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Ground characterization and roof mapping: Online sensor signal-based change detection

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ABSTRACT

Measurement while drilling systems are becoming an important part of excavation operations for rock characterization and ground support design that require reliable information on rock strength and location & frequency of joints or voids. This paper focuses on improving rock characterization algorithms for instrumented roof-bolter systems. For this purpose, an improved void detection algorithm is proposed, where the underlying theory is built upon the concept of mean change detection based on the feed pressure signals. In addition, the application of acoustic sensing for void detection is examined and it is shown that the variance of the filtered acoustic signal is correlated to the strength of the material being drilled. The proposed algorithm has been validated on the data collected from full-scale drilling tests in various concrete and rock samples at the J. H. Fletcher facility.

1. Introduction

Application of rock bolts is standard practice in ground support due to the relatively easy installation, lightweight, convenient transportation, and high anchorage capacity (Fig. 1). Effectiveness of rock bolts is highly dependent on correct identification of the geological conditions, including discontinuities, because they tend to vary, even within a short distance [1]. Various drilling parameters are collected and processed when using roof bolters in underground construction and mining that can potentially be utilized to evaluate the geological conditions at the jobsite [2]. A series of studies has demonstrated the potential for analyzing drilling parameters from roof bolters to estimate rock properties and to identify discontinuities [3–8].

A portable pneumatic roof bolter with the ability to record torque, thrust, revolution, and stroke was utilized [3,4]. Torque and thrust were monitored by using strain gauges installed on the surface of the drilling rod, while penetration and rotation rate were kept constant during the tests. The manufactured blocks included sandstone, sandy shale, and coal samples with three different discontinuity angles of 0 degrees, 30 degrees, and 60 degrees and three types of discontinuities, namely cracks, boundary, and separation of layers. Cracks are discontinuities within a layer. Boundary and bed separation are discontinuities between the layers and often feature a small aperture between layers in the rock mass, often intersected by joints. The average value of torque and/or thrust was found to be an indicative index to allow for classification of the rock layers along the borehole. Furthermore, it has been proposed that patterns of thrust or torque along with neural network algorithms may be used to categorize the discontinuities, but the resulting error was rather large. The feasibility studies of rock mass characterization while drilling for roof bolts in an underground coal mine in Queensland, Australia were studied [6–8]. In these studies, 48 holes were drilled using the instrumented drill unit, and one hole was cored in the test area to provide core for rock strength testing. The system successfully showed the distribution of discontinuities and layer boundaries using the ratio of recorded parameters of torque and thrust.

In a similar approach, J. H. Fletcher & Co. developed a system that monitors drilling operations using instrumented roof bolters to monitor drilling parameters, including thrust (obtained from feed pressure), torque (obtained from rotation pressure), rotation rate, and bit position [1]. The data is processed on board to detect joints and voids as well as rock strength in a relative scale. This system has been successfully employed in various mining operations to detect different kinds of discontinuities including voids, fractures, and bed separations, and to estimate the relative hardness of the rock mass [9]. Variation of thrust or feed pressure has been found among the most suitable identifiers for detecting

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Fig. 1. J. H. Fletcher roof bolter.

discontinuities [1,2,9–14]. For example, a thrust valley concept was proposed by which the presence and the size of discontinuities, such as fractures, joints, and voids in the rock, can be evaluated [10]. Based on this concept, thrust decreases rapidly after reaching a void and increases rapidly again when it goes through the discontinuity to keep the preset level of penetration constant. A drop of more than 50% was then considered as an index to detect discontinuity. The distance between the two sides of the valley was also used to measure the discontinuity aperture. Two models were offered for estimating the size of discontinuity.

A secondary parameter of rotational acceleration was also proposed to detect beddings. This parameter could detect 70% of the interfaces designed in the experimental program using layered blocks. The location of 57% of these interfaces was predicted within 2 in. of the actual locations. This system was further developed [1,15] with the introduction of the drilling hardness (DH) parameter. The DH parameter considers the geometry of the drill bit and contact area between the drill bit and rock, the friction between the drill bit and rock, and the energy lost in kinetic energy, potential, and torsion energies. The slope of the drilling hardness curve and its peak values are used to determine the location of discontinuities and interfaces. Discontinuities are detected using threshold-based algorithms that need to be adjusted for different rock types. This limits the applicability of the system for deployment and utilization in different mining locations. For example, only 25.86% of the discontinuities were detected by DH method within an acceptable error window [1]. He explained that this failure was related to the rocks not being weak enough to be detected by the DH slope approach. A method is developed which is able to detect fractures with an aperture of 1/8 in. or larger [12]. However, this approach was found to be somewhat ineffective for discontinuities of 1/16-in. aperture or smaller.

The instrumented void detection system was subsequently improved to a great extent, but some inaccuracies in detecting the location and, especially, the size of discontinuities is reported from time to time. It is explained that some major voids could not initially be detected by the system during a series of field experiments in a limestone mine, mainly, because of the difference between the hardness of concrete used in the laboratory and the limestone at the roof of the mine [16]. In this situation, the parameters of the roof mapping algorithm in the onboard processing system need to be updated occasionally. Another observation was that unlike the usual pattern observed in the laboratory, in which both thrust and torque would drop simultaneously, a sudden rise in the rotation torque happened just before encountering the voids in the field. Meanwhile, the thrust did not have a consistent reaction when passing through the void in the field. Another issue was reported that the hairline and vertical cracks along with layers of the rocks could not be correctly identified [17].

In a more recent study, vibration and acoustic measurements were used to improve the accuracy of the void detection and rock characterization when using roof bolters [18]. The study concluded that valuable information can be extracted from the high frequency components of the vibration and acoustic signals, which was subsequently used for void detection. This allows for using secondary sensors for void detection and can provide a degree of redundancy in instrumentation and higher detection rate when using a combination of the standard instrumentation with the acoustic and vibration sensors.

This paper focuses on two new void detection algorithms using the standard and new instrumentation of the roof bolters. One is a mean change detection on the feed pressure signal and the other the other a variance change detection problem on appropriately filtered acoustic signal. The corresponding mean and variance change detection problems are then solved using the online CUSUM algorithms [19]. The experimental results suggest that the proposed algorithms can improve the performance and efficiency of the existing void detection algorithm. The new algorithm also enjoys an adaptive threshold that does not need readjusting or fine-tuning when dealing with different rock strengths and various drilling parameters such as desired penetration rates and rpm. Moreover, they can be efficiently implemented using recursive formulations and therefore are well suited for real-time monitoring of the roof condition. The proposed algorithm for mean change detection on the feed pressure is presented for a decrease in the mean value but it can be easily extended to be sensitive to both sudden decrease and increase in the mean of the feed pressure. This phenomenon was reported in literature, where both trends were observed [16]. Finally, it will be shown that the proposed variance change detection on the acoustic signal can be utilized for the relative rock strength estimation.

2. Instrumented roof bolt drilling system by JH Fletcher

J. H. Fletcher & Co. has developed the Fletcher Information Display System, which uses a programmable logic controller (PLC) to monitor drilling operations. This system features a drill control unit (DCU) to automate and optimize the cycle of drilling and bolting for safety and productivity reasons [17]. The DCU processes the drilling parameters including torque, thrust, rotation rate, and position, along with vacuum or water pressure used for flushing, bit breakage, or bending of the drill by controlling the drilling parameters without deteriorating the optimum drilling operation [17]. Several modifications have been made to improve the accuracy of measuring bit position and torque [1]. The software was modified to communicate with the DCU to display the information from four separate drill holes side-by-side so that trends could be easily observed in real time. These graphs can show the material hardness and can display the location of voids or other discontinuities in the mine roof structure. Also, rotation related events, like stalls, and water events, which may indicate that the drill steel is being plugged with soft material, are marked with colored lines and letters. The Information Display System features a rugged touch screen panel, a solid state flash memory for better durability, uninterrupted power supply, a virtual keyboard for entering additional information to the files, a back-up video display, and a print function [17]. The sampling interval in this system is usually 10 Hz or 0.1 s time interval which can be increased up to 100 Hz. In this study, the data were collected using sampling rate of 100 Hz.

2.1. Installation of new sensors

Vibration and acoustic sensors were added to the Fletcher drill unit to collect additional information from the drilling process