

# MINE ROOF GEOLOGY INFORMATION SYSTEM

## *A Method for Quantitative Void/Fracture Detection and Estimation of Rock Strength for Underground Mine Roof*

BY SYD S. PENG, TAKASHI SASAOKA, DAVID X. TANG, YI LUO, AND GENE WILSON

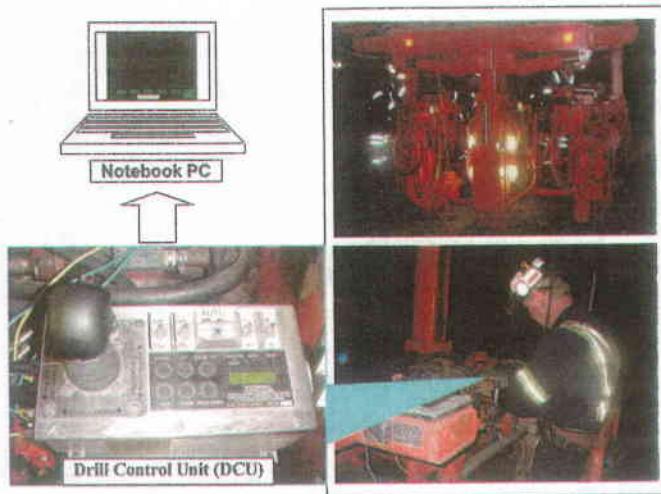


Figure 1 Roof bolter, DCU and data collection system.

Undoubtedly, recent coal mining is being conducted in more geologically disadvantaged coal reserves where the roof is either weak or contains geological anomalies with rapid changes of geological features such as rock type, slickensides, voids/fractures, etc. Thus the underground mine roof is more difficult to predict and control. Since all underground coal mine entries are supported by roof bolts and the design and selection of roof bolts are based on the knowledge of roof geology, it is of utmost importance that the roof geology and its variation over the immediate operation areas be known in advance so that a proper roof bolting system can be designed and/or selected.

The current method of using surface borehole loggings, which normally are spaced more than 1,000 ft apart, is to determine the immediate roof is awfully inadequate. Roof falls that caused injuries/fatalities and/or production delays are mostly localized even though some massive roof falls have been reported. For localized roof falls, the major reason is a change in geology. Obviously a selected roof bolting system must match certain geological features (rock type and stratigraphic sequence). But when geological features change and differ considerably, the selected roof bolting system may not work and roof falls occur.

How can a roof control engineer know the geological features have changed? To prevent roof falls, the roof geology within the bolted horizon must be known in advance from bolt row to bolt row. Only with this knowledge, a roof control engineer can determine if a change in the current roof bolting system is needed. To achieve this objective, a detailed roof geology map depicting geological changes from bolt row to bolt row must be available. In

this respect, if a roof bolter's drilling parameters can be monitored and correlated with the geological features, all changes in geological features can be mapped from bolthole to bolthole when the roof bolts are being installed and the roof bolting system will stay compatible with the roof geological features.

Against this background, a project sponsored by the U.S. Department of Energy under the Industry of Future (Mining) program was initiated five years ago. In this project a patented drill control unit (DCU) installed in the J.H. Fletcher & Co.'s roof bolter was used to record the drilling parameter for experiments conducted in the mines and laboratory. Today, the drilling parameters have been recorded for more than 1,000 roof bolt holes.<sup>(1)-(4)</sup> This article summarizes the results to date including the methods for determining quantitatively the location of voids/fractures and estimation of roof rock strength from the recorded roof bolter drilling parameters.

### DRILLING & DATA COLLECTION

The drilling system consists of a set of sensors and a data control unit (DCU) installed on a J.H. Fletcher & Co.'s HDDR walk-thru type dual roof bolter as shown in Figure 1. One side of the machine has standard hydraulic controls while the other side is fitted with the patented Fletcher Feedback Control system.<sup>(5)</sup> This system allows the operator to pre-set the penetration rate, rotation rate, and the maximum feed pressure (= thrust cap) of the machine. Once the parameters are set, the machine drills without additional operator input. A data logger allows drilling data to be monitored and analyzed.

Table 1 Drilling Parameters

Column	Drilling Parameter
Data 1	Status Byte
Data 2	Feed Pressure
Data 3	Feed Flow
Data 4	Rotation Pressure
Data 5	Rotation Flow
Data 6	RPM Counts
Data 7	Rotation Torque
Data 8	Mast Position
Data 9	Carriage Position
Data 10	Vacuum
Data 11	Temperature
Data 12	Spare Channel
Data 13	Message Counter
Data 14	Feed PWM CMD
Data 15	Flow PWM CMD

The drilling parameters collecting system was originally designed for controlling roof bolters automatically so that overall drilling and bolting consistency can be improved. Drilling parameters are recorded every 0.1 seconds so a 54-inch log hole will have 250 to 850 records, depending on the penetration rate and the condition of roof geology.

The data collection system is designed to collect 15 drilling parameters (See Table 1). The feed pressure measures the hydraulic pressure inside the cylinders applying the axial load. The rotation pressure records the hydraulic pressure in the hydraulic motor that provides rotational force. RPM-counts is measured using an electronic tachometer attached directly to the drill mast and can be converted into rotational rate.

These drilling parameters are collected in terms of sensor output in voltages and then converted to dimensionless numbers. In this paper, all drilling parameters except the data of two mast feed position sensors are not converted from dimensionless machine data (output unit) to engineering units.

**LABORATORY TEST**

To observe the behavior of drilling parameters when encountering voids/fractures and develop the criteria for void/fracture prediction, concrete blocks were constructed to simulate voids/fractures with different sizes and drilling tests were conducted. The laboratory tests consisted of the following three sets of experiments:

The first set of experiments was performed drilling nothing to determine the consistency of the drilling parameters in the air. This data indicates the machine condition and how much feed pressure/rotation pressure was consumed for running the machine itself. These data collected when drilling in the air are referred to as the compensation run data.

The second set of experiments was conducted by drilling in solid concrete block to check the drilling parameters within a single rock type. This concrete block was constructed of high strength concrete (12,000 psi compressive strength). Its dimensions were 3-x 4-x 5-ft.

The third set of experiment was carried out by drilling in the block which was constructed to simulate small voids/fractures. These concrete blocks were also constructed of high strength concrete (12,000 psi in UCS). The block for this test consisted of four individual layers of concrete which were 15-in thick and constructed parallel faces. In between each concrete layer, a void was formed by inserting a narrow steel plate around the block perimeters. The thickness of three steel plates were 1/16, 1/8 and 3/8 inches, respectively to simulate voids/fractures with different sizes. The layers were bolted together and in a steel frame so the block would act as one single unit. The final block dimensions were approximately 3-x 4-x 5-ft, and 1/16-, 1/8- and 3/8-inch voids were located at 15, 30 and 45 inches, respectively.

Several drilling settings were tested in order to determine the effect of both penetration rate and rotation rate on void/fracture prediction. A new bit was used for every hole.

**UNDERGROUND TEST**

To observe the behaviors of drilling parameters when drilling in different rocks and develop the criteria for estimating the strength

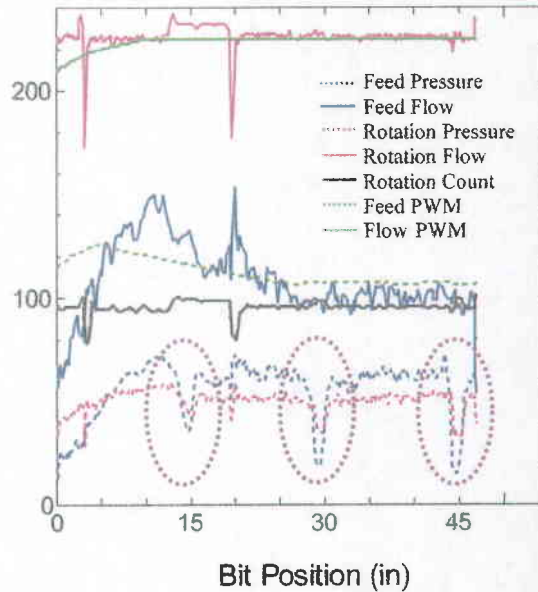


Figure 2 Drilling parameters (Fractured block).

of roof rock, underground tests were conducted. In addition the criteria for void/fracture prediction developed from the laboratory tests were verified.

The last underground tests were conducted in three different coal mines in southern West Virginia. In the testing sites, soft shale roof strata were presented in the roof bolting horizon at mine A and hard sandstone roof strata were presented at mine B and C. In addition, borehole scoping and core sampling were conducted at each test site to verify the roof geology.

Several drilling settings were tested to determine the effect of both penetration rate and rotation rate on drilling parameters and/or drilling conditions. In this series of tests, the role of thrust cap was only for safety. The thrust cap was set at the maximum value (1,000 psi) to eliminate its effect on drilling test as much as possible. A new bit was used for every hole. Moreover, the compensation run, i.e. drilling in the air without steel rod and bit, was conducted before every drilling to check the impact of drilling settings and machine conditions on drilling parameters for running the machine

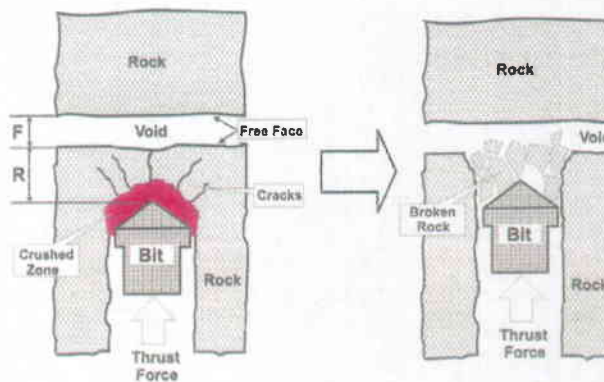


Figure 3 Rock fragmentation when drilling close to a rock void.

Table 2 Results of void prediction

Void Size (in)	Actual Location (in)	Number of holes with available data	Number of correct prediction	Percentage of correct prediction (%)	Average predicted location (in)
1/16	15	22	13	59.09	14.036
1/8	30	22	22	100	29.222
3/8	45	19	18	94.73	44.494

itself. When comparing with drilling data, the amount of feed pressure and rotation pressure consumed for drilling rock can be determined.

**VOID/FRACTURE PREDICTION<sup>6</sup>**

The first step of data analysis is to find the most appropriate drilling parameters for void/fracture prediction. So, all the measured drilling data for a hole are plotted on figures for comparison. An example of the plotted data for a hole drilled fracture block is shown in Figure 2. All data are indicated as the output counts of sensors. From Figure 3, it can be seen that the feed pressure changes dramatically to form valleys around the locations of 15-, 30- and 45-in where the voids are located. It is also recognized that rotation pressure also changes around the locations of voids slightly. But the magnitude of the change is much smaller than that of feed pressure. The other drilling parameters do not change at the presence of voids. Therefore, it can be concluded that feed pressure is the relevant drilling parameter for the existence of voids/fractures.

The phenomenon that a void in rock induces a valley in feed pressure can be explained by the mechanism of rock fragmentation. According to the theory of rock fragmentation due to cutting, cracks will be created and propagate under a thrust force applied to by a drilling bit. (7)-(8) Once the cracks reach the free face of rock void, the whole pieces of the remaining rocks between drilling bit and free face of rock void will begin to break into small chips as shown in Figure 3. Therefore, the feed pressure should drop to the level of drilling in the air. Once drilling bit encounters rock again after going through the void, the feed pressure will rapidly climb back to the level when drilling in rock. This is how the valleys in feed pressure curve are formed.

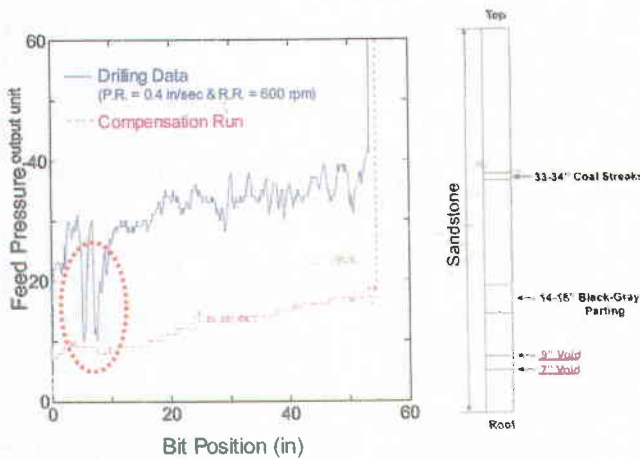


Figure 4 Feed pressure curves and results of borehole scoping (mine B).

The major criterion for void prediction is developed based on the fact that feed pressure should drop to the level of drilling in the air when a void in rock is encountered. But, it was also observed that sometime the bottoms of feed pressure valleys do not reach the level when drilling in the air, for instance around the location of 1/16 in void. This phenomenon has a trend that the smaller the size of the void is, the less possible it is for the feed pressure to fall into the range when drilling in the air. Two possible reasons can be considered for this trend: one is that rough surfaces of concrete layers may make the actual void size smaller than the designed one, or close to zero. Another reason is the small void does not provide enough space for broken rock chips to move in although cracks have already propagated to the void. Consequently, these rock chips are still confined to their original locations before they are further broken into smaller chips and removed by the dust collector. In this situation, the magnitude of feed pressure is much higher than that for drilling in the air. As a result, the valley bottoms of feed pressure will be very shallow or there is no valley at all. Therefore, in order to enhance the prediction accuracy, a supplemental prediction criterion is developed considering not only the magnitude of feed pressure but also the shape of feed pressure valley.

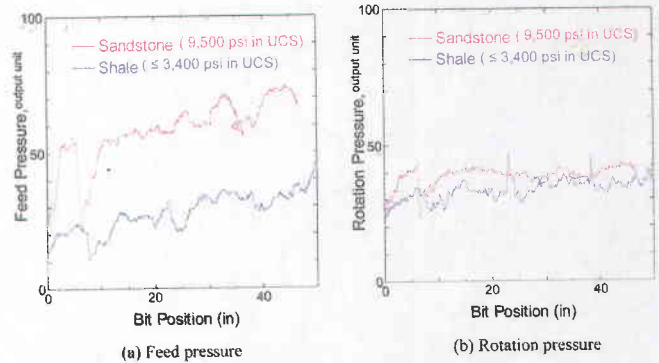


Figure 5 Effect of rock strength on feed pressure / rotation pressure. (P.R. = 1.5 in/sec & R.R. = 600 rpm, Oil Temp = 126 (Sandstone) and 128 (Shale) out put units)

The measured drilling parameters of 22 holes drilled in the fractured block were used to check the criteria for void/fracture prediction. The results are shown in Table 2. The prediction results show that a very high prediction percentage have been achieved for the 1/8-in and 3/8-in voids. But the 1/16-in void does not cause an obvious change in not only feed pressure but also all other drilling parameters. It seems that there is a limitation of the void size that can be detected by the current system. From the result of borehole scoping in mine B (sandstone roof rock) and feed pressure curve (See Figure 4), it can be seen that the locations of the valleys almost agree with the actual void locations and the feed pressure dropped to the level of drilling in the air.

**ESTIMATION OF ROCK STRENGTH**

As the data collection system is designed not for prediction of roof geology but for control drilling, drilling parameters which can be measured are the parameters in the hydraulic

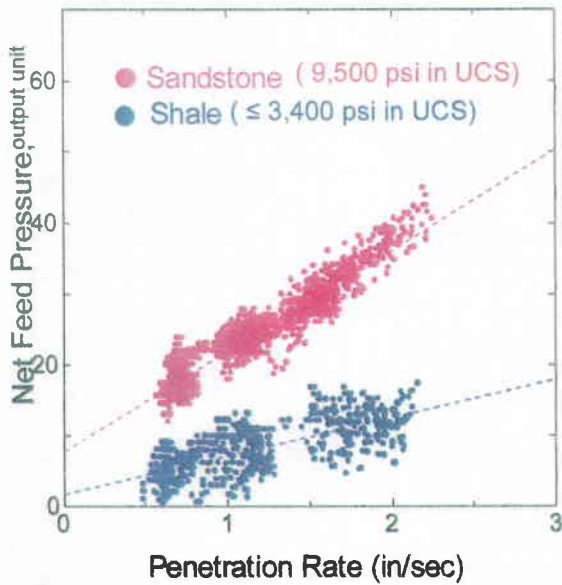


Figure 6 Relationship between net feed pressure and penetration rate for different strengths of rocks (R.R. = 600 rpm).

system. This means that the drilling parameters contain not only for drilling rock but also for running machine itself. First of all, one needs to know how much the drilling parameters, especially feed pressure and rotation pressure, consumed for running the machine itself and how much impact different drilling settings and machine conditions have on them. Consequently, based on the behavior of drilling parameters when drilling in different rock, the most appropriate drilling parameters for estimating rock strength and developing the criterion for rock classification can be found.

The penetration rate, rotation rate and oil temperature have no obvious impact on both the magnitude and trend of feed

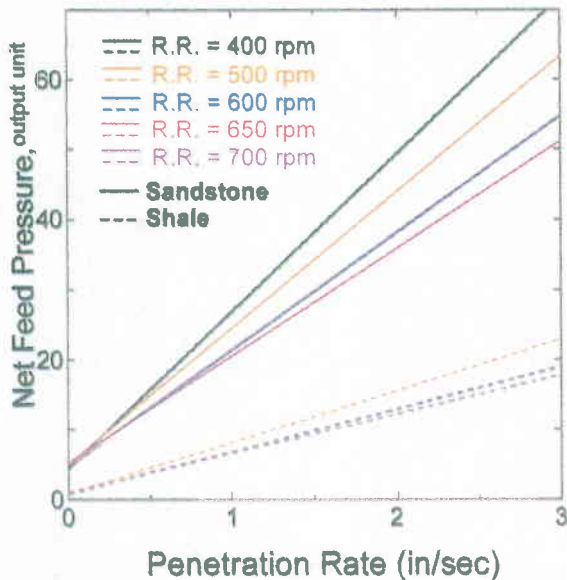


Figure 7 Approximation curves for each setting for different rotation rates and different strengths of rocks.

pressure. These results indicate that once feed pressure for compensation run is measured, it is easy to eliminate the effect of machine itself on feed pressure when drilling rock. On the other hand, different rotation rates and oil temperatures have an obvious impact on the magnitude of rotation pressure. Besides, comparing with the data when drilling rock, their impacts on the magnitude of rotation pressure are too large to be ignored. Therefore, the effects of rotation rate and oil temperature have to be taken into account when the strength of roof rock is estimated based on the magnitude of rotation pressure.

Harder roof rock requires larger feed pressure (See Figure 5). On the other hand, even though the impact of rock strength on the magnitude of rotation pressure can be recognized, it is not so clear cut. Besides, as mentioned above, the magnitude of rotation pressure consumed for running machine itself changes dramatically with the change of rotation rate and machine condition (i.e. oil temperature). Therefore, it can be concluded that feed pressure is the most sensitive and reliable parameter for estimating the strength of roof rock under the current system. As to eliminate the machine effect on feed pressure, the net feed pressure is used for rock strength estimation instead of feed pressure. The net feed pressure is defined as;

$$\text{Net feed pressure}(BP(t_n)) = \text{feed pressure when drilling rock}(BP(t_n)) - \text{feed pressure for compensation runs}(BP(t_n))$$

Where, BP = bit position and  $t_n$  = elapsed time after drilling starts.

The relationship between net feed pressure and penetration rate for different strength of rocks is shown in Figure 6. Blue and red data points indicate drilling data at mine A where the roof is shale and those at mine B where the roof is sandstone, respectively. It can be seen that different penetration rates have an impact on the magnitude of net feed pressure—the higher the penetration rate, the larger the magnitude of net feed pressure. Moreover, harder roof rock influences the impact of penetration rate on the trend of net feed pressure-penetration rate curve more. It is concluded that not only the magnitude of net feed pressure but also the slope of net feed pressure-penetration rate curve is related to rock strength.

It was also found that different rotation rates have obvious impact on the magnitude of net feed pressure. The magnitude of net feed pressure decreases with the increasing rotation rate. This result indicates that the rotation rate helps net feed pressure. Next the effect of rotation rate on the trend of net feed pressure-penetration rate curve is determined. Approximation curves for each rotation rate setting vs. the strength of rock are defined as linear functions for simplification. Figure 7 shows the approximation curves. It can be seen from this figure, the higher the rotation rate is the more gentle the slope of net feed pressure-penetration rate curve is. Besides the harder the roof rock is the larger the impact of rotation rate on the slope of net feed pressure-penetration rate is.

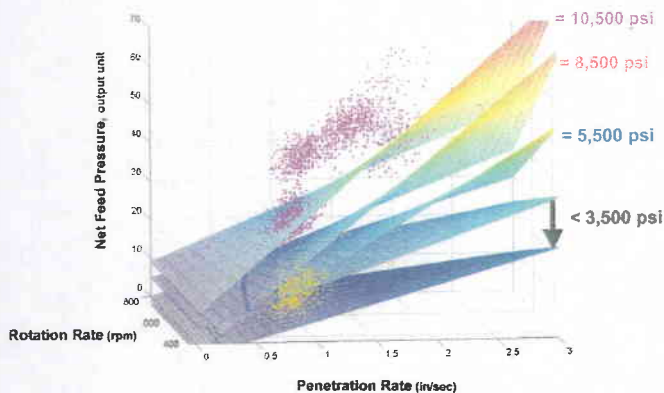
The results obtained so far clearly show that the magnitude of net feed pressure correlates well with the rock strength and both penetration rate and rotation rate have obvious impact on the magni-

tude of net feed pressure. Therefore both parameters have to be considered when roof geology is predicted based on the magnitude of net feed pressure. From Figure 7, the relationship among net feed pressure, penetration rate and rotation rate can be represented by the following equation;

$$\text{Net Feed Pressure}(t_n) = F_{\text{FRS}}(\text{RotationRate}(t_n)) \times \text{PenetrationRate}(t_n) + C_0$$

Where, FRS = function of rotation rate for each strength of rocks,  $C_0$  = constant, and  $t_n$  = elapsed time after drilling starts.

Based on the trend of data sets distributions for different strength rocks, boundary planes for estimating roof rock strength are determined (See Figure 8). In order to verify these boundaries, another set of independent data has been selected and plot them on the net feed pressure-penetration rate-rotation rate graph. From the results of the lab tests, the data from two kinds of blocks were used; one is 12,000 psi high strength concrete block and the other is 4,000 psi concrete. Purple and yellow data points indicate drilling data for 12,000 psi high strength concrete block and 4,000 psi concrete block, respectively. It can be seen that the set of drilling data in 12,000 psi block was distributed above the 10,500 psi boundary plane. On the other hand, that in 4,000 psi block was distributed between 3,500 psi and 5,500 psi planes.



Boundary planes for estimating roof rock strength and distributions of both sets of data points (Concrete Block) (● : 12,000 psi Concrete Block, ● : 4,000 psi Concrete Block)

From the above results, it can be seen that roof rock can be classified based on the magnitude of net feed pressure because it takes both the effects of penetration rate and rotation rate into account. In other words, the relationship among net feed pressure, penetration rate and rotation rate is a good indicator for estimating the strength of roof rock. The strength of roof rock can be determined and/or classified based on the location of data point in the net feed pressure-penetration rate-rotation rate system.

## CONCLUSIONS

A system of quantitatively detecting voids/fractures and estimating roof rock strength in the entry roof using roof bolter drilling parameters has been developed. From the results of series of underground and laboratory tests, the following conclusions can be made:

1. The feed pressure trends of dropping down to the level of drilling in the air when a void is encountered can be used to detect the voids.
2. A void of 1/16-in or smaller cannot be detected by the system developed.
3. Feed pressure is the most sensitive parameters when the strength of roof rock changes under the current system. In order to eliminate the machine effect, the net feed pressure is recommended for estimating rock strength instead of feed pressure.
4. Both penetration rate and rotation rate have obvious impact on the magnitude of net feed pressure.
5. The strength of roof rock can be determined / classified based on the magnitude of net feed pressure because it takes both the effects of penetration rate and rotation rate into account when both penetration rate and rotation rate are controlled.

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## ACKNOWLEDGEMENT

This project is sponsored by the U.S. Dept. of Energy Industry of Future (mining) Program and Coal and Energy Research Bureau, State of West Virginia.

## AUTHOR INFORMATION

Peng is the chairman and Charles T. Holland Professor; Sasaoka is a post doctoral fellow; Tang is a graduate research assistant; Luo is a research associate professor for the mining engineering department at West Virginia University, located in Morgantown, W.Va. Wilson is the manager-product development for J.H. Fletcher & Co., located in Huntington, W.Va. Dr. Peng can be reached at Tel: 304-293-7680 (or E-mail: Syd.Peng@mail.wvu.edu)