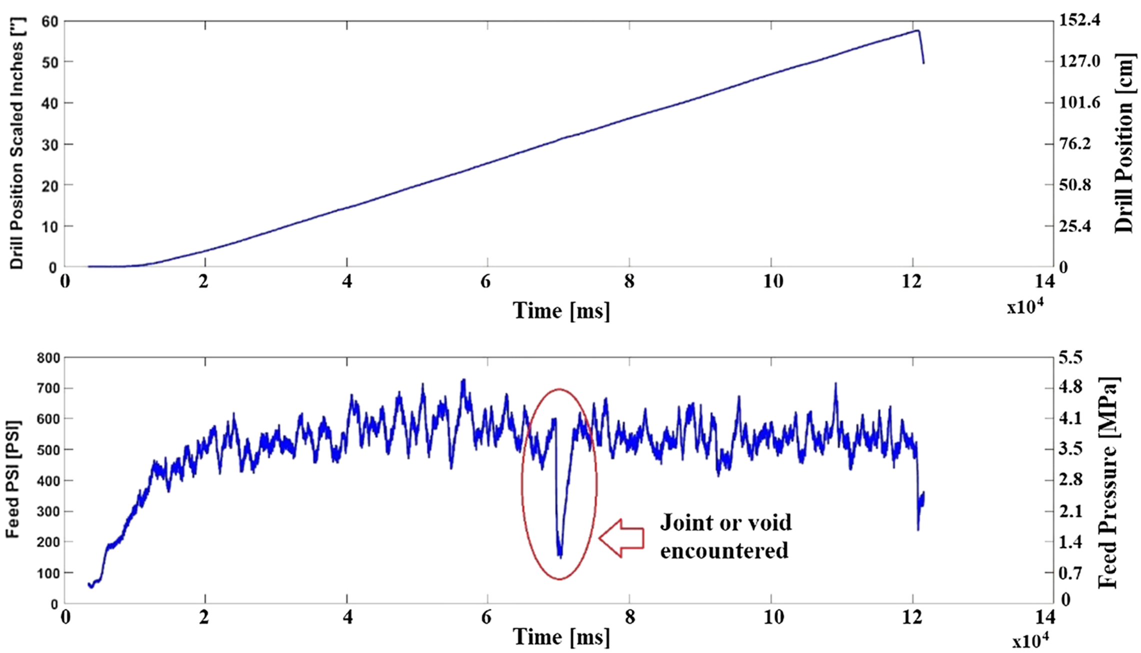

Fig. 5 Drill bit position and feed pressure (thrust) data

Table 2 Summary of joint detection based on CUSUM algorithm in all concrete settings

Concrete settings	Feed pressure		Rotation pressure		Acoustic		Vibration	
	Detection rate (%)	False alarms	Detection rate (%)	False alarms	Detection rate (%)	False alarms	Detection rate (%)	False alarms
S-H	86.7	1	93.3	6	60.0	4	40.0	4
H-S	88.2	1	76.5	4	82.4	3	52.9	2
M-H	100.0	0	100.0	5	100.0	4	76.5	9
H-H	94.4	1	83.3	1	83.3	0	77.8	2
H-M	100.0	2	95.2	16	95.2	4	81.0	7
M-S	100.0	2	100.0	17	100.0	13	88.9	10
S-M	88.9	2	88.9	19	88.9	2	66.7	14
M-M	77.8	1	88.9	10	72.2	0	83.3	16
S-S	100.0	2	100.0	22	81.3	7	87.5	16
Overall (158 holes)	92.9	12	91.8	100	84.8	37	72.7	80

drilling parameter for testing nine different concrete block combinations. As can be seen, the performance and accuracy of the algorithms used for each individual drilling parameter shows significant variation. Overall, the joint detection algorithms based on the CUSUM algorithm has been fairly successful in locating joints in various concrete block settings by using feed pressure, and to lesser extent, the rotation pressure. The average detection rate of current detection algorithms by analyzing feed pressure data was up to 92.9% with 12 false alarms, in a total of 158 bore holes drilling in the nine combination samples. Using rotation pressure data resulted in average detection rate of 91.8% with 100 false alarms by analyzing the same data set. The result of the detection algorithms using acoustic and vibration signal was less accurate. However, these sensors are independent of the drilling parameters that are also linked to the feedback control of the drilling system, and they would not be affected by other drilling parameters, which are interdependent and vary as part of the feedback loop. In this research, the average detection rate of processing acoustic signal was 84.8%, and 37 false alarms. The analysis of vibration signal offered detection rate of 72.7% with 80 false alarms, showing much inferior performance compared to feed and rotation pressures.

Thus, the sensitivity of present joint detection algorithms need to be further improved to increase their detection rate and reduce the number of false alarms by updating the algorithms for change detection, or alternatively, use of combined parameters as part of a normalization scheme, or combined/compounded parameters or indices. Additional confirmation can be obtained by the analysis of acoustic and vibration data.

5 Use of Composite Indices for Joint Detection

The results of using individual drilling parameters to identify joints in the testing of concrete blocks and evaluating their corresponding performances and related deficiencies for joint detection were mentioned earlier. The limitations of joint detection using individual parameters could be due to different reasons. For example, the changes in feed pressure might be due to joints or voids, but could also be caused by the drill control system to adjust the drilling rate. However, using multiple parameters and combined/composite indices could rectify the problems and offer a better means of detecting changes which can be used to detect joints. Such composite indices would be more effective to increase the detection rate and reduce the number of false alarms. It could also reduce the "noises" in drilling parameter signals which might confuse joint detection algorithms.

For this purpose, various combinations of input parameters and their algebraic relation have been examined to find the best composite indices for joint detection. Simultaneously, artificial intelligence systems such as PCA and Decision Tree systems are under evaluation to find the most suitable combination of input parameters for joint detection. One of the composite indices that has had a good performance so far is the ratio of rotation/feed pressure divided by penetration rate, or RP/FP/PR.

Feed pressure and rotation pressure are two essential factors representing thrust and energy consumption of the roof bolter while drilling through the rock. Since the rock is not a homogeneous material, the ratio of rotation pressure to feed pressure, namely the ratio of the energy consumption and thrust (or sometimes referred to as drag factor), was normalized for penetration per second during drilling through various rock materials. Therefore, the composite indices of RP/FP/PR, expresses the drag factor normalized by penetration and in rock excavation, they often have a good correlation. Any interruption and changes in this value can be a good indicator of change in cutting condition as it has been shown by analysis of data in our studies. Close examination of the behaviors of recorded rotation and feed pressure data, as well as penetration shows that the value of this index will rise rapidly, while the drill bit encounters a joint and/or void. This index seems to offer a reasonably good result for joint detection.

$$\mathrm{RP/FP/PR} = \text{rotation pressure}/\text{feed pressure}/\text{penetration rate} \tag{1}$$

where rotation pressure, MPa (PSI); feed pressure, MPa (PSI); penetration rate, cm/s (in./s); RP/FP/PR, s/cm (s/in.).

Figure 6 shows examples of the variation of RP/FP/PR composite index for combinations of nine different concrete block settings. These figures show a distinct change in the index at the location of pre-designed joint. The distinct change could be used for locating the joint and/or a void by pattern recognition algorithms to link the location with drill bit position data or borehole depth.

In this study, an updated CUSUM algorithm was applied to extract the joint and/or the void information from RP/FP/PR data. To implement this algorithm, assuming y_k ($k = 1, 2, \ldots$) to be a time series with a Gaussian random sequence and variation of σ^2 in the mean within the data stream, an unknown change at time of t_0 can be detected if the mean of y_k which was μ_0, shows a notable change as time marches to $\mu_1 = \mu_0 + v$ by the sufficient statistic g_k, defined as:

$$g_k = \max\left(g_{k-1} + y_k - \mu_0 - \frac{v}{2}, 0\right) \tag{2}$$

The detection alarm time was set up as:

$$t_{\mathrm{a}} = \min\left\{k : \left(g_k \geq h\right)\right\} \tag{3}$$

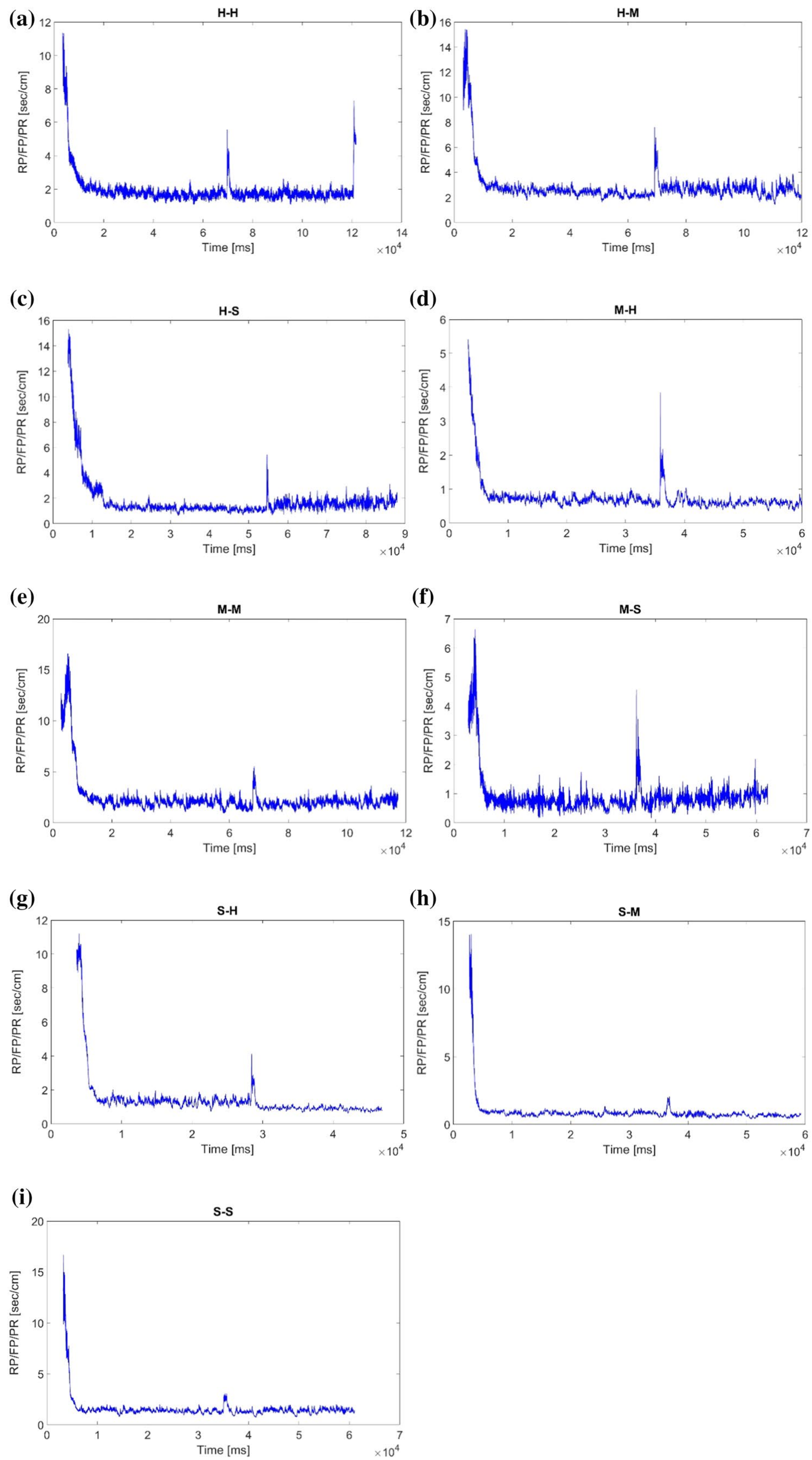

Fig. 6 RP/FP/PR associated with a set of nine concrete block settings. **a** H-H, **b** H-M, **c** H-S, **d** M-H, **e** M-M, **f** M-S, **g** S-H, **h** S-M, **i** S-S

where h is the threshold and $g_0 = 0$. At the time g_k equal or large than this threshold value, a joint or a void is assumed to be located (Basseville and Nikiforov 1993).

A close examination of the behavior and properties of RP/FP/PR data shows that the value of RP/FP/PR in each concrete block setting shows a distinct change when the drill bit encounters the joint. This was observed even when drilling into the samples with different strength. Moreover, to eliminate the noise generated by the drilling unit, the data collected within the first 12.7 cm (5 in.) and last 12.7 cm (5 in.) was not included in the analysis. Meanwhile, the input signal data was also pre-filtered to smooth out short-term fluctuations and noises by using the moving average which allows for higher contrast in the targeted features and highlight the trends. Therefore, the threshold was set up at 40% of the mean for the entire effective RP/FP/PR data (excluding cut off data).

Figure 7 is an example of the data for RP/FP/PR, which was recorded while drilling into a H-H sample setting. Comparing the data for three individual parameters used for joint detection, each of these three parameters shows an apparent change at the depth of around 76.2 cm (30 in.) where was the location of pre-designed joint. However, the change in the value of RP/FP/PR is more distinct compared to the individual parameters examined in early stages of this study. Besides, the rest of RP/FP/PR data shows less variations and noises compared to individual drilling parameters. Thus, monitoring RP/FP/PR may provide a more accurate result for joint detection and allow for reduced number of false alarms.

Figure 8 is the plot of detected joints while drilling into the S-M concrete block setting. A set of 18 bore holes were drilled in this set up and the pre-designed joint which was located at around 76.2 cm (30 in.) was identified in 16 bore holes. Typically, joint information was reflected as a void in each hole (blue points). In addition, two false alarms (red points) were generated in hole #2 and hole #12. In hole #3 and hole #16, the algorithms failed to detect the joints. A trend line (the blue rock break), which was driven from joining the detected voids and located at around 76.2 cm (30 in.), can be considered as a secondary measure for the estimation of the location of the joint by the detection algorithms, if the holes are drilled in a close proximity.

Table 3 summarizes the performance of joint detection algorithms by evaluating RP/FP/PR data. The average joint detection rate could be up to 93.4%; moreover, 12 false alarms were generated by detection process in entire data set of 158 holes. The magnitude of changes, observed in RP/FP/PR data from block setups with relatively low strengths, such as M-M and S-S, are less distinct, and it causes the detection rates achieved from these samples to be lower than the others. The comparison of the performances of various parameters for joint detection is summarized in Table 4. As can be seen, use of RP/FP/PR data offers slightly better

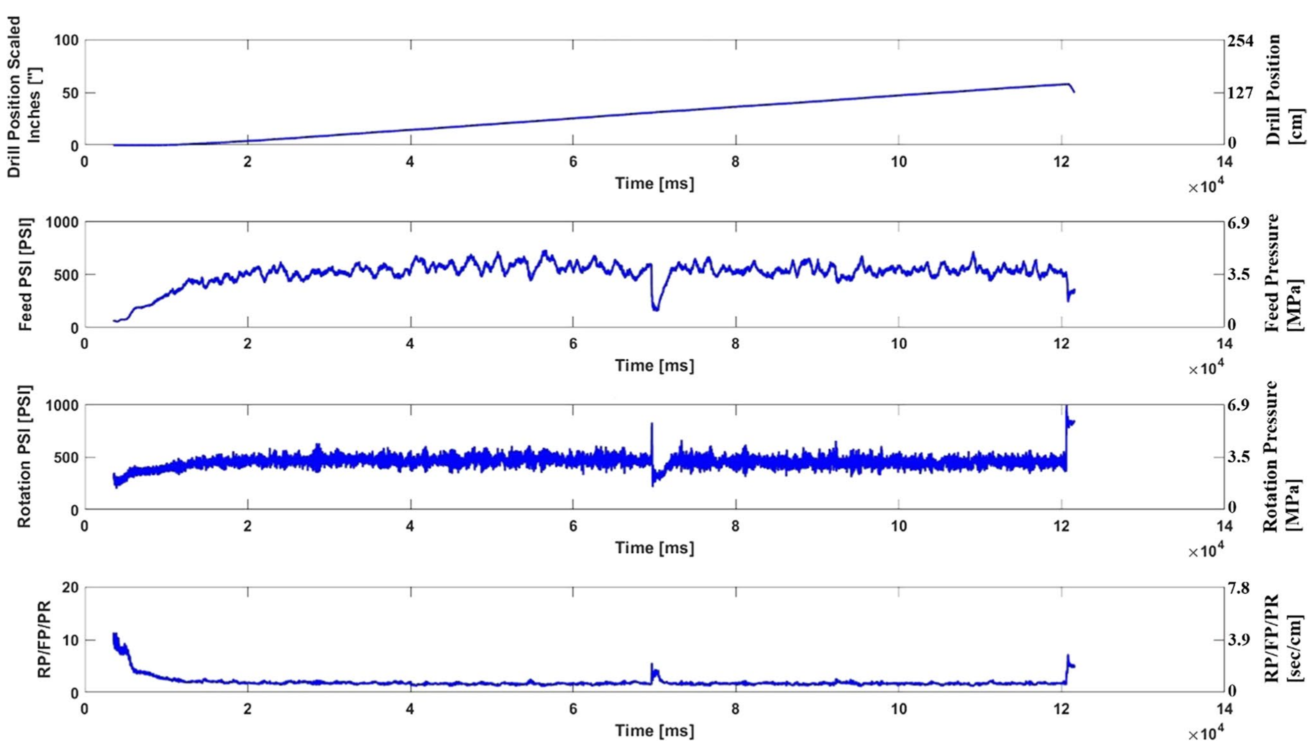

Fig. 7 RP/FP/PR, feed pressure and rotation pressure associated with drill bit position

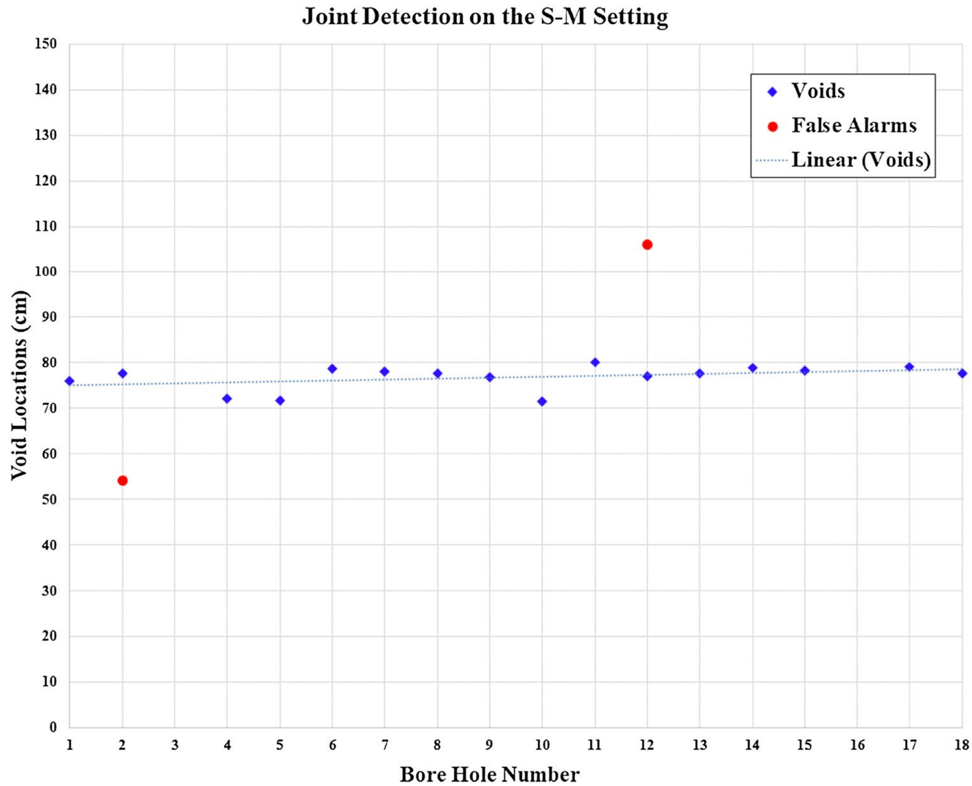

Fig. 8 Joint detection on the S-M concrete block setting

Table 3 Joint detection of using RP/FP/PR based on CUSUM algorithm

Concrete settings	RP/FP/PR	
	Detection rate (%)	False alarms (158 holes)
S-H	86.7	0
H-S	94.1	0
M-H	100.0	0
H-H	100.0	0
H-M	100.0	2
M-S	100.0	2
S-M	88.9	2
M-M	83.3	2
S-S	87.5	4
Overall (158 holes)	93.4	12

Table 4 Comparison of the performance of various parameters for joint detection

Parameters	Average detection rate (158 holes) (%)	Number of false alarms (158 holes)
Feed pressure	92.9	12
Rotation pressure	91.8	100
Acoustic	84.8	37
Vibration	72.7	80
RF/FP/PR	93.4	12

performance for joint detection with the highest detection rate and the minimum number of false alarms. Use of the feed pressure alone shows close performance compared to RP/FP/PR on joint detection with the average detection rate of 92.9% and 12 false alarms. Overall, it seems like the use of a composite index such as the RP/FP/PR could provide better results to allow for more accurate joint detection and less false alarms with higher reliability than just analyzing individual drilling parameter.

To evaluate the joint detection results, bore-scope was used for identification of the actual position of the joints in drilled boreholes. Figure 9 shows the screen shot of the view from bore-scoping device and an example of the picture at the location of the joint while testing at J.H. Fletcher & Co. facility.

6 Testing on Samples with Simulated Angled Joints

The preliminary laboratory tests at J.H. Fletcher & Co. facility was conducted in samples where one joint, perpendicular to the drilling direction, was simulated in each test sample. In the following study, new laboratory tests were carried out in samples with multiple inclined joints (15°, 30°, and 45°). The Teflon material was used to simulate the joint, and the aperture of angled joints were pre-designed at

Fig. 9 The screen shot of the view from bore-scoping. (Reproduced with permission from Bahrampour et al. 2014, 2015)

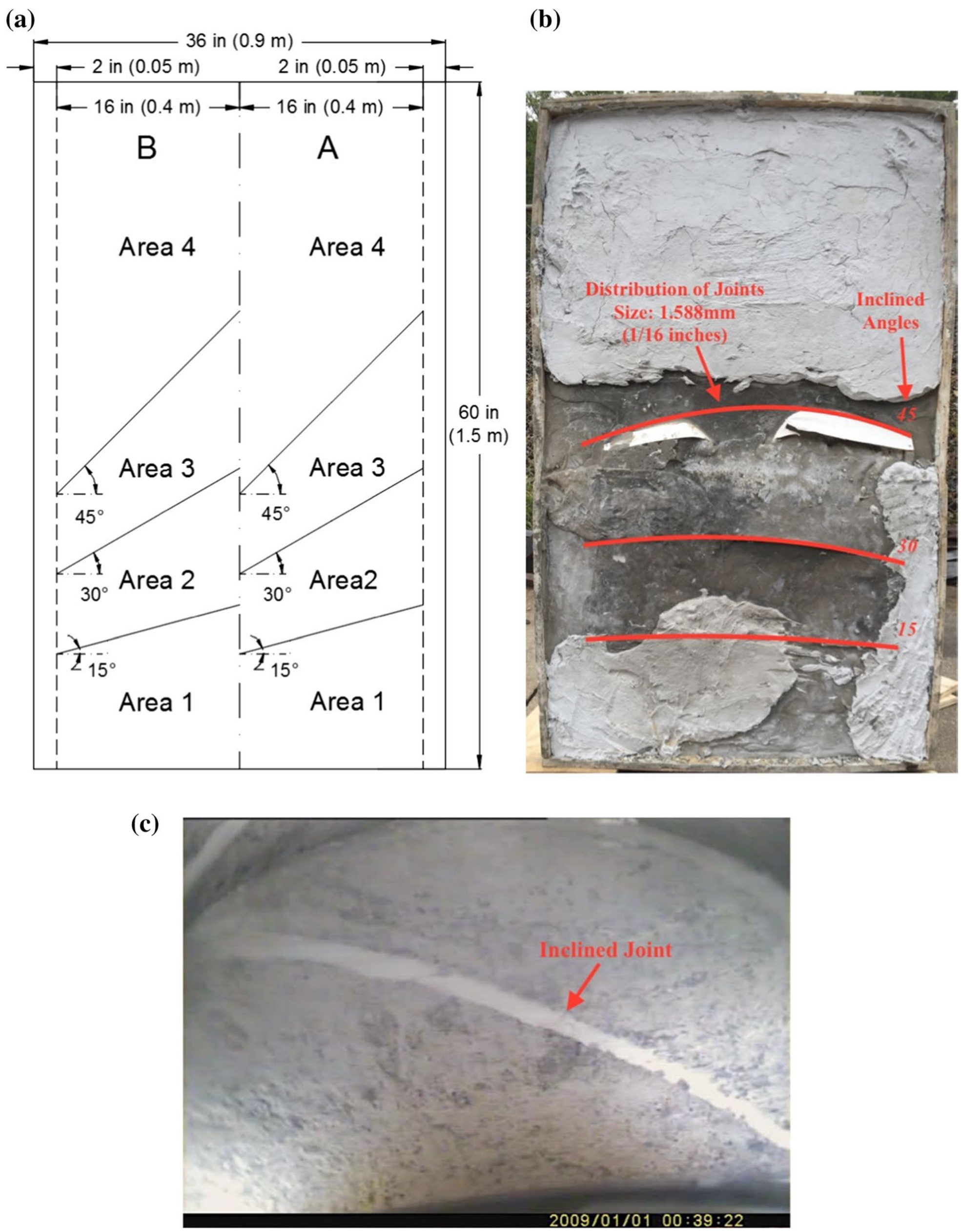

Fig. 10 **a** Distribution of inclined joints (left-side view of the block), **b** picture of the block (front-side view of the block), **c** a bore-scoping image of the joint in test sample

1.588 mm (or 0.063 in.). Figure 10 shows the distribution of pre-designed inclined joints in each test sample. Each testing block included two testing areas (A and B) that were located to line up side by side when drilling the sample. Figure 10a shows the distributions of inclined joints and Fig. 10b shows the front view of the block, namely the top half of the block (or sample B). A picture of an inclined joint inside the borehole observed by bore-scoping is also shown in Fig. 10c.

Figure 11 shows the plot of recorded feed pressure data as well as RP/FP/PR data for drilling in the sample with inclined joints. There are three distinct changes on feed pressure data and calculated RP/FP/PR index at the location of three inclined joints. In addition, this figure clearly shows the suitability of RP/FP/PR for joint detection due to lower variation and noise, and more distinct features for locating changes in the mean values of the data.

7 Conclusions

Although many improvements have been made to instrumented roof bolters as well as the instruments, sensors, and software to identify anomalies such as joints, voids, and cracks in the rock, there are still several issues that must be resolved to improve the capabilities and accuracy of the existing joint detection systems to reduce the number of false alarms, and to be able discriminate joints and/or voids with smaller aperture (less than 3.175 mm or 0.125 in.).

The sensitivity and precision of the algorithms using individual drilling parameters to locate joints and/or voids in ground are very limited and prone to errors and need frequent adjustments for detection threshold. One of the approaches to detect joints with smaller apertures is the use of systems with enhanced capability for processing the recorded drilling parameter to sense small changes in the data stream. In other words, the capability of analyzing the data from drilling operation to capture distinct changes, while the bit encounters a joint is the limit of the systems designed for this purpose. Using the composite indices, such as the RP/FP/PR, for joint detection can be one of the effective methods to improve detection rate and filter noises in the data stream which may confuse detection algorithms and cause false alarms. The preliminary analysis shows that the use of combined or composite indices can generate more reliable results than analyzing the signals from individual drilling parameter.

In this study, the combined ratio of rotation to feed pressures, divided by penetration rate (RP/FP/PR), was used as a composite index to evaluate the performance of the joint detection algorithms in locating pre-designed joints in nine different concrete block settings. The comparison of the results obtained by using RP/FP/PR with those of the past analysis using individual parameters has indicated a better performance with the highest detection rate as well as low number of false alarms. Furthermore, the analysis of RP/FP/PR index shows lower noise in the data and somewhat more distinct change at the location of the joint. This index has also shown better performances in detection of joints in samples with inclined/angled joints. Detecting small joints/cracks and the location of voids that are not visible from the surface to be drilled provides critical information about the rock mass that can be subsequently used for optimization of ground support measures. Additional studies and full-scale testing is underway to evaluate the best combination of input parameters and their respective ratios/composition to improve the pattern recognition and performance of the detection algorithms.

Acknowledgements The authors would like to acknowledge and contribution by J.H. Fletcher staff and engineers including Greg Collins, Joe McQuerrey, Lyle Crum, Edwin Lewis Warnick IV and Brad Parks. This research was funded by a grant from National Institute of Occupational Safety and Health (NIOSH) ground control group under the contract No. 211-2011-41138. Authors would like express their gratitude to the above contributors as well as Dr. Eric Keller, Dr. Ali Naeimipour, Soheil Bahrampour.

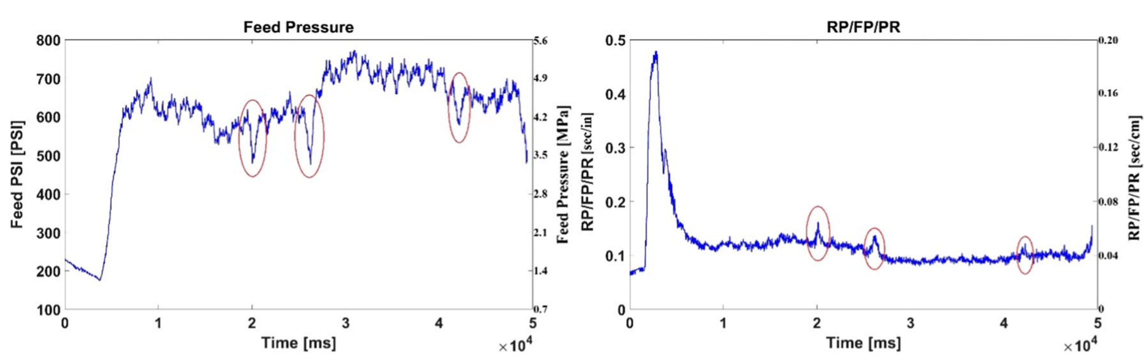

Fig. 11 Plot of feed pressure data and RP/FP/PR data for drilling in sample with inclined joints

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