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ABSTRACT

Collecting geological information allows for optimizing ground control measures in underground structures. This includes understanding of the joints and discontinuities and rock strength to develop rock mass classifications. An ideal approach to collect such information is through correlating the drilling data from the roofbolters to assess rock strength and void location and properties. The current instrumented roofbolters are capable of providing some information on these properties but not fully developed for accurate ground characterization. To enhance existing systems additional instrumentation and testing was conducted in laboratory and field conditions. However, to define the geology along the boreholes, the use of probing was deemed to be most efficient approach for locating joints and structures in the ground and evaluation of rock strength. Therefore, this research focuses on selection and evaluation of proper borehole probes that can offer a reliable assessment of rock mass structure and rock strength. In particular, attention was paid to borehole televiewer to characterize rock mass structures and joints and development of mechanical rock scratcher for determination of rock strength.

Rock bolt boreholes are commonly drilled in the ribs and the roof of underground environments. They are often small (about 1.5 inches) and short (mostly 2-3 meter). Most of them are oriented upward and thus, mostly dry or perhaps wet but not filled with water. No suitable system is available for probing in
such conditions to identify the voids/joints and specifically to measure rock strength for evaluation of rock mass and related optimization of ground support design.

A preliminary scan of available borehole probes proved that the best options for evaluation of rock structure is through analysis of borehole images, captured by optical televiewers. Laboratory and field trials with showed that these systems can be used to facilitate measurement of the location, frequency and partially condition of discontinuities. Two of the more promising tools have been tested during this project, which are QL40OBI Optical TV and Slim Borehole Scanner (SBS) manufacture by ALT-Mount Sopris and DMT, respectively. The field experiment with QL40OBI showed that the images generated for downward and sub-horizontal boreholes are of good quality and can be used to evaluate the joint conditions. However, this device is not suitable for use inside the upward drillholes. The Slim Borehole Scanner (SBS) manufactured by DMT in Germany has the required features for borescoping the roofbolt holes. This includes the ease of operation and suitable geometry along with an unwrapped 360-degree picture of the borehole wall. This instrument was concluded to be the best option yet for obtaining images from boreholes with any arbitrary orientation.

In addition, a new tool, called Rock Strength Borehole Probe (RSBP), was developed for estimation of the rock strength through scratching the rock surface in the borehole. This device is designed to be a light, flexible, quick, non-disruptive,
and cost effective alternative to estimate the rock strength inside the boreholes in underground mines and tunnels. An extensive number of laboratory tests under variable conditions were conducted to develop equations to estimate the Uniaxial Compressive Strength (UCS) and Brazilian Tensile Strength (BTS) of the rock from measured cutting forces. In these experiments, 27 different rock types were tested by full scale scratch tests, including the cutting tests by a miniature disc. The results show a good correlation between the normal force and the compressive strength of sedimentary/metamorphic rock if the depth of scratch is known. No significant correlation was observed for igneous rocks, due to the impacts of grain size.

Current studies show promising results for using RSBP. The laboratory and field tests proved the functionality of this tool. This probe is capable of entering boreholes of 45 mm (1¾ in) diameter in any direction and create a groove on the walls and by measurement of the location and cutting forces, estimate rock strength. Additional testing in various underground operations are needed for fine tune the operational features of this probe and make it more accurate.

The combination of rock strength and joint conditions will allow for development of rock mass classification that could be used for 3D imaging of the ground conditions around an underground opening as well as hazard maps for the roof.
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Chapter 1

Introduction

Roof and rib collapses are among the deadliest hazards. A report by MSHA, Mine Safety and Health Administration, mentions 7 fatalities and 500 injuries as a result of 1300 major roof collapses in 2006 [1]. To prevent these casualties, engineers need quantitative data about the condition of the rock masses surrounding the underground space to design the suitable support system. One of the common support systems in construction of underground spaces is rock bolt. The application of rock bolts has become a standard practice in ground support due to their effectiveness in reinforcing the ground and allowing the use of the ultimate strength of rock. In addition, they are relatively easy to install, lightweight, convenient to transport, and when applied correctly, bolts offer high anchorage capacity and consequently, increase rock mass strength. Effective installation of rock bolts is highly dependent on correct identification of the geological conditions, which includes the rock type, strength, jointing frequency, and joint conditions. Achieving this goal, however, is very challenging because the ground conditions tend to vary even within a short distance [2].

Ground characterization is often derived from qualitative geological reports and far-apart geotechnical borings. To tackle this issue, conventionally, localized diamond drillings are performed at the roof and ribs to obtain more accurate strata information. This is very costly and disruptive to the operations, and therefore unfeasible in many applications. Furthermore, testing the obtained cores in rock mechanics laboratories give limited, small-scale information about the rock mass [3]. As a result, these approaches have limited capabilities to assist for design of optimized support systems, especially rock bolts.
A series of studies has demonstrated the potential for analyzing drilling parameters from roof bolters to obtain detailed geological information, estimate rock properties and to identify discontinuities [4]–[9]. In a more recent study, it has been shown that vibration and acoustic measurements along with signal processing tools can also be used to improve the accuracy of the void detection and rock characterization algorithms [10]. Based on these promising results and in order to enhance the safety of operators, various manufacturers have developed Measurement While Drilling (MWD) systems, which are recently getting some tractions and have achieved some advances. In these systems, the drilling machine collects additional information such as torque, thrust and penetration rate while it is drilling boreholes for the applications such as probing, blasting, or rockbolting. For instance, J.H. Fletcher & Co. ™ has developed instrumented roof bolters which can detect bedding and discontinuities as well as relatively estimating the strength of the rock masses they drill through by analyzing drilling data and mainly using the feed pressure (thrust). This information can subsequently be post-processed and the outcomes can be visualized in 3D as well as in 2D map of the roof of other surfaces such as hazard maps.

In order to obtain reliable outputs and high detection accuracy, a large number of field tests should be conducted to train the smart drilling system and the results from the instruments should be compared and verified with the actual ground conditions. The conventional approach for this verification is coring, however, taking core of all the drillholes are not only very time consuming and expensive, as mentioned earlier, they are also discrete and in some cases inaccurate due to drilling operation issues such as washout and recovery. Moreover, these cores are obtained from a borehole which is near the tested drillhole and not exactly at the same point, which might also cause more inaccuracy. Meanwhile, there have been much progress in the area of ground characterization using various probing devices. Borehole probing (logging) is the practice of recording continuous information on some physical properties of rocks in the borehole. Operation of this approach is
faster, relatively economical, more informative and with continuous results, which can readily be archived and compared with the other boreholes.

This dissertation is part of a major project supported by National Institute of Occupational Safety and Health (NIOSH) and with the title of “Instrumentation of Roof Bolt Drill for Ground Characterization, Mapping, and Support Design”. The current study is also the continuation of the studies by researchers at West Virginia University (WVU) in collaboration with J. H. Fletcher & Co. since 1999 for about 10 years. During this time a series of manufactured roof rock blocks were tested in the laboratory. Some underground tests were also conducted. Several theses [2], [11]–[13] and papers [14]–[17] have been published and are available for review. Their results show that it is possible to identify the relative strength of the rocks encountered in the borehole. In addition, fractures and bedding planes were identified by the changes in the drilling patterns, most notably thrust.

The ongoing studies at the Pennsylvania State University (PSU), as indicated in the project proposal, aim to: “(1) advance the existing roof bolt drilling systems so that they can collect additional information which can be used for estimating the rock strength and evaluating rock mass conditions, (2) generate a 3D geological, hazard map of the underground spacing, and, (3) incorporate the acquired data into ground support programs to evaluate the suitability of designed support system.” To achieve these goals four phases and several tasks are planned. The phase 1 is related to instrumentation of the roof bolter and enhancement of the existing systems and phase 2 is titled “Borehole mapping using various sensory devices”.

This dissertation is focused on the second phase of this project and tries to offer solutions to make borehole mapping a reliable, efficient and cost effective means for characterization of the rock mass that is drilled by the developed smart roofbolter, in order to facilitate the assessment of the instrument performance. To extract the geological information, these roofbolters analyze the drilling data using a pattern recognition algorithm, which is developed based on the laboratory
trainings. However, as mentioned earlier, the algorithm performance needs to be evaluated in the field through running extensive number of drilling tests. This evaluation is solely conducted based on the in-situ geological data from borehole probing. In other words, in the field the borehole probing data is the only criterion to reject or accept the algorithm outcomes. The developed algorithm is trained to identify various rock strata and joints based on the results of probing as ground truth. Field testing is the only way to ensure the reliability of the developed algorithm. As a result, borehole probing is one of the crucial parts of this project that required an extensive study.

Borehole logging or well logging is the practice of recording continuous information on some physical properties of rocks in the borehole. Well logging is commonly used in boreholes drilled for the oil and gas, groundwater, minerals, geothermal, environmental, and mining applications. There are many different logging methods namely electric, radiation, sonic and acoustic, and optical. Well or borehole logging systems consist of various sub-groups to measure a target physical parameter in a particular situation. Various borehole logging and probing systems has been proposed and used in recent years to offer an estimate of rock strength and rock mass structural features such as joint frequency and joint conditions. These probes have been fairly successful in larger down holes drilled for various applications but have limited or no use in shorter, smaller size boreholes often used in underground applications. Thus, there is a dire need to look into probing and logging systems that can be used in underground mining and construction for rock characterization.

As a result, the current study focuses on slimmer, lighter probes, which are needed to be used in the roof bolt holes. These holes are typically about 25-50 mm (1-2 inch) in diameter, about 1-6 m (3-20 ft) long, and should be accessed from smaller spaces where they can be set up and drilled. Some attempt has been made in the past to employ borehole-logging methods to verify the validity of the results from the instrumented roof bolter in field tests. Gu (2003) and Tang (2006) mentioned application of a simple borehole camera system in addition to coring to verify the
sequence of formations encountered by roof bolter during the underground tests [2], [13]. In addition, various geophysical methods have been examined to estimate different properties of the rock mass especially the rock strength [18], [19]. Also, borehole televiewers and cameras are often used to take a picture of the borehole wall to detect discontinuities [20], [21].

Uniaxial Compressive Strength (UCS) of intact rock and condition of the discontinuities are the two most important parameters for rock mass classification for ground support design and evaluation of ground stability. While condition of the discontinuities can be examined by borehole televiewers like optical TVs, estimation of UCS remains to be a challenge in development of rock mass classification. UCS of the rock is commonly correlated to the results from the sonic logging method. But sonic methods are not optimized for application in upward holes and do require some sort of fluid in the hole for transmission of sonic waves. Hence, probing upward/slim/short/dry boreholes, which is the focus of this study, is a logistical issue that should be addressed to pave the way for further investigation of the application of borehole logging for rock characterization within the boreholes drilled for roof bolting.

In this chapter, firstly, the objective of this project is defined and then the problem is stated in details. In the next section, the methodology used to resolve this problem is depicted. Finally, the structure of this dissertation is explained and subjects of each subsequent chapter is introduced.

**Objectives**

Collecting geological information allows for optimizing ground control measures in mines. An ideal way to collect this information is through correlating the drilling data from the roofbolters to the rock and void properties. The current instrumented roofbolters are not accurate and fully developed for providing accurate ground characterization data. To enhance existing systems
additional instrumentation and testing is needed. To define the geology along the boreholes, which are drilled during the tests, the most efficient approach is borehole probing/logging.

The objective of this research study is to introduce and test suitable borehole probes for the measurement of rock properties, namely the intact rock strength and the discontinuity features, in the rockbolt drillholes. This paves the way to improve the algorithms of instrumented roofbolters to accurately define the rock strength and jointing system.

Statement of the problem

Rock bolt boreholes in the ribs and the roof of underground environments are often small (about 1.5 inches) and short (mostly 2-3 meter). Most of them are oriented upward and often dry. No suitable system is available for probing in such conditions to identify the voids/joints and specifically to measure rock strength for evaluation of rock mass and ground support design.

Hence, this research focuses on selection and evaluation of proper borehole probes, for the aforementioned condition, in particular borehole televiewer and mechanical rock scratcher for determination of rock mass properties. This include analyzing the results from the field and lab logging operations.

Methodology

Efficient measurements of the rock strength and frequency of the discontinuities, which are the main parameters for rock mass classification, is the main focus of this study. For this purpose, borehole images, captured by an optical televiewer, can be used to facilitate measurement of the location, frequency and partially condition of discontinuities. Also, a new method for estimation of the rock strength through scratching the rock surface in the borehole is developed.
In the preliminary stages, the common rock types to be tested were determined and collected from the mines to be transferred to J.H. Fletcher & Co.™ test facilities for preparation of new samples. In the next step the rock and concrete samples are tested in the Geomechanical laboratory located in the Hosler and Dieke buildings and Penn State Civil Infrastructure Testing and Evaluation Laboratory (CITEL), respectively, to get Geomechanical properties such as Uniaxial Compression Strength. These samples were utilized to run new drilling tests with the instrumented roof bolter located at J.H. Fletcher & Co.™ test facility, and a number of algorithms were developed by one of the research partners, based on the samples properties.

As the goal of this study was to develop proper probes for the estimation of mechanical and structural properties of various strata. The main challenges in this study include developing slim, explosion proof probes, which can retrieve acceptable data from the upward/dry/short boreholes.

Optical TV tools were considered to be the ideal device for the evaluation of discontinuities, which is one of the main factors involved in rock mass classification. Hence, to evaluate the performance of the more promising products, several of these probes were utilized in field applications. A Q40OBI-1000, Optical televiewer and its accessories manufactured by Mount Sopris Instrument Co., Inc. was used in field studies. This tool was tested in two surface coal mines and an underground limestone mine in Pennsylvania. The second OPTV product that was evaluated was Slim Borehole Scanner (SBS) manufactured by DMT Company in Germany. This product was tested in several underground mines across the US with the collaboration of DMT. Comparing these two products, it was concluded that SBS is the superior product for our application and given operational conditions.

Field testing by borescopes was followed by use of scratch test as the suitable means for estimation of the rock strength. A miniature linear cutting machine was designed and fabricated for this purpose. Twenty-seven rock samples were tested by this machine using a miniature cutting
wheel. Using the recorded normal and rolling forces of these tests along with the Uniaxial Compressive Strength (UCS) and Brazilian Tensile Strength (BTS) of the samples, number equations were developed for estimation of the rock strength, i.e. UCS and BTS, using the cutting forces recorded in the tests.

A borehole strength measurement probe that could meet the conditions of this project application, was designed and fabricated. This tool is call Rock Strength Borehole Probe (RSBP) and is capable of estimating rock strength based on the scratching of the borehole wall by a miniature disc, similar to the simulated tests on the laboratory cutting machine. The design of components for RSBP has gone through several iterations and modifications. The latest product is able to record the normal and rolling forces and the position of the scribe within the borehole, which can be used to estimate the strength of the strata it has encountered along the hole based on the analysis of laboratory tests of various rock.

**Dissertation outline**

This dissertation is composed of nine chapters. In the first chapter, the introduction chapter, the project is introduced by giving a brief background, explain the problem and the objectives of the project as well as the methodology that is employed to achieve these goals.

In chapter 2, the history of the smart roofbolters to date, is discussed and the Coal Mine Roof Rating (CMRR) classification system is explained. Chapter three would explain well logging/probing approaches followed by their applications in mining industry and rock characterization. The focus of this investigation is mainly on the methods for estimation of the rock strength and discontinuity evaluation. This chapter ends by short discussion on the history of borehole probing in smart roofbolter projects.
Chapter four covers the process of selecting the suitable probes for the roofbolter project and various tools are compared to each other and their advantages/disadvantages are explained. Chapter five present the results of field tests run by the selected borehole imaging tools, which are Q40OBI-1000 and SBS. These two products are compared based on these field experiments and the more ideal tool for this project application is introduced.

The new method developed for estimation of rock strength is explained in chapters six through nine. The scratch test tools and operation procedures are introduced in chapter six followed by the test results, which are conducted under selected conditions and on twenty-seven different rocks, that are presented in chapter seven. Similarly, the developed probe design and testing are described in detail in chapters eight and nine, respectively.

Conclusions made in this study are summarized in chapter ten and some recommendations on improving the project outcomes are listed at the of this chapter.
Chapter 2

Project background

Introduction

There have been a vast number of studies to determine rock mass properties, especially those related to the strength and fracture systems, by means of instrumented drills. Among different methods of rock characterization, instrumented roof-bolter systems seem to be most favorable since, unlike the other methods, no additional operation is needed to characterize the ground surrounding the underground opening. Instead, while the boreholes are drilled for installation of roof/rib supports, the information is automatically recorded and analyzed to estimate rock properties. However, instrumented roof-bolters should use proper programs and pattern recognition systems that are trained under varied geological conditions to properly identify the joints and estimate rock strength values. In this chapter, the previous studies on the intelligent drilling systems are discussed and a brief explanation of rock mass rating systems with the focus on Coal Mine Roof Rating (CMRR) approach is offered.

Intelligent Drilling Systems

Several research groups have attempted to estimate the condition of the ground surrounding the underground structures. Studies by Itakara et al. [4]–[9], [22], [23], LaBelle et al. [24] and WVU research team are most notable [2], [11]–[17], [25]–[29] are good examples of such studies. Based on the literature, so far, four real-time rock characterization systems have been developed and tested. These systems were developed by Parvus Corporation (USA) in 1990 [30], Muroran Institute of Technology (Japan) in 1993 [6], Robotics Institute of Carnegie Mellon University [24]
and J. H. Fletcher & Company and West Virginia University in June 1999 [31]. A brief review of these studies are offered in the following sections.

**System Developed by Parvus Corporation**

The system developed by Parvus Corporation consists of a standard-sized roof bolter mounted on a mast, as shown in the Figure 2-1 [30]. The drill is powered by a portable hydraulic power pack. A hydraulic cylinder applies thrust to the drill head. Direction and flow control valves can be used for manual control or the drill can be controlled from a personal computer. The automatic hydraulic system for the model drill was designed by Rory McLaren and Associates, built by Fluidics, instrumented by Parvus Corporation, and used by USBM, Spokane research center.

![Figure 2-1: Artist's sketch of the expert drill developed by Parvus Corporation [30].](image)

For the data acquisition, an external bus system was chosen that can communicate with almost any computer via a RS-232 port. The data acquisition and control hardware consists of an assortment of modules ranging from nodes, communication devices, direct I/O devices, and test
devices. These modules are grouped together into strings. The parvNET network, made by Parvus Corp. was selected as the heart of the communications system among data accumulating nodes, data processing nodes, and the PC.

The system had four data recorder to measure revolutions per minute (rpm) of the drill head, height of the drill head, and the hydraulic pressures used to rotate and raise the drill head. These four parameters were all that are needed to control rpm, thrust, and rate of penetration independently, and allow applied torque to be calculated. The signal from the rotating drill steel was detected and then amplified and converted to rpm by the tachometer module. The rpm sensing was done with a magnetically coupled field sensor that can detect the presence or absence of metal. The position of the drill-head was estimated from the string potentiometer. By attaching one end to the base of the bolter and the other end to the drill head, the height of the head could be determined. Penetration rate was then calculated by the multipurpose node as a function of the change of position over time. The hydraulic pressure differential across the motor was used to calculate drill torque. The torque applied to the drill head is calculated differentially across the input and output of the hydraulic spin unit using model EA PSIG pressure transducers. The hydraulic pressure differential across the cylinder was used to calculate the drill thrust using the same type of pressure transducers used to measure torque and by subtracting the output from the input pressures, the upward thrust of the drill head was determined.

Rotation rate and thrust were controlled on the PC acting as the master node. The user interacted with the parvNET system through a graphically oriented data acquisition (SCADA) program that runs in the foreground with the parvNET terminate-and-stay-resident (TSR) network controller in the background. A typical monitoring and control screen may include a block diagram of the system being monitored and controlled. Numbers, bar graphs, and trend plots provide a natural systems interaction environment. Information was transmitted to the network through the asynchronous converter/monitor node.
System Developed by Muroran Institute of Technology

Itakura et al. (1997) with the aid of Muroran Institute of Technology, also developed a mine roof characterization system by rock bolt drilling unit, which could measure the drilling parameters such as torque, thrust, revolution and stroke [6]. An Australian-made pneumatic portable roof bolter, Wombat L.P., was chosen for the laboratory and field tests. The thrust in proportion to leg air pressure changed according to the stroke because the leg was a telescopic structure with three stages. The maximum extended length was 3.8 m. Figure 2-2 shows a potentiometer and wire displacement transducer attached to the leg for stroke detection. A pressure transducer was also attached to the machine body to detect thrust. Strain gauges and a proximity switch, installed into the segment between the drilling rock and chuck, were used to detect torque and the revolution of the machine, respectively. The power for the bridge circuit and the strain data, which are proportional to the torque, were transmitted by electromagnetic coupling. All data are recorded on a removable memory card installed in a digital data-logger strapped to the machine handle.

Figure 2-2: Layout of prototype logging system and drill developed by the Muroran Institute of Technology [6].
After developing the data acquisition system for pneumatic roof bolter, Itakura (1998) designed and manufactured a new hardware system of mechanical data logging for hydraulic roof bolter [7]. This system could be used for most hydraulic drilling machines, because machine torque and thrust were detected by pressure transducers attached to the hydraulic control unit, and stroke and revolution monitored by a flow rate transducer for hydraulic fluid attached directly to the drill. The system was mounted on a Ram Track 2300N manufactured by CRAM Australia Pty., Ltd [7], [8]. Itakura et al., (2008) also instrumented a portable pneumatic drilling machine (Trussmaster 1 P/N TRUSS001-1828, Rambor Ltd.) to display changes of strata and crack distributions [9]. Figure 2-3 indicates the external view of the Trussmaster drilling machine with its built-in sensor for measuring the mechanical data while drilling. Four sensors were installed on the machine to detect torque, thrust, revolution, and stroke. A strain-gauge-type torque converter was used for measuring the torque. A proximity switch was used for the revolution measurements. A pressure sensor was used for thrust measurements. A wire-winder-type potentiometer was used for stroke measurement. The outputs of these measuring devices were amplified through an IS barrier amplifier circuit and recorded on a USB memory, with sampling time of 10 or 100 ms. The data logging system used in this system could function for more than 24 hr by on its rechargeable battery. The USB memory is water-proof, dust-proof, and exchangeable in the underground.
In the laboratory tests Itakura et al. (1997), after detecting the location of the discontinuities, classified the discontinuities into boundary layers, boundary separation, and cracks in rock [6]. This classification was carried out by comparing averaged torque values before and after the discontinuity point and variation patterns of torque data as shown in Figure 2-4. From the laboratory experiments it was found that the level of torque or thrust of a drilling machine reflected the differences in rock type, and the separation of strata and cracks appeared as a specific pattern in the log of torque/thrust ratio. The field tests in a coal mine indicated that the mechanical data logs reflected the geological structure and the perception of the machine operator. The neural network analysis was also applied to the operational data and the locations of discontinuities were successfully estimated by using the adaptive theory and simple back-propagation network sequentially. It was stated that pattern recognition using neural networks could not tell the difference between cracks and layer boundaries. A new data acquisition system was then developed, for the hydraulic roof bolters and the system was improved for the estimation of 3-D geo-structure of strata and the designing of rock bolting, and tested in some coal mines [7], [8]. Field experiments using the instrumented roof bolter showed that the hardware system could detect torque, thrust, revolution, and stroke of the machine, and software analyzes the mechanical data
log and display locations of discontinuities using the Neural Network techniques. It was explained that the system was able to estimate roof rock 3-D geo-structure for various rock types and discontinuity distribution in cases of a drill hole array arrangement in roof rock [9].

Figure 2-4: Typical patterns corresponding to discontinuities [7].

Moreover, Li and Itakura (2011a, 2011b) proposed an analytical model to describe rock drilling processes using drag bits and rotary drills, and to induce relations among rock properties, bit shapes, and drilling parameters (rotary speed, thrust, torque, and stroke) [23], [32]. In the model, a drilling process was divided into successive cycles. Each cycle included two motions: feed and cutting. According to the model, drilling torque includes four components generated from cutting, friction, feed, and idle running respectively, the first three items are all proportional to the uniaxial compressive strength (UCS) when the penetration rate is constant. Laboratory tests verified the correctness and effectiveness of the proposed model qualitatively. Especially, the influence of friction on the flank face and the idle running was confirmed. Field experiments using a portable intelligent drilling machine showed good correlation between the torque, penetration rate, and UCS. The proposed model and equations demonstrated the possibility of eliminating useless components
of cutting forces when investigating the relation between mechanical data and physical properties of rocks. Li and Itakura (2012) proposed an in-situ method of evaluating UCS of rocks using specific energy, based on an analytical model of drilling processes [33]. They showed that the laboratory experiments verified the analytical model. Using the data obtained from a field experiment using an intelligent drilling machine, a regression equation was inferred, showing a good relation between UCS and the effective specific energy. To verify this prediction method, another field experiment was performed. The results showed that the uniaxial compressive strength of the rocks could be predicted reliably from the effective specific energy.

System Developed by Robotics Institute of Carnegie Mellon University

The other intelligent drilling apparatus was designed and built by Robotics Institute of Carnegie Mellon University which consists of a portable, hydraulically-powered, manually-operated, water-cooled coal mine drill, instrumented with proper sensors, data acquisition, and a laptop computer (Figure 2-5). The electronic hardware of system is isolated from the drill so that it can operate in a real mine environment. The data acquisition system was in a waterproof box, with one cable running to the sensors and another cable connecting to the laptop which can be taken several feet away from the actual drilling site [24].
The drilling parameters which are recorded were torque, thrust, rotary speed, hydraulic pressures and drill position. A highly accurate six-axis, decoupled force-torque sensor was connected in-line between the drill motor and the drill carriage. Hydraulic pressures of the thrust and rotation motors inlet and outlet were recorded. This is a redundant sensing scheme because motor pressures were proportional to thrust and torque. The sensors were installed for the purpose of assessing the feasibility of measuring thrust and torque values from less expensive sensors that were more appropriate for a real world drilling system. The rotary speed was measured using a magnetic sensor and a collar with 4 embedded magnets attached to the spinning drill chuck. The linear and rotary movement of drilling is controlled manually while the computer controls the data acquisition. The thrust motor valve was held fully open, while a hydraulic restrictor valve was used to keep the flow rate at certain value, with the goal of keeping the penetration rate as constant as possible. The rotation motor valve was fully open, but the flow was not controlled so rotary speed varied with the load on the system. To keep the drill hole as clean as possible from drill fines, the

Figure 2-5: The intelligent drilling system developed by the Robotics Institute of Carnegie Mellon University [24].
flushing water was set to full-flow each time a hole was drilled, the reason being to keep the drilling energy at a constant minimum as much as possible.

LaBelle et al. (2000) and LaBelle (2001) methodology 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 the sensors over time [24], [34]. In their study, five different layers of concrete were successfully classified using the sensors attached to the drill. Figure 2-6 shows an example of sensor data recorded while drilling a hole through five layers of concrete. The experiments using the collapsed data from the concrete test block were performed primarily to test whether or not a neural network could even classify materials using drill parameters in a very simple format. These results suggested that drill parameters could be used to classify rock strata with a trained network, and that using the additional features derived from the drilling parameters. Since the main purpose of the research was to classify the coal mine strata in real-time, ten preliminary field experiments were performed with the hand-labeled data files, using 4 different attribute sets to train a neural network to classify the materials. The coal and shale could not be accurately classified in most of these preliminary field experiments. It was stated that an accurate assessment of classifying mine data would only be possible when a required number of data sets were used for training of the system.
This feedback control system was first developed by Structured Mining System, Inc. and J. H. Fletcher & Co. in 1998. This system can be controlled automatically after selecting the preset drilling parameters. The major reason for developing this system was to improve drilling consistency and bit life. The system was then improved in cooperation with West Virginia University. The improved controls were result of the closed control loops for the feed and rotation. The sensors (such as thrust, torque, and position sensors) input information to the controller where the condition statements and subroutines acted on the information to regulate the output to the control valve solenoids. The control system on the mast feed machines accepted information from a feed force cell located in the drill head trunnion, a rotation rate counter located in the drill head, and a vacuum transducer located on the valve mount tray [2], [31]. The system was designed to record the drilling parameters of thrust, rotational velocity, torque, and penetration rate. The thrust and rotational velocity were direct measurements, while the torque and penetration rate were
indirect. The thrust was determined from the hydraulic pressure inside the cylinders that apply the axial load. The rotational velocity was measured using an electronic tachometer attached directly to the drill mast. The torque was determined by measuring the hydraulic pressure and flow in the hydraulic motor that provides rotational force. The penetration rate was determined from an axial velocity sensor. The drilling parameters were recorded every millisecond and the data was stored on an internal chip within the system housing [11]. The Feedback Control Station used on this unit has the following capabilities [2].

- It can directly monitor the drilling parameters, such as feed force, penetration rate, rotation rate, drill bit position, and vacuum condition.
- All the parameters (i.e. thrust cap, penetration rate, and rotation rate) can be preset.
- The approximate sampling interval is 0.1 seconds.

Figure 2-7 and Figure 2-8 show the J.H. Fletcher & Co.’s model HDDR walk-thru type dual head roof bolter and drill control unit. This system allows the operator to preset the penetration rate, rotation rate, and the maximum feed pressure 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. Data collection system was originally designed for controlling roof bolter automatically so that overall drilling and bolting consistency can be improved. Drilling parameters are recorded every 100 milliseconds so a 54-in long hole will have 250 to 850 records, depending on the penetration rate and the condition of roof geology. The drilling parameters collecting system is designed to collect 17 or 15 drilling parameters. 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 speed. These drilling parameters are collected in terms of sensor output in voltages and then converted to
dimensionless numbers ranging from 0 to 4095 for feed and rotation flow, and from 0 to 255 for others since the resolutions of A/D converter are 12 bits and 8 bits, respectively. All drilling parameters are collected and stored by a notebook PC into ASCII files [13].

Figure 2-7: J.H. Fletcher & Co.’s HDDR dual head roof bolter [13].
In the research conducted by West Virginia University and J.H. Fletcher & Co. variation of thrust or feed pressure had been found to be the most suitable identifier of discontinuities [2], [11]–[14], [16], [17],[35]. For example, Finfinger (2003) proposed a thrust valley concept by which the presence and the size of discontinuities, such as fractures, joints, and voids in the rock, can be evaluated. 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 [11]. 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 inches of the actual locations. This system was further developed by Gu (2003, 2005) with the introduction of the drilling hardness (DH) parameter [2], [36]. 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 were used to determine the location of discontinuities and interfaces. Discontinuities were 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, Gu (2003) mentioned that, in one mine site, only 25.86% of the discontinuities were detected by DH method within an acceptable error window [2]. He explains that this failure stemmed from the fact that the rocks encountered were not weak enough to be detected by the DH slope approach. More recent studies show that the feed pressure is the most indicative parameter for identifying discontinuities, provided that the penetration and rotation rates are constant or under control [13]. Tang developed a method that is able to detect fractures with an aperture of 1/8 inch or larger [13], [17], [25], [27], [29]. However, this approach was found to be somewhat ineffective for discontinuities of 1/16-inch aperture or smaller. Moreover, the accuracy of the drilling parameters recorded by the available system was insufficient to determine the size of discontinuities smaller than 1/2 inch. The research team also developed a software package, MRGIS (Mine Roof Geology Information System), to better manage the large amount of measured data, interpret and visualize it.

Although the instrumented system has been improved to a great extent, there are still some inaccuracies in detecting the location and, especially, the size of discontinuities. Collins, et al. (2004) explained that some 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 [26]. It was found 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. Meanwhile, the thrust did not have a consistent reaction. New theories were developed later to
describe the observed trends. Another problem was reported by Anderson and Prosser (2007), in which the hairline and vertical cracks along with layers of the rocks were not correctly identified [37]. Moreover, as mentioned before, Tang (2006) elaborated that the applicability of the developed system is limited to voids with size of 1/8 inch or larger [13].

Ground Characterization for rock mass classification systems

As mentioned at the introduction, the geological reports are qualitative and laboratory tests give limited, small-scale information about the rock mass competency [3]. As a result, rock mass classification systems, most renown ones such as Deere’s Rock Quality Designation (RQD), Bieniawski’s Rock Mass Rating (RMR) and Barton’s Q-system, have been developed [38]–[40]. These systems were successful and widely used because they:

- Provide a methodology for characterizing rock mass strength using simple measurements;
- Allow geologic information to be converted into quantitative engineering data;
- Enable better communication between geologists and engineers; and
- Make it possible to compare ground control experiences between sites, even when the geologic conditions are very different [41].

However, these conventional rock mass classification systems are not completely suitable for special applications such a coal mine stability analysis, which is the main focus in this research project. This is because:

- They tend to focus on the properties of joints, whereas bedding is generally the most significant discontinuity affecting coal mine roof.
- They rate just one rock unit at a time, whereas coal mine roof often consists of several layers bound together by roof bolts.
- The dimensions and stability requirements of tunnels are often very different from those of mines [1].

Therefore, in 1994 the Bureau of Mines (USBM) developed Coal Mine Roof Rating system, CMRR; [3], to eliminate the above mentioned shortcomings. CMRR evaluates the structural competency of mine roof using simple field tests and observations, which are obtained from underground exposures in roof falls or overcasts. The basis of the CMRR is a weighing system, which converts descriptive geologic roof rock data to a numerical value [42], [43]. The CMRR considers six parameters in determining the unit rating: (1) Compressive strength of intact rock, (2) discontinuity cohesion, (3) discontinuity spacing, (4) discontinuity roughness, (5) discontinuity persistence, and (6) moisture sensitivity. Figure 2.9, illustrate these parameters for cross section of an opening.

![Components of the CMRR system](image)

**Figure 2.9:** Components of the CMRR system [43].

A disadvantage of the CMRR is that it cannot be determined in advance of mining, because it requires underground observations. Therefore, Mark and Molinda (1996) developed a methodology for the assessment of CMRR from drill cores to help for the areas, where the underground exposures are not available [44]. This procedure was revised and simplified in 2002.
by Mark et al [45]. In the revised version of CMRR, just three types of information are required: (1) Unconfined compressive strength, (2) fracture spacing, and (3) diametral Point Load (an index of bedding plane shear strength). Subsequently, the CMRR was implemented in a computer program facilitating calculation of the CMRR from either underground or drillcore data [46]. The CMRR has become truly international, with involvement in mine designs and funded research projects in South Africa, Canada, and Australia. Worldwide experience has shown that the CMRR is a reliable, meaningful, and repeatable measure of roof quality [47].

The final rating score of the CMRR for the quality of rock mass is in the range of 0-100, which has a similar cumulative rating system as the Bieniawski’s RMR [1]. Classification of rock mass, i.e. weak, moderate and strong, based on CMRR is summarized in Table 2-1. This table also gives an example of geological condition for each of these classes. CMRR correlates the stability of the rock mass to the discontinuities rather than the strength of the intact rock [43]. This system unlike other rock mass classifications, which just rate one unit at a time, gives a rate for all the layers within the drilled interval at the mine roof/rib [48]. The diagram in Figure 2-10, depicts the new CMRR rating procedure for drill cores and the range of score corresponding to each parameter.

Table 2-1: CMRR classes in the U.S. [48].

<table>
<thead>
<tr>
<th>CMRR Class</th>
<th>CMRR Region</th>
<th>Geological Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weak</td>
<td>0 – 45</td>
<td>Claystones, Mudrocks, Shales</td>
</tr>
<tr>
<td>Moderate</td>
<td>45 – 65</td>
<td>Siltstones and Sandstones</td>
</tr>
<tr>
<td>Strong</td>
<td>65 – 100</td>
<td>Sandstones</td>
</tr>
</tbody>
</table>
This diagram shows that the Uniaxial Compressive Strength (UCS) and the discontinuity condition have the dominant impact on the final score. This matter can be observed in other rock mass rating systems as well, since these two factors play the major role in rock mass behavior. As a result, in this research study the focus is on these two parameters and finding the best method to provide the closest estimates to the reality.

**Conclusion**

The literature review presented in this chapter shows that there are promising evidences, which make reaching to a reliable instrumented drilling machine more convincible. However, there is still a long way to go to accomplish this goal and, as mentioned before, this path inevitably passes
through the extensive field experiments and evaluation of the smart machine outcomes. This evaluation is performed based on the actual condition of the rock mass that is drilled through. Compared to the conventional exploration methods, we believe that borehole probing (logging) is in a number of aspects an efficient approach that can simplifies the rock characterization inside the drilled boreholes. As a result, in chapter 3 different borehole probing technics are discussed. Subsequently, in chapter 4 based on the CMRR rock characterization components, mainly the UCS and discontinuity condition, the suitable borehole probing technics are introduced and in the next step, considering the borehole environment, appropriate tools are selected.
Chapter 3

Ground characterization based on borehole logging data

Introduction

As explained earlier, further development of the MWD systems depends on extensive field tests and how fast and accurate the properties of rock mass inside the drillholes can be examined. Borehole probing (logging) is an effective way to address this issue. Borehole logging or well logging is the practice of recording continuous information on some physical properties of rocks in the bore hole [49]. Well logging is one of the geophysical approaches, which is commonly used in boreholes drilled for oil, gas, groundwater, minerals, geothermal, environmental and for mining applications. There are many different logging methods namely electric, radiation, sonic and acoustic, and optical. Each of these methods consist of various sub-groups to measure a target physical parameter in a particular situation, e.g. lateral resistivity, neutron and gamma absorption, caliper measurement, TV logs and sonic or acoustic televiwers. While well logging in oil industry utilizes probes with relatively large size and in long vertical holes filled with water/oil based mud, in civil, environmental and mining operations slimmer and shorter devices should be used to log the boreholes. In almost all of these cases, the logging operation is conducted inside downhole wellbores, which are usually filled with kind of conductive fluid. In this project, however, even slimmer and lighter probes are needed to be used in the boreholes, which are typically about 25 mm (1 inch) in diameter, about 2-3 m (6-10 ft) long. These holes are often dry due to their upward direction.

In the first section this chapter, downhole wellbore logging methods suitable to determine rock mass properties is briefly reviewed. This is followed by a short introduction for applications
of borehole logging in mining industry. These methods have been employed commonly in this field to estimate different properties of the rock mass, especially the strength [18], [19]. Also, borehole televiewers and cameras are often used to take a picture of the borehole wall to detect discontinuities [20], [21].

Recently, mining research groups have tried to go even one step further and use a number of simple borehole probing methods/tools for rock mass rating. This system can simplify and accelerate the procedure of rock mass rating and minimizes the errors, which are related to variation of personal judgments. This is particularly important for this project, since one of the main goals of those research studies is also rock characterization in a fast and reliable way. In addition, similar to this project these efforts, are towards rock mass rating by systems such as CMRR. Therefore, a significant attention is paid to this literature and they are summarized in section three of this chapter.

Finally, in section four the attempts of West Virginia University (WVU) to characterize the rock mass in the field, is briefly explained. Apparently, coring was the major method of field test verification and the only borehole probe used in that project was a simple borehole camera system [2], [13].

**Downhole borehole or well logging**

As mentioned, Borehole logging is employed in different fields and directly or indirectly measures rock properties based on changes in their physical feature(s). Some of the major methods of borehole logging are mentioned Table 3-1 in through Table 3-4. Each logging operation generally employs the following equipment:

1. Probe (or sonde)
2. Armored, multi-conductor electric cable
3. Winch and mast or tripod
4. Calibrated sheave
5. Surface power unit
6. Electric recording system

Figure 2-1 schematically shows some of the above mentioned parts. This figure shows the setting required typically for normal electric logging. Sheave in logging operations is not only useful to move the probe along the hole but also to measure the depth of the probe in the hole. For small operations like what is shown in Figure 2-1 a tripod is sufficient; however, for large operations mast is the suitable option.

Figure 3-1: Different tools needed for a borehole logging operation [49]
Table 3-1: Some of the main electric logs and their features.

<table>
<thead>
<tr>
<th>No.</th>
<th>Method</th>
<th>Property measured</th>
<th>Governor</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>single point</td>
<td></td>
<td></td>
<td>1. Stratigraphic control purposes (true and invaded zones resistivity).</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2. Estimate the porosity of the porous, permeable zones. (under circumstances)</td>
</tr>
<tr>
<td>2</td>
<td>normal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>lateral</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Micro</td>
<td>electrical resistivity of the formation</td>
<td>1. Presence and salinity of the interstitial water.</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2. Size of interstices</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Focused-current</td>
<td></td>
<td></td>
<td>1. Locate and delineate porous, permeable beds.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2. Estimate the porosity of these beds.</td>
</tr>
<tr>
<td>6</td>
<td>SP</td>
<td>spontaneous potential existing within the borehole</td>
<td>salinity difference between borehole fluid and the fluid saturated the adjacent formation</td>
<td>Indications of the permeable beds.</td>
</tr>
<tr>
<td>7</td>
<td>induction</td>
<td>electrical Conductivity of the formation</td>
<td></td>
<td>Presence of fractures in crystalline rocks (low porosity) – thin low resistivity logs. (true resistivity of the formation)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>- The bed definition is good when the formation thickness is greater than the spacing between the main transmitter and receiver coils.</td>
</tr>
</tbody>
</table>
Table 3-2: Some of the main radiation logs and their features.

<table>
<thead>
<tr>
<th>No.</th>
<th>Method</th>
<th>Property measured</th>
<th>Governor</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>natural gamma</td>
<td>The natural radioactivity of the formation</td>
<td>Radioactive elements in rock particularly in shale, clays and acidic volcanic rocks.</td>
<td>Stratigraphic control purposes, shale and clay content of the sedimentary formations and discontinuities.</td>
</tr>
<tr>
<td>2</td>
<td>neutron</td>
<td>Formation reaction to Neutrons and Gamma bombardment</td>
<td>the concentration of Hydrogen nuclei</td>
<td>1. Good indication of porosity. (In water- or hydrocarbon-saturated porous formations, where disseminated clay minerals are absent)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2. Under certain circumstances can estimate the strength of the crystalline rocks. (along with electric logs)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>3. When used in combination with the gamma-ray log, the neutron log provides a means for identifying lithologies and for obtaining the porosities of porous zones.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>4. In combination with the density or acoustic logs, the neutron log can also be used to indicate the presence and degree of fracturing in crystalline rocks.</td>
</tr>
<tr>
<td>3</td>
<td>gamma-gamma density</td>
<td>the electrons and hence the back-scattered gamma rays</td>
<td></td>
<td>1. Bulk density measurement, Inversely proportional to the bulk density of the formation.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2. Mechanical properties of rock mass like strength and deformability? (along with sonic logs)</td>
</tr>
</tbody>
</table>
Table 3-3: Some of the main sonic-acoustic logs and their features.

<table>
<thead>
<tr>
<th>No.</th>
<th>Method</th>
<th>Property measured</th>
<th>Governor</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sonic</td>
<td>Propagation velocity of the elastic</td>
<td>Mechanical properties and degree of fracturing.</td>
<td>Estimate the mechanical properties of rock mass, strength, deformability and</td>
</tr>
<tr>
<td></td>
<td></td>
<td>compressional waves (sometimes shear</td>
<td></td>
<td>etc., and degree of fracturing.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>waves as well)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Televiewer</td>
<td>Amplitude of the ultra-sonic waves</td>
<td>smoothness of the wall and the intersected</td>
<td>The borehole wall picture and indication of intersected discontinuities.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>reflected from the well wall</td>
<td>discontinuities</td>
<td></td>
</tr>
</tbody>
</table>

Table 3-4: Some of the miscellaneous logs and their features.

<table>
<thead>
<tr>
<th>No.</th>
<th>Method</th>
<th>Property measured /Governor</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>caliper</td>
<td>the average diameter of the hole and in some cases the fractures</td>
<td>1. Correct the results of other logs sensitive to borehole diameter changes.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2. Changes in lithology or fracture detection.</td>
</tr>
<tr>
<td>2</td>
<td>temperature</td>
<td>The temp. Of the borehole fluid</td>
<td>Temperature of fluid and adjacent formation for future calculations.</td>
</tr>
<tr>
<td>3</td>
<td>Directional survey</td>
<td>dip and dip direction of the borehole</td>
<td>Determining the dip and dip direction of the borehole and the intersected discontinuities.</td>
</tr>
<tr>
<td>4</td>
<td>Dipmeter</td>
<td>dip and dip direction of the intersected discontinuities</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>inclinometer</td>
<td>the deviation of the borehole</td>
<td>Inclinometer, relative dip and caliper: formation dip and azimuth</td>
</tr>
<tr>
<td>6</td>
<td>TV logs (OPTV)</td>
<td>picture of the borehole wall</td>
<td>1. Picture of the log, lithology changes, fracture detection and etc.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>2. Best for clear water-filled and air-filled boreholes</td>
</tr>
</tbody>
</table>
Table 3-5 compares cost, time requirement, and the difficulty of operation among some logging approaches in addition to the purpose of logging and the measured property. In this table, “1” indicates least expensive, time consuming or difficult, for example acoustic televiewer is one of the most expensive, time consuming and difficult methods while methods like caliper and resistivity are among the least expensive, time consuming and difficult operations.

Table 3-5: Relative comparison of cost, time and difficulty among some logging methods (USGS website).

<table>
<thead>
<tr>
<th>No.</th>
<th>Method</th>
<th>Purpose</th>
<th>Property measured</th>
<th>Cost</th>
<th>Time</th>
<th>Difficulty</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Caliper</td>
<td>Generate continuous profile of borehole diameter</td>
<td>Borehole diameter</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>Single-point resistance</td>
<td>Delineate changes in lithology, porosity, and (or) clay content of surrounding formation or changes in porosity and total dissolved solids in the formation water</td>
<td>Resistance of formation, fluids in formation, and borehole fluids</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Normal resistivity</td>
<td>Determine changes in resistivity of the fluids in the formation and (or) lithology</td>
<td>Resistivity of the formation; with additional data, true resistivity can be calculated</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>Electromagnetic Induction</td>
<td>Delineate changes in rock type or in electrical properties of fluids in the rock formation; corroborate surface resistivity surveys</td>
<td>Bulk apparent conductivity of the formation and pore fluids surrounding the borehole</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>Fluid resistivity</td>
<td>Identify differences in concentration of total dissolved solids in borehole fluid; these differences typically indicate sources of water that have come from different transmissive zones</td>
<td>Electrical resistivity of borehole fluid, from which specific conductance is calculated</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>6</td>
<td>Fluid temperature</td>
<td>Identify where water enters or exits the borehole</td>
<td>Temperature of borehole fluid; differential temperature (rate of change of the...)</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>
Borehole logging in Mining

Many researchers have studied geophysical methods in order to be able to estimate different properties of the rock mass, including strength and discontinuity, which are the main rock features in general and specifically in this study. In this section, the findings of researchers for estimation of rock strength and applications of borescope is discussed.

3.3.1. Rock Strength estimation by borehole logging

Carroll (1966 and 1968) investigated the relations between rock strength and sonic velocity or interval transit time [50], [51]. He found exponential correlations between both uniaxial

| 7 | Heat-pulse, electromagnetic, and spinner flowmeter | Map fluid flow regime and transmissive fractures in the borehole | Direction and magnitude of vertical flow within the borehole | 3 | 3 | 3 |
| 8 | Camera | Characterize rock type, identify changes in rock type and small-scale geologic structures, locate and describe fractures, describe borehole construction, and identify problems with borehole integrity and (or) possible signs of contamination | Visual fish-eye view and side-looking view of borehole | 2 | 2 | 2 |
| 9 | Acoustic televiewer | Map location and orientation of fractures intersecting borehole and generate a high-resolution acoustic-caliper log | Amplitude and travel time of the reflected acoustic signal | 3 | 3 | 3 |
| 10 | Deviation | Three-dimensional geometry of the borehole | Azimuthal direction and the inclination of the borehole | 2 | 2 | 2 |
compressive strength (UCS) and elastic modulus, with sonic velocity in volcanic and volcano-clastic rocks.

British researchers have studied the relation between rock strength and N-N log response in coal measures rocks [52], [53]. They found a correlation between neutron porosity and strength indices such as the point load test and the NCB core indenter.

McNally (1987) reported the study of downhole geophysical logs, particularly neutron-neutron and sonic, for estimating the overburden strength at ten mine sites in Australia [54]. Empirical relations for estimating UCS from neutron and sonic log responses were developed in his study. It was stated that high resolution sonic logging tools were proved to be the most useful. However, neutron logs might be relatively more capable in indicating the strength variations in massive strata. Neither of the tools could identify the joints very well, although fractures sometimes showed up as cycle skips on the sonic log. McNally (1990) also explained the results of his extended studies in another paper [55]. He showed that static elastic modulus could be correlated with both sonic and neutron response, however, the sonic correlation was more reliable. In neither cases, the correlation was as good for UCS. Moreover, he found a poor correlation between the indirect tensile strength and sonic transit time.

Payne and Ward (2002), explained the strata management studies in weak roof conditions at Crinum Mine [56]. In this study, strata were interpreted into Geomechanical units using the sonic velocity logs, which makes it possible to identify similar zones across the mine. They stated that systematic evaluation of sonic logs can provide a general understanding of the variation in roof strength. As a result, areas of concern can be determined to provide the basis for delineation of roof support categories.

Zhou et al. (2005) proposed two approaches based on the Radial Basis Function (RBF) and Self Organizing Maps (SOM) methods to estimate rock strength from the specialist nuclear SIROLOG (spectrometric natural gamma, Prompt Gamma Neutron Activation) tool [18]. Unlike
other methods, such as McNally (1987)'s approach, the RBF and SOM methods did not depend on any pre-existing assumptions or models. They used both the specialist SIROLOG and conventional geophysical logging data from the Newlands Mine (Collinsville) to demonstrate the effectiveness of the SOM and RBF algorithms to estimate the UCS. Promising results were reported from both RBF and SOM algorithms, which indicates the viability of these new methods for estimating rock strength from geophysical logs.

Bajpayee et al. (2008) discussed the applications of micro-seismic systems to monitor roof stability in a large underground stone mine in Center County, Pennsylvania [57]. The system using triaxial geophones in surface boreholes detected the first rock fracture event 17 minutes before the rock fall happens. It was stated that the geophone array was sensitive enough to identify all large rock fracture, impact, and blast events as well as medium-size rock fracture events occurring close to the geophone array.

Oyler et al. (2010) described a research recently conducted by NIOSH to demonstrate that the logging tools and techniques available in the US could be used to obtain an equation similar to the one developed by McNally (1987), which is commonly considered acceptable in Australian practice [19]. In order to have a broad range of coal measure rock types, seven boreholes in five states were drilled by diamond coring machine and logged by a sonic instrument. Two of these boreholes were located in Illinois, two in Pennsylvania, and one borehole in Colorado, western Kentucky and southern West Virginia states. Subsequently, the sonic velocity logs were compared with UCS values obtained from Point Load tests. Considering the entire dataset, an exponential equation with correlation coefficient of 0.72 was proposed to estimate the UCS by means of sonic travel time data. This relatively high coefficient of determination can ensure the reliability of the outcomes, which can be helpful for design/revision of roof support systems. The paper also addressed the steps that were necessary to ensure that the obtained sonic logs are of high-quality for use in estimation of UCS values.
Applications of borehole TVs in mining

Thomas (1966) was one of the first people who tried to take a picture of borehole wall [58]. He used a type of periscope called introscope to examine short boreholes in an underground space for use in British collieries. Before 1970, the U.S. Bureau of Mines started to frequently survey boreholes to examine the geometry (spacing, orientation, and aperture) of fractures in underground mines [59]. The earlier borescopes had a rigid configuration that required a borehole diameter larger than diameter of roof bolt holes. In addition, due to the rigidity of the borescope, the hole had to be straight, undeformed, and constant in diameter. At the end of 1970s, the U.S. Bureau of Mines developed a fiberoptic flexible stratascope. Field testing in both metal and coal mines indicated that the developed instrument could be easily transported and be used by a single operator. The size and flexibility of the instrument eliminated the need for drilling larger holes [60].

Tennant (1982) discussed a borescope application at Martinka Mine of Southern Ohio Coal Company [61]. He stated that borescope wasn't a cure-all to roof control problems, but it assisted with improving roof control, especially for longwall panels. Shepherd et al. (1986) explained the results of borescope studies performed by Australian Coal Industry Research Laboratories [62]. He concluded that the borescope technique was very useful in evaluation of ground stability for ahead of advancing faces, in addition to the advancing face itself and back-bye in longwall gate roads. Unrug (1994) described a method for a realistic design of strata support systems with emphasis on their application for longwall mines. This approach is based on the borescoping and measurement of rock in situ strength [63]. Unrug also mentioned that identification of certain rock layers and roof mapping by means of borescope is of primary importance to determine the length of rockbolt. He also suggested to employ this method to design secondary reinforcement for the entries that are under abutment pressure. On the other hand, these tools can also be used for optimization of ground support. Ellenberger (2009) stated that borehole cameras and gamma ray, sonic, or acoustic logging
tools have recently been used in the roof holes for identification of rock types, fractures and formation boundaries [20]. However, he states that the borescopes are relatively easy to use and can be operated with little training. An engineer or geologist should be able to easily recognize features in the roof using a borescope. Since there are relatively few features that can be observed in the boreholes, virtually any interested party can be trained to operate the borescope.

**Ground characterization by borehole probing systems**

The studies discussed in the previous section are mostly focused on measurement of one specific property of the rock mass. Although, each of these parameters are valuable and important to determine, they are not able to give a comprehensive view of the rock mass in a relatively large scale. Therefore, different approaches and methods were developed by researchers to classify the surrounding ground of underground mines. This variety spans from simple borehole probes such as borescope [20], [64], [65] to more sophisticated geophysical probes such as sonic, gamma and etc. [66]–[70] (Medhurst and Hatherly (2005); Hatherly et al. (2007, 2008, 2009), Bajpayee and Schilling (2009)).

Majcherczyk et al. (2005) and Malkowski et al. (2008) presented a method for rock mass quality, called as Endoscopic Rock Mass Factor (ERMF), which is based on the endoscopic observations of boreholes [64], [65]. In this method, five different properties of fractures are measured: Number of fractures, total separation, range of fracture zone, number of fracture zones, and type of fracture. The ERMF makes it possible to have a quantitative and qualitative estimation for the number and size of fractures that exist or develop around the underground roadways. The method was compared to the commonly known rock mass classification methods such as RMR, RQD and Q. From this comparison, it was concluded that ERMF suitable for evaluation of rock mass quality.
National Institute for Occupational Safety and Health (NIOSH) also developed the Roof Fall Risk Index (RFRI) as a tool for systematically identifying and predicting roof fall hazards in operating mines [71]–[74]. The borescopes are commonly used in determination of vertical strata separation in this method. The RFRI focuses on the character and intensity of defects, which are caused by a wide range of local geologic, mining and stress factors and is equated directly to changing roof conditions that can lead to roof fall hazards. The procedure for measurement of RFRI is based on the determined values of defect categories and their respective weights. The major classifications for computation of RFRI are (a) geologic factors, (b) mining-induced failures, (c) roof profile, and (d) ground water influx. A significant range of defects found at underground stone mines are classified into 10 categories (known as defect categories), each of which is assigned to an assessment value. The total rating varies from 0 to 100, with values approaching zero representing safer roof conditions, while an RFRI approaching 100 represents a serious roof fall hazard. It was claimed that this method produces a more comprehensive assessment of roof condition alteration than was previously possible. Esterhuizen et al. (2007) reviewed and evaluated the monitoring and observational technologies that are used in 34 underground limestone mining operations in the Eastern and Midwestern U.S. as well as methods of assessing potentially unstable roof conditions [75]. They concluded that technologies such as RFRI, automated drill recording, displacement and micro-seismic monitoring could assist mine personnel in identifying and monitoring roof conditions as part of a comprehensive ground control management plan. Bajpayee and Schilling (2009) presented the application of an integrated RFRI mapping technique that provides a convenient way of plotting comprehensive color-coded RFRI maps [70]. RFRI maps help to identify areas of potential roof instability. They integrated the field observations at the test mine with RFRI mapping software, which was developed by West Virginia University. The system was designed to combine field study data related to geologic factors, mining-induced damages, roof profile, and ground water influx to generate RFRI maps.
A Roof Quality Index was developed to identify the roof control using the borescope data from 34 stone mines in USA [20]. Roof holes at 13 stone mines in six states were scoped. A total of 71 holes were logged, consisting of over 700 feet of hole. Considering the overall amount of hole length examined, the features observed on a regular basis were relatively few. Stylolites, partings, contacts and cracks (later split into closed or open cracks) constituted nearly all of the features observed. As mentioned in this paper, NIOSH plans to incorporate the borescoping assessment into a Roof Fall Risk Assessment procedure that will be used to assist in design of spans in underground stone mines.

In an interesting and inspiring paper, Medhurst and Hatherly (2005) described the results from the studies that had provided a more comprehensive method of geotechnical strata characterization [66]. In this research, borehole logging data is utilized to obtain detailed lithological interpretations and to estimate properties of clastic strata, which are typical in coal mining regions. They used porosity and the proportions of quartz and clay content to develop an advanced method for prediction of rock strength. They also proposed a rock classification scheme, Geophysical Strata Rating (GSR), based on geophysical log analysis. The GSR takes into consideration the bedding features and intact rock characteristics such as porosity, cohesion, quartz and clay content. A good correlation was also found between the GSR and the Coal Mine Roof Rating (CMRR). Hatherly et al. (2007) further developed the GSR by including the fracture score and provided the examples of its application [67]. It is claimed that the GSR was objective, repeatable, inexpensive to conduct, and representative of the state of the rocks as they were in the ground. Furthermore, Hatherly et al. (2008) introduced a means of converting acoustic impedance to the GSR [68]. Acoustic impedances have values that are meaningful to coal mine engineers, when expressed in terms of GSR. Hatherly et al. (2009) and Medhurst et al. (2010) presented the applications of the GSR at Crinum Mine and Bowen Basin underground operations. They
concluded that the GSR analysis was able to identify subtle changes of strata characteristics that could often be associated with strata control management issues [76], [77].

**Borehole probing systems for smart roofbolter training**

Unlike these studies that most of the logging operations are done in downhole boreholes, except studies on borescoping, in this project logging of the upward boreholes which are primarily dry are required. This is an issue that should be solved in order to pave the way for further investigation of borehole logging applications for training of the instrumented roof bolter. No paper was found that exactly addressed the above mentioned issues especially for estimation of rock strength.

To characterize the strata along a borehole for training of an intelligent roof bolter, the a fast and effective borehole probing system should be identified and developed. During WVU studies limited attempts were made to employ borehole probing methods to verify the validity of the field results from the instrumented roof bolter. Gu (2003) and Tang (2006), mentioned the application of a simple borescope system, which was used in addition to coring to verify the rock units along the hole [2], [13]. The borescope offers a limited view of the borehole wall. As a result, the measured position of voids and separations is only a rough estimate, while this project requires relatively accurate and reliable tools to get the full picture of actual condition.
Figure 3-2: Borescope device used in West Virginia University field tests for verification of instrumented roof bolter results [2].
Chapter 4

Selection of suitable borehole logging tools

Introduction

As noted earlier, to develop reliable instrumented roof bolters, an extensive number of field experiments had to be performed in various ground conditions. This was to have a reliable and accurate understanding of the in-situ condition of the ground drilled through during the tests by the smart roofbolter. Borehole logging can be an advantageous approach to measure the properties of the rock mass inside rockbolt or production drillholes. However, the very specific conditions of rockbolt boreholes make it significantly difficult to use the conventional logging or probing devices with the exception of the borecam. Rockbolt boreholes are slim (usually 1” or 1 3/8” in diameter), short (3-20 ft long), and upward. The conventional logging operations are often performed in larger diameter boreholes (at least 2”), which are also long and downhole. Having larger diameter borehole enables the operators to employ larger/more sophisticated instruments. This is also an advantage for the manufacturers so that they can have more space to accommodate the required components, which also means that they have more alternatives to choose from. The length of these downhole wells might exceed hundreds of meter, and as a result the length of the probe is usually not a limiting factor. The other feature of these holes is their downward orientation. This condition makes it possible to take advantage of the gravity to descend the probe into the ground. Moreover, the hole can be filled with a fluid (water/oil-based fluids) for a good conductivity with the ground. This feature is essential for the logging approaches that work based on the electrical conductivity properties of the ground, as well as those that work based on wave propagation from the probe to the strata. Therefore, these methods cannot be used in empty (air-filled) boreholes.
The aim of this project is to characterize the ground surrounding the drillholes based on CMRR rating system. Figure 4-1, shows the steps and parameters needed for the calculation of CMRR as well as the conventional logging methods that can be used to measure each parameters. As it can be seen, most of the parameters can be determined by sonic (acoustic) and Optical Televiewer (OPTV) methods.

As it can be seen, most of the parameters can be determined by sonic (acoustic) and Optical Televiewer (OPTV) methods.

Some of the parameters, such as diametrical Point Load test (PLT) and surcharge need more studies to determine which method is suitable for their estimation. In addition, a parameter like moisture sensitivity could be estimated by knowing the lithology of the rock mass, which could be done by simply recognizing the layers in a specific field by OPTV probe or by using more
sophisticated lithology detection probes such as gamma, and having a rough estimate of its water sensitivity based on clay content (or similar).

Another approach to estimate the moisture sensitivity is by measuring shale volume and porosity. Hetherly et al. (2007) presented a method to estimate this parameter [67]. The OPTV probe is mainly useful for getting the information related to geometry of the borehole, joint location and orientation, and rock layers. In addition, detection of the fractures and their orientation, and possibly their roughness, can be estimated by OPTV.

This device is chosen because it can be used in dry holes. However, it is possible that OPTV may not be able to identify all the fractures and bed separations in the roof of the coal mines which are usually consisted of dark and carbon rich formations. An alternative to that might be acoustic televiewer (also known as borehole TV); however, this technique like other sonic methods needs fluid inside the borehole and it is generally not very easy to be run. Caliper log, on the other hand, might be a good solution for this shortcoming. For estimation of rock strength, sonic log (mostly full-waveform) is the most commonly used method. This system needs to be run in fluid filled borehole as well. Filling the upward holes with a fluid is very complicated and needs to consider packers. Hence, the conventional sonic probes or acoustic televiewers are not applicable in this particular condition, a new method/tool needed to be developed. In this chapter, different borehole imaging tools are compared and the suitable probes for this application are introduced.

**Evaluating Discontinuities**

Condition of discontinuity is one of the main factors that control ground stability in underground space. There are methods which employ borescope or endoscope as the device for evaluation of the joints, voids, bedding planes, and other discontinuities [20], [64]. Figure 4-2 (a) shows a strata-scope. As it can be seen, this device is a simple monitoring tool for checking the
underground structures’ roof condition mainly to see if there is any fracture near the structure roof or if any fracture is initiated because of the mining operations. A more advanced tool with almost the same application is bore-scope. Different components of a bore-scope are shown in Figure 4-2 (b).

Bore-scope is different than strata-scope in that the picture of the borehole can be recorded for future reference. In some cases, it is also possible to record the operator voice to make the video more informative. This enables the operator to document at which depth a specific discontinuity is observed or simply mention the probing depth in arbitrary intervals, such as every half foot, as they operate it. Another feature is that the real-time picture can be seen in a LCD monitor. Both strata-scope and bore-scope are designed to be used in slim boreholes with the diameter of one inch or more. Also, one operator with a brief training can conduct all the operations and carry the equipment around. These tools are generally inexpensive. However, since these types of instruments provide a narrow directional, and not 360-degree image of borehole wall, they can be used for limited applications. It should also be highlighted that even if the recorded video was available for future evaluations, it is not convenient to review the information and compare the data from multiple boreholes. Furthermore, some features, such as hair cracks, cannot be detected easily with these tools.
Figure 4-3 shows two sample pictures from borescoping operation in R&D facilities of J.H. Fletcher & Co. in Huntington WV, taken as part of the current study on the instrumented roof bolter. The aim of this operation was to investigate the condition and location of the contact area between the concrete blocks, stacked on top of each other, and the rock blocks embedded inside the concrete block samples, after they are drilled by the roof bolter.

More advanced and therefore more expensive tools for borehole imaging are available and have been considered for our study. Borehole image probes provide images of the rock mass with resolution and coverage between what one can get from cores and 3D seismic operations. There
are three methods to get an image from the borehole wall which are resistivity, sonic, and optical. For each of these methods several products are manufactured by various companies across the world.

Figure 4-4 shows some of the common acoustic tools in oil and gas industry which are Circumferential Borehole Imaging Log™ (CBILTM) (Baker Atlas), Ultrasonic Borehole Imager (UBI) (Schlumberger) and Circumferential Acoustic Scanning Tool-Visualization (CAST-V™) (HALLIBURTON). These methods work based on Amplitude and travel time of the reflected acoustic signals. The obtained images are particularly suited to fracture and fault analysis. They can also be used for interpretation of the near-wellbore stress field from borehole breakouts and drilling-induced fractures. The transducer in this probe rotates to scan the entire circumference of the borehole wall, generating sharp images and boundary delineation. These devices don’t require contact with the borehole wall which make them quite effective in horizontal wells.

Figure 4-4: Different acoustic borehole imagers manufactured by Baker Atlas, Schlumberger and Halliburton companies.
Typical specifications of these tools are summarized in Figure 4-5. This figure shows the specifications of Cast-V tool manufactured by Halliburton. However, the other tools have almost the same geometrical features. As it can be seen, the smallest size of the probe is 92.1 mm [3.625 in] which is way larger than the typical diameter of rockbolt boreholes which are generally about 25 mm (1 in). Other factors such as the length and weight are also in appropriate for the small scale operation we are dealing with during this research study.

**Figure 4-5:** Specifications of Cast-V acoustic tool manufactured by Halliburton.

The other imaging method is electrical resistivity. Some of the common tools in petroleum industry is shown in Figure 4-6. These images can be used for differentiation of fracture types, near-wellbore stress field determination, sedimentary facies, and depositional environment interpretation. The sensor pads shown in the figure should necessarily be in a good contact with the borehole wall to provide a high quality image. Moreover, it is essential that the operation is performed in wellbore with water-base mud.
Typical requirements of these tools, Figure 4-7, are not compatible with the conditions of boreholes this study. Resistivity and acoustic methods are mainly useful when the wellbore fluid is not clear and the rock masses have got a dark color.

Figure 4-8 compares the image log obtained from typical wireline tools with that of a real-time probe like RAB (Resistivity-At-Bit) manufactured by Baker Atlas. The image obtained from the RAB has got low resolution; however, it is comparable with the wireline one.

Figure 4-6: Different Electrical resistivity borehole imagers manufactured by Baker Atlas, Schlumberger and Halliburton companies.

<table>
<thead>
<tr>
<th>Electrical Micro Imaging Service (EMI™) Specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Model</strong></td>
</tr>
<tr>
<td>-----------</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>EMI Tool Only</td>
</tr>
<tr>
<td>EMI Tool String</td>
</tr>
</tbody>
</table>
In summary, both resistivity and acoustic televiewers need some type of fluid inside the borehole. In resistivity logging it is essential that the operation is performed in wellbore with water-base mud. Acoustic methods work based on Amplitude and travel time of the reflected acoustic signals. Resistivity tools provide the image by means of the sensor pads, which record the resistivity difference between various strata along the borehole wall. Unlike the borescopes, these tools produce an unwrapped 360-degree picture, and not a video of the points on borehole wall; therefore, comparison of different logs is more convenient. The depth relative to the opening of the borehole is also recorded automatically. The orientation of boreholes can be determined by the built-in 3-axis magnetic compass and three accelerometers. However, all the aforementioned tools need a fluid inside the borehole, which is not a likely possibility for the rockbolt upward boreholes. Optical TVs (OPTVs) can be used in borehole filled with clear, fresh fluid (water) or empty borehole, and therefore, can be a suitable method for current study and related application. In addition, OPTV
takes a 360° picture of the borehole wall using a small camera with the aid of a fish-eye mirror, LED light ring and image sensor, as shown in Figure 4-9 (a). This means that OPTV can be used in the air-filled/empty boreholes and at the same time an unwrapped 360° image of the borehole wall as well as the position and the orientation of the borehole can be recorded. However, the geometry and physical features of the probe should be checked to make sure it will suit to be applied inside upward, slim/short holes in underground spaces. There are certain products by a few manufacturers that are designed for relatively slim boreholes. Two of the more promising products are Q40OBI-1000 and Slim Borehole Scanner manufactured by Mt Sopris and DMT and are illustrated in Figure 4-9 (b) and (c), respectively. These tools are introduced more in detail in the following section.

![Figure 4-9](image_url)

Figure 4-9: (a) Main components of usual OPTV probe head; OPTV probe head of (b) ALT-Mt Sopris Q40OBI-1000 (“Q40 OBI-1000.” 2013); (c) DMT Slim Borehole Scanner (“DMT SlimBoreholeScanner.” 2013), tools.
Q40OBI-1000 OPTV

The diameter of these probes are around 40 mm which is larger than the usual roofbolt boreholes and the weight is approximately 7 Kgs (15 lbs) which might make the operation in the upward borehole and the transportation in the underground spaces difficult. In addition, some of the probes are not explosion proof thus there are limitation for using such tool in gassy tunnels and coal mines.

Figure 4-10, shows features of a typical OPTV probe manufactured by ALT (Advanced Logic Technology)-Mt Sopris company. These probes sometimes have the option of including another geophysical probe like natural gamma and their diameter is usually around 40 mm or more which is larger than the usual bolt boreholes. In addition, they are not explosion proofed in case they are meant to be used in coal mines or any other underground space with explosive gases.

Slim Borehole Scanner

Another available tool for capturing the inside image of a small borehole is the Slim Borehole Scanner which is an explosion proofed OPTV image tool produced by DMT in Germany. This tool is specifically designed for application in coal mine. Additionally, the device is designed without a cable so that generally there is no need for tripod and winch, and it is light enough to be used by one operator. The diameter of this probe is 23-mm, which makes it very suitable for employment in normal 1-inch bolt boreholes. This product has the good features of borescope related to the ease of operation and suitable geometry along with advantages of regular OPTVs for getting an unwrapped 360-degree picture of the borehole wall, orientation of the borehole including the depth of log from the collar. However, the real-time picture of the borehole wall cannot be seen
during logging operation. This system is not waterproof and has limited battery life and memory space for each set of logging operation.

Applications:

The purpose of the optical imaging tool is to provide detailed, oriented, structural information. Possible applications are:

- Fracture detection and evaluation
- Detection of thin beds
- Bedding dip
- Lithological characterization
- Casing inspection

Technical specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
<td>40mm</td>
</tr>
<tr>
<td>Length</td>
<td>approx. 1.7m</td>
</tr>
<tr>
<td>Weight</td>
<td>approx. 7 kgs</td>
</tr>
<tr>
<td>Max temp</td>
<td>50°C</td>
</tr>
<tr>
<td>Max pressure</td>
<td>200 bars</td>
</tr>
<tr>
<td>Borehole diameter</td>
<td>1 3/4” to 24” depending on borehole conditions</td>
</tr>
<tr>
<td>Logging speed</td>
<td>variable function of resolution and wire line</td>
</tr>
<tr>
<td>Cable type</td>
<td>mono, four-conductor, seven-conductor</td>
</tr>
<tr>
<td>Digital data transmission</td>
<td>up to 500 Kbps depending on wire line, real-time compressed</td>
</tr>
<tr>
<td>Compatibility</td>
<td>Aben-MGXII (limited to 41 Kbps) and Matrex</td>
</tr>
</tbody>
</table>

Sensor:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensor type</td>
<td>downhole DSP based digital CCD camera</td>
</tr>
<tr>
<td>Optics</td>
<td>plain polychromatic cone prism system</td>
</tr>
<tr>
<td>Azimuthal resolution</td>
<td>user definable 90/180/360 or 720 pixels/360°</td>
</tr>
<tr>
<td>Vertical resolution</td>
<td>user definable, depth or time sampling rate</td>
</tr>
<tr>
<td>Color resolution</td>
<td>24-bit RGB value</td>
</tr>
<tr>
<td>White balance</td>
<td>automatic or user adjustable</td>
</tr>
<tr>
<td>Aperture &amp; Shutter</td>
<td>automatic or user adjustable</td>
</tr>
<tr>
<td>Special functions</td>
<td>User configurable real time digital edge enhancing</td>
</tr>
<tr>
<td>Orientation</td>
<td>3-axis magnetometer and 3 accelerometers</td>
</tr>
<tr>
<td>Inclination accuracy</td>
<td>0.5 degree</td>
</tr>
<tr>
<td>Azimuth accuracy</td>
<td>1.0 degree</td>
</tr>
</tbody>
</table>

Logging parameters:

- 360° RGB oriented optical image
- Borehole azimuth and dip
- Tool internal temperature

Figure 4-10: Specifications of OBI OPTV probe manufactured by ALT-Mt Sopris.

Figure 4-11 (a) shows the tool after complete assembly. In this device, by moving the probe inside the hole the wire rotates a sheave which activates the recording, as shown in Figure 4-11 (b). Movement of the strong activates the recording system to capture the image inside the borehole and record the depth simultaneously. Figure 4-12 shows the SBS operation under different conditions.
Figure 4-11: (a) Typical view of DMT OPTV tool after complete assembly; (b) Connecting probe to recording system using a special wire.

Figure 4-12: Application of DMT OPTV in two under two different conditions.
Since this operation requires dealing with a large amount of data, companies usually provide a software package for data management as well as some other purposes like 3D visualization of the discontinuities and image processing, Figure 4-13. is screen shot of an image processing software that shows the orientation of the discontinuities, their aperture and depth. For instance, in Figure 4-14 on the right the dip of the upper fracture is 69 and the lower one is 29 and has an aperture of 9 mm.

Figure 4-13: Some applications of the software for OPTV logs including data management and analysis.

Figure 4-14: Structural analysis of an OPTV log.
4.1.1. Summary and conclusion

All information provided in borehole televiewer is summarized in Table 4-1. As it can be seen DMT product has the required features of borescope related to the ease of operation and suitable geometry along with advantages of regular OPTVs for getting an unwrapped 360-degree picture of the borehole wall, orientation of the borehole including the depth of log from the collar. However, the real-time picture of the borehole wall cannot be seen during logging operation. This system is not water proofed and has got limitations related to battery charge life and memory space for each set of logging operation. This device is protected against splash water and dust according IP64. Also, the system allows data storage for 2 GB which is enough for approximately 40m borehole length logging. The capacity of batteries is for roughly 1.5 h registration and 10 h standby. The results of the field experiments with these tools are summarized and compared in following section.

Table 4-1: Summary of features of varied borehole image logs and their comparison.

<table>
<thead>
<tr>
<th>method</th>
<th>Cost</th>
<th>Difficulty</th>
<th>Recording</th>
<th>360 view</th>
<th>Special setup</th>
<th>Weight</th>
<th>Diameter</th>
<th>Probe length</th>
<th>Image analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>strata-scope</td>
<td>1</td>
<td>1</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>N</td>
</tr>
<tr>
<td>bore-scope</td>
<td>2</td>
<td>2</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>N</td>
</tr>
<tr>
<td>Regular OPTV</td>
<td>3</td>
<td>3</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>Y</td>
</tr>
<tr>
<td>DMT OPTV</td>
<td>3</td>
<td>2</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>Y</td>
</tr>
<tr>
<td>Acoustic and Electric Televiewers</td>
<td>4</td>
<td>4</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>Y</td>
</tr>
</tbody>
</table>

Estimation of rock strength (UCS)

For estimation of rock strength (UCS), sonic logging is the most commonly used method in comparison with other neutron, gamma ray and density logs [55], [78]. Full wave-form sonic probes and acoustic TVs can provide many useful information related to the strength of the rock in
addition to the conventional sonic tools [78]. As mentioned earlier, McNally (1990) and Oyler et al. (2010) developed equations to estimate UCS in mines located in Australia and the U.S., respectively [19], [55]. Using Acoustic TV can also be considered. The advantage of this method is that the transmitter works as the receiver as well, which maximizes the coverage area. However, the initial processed data from this log is qualitative and just indicates the rock strength relative to the adjacent layers and feature. More studies should be conducted to produce localized or general quantitative information about the UCS of the rock for the use of Acoustic televiewers. Guo and Zhou, (2011) offer more detailed information about this method [78].

However, most of the aforementioned studies were done on the surface and in down-hole boreholes. In these cases, filling the borehole with a fluid was not a significant issue; however, in mining/tunneling applications the borehole is most likely upward and thus, dry. The initial remedy to address this issue was employing rubber packer system for filling the upward dry hole with a fluid such as water or gel and conducting sonic logging through the packer. The initial concept is shown in the drawing below (Figure 4-15). This method seems to be the conventional method for similar situations, as indicated in some papers [79], [80].

In addition, the geometry of the borehole in current study is not compatible with the size and length of the strength measurement probes that are available. The height restriction of the underground spaces especially in small mine entries can also be a problem for inserting the probe in the borehole. These probes are typically 40-50 mm in diameter and around 1.7-2 m in length (6-7 ft).
Besides, there are many errors inherent in the sonic log method such as cycle skipping which makes it more complex to interpret. To get a more accurate data from the closely bedded layers, a high vertical resolution is needed which needs employment of more receivers in the sonic log. This will lead to a longer probe which makes them more unfavorable where they are already too long for the logging operation in an underground space. Overall, these issues make the use of conventional sonic televiewers in mining and tunneling applications very unlikely.

Therefore, correlating the information from other logs suitable for dry holes to strength the strength of the rock strata had to be considered. In this approach, information from tools such as neutron, gamma and density logs, were correlated to Uniaxial Compressive Strength of the intact rock through some theoretical equations or employing neural network methods. The initial studies show that previous conventional methods of correlating the direct results of these logs to UCS of the rock is not a promising and accurate anyway.
As an alternative, mechanical probes could be developed and manufactured to measure UCS. Stamp test and borehole penetrometer test are among the methods that could be used in the borehole to estimate the strength of the rock mass [63], [81], [82]. However, these methods will give a non-continuous, spot measurement of the rock strength along the borehole and as result they might not be as efficient and fast. On the other hand, scratch test has proven to be a relatively accurate and reliable approach [83], [84]. This method can provide continuous information about the strength of the rock strata surrounding the borehole by making a scratch on borehole wall. The existing scratch test devices are only capable of measuring the rock strength by testing on core samples or on a flat/sawn rock surface. These systems have not been used in borehole for rock strength measurement.

To develop a suitable borehole scratch test device, the research team decided to initiate a series of testing on various drag type tools to assess the magnitude of forces on various bits to be used for inscribing a scratch inside the borehole. For this purpose, a milling machine was acquired to conduct scratch tests with (Figure 4-16 (a)). The milling machine was later equipped with a triaxial load cell and a 3D positioning system to measure the normal and drag forces while performing the scratch tests. In this series of experiments different rock types were tested using various testing conditions including different bit geometry, cutting parameters such as depth of penetration, and rock surface curvature. The information from these tests was utilized to design the Rock Strength Borehole Probe (RSBP). The initial tests helped estimate the normal and tangential forces needed to be press the scribe to penetrate the surface inside the borehole as well as selecting the suitable geometry of the bit to be used.

During these tests some of the rock samples were cored to measure the strength and other properties of the specimens via standard geomechanics lab tests such as Uniaxial Compressive Strength (UCS) test. The initial idea was to cut and use the cored blocks for running scratch tests inside the drilled holes with designated curvature and the sample flat surface as schematically
shown in Figure 4-16 (b). The process for preparation of rock samples and schematic geometry of bits are presented in Figure 4-16 (b) and (c), respectively. This approach showed to be impractical and alternative methods were used to simulate scratching inside the borehole. This was due to very high accuracy needed in scratch test, that made it almost impossible to cut the sample in a way that the curved surface could be scratched with 0.1 mm accuracy.

The details of these tests and the equipment used are explained in the following chapters were detail design and operation of the testing unit is briefly discussed.

Figure 4-16: (a) Milling machine for conduction of scratch tests; (b) Schematic process for sample preparation; (c) Varied geometry of bits including disc shape and bits with sharp, round and rectangular tips.

The scratch test background and theory

The scratch test method has been proved to be a promising to estimate the rock strength through testing of a small area of the rock surface. Scratch test offers several advantages; first, minimum to no sample preparation is needed and secondly, the test requires small pieces or surfaces that are for the most part, often available. Also, the scratch test allows for strength to be
continuously recorded along the core sample, which is beneficial compared to the discrete nature of measured strength along a core sample where the UCS specimen is selected. These features have made this method appealing in various areas of application. One of the benefits of the scratch test, which was the key reason of its consideration for this study, was its adaptability in the field for measuring in-situ strength of the rock inside the boreholes.

The scratch test is based on the rock cutting mechanisms and is related to the cut geometry, cutting forces, and mechanical properties of rock. This relationship has extensively been studied for decades [85], [86]. The Scratch test was developed in 1990’s in University of Minnesota based on the initial studies on the cutting models of drag bits [87] and PDC cutters [88]. The initial work was followed by correlating the rock strength to the cutting test results [89], [90], which then resulted in development of a device called “Rock Strength Device (RSD)” [91], [92]. Scratch test was the subject of several studies, which produced a method for rock strength measurements on core samples from the oil field drilling operations [89], [93]–[100]. More recent studies on scratch test, is focused on estimation of fracture toughness [101]–[107].

The scratch test basically consists of a system for measuring the cutting forces required to scratch a rock core (along its axis) with a Polycrystalline Diamond Compact (PDC) cutter. The scratch test is kinematically controlled, i.e. both the depth of cut “d” and the cutter speed “v” are maintained constant during the test. The depth of cut typically varies between 0.1 and 2 mm, while the cutter speed is usually set at a few mm/s, (e.g. 0.1 to 12 mm/s) [92]. Both components of the force acting on the cutter are measured. This includes the component “Fs” in the direction of motion of the cutter, and “Fn” normal to the scratched surface. From the force measurements, the specific energy “SE” can be calculated. In addition “Fn/Fs” is estimated to evaluate the wear of the cutter [84]. More than 350 different rock samples [108], mainly sedimentary rocks, as well as construction materials, such as bricks, cement and plaster, refractories [109], [110], mortars [111], [112], and iron ore [113] were tested by this method.
In addition to the uniaxial compressive strength of the rock, Young’s Modulus was estimated from scratch test [84]. Another parameter that can be estimated by this method is the internal friction angle of the rock, which can be estimated by friction coefficient of the rock / blunt cutter (wear flat) interface [114].

Suárez-Rivera et al. (2002), employed scratch test method to assess core heterogeneity, and to compare scratch results with the mechanical properties predicted by logging of reservoir sandstone, mainly to improve analyses such as sand prediction [83], [115]. Germay and Richard (2014), also have recently evaluated the correlation between the strength and petrophysical properties [116]. The alteration of concrete strength as a result of contamination and the effect of temperature on refractory brick are also investigated by scratch test method and promising outcome has been reported [115]. Both of these cases take advantage of continuity of scratch test results. Digrain and Germay [115] and Digrain et al. [117], employed the minimum sample preparation/requirement feature of scratch test and estimated the strength of rocks such as shale. Attempts are also made to estimate the properties of the masonry mortars of a heritage building in Belgium, in order to stabilize its foundation [111], [112], [115], and more recently scratch test was used in order to estimate the lump to fine ratio and mineralogy of iron ores through their strength [113].

Figure 4-17: Scratch test configuration [114]
The cutter–rock interaction is generally characterized by the coexistence of two processes, namely rock fragmentation in front of the cutting face of the tool and frictional contact along the wear flat/rock interface [87]. Moreover, two different cutting or failure mechanisms, ductile and brittle, are observed in the process. The mechanism of the failure is controlled by the depth of cut [92], [94], [96]. In the ductile mode the energy consumed is related to the volume of the rock removed and as a result the strength of the rock. In brittle mode, however, the amount of consumed energy depends on the surface of the cracks that forms chips, which in turn, is correlated to the fracture toughness and ultimately tensile strength of rock [92].

The scratch test is based on a phenomenological model of cutter/rock interaction in the ductile regime, which was proposed by Detournay and Defourny (1992) [87]. This model is based on three key assumptions applicable to a particular cutter–rock combination, irrespective of the cutter wear, namely (i) the forces on the cutting face, are averaged over a distance, which is large compared to the depth of cut, and is proportional to the cross-sectional area of the groove traced by the cutter; (ii) the inclination of the average force on the cutting face is constant (in other words, angle of resultant force); and (iii) there is frictional contact at the wear-flat rock interface. Such a model is characterized by three parameters: the intrinsic specific energy associated with the cutting process, the inclination of the force acting on the cutting face, which is based on the ratio of drag to normal forces, and the friction coefficient mobilized across the wear flat. Phenomenological model assumes that the intrinsic specific energy is independent of the depth of cut and it is a constant quantity characterizing a particular combination of cutter geometry and rock. It is important to distinguish the difference between the intrinsic specific energy and the specific energy. The latter quantity accounts for both the energy expended in cutting the rock and the energy dissipated at the frictional contact between the wear flat and the rock, while the former, the intrinsic specific energy, only characterizes the energy used to fragment the rock ahead of the cutter.
Since the introduction of scratch test, this device has improved and some companies have developed their own devices with different names. There are three commercially available apparatus, which are Rock Strength Device (RSD), profiler core scratch test system, and Wombat.

Rock Strength Device (RSD) is the first scratch test apparatus, which was fabricated in University of Minnesota at the end of 1990s [91]. RSD is gradually optimized and a number of prototypes have been developed over the years [110]. Despite gradual improvements, the main components of RSD seem to be the same in all versions. It mainly consists of a frame, a load sensor, a driving motor and a data acquisition system [117]. Its cutting element, sharp or blunt, accepts replaceable polycrystalline diamond cutters of 10 mm width and back-rake angle of 15° [84]. Blunt cutters have a wear flat length varying from a fraction of millimetre to a couple of millimetres [108], with a small forward inclination about 2° to ensure conforming contact with the rock [91]. The range of force measurements is from 10 N to 4000 N, and is recorded with a resolution of about 1 Newton [92]. The data acquisition rate is up to 1000 Hz [92] and the scanning rate is typically at 25 samples/mm [108]. One of the earlier prototypes of RSD is shown in Figure 4-18.

Figure 4-18: An early prototype of Rock Strength Device (RSD) developed at University of Minnesota [84].

Another device is “profiler core scratch test system”, which is a patented technology developed by Schlumberger for continuous measurements of rock UCS by cutting (scratching) the rock surface [118]. Wombat is a new apparatus, shown in Figure 4-19, which is manufactured by
Epslog SA and is commonly used in the petroleum industry [113]. Wombat seems to have very similar components as the RSD. If the sample is sufficiently competent, it can scratch and analyse up to 3 meters of core per hour [116].

Figure 4-19: Pictures of Wombat scratch device [113]

The scratch methods that were discussed here use rock core from the diamond drilling to estimate the rock strength. Although this approach has addressed some of the issues related to rock testing regarding the sample preparation and continuous strength results, it still has the disadvantages of not being truly in-situ, providing small amount of information from the relatively scattered boreholes and being relatively costly and time consuming from the initial stage of coring and handling, to setting up the samples for running the scratch test. While this system is suitable for its current applications, it cannot offer rock strength measurements that meets work flow of many mining and tunnelling applications.

The scratch probe device proposed by our study can overcome some of these shortcomings by testing the rock in-situ and inside drilled boreholes in the underground openings. This system is based on using the holes that would be drilled in the normal operation cycle in development of a tunnel, drift, mine entries, or a stope for roof bolting or blast rounds. No sample preparation is needed for this method other than drilling boreholes, which is several times faster than
diamond/core drilling. Also, the evaluated strength values are continuous along the borehole, and can be readily obtained on site by analysis of the probing data with specialized software.
Chapter 5

Application of Optical Televiewers

Introduction

The capabilities and applicability of two Optical televiewers namely QL40OBI and Slim Borehole Scanner (SBS) for logging slim roof bolt holes were investigated in this study. These tools are manufactured by ALT-Mount Sopris and DMT GmbH & Co, respectively, and although they target different markets and applications, they are both powerful tools for capturing high-resolution 360° images from the wall of slim boreholes. QL40OBI is a well-established probe which is commonly used in down-hole applications such as geological and hydrological investigations in civil, mining and environmental industries. SBS, however, is designed for a very specific market. This instrument is developed to be used in upward roofbolt holes and has features that make it permissible for underground coal mine applications. The details of our investigations on these devices is elaborated on in the next two sections.

QL40OBI Optical TV

ALT-Mount Sopris, QL40OBI Optical televiewer, is 42 mm in diameter and about 1.3 m in length. It can be used in boreholes with diameter range of 50-500 mm (2-21 inches) depending on the borehole conditions. The camera is a DSP based digital CCD with 24-bit RGB color resolution. The horizontal resolution of the camera is 90-720 pixels per turn (360o). The higher resolution is used in larger diameter borehole. The vertical resolution depends on different parameters specifically the smoothness of the wall and speed of the logging operation. This
parameter can be adjusted by changing sampling rate, which can be set based on the time or depth sampling mode. The vertical resolution of as low as 2 mm is achievable by this tool (Lahti 2004). Logging speed is commonly between 1-3 m/min; however, for high vertical resolution speeds in the range of 0.1-0.3 m/min might be needed.

During the logging operation the tool can record and display various information, namely image, Temperature (°C), deviation sensor temperature, azimuth from the magnetic North (Azimuth, deg), inclination from verticality (Tilt, deg), tool relative bearing calculated from both accelerometer (Roll, deg) and magnetometer (MRoll, deg), magnetic field surrounding the borehole (MagnField, μT) and absolute value of the Earth gravity (Gravity, g). The 3-axis magnetometer/3 accelerometers APS 544 sensor enables the device to record the orientation of the borehole assuming that the axis of the tool and borehole are always parallel. The accuracies for azimuth and inclination measurements are ±0.5 and ±1.2 degree, respectively.

The data is transferred from the probe by a coaxial, 4 or 7-conductor wire cable to the data logger attached to the winch system. Data transmission speed can be as high as 500 Kbits per second depending on the wireline. The wire cable also has the function of winch wire to facilitate moving the probe inside the borehole. This cable passes through a depth encoder, which digitally records the position of the probe relative to the borehole collar, and the obtained image will be adjusted with position data. For accuracy of depth measurement, the wire should be kept stretched during the logging. The weight of probe will help achieving this goal. Also for this reason, the depth measurement is more accurate when the logging is done from the bottom to the collar. Depth information can further be calibrated using cores and by knowing the exact depth of some more distinctive geological features.

The optical televiewer used in this study, QL40OBI, was tested in three different surface and underground mines to check the suitability and capabilities of the device for probing horizontal
and upward holes. Since this device is designed for down-hole applications, some extra equipment was developed and used for logging upward boreholes. In these field experiments, logging in down/up-ward and sub-horizontal boreholes was examined and the details are discussed in the following sections.

**Logging in downward boreholes**

The first set of operations was carried out in King Coal Crown and Welker Coal Mines which are two surface coal mines near Philipsburg, PA. Boreholes in these mines were downward and about 8 inches in diameter. All the loggings were performed with about 1 m/min speed and 360 azimuth resolution (point/turn). The image property setting used in these tests was lightness 60% (recommended by manufacturer for normal dry boreholes), Chroma of 50%; normal (Default) image, gamma correction “on” (as default), and sampling rate of 0.004 m.

Figure 5-1 shows pictures of the setting used in logging the hole during field operations. Figure 5-2 shows resulting images taken from the borehole in downward (collar to bottom) and upward movement on the left and right, respectively. These images are almost identical for both directions of logging. The first borehole image set in Figure 5-2 (a) is an exception in which the probe head passed the ground water level, which starts at the point the image become unclear, and the deposited fines at the bottom of the hole blurred the image. This incident left some dirt on the window of the probe, as can be seen on the image on the right. Considering the accuracy of the depth measurement, upward logging proved to be a better approach in this case since the winch wire was always stretched. These operations helped to understand the possible issues with the operation of the device without considering the challenges in the upward-borehole logging practices. As the Figure 5-1 (a) shows, two non-metal centralizers were installed on the probe to help keep the probe centered and improve the quality of images. Figure 5-1 (b) shows the tripod,
winch, depth encoder and data logger manufactured by Mt Sopris Inc. Unlike Figure 5-2 (a), some dark inter-beds, probably coals, can be observed in Figure 5-2 (b).

Figure 5-1: Pictures of the setting for borehole Logging operations in King Coal Crown Mine with QL40OBI probe.

Figure 5-2: The Images resulted from logging operation in (a) King Coal Crown Mine; (b) Welker Coal Mine, with QL40OBI probe.
Logging in upward boreholes

Some upward boreholes of about 2-inch diameter were also tested for probing with the optical televiewer. These probing operations were done in Graymont underground limestone mine near Pleasant gap, PA. For this set of experiments, a special centralizer, a drum and couple of push rods were designed and fabricated at Penn State University. The concept of upward logging and the designed equipment are shown in Figure 5-3. All these loggings were performed with 360-azimuth resolution (point/turn). It was not possible to maintain the speed of logging constant mainly because the probe got stuck in the borehole. The imaging parameters were set as lightness 60% (recommended by manufacturer for normal dry boreholes), Chroma: 50%; normal (Default), gamma correction “on” (as default) and sampling rate 0.004 m.

Figure 5-3: The concept of upward logging operation and the devices, centralizer and drum, designed and made for this setting.

The additional pieces to some extent helped improving the results and facilitate the upward logging. However, since the device was relatively heavy (approximately 7 Kgs or 15 lbs), with a diameter close to the diameter of the hole, there were many difficulties during the operation including keeping the wire in a constant tension to have a smooth probing with constant speed.
Also, the probe was stuck a few times in the borehole, which needed a significant force and displacement to release it. A constant wire speed is essential for accurate measurement of the depth, and variable speed logging will lead to unclear and grainy images. Figure 5-4 shows the setting for this operation and the Image from one of the boreholes. In Figure 5-4 (a), abrupt changes in azimuth and magnetic field records can be noticed due to retrieving the probe after it was stuck. This set of logging needed at least three people to control all the components involved during the operation, as shown in Figure 5-4 (b). This made the probing operation inefficient, labor intensive, and hard to manage.

Figure 5-4: Upward borehole logging with QL40OBI probe at Graymont mine and a typical resulted image.

**Logging in sub-horizontal boreholes**

Some sub-horizontal boreholes were also drilled and logged in Graymont mine. Figure 5-5, shows the operational setting and the Image from a borehole. Six boreholes were logged in this
study. The images resulted from the first five adjacent boreholes are shown in Figure 5-5 (a) according to the relative position the boreholes have from each other. The main goal in this series of operations was to check the effect of azimuth resolution and logging speed on the quality of the images. Azimuth or peripheral resolution of 180, 360 and 720 (point/turn) and logging speeds of 0.1, 0.2 and 0.3 m/min were investigated. The other image setting parameters were kept constant, including brightness 60% (recommended by manufacturer for normal dry boreholes), Chroma: 50%; normal (Default), gamma correction “on” (as default) and sampling rate 0.004 m.

The logging process was generally the same as down-hole probing. However, in this set the extension rods were employed to push the probe to the borehole. The image of the borehole was not recorded at entry cycle, but when retrieving the probe by the winch. The operation went smooth enough that logging speeds as low as 0.1 m/min could mostly be maintained. It was concluded that the minimum peripheral resolution (180) would be sufficient for the small boreholes tested (2 inches). Also, using lower speeds wasn’t found to have much effect on the image quality for 4-mm sampling rate condition.
Analysis of the images

For further analyses of the images at this stage, it was decided to just evaluate the images obtained from the last series of the logging operation in the sub-horizontal boreholes. In the five adjacent boreholes logged, three fractures were detected, one in the right middle (RM) borehole and the rest in center borehole (Figure 5-6 (a)). Also, two sub-parallel cracks were found in right middle and left side (LS) boreholes (Figure 5-6 (b)). The three detected fractures and discontinuities were analyzed by WellCAD software developed by ALT Mont Sopris Company. Prior to analyzing the structural features, the images were processed. In this procedure, the bad traces were compensated for the brightness and contrast of the images were corrected.
Before getting the structural data from the images, they should be corrected relative to the common global coordinate system (horizontal datum is the surface) (Figure 5-7 (b)). This means that the recorded images are all captured considering the local (probe) coordinate system, which is parallel to the axis of the borehole (Figure 5-7 (a)). Although these images are shown in local system; however, the true and not apparent values for apertures, dips and azimuth are stored in the files.
As shown in Figure 5-8, the semi-automatically selected fractures in the images are corrected to the global coordinate system. This change of system is more complicated than just adding the tilt of the borehole axis to the apparent dip angle. In these calculations both dip and azimuth values will change. The azimuth of the image was also corrected from the tool recorded magnetic north to the true north. The difference between these was determined to be 10.91 degree at Graymont mine. Table 5-1 summarizes the obtained results for the joints detected in this exercise.

Table 5-1: Depth, azimuth and dip of the detected structures in local, true coordinate system and true north.

<table>
<thead>
<tr>
<th></th>
<th>BH Name</th>
<th>Depth</th>
<th>Azimuth</th>
<th>Dip</th>
<th>Depth</th>
<th>Azimuth</th>
<th>Dip</th>
<th>Azimuth</th>
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<tr>
<td>1</td>
<td>GR-BH-C-720</td>
<td>2.65</td>
<td>357.90</td>
<td>65.70</td>
<td>2.65</td>
<td>158.70</td>
<td>23.90</td>
<td>147.80</td>
<td>23.90</td>
</tr>
<tr>
<td>2</td>
<td>GR-BH-RM-720</td>
<td>4.00</td>
<td>358.90</td>
<td>65.40</td>
<td>4.00</td>
<td>158.80</td>
<td>25.00</td>
<td>147.90</td>
<td>25.00</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td>4.08</td>
<td>358.60</td>
<td>61.60</td>
<td>4.08</td>
<td>158.80</td>
<td>27.00</td>
<td>147.90</td>
<td>27.00</td>
</tr>
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</table>
The corrected data can be used further for defining the structural features of the ground as needed for rock mass classifications or other applications. In this particular field test, not many voids/fractures/joints were detected and as a result the obtained information from structural analyses are limited. Figure 5-9 (a, b) shows stereonet or Wolff (angle-equal/lower hemisphere) and Rosette plots for the fractures in center borehole in depth range of 2.14-4.29 m. As it can be seen, the fractures have a more or less similar dip/dip direction and the mean values are not much different. The dip and azimuth of all the detected fractures are more or less the same. However, since they are just found in two out of five nearby boreholes, it is hard to assume that these fractures belong to a joint system.

Figure 5-8: Structures detected and the changes of the structure shapes after coordinate system correction.
Figure 5-9: (a) Wolff (lower hemisphere), and (b) Rosette plots for the middle borehole.

**Slim Borehole Scanner (SBS)**

The field testing and subsequent analysis showed that it is very difficult to use the optical televiewers that are designed for down-hole applications for logging horizontal and upward holes with smaller diameter. Thus, further investigation to find alternative methods with similar capabilities was needed. One strong alternative found to be Slim Borehole Scanner (SBS) probe manufactured by DMT GmbH & Co in Germany. This tool is specifically designed for application in coal mines and is explosion proof. The product is cable-less, which means that there is no need for a tripod and winch, and it is light enough to be used by one operator. The SBS is 23-mm diameter and around 120 cm in length when fully assembled, which makes it very suitable for use in normal 1 to 2-inch roof-bolt boreholes. This product has the good features of borescope related to the ease of operation and suitable geometry along with advantages of regular OPTVs for getting an unwrapped 360° picture of the borehole wall, orientation of the borehole including the depth of log from the collar. However, the real-time picture of the borehole wall cannot be seen during logging operation. This system is not fully waterproof and has got limitations related to battery charge life and memory space. Moreover, although the tool has magnetometer and accelerometers,
unlike the QL40OBI tool, it is not readily possible to extract the borehole orientation data by means of its software and therefore more manual analyses is needed.

SBS had never been used by any mining operations in the US prior to this study. Therefore, PSU research team contacted DMT directly and got their approval to try their SBS system in some mining operations as a borrowed unit. A representative of DMT traveled to the US for field trials and demonstration of SBS to different companies. Despite successful trial of SBS units in the mines in the US, none of the companies took the initiative to acquire a unit due to relatively high price of the tool lack of permissibility from MSHA (Mine Safety and Health Administration) to use the tool in the US coal mines.

During the field trial tour, SBS was tested in an underground limestone mine and three coal mines, in three States. These mines included Graymont limestone mine, Nolo (Amfire), Buchanan and Bridger coal mines. The first two mines are located in Pennsylvania while the other two are in Virginia and Wyoming, respectively. Aside from going to the mines, a meeting was also arranged with MSHA to discuss the legal procedure to obtain approval for SBS for use in the US coal mines. Although SBS is permissible in Europe and Australia, obtaining MSHA permits for using this tool in US mines would still be lengthy and costly procedure.

Figure 5-10, shows the images captured from number of boreholes in the above mentioned mines. In Graymont and Buchanan four boreholes, and in Nolo and Bridger, five and two boreholes are tested, respectively. It is noticeable that the images recorded in Graymont limestone mine are significantly more clear and the rock mass fractures are visible, although due to not having the tool at the center of the borehole, some parts are much brighter than the others. The images from the coal mines are comparable with the images captured by QL40OBI from down-holes of coal mines. The dry surfaces are mostly light brownish and might contain thin coal seams as, for instance, it is visible in Nolo mine images. At wet locations of the boreholes, color changes to dark green, which might be because of wetting effect. In addition, since many of the rock types around the coal mines,
such as shale, are usually water-sensitive and can easily be washed out, a kind of dark mud flow might also form and gradually cover the borehole wall. The quality of the Bridger mine’s images is even worse because of the presence of water, which was constantly dripping from the boreholes. Of course, these shortcomings are not related to this specific tool but is a common issue of optical televiewing approach. The effect of this issue can be minimized by taking particular measures, such as blowing out the hole with air before probing.

It should also be pointed out that, almost all of the analyses that was carried out for QL40OBI data, can also be done on SBS data by either using the program that is exclusively developed by DMT or WellCAD program, which is used for QL40OBI device. Figure 5-11, shows an example of analyzing SBS data, including the image as well as accelerometers/magnetometers data, in WellCAD. As mentioned before, more analyses are needed to extract accelerometers and magnetometers data from SBS. In this figure, the image number 2 is the original captured data and the image number 1 is the image after orienting the pixels to their actual position by accelerometer and magnetometer data. This figure is prepared by a representative company of WellCAD, to make sure that the adjustment procedure was implemented correctly. This is despite the fact that the data processing was done by manually on the image and similar analyses was performed with WellCAD on the image files.
Figure 5-10: 360-degree unwrapped images obtained from testing number of boreholes by SBS in, (a) Graymont; (b) Buchanan (Consol) (VA); (c) Nolo (Amfire)(PA); (d) Bridger (PacifiCorp)(WY), mines.
Conclusion

Borehole probing by means of optical TV, as explained in previous sections, is one of the most difficult, costly and time consuming logging methods. This method is often used for downhole applications. Logging upward/narrow/short boreholes with this method is much more complicated, as explained in herein. Our field experiments showed that QL40OBI, which is conventionally used for downhole probing, is not suitable for performance of upward logging due to difficulties in the operation. Especially, the relatively high weight of it makes it very difficult to have a smooth operation beside the point that the logging procedure is very tedious under this condition. The issues related to this device for this application are summarized as below:
- Irregular (uncontrolled) logging speed due to the high weight of the probe (~5 Kg)
- Different route of wire (depth indicator) and probe-push rods (actual depth)
- Issues related to jamming of the winch wire and keeping wire fully stretched at all time (important for depth measurement)
- The need for at least 3 people to run the logging

As a result, SBS was considered and tested in the field as well. The main advantages of this probe are its small diameter, light weight and its unique depth indicator system. This is because this device is designed for upward probing applications, which makes it the best commercially available device to get 360° image of drilled holes at the roof/ribs of underground structures, especially coal mines. Unfortunately, this product does not have any customer in the US to date, and therefore users are unable to rent and use this tool to run more field experiments. Although this device is the best option to-date for the applications of this project, based on our field experiments, it is worthy to summarize the shortcomings of this tool in the US as following:

- No real time images available during logging.
- It has the limitations of using battery and low charge of battery significantly affects the image recording operation.
- The depth encoder wire can get twisted inside narrow/muddy boreholes, and might get tangled.
- Operation in muddy/constantly wet boreholes is cumbersome and the image quality is significantly decreased.
- The device records the orientation of the borehole, however, indication of depth and orientation of the borehole needs to be done manually in the current edition of the software.
- Although the device is designed to be light, logging more than 5 boreholes in a row with SBS is not an easy task.
- Although SBS is intrinsically safe and has EU and Australia approval, it is not MSHA approved for underground uses, which limits its application within the USA.
Chapter 6

Estimation of Rock strength by scratching method

Introduction

As introduced previously, to estimate the strength of the intact rock, scratch tests can be used, in which the forces needed to scratch the rock surface to a particular depth and by a scribe with a chosen geometry, are correlated to the Uniaxial Compressive Strength (UCS) and Brazilian Tensile Strength (BTS) of the rock. These correlations are based on the tests run on a flat/level surface, as it is relatively easier to prepare. Since the borehole wall is a curved surface, the tests are repeated for a selected number of samples, at the same condition but on curved surface with a curvature radius similar to what is expected in the field, and the results are compared with the initial tests on flat surfaces.

There are various parameters involved in the scratch test, including cutting velocity, scratch depth, distance between the scratches, type/geometry of scribe, rock type and bit wear. During the tests the cutting velocity was kept constant to about 2.6 m/min in most of the tests. This value is measured by a precise digital readout positioning system mounted on the linear cutting test machine. One of the main parameters involved in this test is the scratch depth. In this study, cutting depth varied between 0.2 mm and 1 mm with an interval of 0.2 mm was used. In order to minimize the effect of the adjacent scratches, a distance or cut spacing of 10 mm or more was used, which is at least 10 times more than the depth of maximum penetration used in the testing. Mostly, no interaction between the cuts was observed and cuts can be considered isolated. Considering the length of the sample, the local breakages can be ignored.

All the scratch tests were run by a miniature linear cutting device, which was designed and fabricated at Penn State University by using an existing milling machine and instrumenting it to
measure displacements and forces. The cutting tool was mounted on a load cell for force measurements. This mounting system was designed in a way to maximize the range of penetration for the cutter into the sample and to minimize the probability of the holder getting stock by cutting fragments. The rock sample is cast in concrete to provide a confining support for the specimen. The sample is either mounted and fixed on the machine’s table by a vice or it is already cast in a steel box, which can be bolted on to the sample table. The position and speed of the table can be adjusted and controlled with relatively high accuracy in all three dimensions.

A round triaxial load cell with 3000 lbs (~14000 N or 1360 Kgf) capacity measures the cutting forces in three directions and is resistant to dusty/wet environment. Although the load cell was factory calibrated, it was re-calibrated on regular basis in the laboratory after the scribe structure was mounted on the load cell by applying a set of predetermined loads to the tip of the cutting tool through a small hydraulic jack and a manual hydraulic pump. The load cell data was recorded by a NI USB-6341 X series data acquisition system (DAQ). The cutting test apparatus shows and records the position of the cutting tool. The positioning data is collected from a readout system installed on the milling machine and connected to the DAQ system. This readout system shows the absolute/relative position of the cutting tool relative to the milling machine table in X, Y, Z directions with the accuracy of 0.0001 mm.

As noted earlier, all the samples were subject to cutting test and cut depth of 0.2 mm to 1 mm with 0.2 mm intervals. Each identical test was repeated 3 times for most of the rock samples and in cases of bit wear measurement, the repetition was 10 times. Figure 6-1, shows a typical record of cutting forces in X, Y and Z directions at the depth of 0.6 mm on the limestone sample. Each test is well documented by taking photos and in some cases video of scratching operation. For many tests, the controlling variables and results such as rock type, the average, maximum and minimum of normal, rolling, side forces are measured along with the rolling/normal force ratio, and description of the sample surface was recorded.
Test results allow for establishing correlations between cutting parameters and strength properties of the rock samples, such as UCS and BTS. In addition, the effect of cutting velocity and surface condition/geometry on these equations can be examined. Finally, the results of testing a sample, that was made by sandwiching three different rocks showed how the results are affected during the transition between various rocks and if the initially developed equations can still be applied at this condition, which is a better simulation of the reality in a borehole.

**Equipment and rock samples for the scratch test**

**Miniature linear cutting machine**

The miniature linear cutting machine designed and fabricated at PSU for this project is simply a full-scale linear cutting machine, but in much smaller dimensions. This machine has been used for rock cutting experiments for decades, especially for TBM (Tunnel Boring Machine) design.
and optimization. Schematic drawing of a typical full-scale linear cutting machine (LCM) is illustrated in Figure 6-2.

Figure 6-2: A schematic drawing of a full-scale linear cutting machine [119].

This test is run under relatively high load and accuracy. As a result, a rigid milling machine was chosen to be used to minimize the changes of the sample and scriber position while running the test. In this case the sample mounted on the table of the machine will move while the scriber mounted on the machine arm is rigidly fixed which allows for relative movement of scribe and sample and by adjusting sample position, a small scratch can be made on the sample with relatively high accuracy.

The table of the milling machine can move in three directions with the three knobs located on the machine. A handle can also be used to move the table in all directions using the machine power. Speed of the table can be adjusted to a constant value of ½ to 20 inches/min. A safety mechanism was installed as a hard stop for locking of handles as the table reached its limits. The main components of the scratch test apparatus are shown in Figure 6-3 and labelled respectively as following:

1. On/Off switch of the milling machine and the milling operation activation swing handle.
2. Manual wheel for position adjustment along the “x” (table) direction.
3. Table traverse speed modifier (cutting speed).
4. Manual adjustment handle for position adjustment along the “Z” (table height) direction.
5. Manual wheel for position adjustment along the “y” direction (perpendicular to table).
6. Rapid traverse handle for fast adjustment of table position.
7. Milling machine table.
8. NI DAQ unit.
9. Strain gauge amplifier control unit.
11. AC motor
12. Gear box
13. Laptop stand
14. Control box
Triaxial Load cell and accessories

For this series of tests, the cutting forces need to be measured. As a result, a round triaxial load cell manufactured by Michigan Scientific Corporation was selected. The model is TR3D-A with 3000 lbs (~14000 N or 1361 Kgf) capacity in all directions, Figure 6-4 (a). The load cell was factory-calibrated and consisted of three four-arm strain gage bridges with full-scale output of 4 mV/V. The load cell is waterproof and resistant to corrosion and environmental conditions. It also can be used in a wide range of temperatures without affecting the transducers output.

Other accessories purchased along with the load cell are AC Remote Amplifier Control Unit, model PS-AC, and Three Channel Strain Gage Amplifier Box, SGA3A. PS-AC provide the power for the amplifiers, controls strain gage bridges excitation, and facilitate application of shunt calibration resistor to the appropriate arm of the strain gage bridge. The bridge excitation off feature allows the user to detect self-generated system response (noise) from undesired environmental conditions. The SGA3A supplies highly accurate excitation voltage to the load cell, a stable differential amplifier, and a remotely activated shunt resistor for system span verification. The
result is an accurate high-level voltage output signal. (reference Michigan brochures). Figure 6-4 (b) and (c) show PS-AC and SGA3A, respectively.

Data acquisition

For recording the data obtained from the load cell, NI USB-6341 X series data acquisition system (DAQ) is selected (Figure 6-5). This 16-bit resolution DAQ system can accommodate up to 16 analog inputs with a voltage ranging from -10 to +10. The feature of having four 32-bit counter/timers can assist to increase the accuracy of the displacement encoder from 20 microns to 5 microns.

Figure 6-5: Data acquisition system selected for the scratch test apparatus.
**Readout system**

One of the desired features of the scratch test apparatus is that it can measure relative to the position of the scriber. This will help us interoperate the changes of the load level along the sample. The readout system employed for this reason is ACU-RITE 200 series, Figure 6-6. This readout system shows the absolute/relative position of milling machine table in X, Y, Z directions. This system is capable of measuring the bit position in mm and inches with an accuracy of 0.0001 mm. The output data can be accessed through RS-232-C/V.24 port.

![ACU-RITE 200 series readout system](image)

Figure 6-6: ACU-RITE 200 series readout system, installed on the scratch test apparatus.

**Surface scraper**

The high accuracy of the testing device and fine control of the scratch depth requires very precise sample preparation. The sample surface needs to be flat and level relative to the machine table. Commonly grinding machine is used to level the sample surface. However, this was not a possibility for our testing set up. As a result, a surface scraper was designed and fabricated to shave the surface of the sample. This device is mounted on the milling machine table and by linearly movement of the table relative to the scriber can level the surface of the sample. This cutting is
done by a special flat PCD bit with the width of about 2 cm. Figure 6-7 (a) and (b), show the cutting tool (scribe or miniature disc) and surface scraper assemblies, respectively.

![Figure 6-7: (a) and (b), show the cutting tool (scribe or miniature disc) and surface scraper assemblies, respectively.](image)

**Scribers**

The rock samples were initially scratched with two types of scribers including miniature disc and drag. The disc scribe is made of Tungsten Carbide and the drag types are made of PCD (Polycrystalline Diamond). The PCD scribers were designed based on the needs of the project and manufactured by US Synthetic Corporation. Error! Reference source not found. shows the designed scribers and Figure 6-9 shows the scribers, which are modified by the manufacturer. The disc cutter, which is used in this project is a ceramic tile cutter manufactured by Ishii Co., Figure 6-10 (a). The designed PCD disc scribe for this project purpose, found to be economically unsuitable, Figure 6-10 (b).
Figure 6-8: Designed scriber based on the needs of the scratch test.

Figure 6-9: Modified drag scribers by the manufacturer; (a) narrow flat tip, (b) wide flat tip, (c) triangular tip, (d) rounded tip, scribers.
Scriber holders

The designed scribers need to be mounted on metal structures, which are attached to the load cell. For this reason, two kinds of holders are designed and made for disc shape and drag type scribers, Figure 6-11 and Figure 6-12, respectively. The holder for disc scriber is designed in a way that it maximizes the penetration of the disc into the sample and minimizes the probability of cutting fragments to be stock the scriber bearing. The drag scriber holder is designed to minimize the possibility of scriber wobbling during the scratch test operation and to enable the operator to scribe the sample along its length and width. Two different mounting systems were made for the drag scriber to perfectly accommodate 2/4-mm-thick scribers.
Figure 6-11: Scriber holder designed for disc shape scribers.

Figure 6-12: Scriber holder for drag type scribers.
**Rock box**

For scratch tests, the samples were prepared in two ways. The first method involved the rock blocks to be cut into approximately 75 mm (3”) wide to 250 mm (10”) long pieces, and arranged side by side inside a specially designed steel box. A high strength concrete mix was then prepared and gradually poured into the box to hold and confine the rock samples. To get the best result, rock sample were laid out on a flat surface covered by non-stick sheet of plastic to allow for easy lifting of sample from the surface. The concrete mix and the steel frame provide the rock samples with adequate confining support, so that during the tests they would not move/wobble or get damaged. This arrangement facilitates cutting of various rock types in a composite sample. Figure 6-20 (a), shows the prepared sample consisting limestone, siltstone, coal, and conglomerate. The designed rock box is made of steel with the dimension of 16x12 inches at the top and 4 inches high. ½” thick steel plate is used to make a flange of the box, and 3/16” thick steel plates are used to fabricate the rest of the box. The side plates are welded with 10° degree angle to create a tapered molding of concrete for additional confinement during the testing. The tapered mold will also help to avoid the sample to vertical movement under load and facilitate removing the sample out of the box. Since the surface of the sample needs to be shaved and scratched several times, a suitable height of the sample needs to stick out of the rock box. To achieve this, a wooden frame was designed/made in a way that rock block can be placed on top of it for casting and when removed, it exposes the top of the cast. Figure 6-13 and Figure 6-14, show the design and picture of the rock box, respectively.

Most of the available samples, however, were cast in smaller wooden molds in a similar way with no steel frame, as shown in Figure 6-20 (b). For individual samples, the rock samples were cut and cast in a wooden box.
The cutting tests were performed on various samples ranging from soft (coal), medium strength (i.e. limestone), to hard rocks (granite). Some of the samples were collected from the nearby coal/limestone mines in Pennsylvania, USA and the majority of samples were obtained from
quarries around the world as part of scanning available dimension stones in the construction market.

The samples can be categorized as limestone, marbles, travertines, and igneous which represent igneous and metamorphic rocks. There are also some other sedimentary rocks, namely siltstone, coal and conglomerate. These samples were tested for standard rock mechanic properties before running cutting tests. This includes Uniaxial Compressive Strength (UCS) and Brazilian Tensile Strength (BTS). The test results are summarized in Table 6-1. The results for Siltstone were estimated based on the point load (PLT) tests. The mean grain size (MGS) of most samples were evaluated and are also listed in this table. Under the “rock type” column, CL, CT and CM are abbreviations for Limestone, Travertine and Marble; MF, MM and MC are Igneous rocks with fine, medium and coarse grain sizes; and CG, CO and SL are conglomerate, coal and siltstone, respectively. In Figure 6-15, the typical igneous rocks with fine, medium and coarse grain sizes are illustrated.

Table 6-1: Geomechanics test results on selected rock samples [120]–[124].

<table>
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<th>Rock Type</th>
<th>ID</th>
<th>UCS (MPa)</th>
<th>BTS (MPa)</th>
<th>MGS (mm)</th>
</tr>
</thead>
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<td>MC</td>
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<td>9.06</td>
<td>15.18</td>
</tr>
<tr>
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<td>S2</td>
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<td>8.20</td>
<td>4.89</td>
</tr>
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<td>CL</td>
<td>S2-GL</td>
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<td>6.83</td>
<td>NA</td>
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<td>MM</td>
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<td>186.00</td>
<td>11.72</td>
<td>6.36</td>
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<tr>
<td>CG</td>
<td>S3-CG</td>
<td>154.14</td>
<td>8.55</td>
<td>NA</td>
</tr>
<tr>
<td>CO</td>
<td>S3-CO</td>
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<td>1.98</td>
<td>NA</td>
</tr>
<tr>
<td>SL</td>
<td>S3-SL</td>
<td>(42.50)*</td>
<td>(4.25)*</td>
<td>NA</td>
</tr>
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<td>163.00</td>
<td>9.66</td>
<td>11.97</td>
</tr>
<tr>
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<td>6.88</td>
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<td>151.00</td>
<td>11.02</td>
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<tr>
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<td>7.40</td>
<td>0.067</td>
</tr>
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</tr>
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<td>CM</td>
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</tr>
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<td>CT</td>
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<td>75.00</td>
<td>4.47</td>
<td>0.004</td>
</tr>
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<td>CT</td>
<td>S24</td>
<td>51.00</td>
<td>3.93</td>
<td>0.006</td>
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<td>23.14</td>
</tr>
</tbody>
</table>

*Estimated based on the PLT Axial result.
Bit wear evaluation

Possibility of changing cutting forces due to bit wear was examined by scratching the surface of two limestone, an igneous rock, a travertine and a marble sample and checking the tool wear by means of a microscope and a precise 3D scanner. This 3D scanner can get a 400x400 micron image of the scribe tip, which can be used further to quantitatively assess the wear by analyzing any arbitrary cross section of the image, as shown in Figure 6-16. Negligible or no bit wear was observed after making ten 1-mm-deep scratches in the selected rock samples and therefore, it was concluded that the bit wear was not progressing rapidly and therefore it practically doesn’t affect/impact the results and conclusions of this study. However, the disc cutters are replaced occasionally with a new disc to eliminate any possible wear effect on the results and malfunctioning due to bearing resistance.

Figure 6-15: Pictures of typical igneous rocks with (a) coarse, (b) medium, and (c) fine grain size.
Calibration of the load cell

For the calibration of the scratch test device, different approaches were tried and the results are compared in this section. Based on the advantages and disadvantages of these methods, one method is suggested as the standard way of calibration. The methods used for calibration are:

1. Shunt calibration
2. Dead weight calibration
3. Calibration by hydraulic jacks in various configurations

The preliminary results showed that calibration by a hydraulic jack was the most reliable and relevant to this application. This operation requires more time and additional equipment. One of the main issues with this method is that if not performed carefully, it may damage the load cell as a result of direct jack pressure.

For this purpose, an Enerpac hydraulic pump was used to apply pressure to a small jack with an effective area of 0.76 inch² and the pressure was measured by a dial gage. The pressure was
increased in 100-PSI increments up to 1000 PSI and was kept constant at each increment while the data was recorded by the data logger.

In the next step, the load for each pressure level and relevant recorded voltage was plotted to estimate the calibration factors. Figure 6-17: Calibration chart for (a) X, (b) Y, and (c) Z, axis by perpendicular jack calibration method. (a)-(c) show typical calibration charts.

As it can be seen, all the regressions have R-squared value of 0.99 and higher showing a linear variation of voltages and pressure.

Figure 6-17: Calibration chart for (a) X, (b) Y, and (c) Z, axis by perpendicular jack calibration method.
Additional calibrations were performed using the jack in an inclined position to load the load cell in two different directions simultaneously. A special steel wedge plate was designed and fabricated so that the hydraulic jack can insert load with an angle of 10 degrees to the load cell. (Figure 6-18 a). To prevent damage to the scriber, a piece of Aluminum was placed between the jack cylinder surface and the insert tip (Figure 6-18 b).

Figure 6-18: (a) Calibration hydraulic jack system; (b) Aluminum plat to protect the cutter wheel from damaging under jack pressure.

Figure 6-19, shows the calibration chart for “XZ” plane.
Testing procedure

Sample preparation

For the scratch test, the samples were made in two different ways as noted before Figure 6-20 (a), shows the prepared sample consisted of limestone, siltstone, coal and conglomerate. Most of the available samples, however, were cast in smaller molds with no steel frame as shown in Figure 6-20 (b).
Figure 6-20: Picture of rock samples prepared for cutting test. Sample made using (a) rock box; (b) wooden mold.

Error! Reference source not found. (a) and (b) show the casting procedures and Figure 6-22 shows rock samples molded in wooden frame.

Figure 6-21: Casting rock samples inside the steel box (a) installation of wooden frame around the steel box; and (b) pouring concrete around the rock samples.
Scratch test operation

After the sample is fully cured and secured on the miniature linear cutting machine table, its surface needs to be prepared before running the test by scraping operation as discussed before. This will ensure that the finished surface is level and high precision measurement of cutting depth is possible. The depth of cut for shaving was between 50 and 200 microns for very hard to weak samples, respectively. Scraping started with a lower value and gradually increased based on the hardness of the sample and observation of surface conditions. For instance, if the scraping caused chipping of relatively large fragments due to the sample grainy texture, lower scraping depth was maintained.

A dust collector, attached to the cutting arm in front of the scriber reduced the respirable dust in the cutting tests. Figure 6-23 (a) shows a typical damage that can occur to the scribe because of not having enough clearance distance with the sample surface at the returning stage. An overlap of 5 mm is often considered between each path of scrapping. In Figure 6-23 (b), a groove developed after a round of scrapping operation, is illustrated. Similar to preparation of the flat surface, the curved surfaces are also scrapped by a PCD scriber. Unlike the previous operation, circular/rounded
scribes were used to simulate the curvature inside the borehole. To mimic the curvature of inside various boreholes, the surface was prepared by round bits with a 1”, 1 3/4” or 1.5” diameter. A round surface formed after several scrapping rounds, as shown in Figure 6-23 (c). At the end of the scrapping operation, the sample surface was checked with a displacement gage to make sure it was reasonably level/flat in all the parts, as shown in Figure 6-23 (d). Variations of below 0.002 inches (0.05 mm) is considered to be acceptable.

Figure 6-23: (a) A damaged PCD scrapping scriber; (b) trace of the flat PCD scriber after one round of scrapping; (c) a curved surface made by a round PCD scriber; and (d) evaluation of surface flatness/levelness by a displacement gage.
Once the sample surface was prepared, the scrapping mount was replaced by the disc cutter holder or other drag type scribes. One more time the zero point was reset. Although the surface is already levelled, the zero level at 2-3 points along the test path was checked. At this stage the sample should not be removed from its location unless another round of leveling was used.

To perform the tests, the cutting velocity was selected and the cutting arm was positioned at the start point and the desired depth of cut. A MATLAB code was utilized to record and store the test data. By simply hitting the start button in the program and running the scratch machine, the cutting forces were recorded into a data file. The program is also able to trigger/stop the data recording automatically, since it receives/records the position data from the 3D readout system installed on the machine.

For each penetration depth, the test was repeated 3 to 10 times under the same circumstances. Also, photos were taken before and after each scratch test. Figure 6-24 is a typical picture of the rock surface after the test. The label on the ruler in this example indicates that the test was run on sample S2, with disc scriber number one and at the depth of 0.8 mm at y=110 mm location. These photos can clear some questions at the time of data processing. As mentioned earlier, the spacing between the tests are often consider to be 10 mm and in some cases 5 mm. In addition, a minimum of 5 mm distance was used to locate the first cut in the sample.

The tested samples are stored in for the future reference.
Scratch test data processing

A MATLAB code was developed to process the scratch test data. This code is designed to call the desired data files and select the data window that needs to be processed for each file/test. The window is selected to best represent the rock cutting section.

The code resets the zero point by using the first 1000 data points while scribe is not cutting. It uses measured load cell signal in “mV” to determine load and position based on the triaxial calibration coefficients. The window for data analysis is selected for each test by two vertical dash lines shown on the plot of measured forces versus location of scribe (X). The average normal and rolling forces within the specified data window along with their local maximums and minimums are calculated. The side forces are also calculated and stored. The average of the local minimums, maximums cutting forces for the entire window of data are presented as horizontal dashed lines in different colors, on the same graphs, which represent the lower, upper and the total averages of the data, respectively. Figure 6-25 presents the aforementioned plots for one of the tests.

Figure 6-24: Typical photo captured after a scratch test.
All the averages of all the measured forces are recorded in a table. As a result, a table with six columns (three components of forces and average and max for each force) is generated in which each line represents the results of one single scratch test. The raw data is sorted based on the penetration depth and the results related to each penetration depth, are stored in separate tables. The final results are manually transferred to an Excel file for further processing. A typical resulted table in Excel environment is shown in Table 6-2.

Figure 6-25: Graphs generated by the MATLAB code for a typical scratch test; (left) the test results (forces vs position) in metric and English scale; (right) the windowed data for normal/rolling forces vs position along with the averages of all the data (black dashed lines), local maximums (red dashed lines) and local minimums (green dashed lines).
This program also allows for a separate series of graphs to be generated where the UCS and BTS are calculated from the developed equations, which will be discussed later. This module allows the average values of the UCS and BTS to be written at the top left corner of this plot. A small window averaging scheme is used to show the variation of average forces for better identification of possible changes in rock and related UCS/BTS values. These graphs are shown in the lower section of the Figure 6-26. Two histogram plots are also generated, as shown in the upper section of the Figure 6-26. These histograms show how the values of the recorded normal and rolling forces are distributed and show range of variation of measured forces for qualitative analysis of cutting forces for given rock samples.

Table 6-2: The table of the final results of MATLAB code for sample S1, generated in an Excel.

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<th>Sample ID</th>
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<th>Ave_mean FN</th>
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After transferring the processed data from MATLAB to Excel environment, the replicates of each test are combined and the outliers are discarded. The outliers are chosen based on the apparent closeness of the results for the tests with 3 repetitions and for tests with 5 or more repetitions, the outliers are found by the interquartile range method. The remaining values for each penetration depth of a sample are then averaged. To summarize these results, a new table was prepared, which includes the average of Normal and Rolling forces for each penetration depth, i.e. 0.2, 0.4, 0.6, 0.8 and 1 mm, for all the samples, as shown in Table 6-3.

Figure 6-26: Histogram plots of the normal and rolling force data points (upper section); UCS and BTS calculated based on the developed equations using the normal force data (lower-left section); calculated average of normal and rolling forces in nine equal spans of the data window (shown in solid black lines in the lower section).
Having these final summary results, paves the way for the subsequent statistical analyses. Prior to that, the Normal and Rolling forces are plotted versus penetration depth for each rock to examine the correlation between the forces and the penetration depth, as shown in Figure 6-27.

Table 6-3: Summary of the scratch test results for four samples, averaged values of normal and rolling forces for each penetration depth after discarding the outliers.

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<td>S3</td>
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<td>136.28</td>
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</table>

Figure 6-27: Plot of normal forces vs. scratch depth for metamorphic rock samples.

More importantly, the average normal and rolling forces of each scratch test depth are plotted versus the UCS and BTS of the pertinent rock samples in order to visually evaluate the existence of any probable correlation between the forces and the UCS and BTS values. In Figure 6-28, the resultant plot for the scratch depth of 0.8 is shown.
In the final stage, average of cutting force are analyzed by SPSS program to find the best curve fit between the UCS and BTS and forces in various cutting conditions. This includes examining the correlation with scratch depths, forces, and strength of rock samples, using different regression functions and methods. The best estimator of UCS and/or BTS for each group of samples is selected based on the significance of the predicted correlation and the adjusted R-square values. Correlations with the significance of more than 0.05 (less than 95%) and/or adjusted R-square of less than 0.5 are discarded. Figure 6-29 is an example of the results of regression analyses, which shows the correlation between the UCS values of the sedimentary and metamorphic rocks and their pertinent average normal force values for a given depth of penetration.
Figure 6-29: Best curve fit of UCS vs normal force, and its formula for the sedimentary and metamorphic rocks.

\[
UCS = 25.099e^{0.0003FN}
\]

\[
R^2 = 0.767
\]
Chapter 7

Analysis of scratch test results

Introduction

So far, around 1000 tests have been run on different rocks with different strength, origin, and grain structure under variable conditions. Initially, all of the samples were tested by scratching the flat surface at a constant cutting speed of about 2.6 m/min. These experiments were performed at cutting depths of 0.2, 0.4, 0.6, 0.8 and 1 mm, and each test was repeated at least three times. Since these tests were run with the objective that their results are incorporated into the RSBP tool design and ultimately for estimation of rock strength from cutting forces. For this reason, the borehole and probing operation conditions were considered and their effect on the initial scratch test results were examined. Two main factors that are likely to affect the scratch results are the cutting velocity and the surface geometry.

The main purpose of studying the impact of cutting speed on the cutting forces, i.e. normal and rolling forces, is to evaluate the significance of probing pace variation on the estimated strength results. This is related to the fact that the RSBP is deployed by an individual and therefore the operator’s physical strength and condition of borehole/underground environment can impact logging speed and thus estimated rock strength. Moreover, because of the variation of borehole profile due to drilling operation, practically the probing involves lurking and twitching movements rather than just smooth operation under a constant speed. Furthermore, in case this probe is intended to be used in a long borehole, it would be very desirable to increase the speed of logging to minimize the operation time. As a result, speed of logging can impact the accuracy of the results.
The procedure of this series of tests was for the most part similar to the primary tests. However, based on the results obtained from the initial tests, some modifications were made to optimize the number of tests that needed to be run. In these experiments, the impact of cutting depth is only evaluated for 0.6, 0.8 and 1 mm due to more consistent results generated at these cutting depths. In addition, the tests were run just on seven selected samples and not the entire collection. This selection was based on the type of formation, i.e. igneous, sedimentary and metamorphic, grain size and strength. The chosen samples are S2, S5, S11, S15, S16, S17, and S22. Moreover, five cutting speeds of 115, 510, 1525, 2540 and 3050 mm/min (4.5, 20, 60, 100 and 120 inches/min) were selected to evaluate their effect on the cutting forces. The very low speed, i.e. 112 mm/min (4.5 inches/min), represents the situation in which the probing is slowed down because of the changes in direction/tightness of the borehole at a specific location. The reason for selecting high speeds is the twitching of the probe after it is stuck or slowed down in the borehole. As mentioned before, the experiments carried out in the major part of this study are done under the speed of about 2600 mm/min (100 inches/min).

Surface geometry is another important factor that was evaluated in this study. Since the actual tests were run inside boreholes with different diameter values, several tests were conducted on curved surfaces as well. As mentioned in the previous chapters, in order to simulate the borehole condition, the surface of the rock samples is scrapped by round PCD bits. Three PCD bits with curvature diameters of 19, 25.4 and 38.1 mm (¾, 1 and 1.5 inches) are designed and fabricated for this purpose. Similar to the cutting speed test series, the effect of curvature on the cutting forces are assessed by testing a limited number of samples and under selected conditions. Sedimentary rock samples S5, S15 and S17 were tested under constant cutting speed of 500 mm/min (20 inches/min) for the penetration depths of 0.6 and 1 mm. The selected number of tests was based on the previous experiences and the fact that surface preparation for these tests is more complicated and time consuming. Table 7-1 summarizes the features of each series of tests.
Furthermore, a sample consisted of three different rock types with various widths was prepared to see how the forces change when the disc scribe passes from one rock type to another and how well that specific layer of the rock is visible in the graphs. This partially simulates the reality inside the borehole, where the probe goes over a sequence of rock layers. Sedimentary rock samples S6, S18 and S25 are picked for the purpose of these experiments. This selection was based on the origin, grain size and most importantly the range of the UCS value. These rock types have UCS values of 130, 90 and 60, respectively. As mentioned, the width of each of these samples S6, S18 and S25 were 2”, 2.5” and 1.25”, respectively. S25 which has the lowest UCS value was selected to have the lowest width, since it was believed that it would represent the worst case scenario for detecting a layer of the rock with the RSBP is to detect significantly soft and thin layered strata. Figure 7-1 shows the fabricated sample or “sandwich rock sample”.

<table>
<thead>
<tr>
<th>experiment name</th>
<th>number of samples</th>
<th>cutting speed</th>
<th>surface condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>preliminary</td>
<td>27</td>
<td>100</td>
<td>flat</td>
</tr>
<tr>
<td>cutting speed check</td>
<td>7 (S2, 5, 11, 15, 16, 17, 22)</td>
<td>4.5, 20, 60, 100, 120</td>
<td>flat</td>
</tr>
<tr>
<td>curved surface check</td>
<td>3 (S5, 15, 17)</td>
<td>20</td>
<td>curved (3/4”, 1”, 1.5”)</td>
</tr>
<tr>
<td>sandwich rock</td>
<td>3 (S6, 18, 25)</td>
<td>20</td>
<td>flat</td>
</tr>
</tbody>
</table>

Table 7-1: Summary of the features for the designed/conducted scratch tests.
Figure 7-1: Sandwich rock sample with partially scrapped surface.

It should be noted that, for the convenience, the rest of this chapter will focus on the average of normal and rolling forces, referred to as $F_n$ and $F_r$, respectively.

**Primary analysis of test results**

**Initial results**

As explained in the previous chapter, after the tests were completed, for each test the appropriate data window was selected to represent the rock signature and then the average of normal and rolling forces were calculated within that range by using the developed MATLAB code. The results for each penetration depth were subsequently evaluated and the outliers were discarded. The average of normal and rolling forces and local maximums and minimums were calculated for the acceptable results of each penetration depth. Figure 7-2 show the measured forces at various depth of penetration for different rock types.

A quick review of the charts in Figure 7-2 indicates reasonable linear correlations between measured forces and penetration for all the sample with good R-squared values. Similar correlations exist between the penetration and rolling forces.
The summary of the primary scratch tests is summarized in Table 7-2. In this table the mean grain size (mm), BTS and the UCS of all the samples are also mentioned. As it can be noticed from this table, samples S14, S16 and S24 are broken under the pressure of 1-mm-deep scratch test.

Figure 7-2: Normal force vs. penetration depth for (a) igneous, (b) metamorphic, and (c) sedimentary rock samples.
The 1-mm-deep resulted forces for these samples are lower than the load recorded for the 0.8-mm-deep tests.

Table 7-2: Summary of the primary scratch test results.

<table>
<thead>
<tr>
<th>Type</th>
<th>ID</th>
<th>MGS (mm)</th>
<th>Zp2</th>
<th>Zp4</th>
<th>Zp6</th>
<th>Zp8</th>
<th>Z1</th>
<th>UCS (MPa)!</th>
<th>BTS (MPa)!</th>
</tr>
</thead>
<tbody>
<tr>
<td>MC</td>
<td>S1</td>
<td>15.18</td>
<td>281.97</td>
<td>660.61</td>
<td>1426.60</td>
<td>1781.64</td>
<td>2720.53</td>
<td>176.00</td>
<td>9.06</td>
</tr>
<tr>
<td>MM</td>
<td>S2</td>
<td>4.89</td>
<td>149.28</td>
<td>822.95</td>
<td>1272.62</td>
<td>2389.93</td>
<td>3347.29</td>
<td>145.00</td>
<td>8.20</td>
</tr>
<tr>
<td>CL</td>
<td>S2-GL</td>
<td>NA</td>
<td>160.71</td>
<td>817.23</td>
<td>1621.26</td>
<td>2583.11</td>
<td>3073.44</td>
<td>154.69</td>
<td>6.83</td>
</tr>
<tr>
<td>MM</td>
<td>S3</td>
<td>6.36</td>
<td>235.79</td>
<td>606.19</td>
<td>1361.15</td>
<td>2540.34</td>
<td>3614.13</td>
<td>186.00</td>
<td>11.72</td>
</tr>
<tr>
<td>CG</td>
<td>S3-CG</td>
<td>NA</td>
<td>152.77</td>
<td>777.06</td>
<td>1618.26</td>
<td>2223.60</td>
<td>3389.38</td>
<td>154.14</td>
<td>8.55</td>
</tr>
<tr>
<td>CO</td>
<td>S3-CO</td>
<td>NA</td>
<td>29.24</td>
<td>146.05</td>
<td>359.31</td>
<td>522.08</td>
<td>605.66</td>
<td>28.98</td>
<td>1.98</td>
</tr>
<tr>
<td>SL</td>
<td>S3-SL</td>
<td>NA</td>
<td>209.79</td>
<td>602.51</td>
<td>1010.33</td>
<td>1587.09</td>
<td>2056.41</td>
<td>42.50</td>
<td>4.25</td>
</tr>
<tr>
<td>MC</td>
<td>S5</td>
<td>11.97</td>
<td>107.37</td>
<td>554.85</td>
<td>1455.00</td>
<td>2338.08</td>
<td>3203.26</td>
<td>163.00</td>
<td>9.66</td>
</tr>
<tr>
<td>MM</td>
<td>S6</td>
<td>7.86</td>
<td>138.73</td>
<td>548.49</td>
<td>1482.09</td>
<td>2363.33</td>
<td>3294.53</td>
<td>134.00</td>
<td>6.88</td>
</tr>
<tr>
<td>MF</td>
<td>S7</td>
<td>2.91</td>
<td>43.18</td>
<td>568.95</td>
<td>1501.57</td>
<td>2417.22</td>
<td>3008.82</td>
<td>151.00</td>
<td>11.02</td>
</tr>
<tr>
<td>MM</td>
<td>S8</td>
<td>7.97</td>
<td>311.10</td>
<td>1035.82</td>
<td>1631.41</td>
<td>2712.63</td>
<td>3570.43</td>
<td>164.00</td>
<td>14.15</td>
</tr>
<tr>
<td>MM</td>
<td>S9</td>
<td>4.52</td>
<td>110.17</td>
<td>797.53</td>
<td>1568.49</td>
<td>2625.05</td>
<td>3352.04</td>
<td>194.00</td>
<td>8.21</td>
</tr>
<tr>
<td>MC</td>
<td>S10</td>
<td>27.73</td>
<td>370.99</td>
<td>732.88</td>
<td>1630.26</td>
<td>2322.88</td>
<td>3046.03</td>
<td>174.00</td>
<td>9.48</td>
</tr>
<tr>
<td>MF</td>
<td>S11</td>
<td>1.47</td>
<td>700.02</td>
<td>1388.52</td>
<td>2074.68</td>
<td>2404.85</td>
<td>3424.56</td>
<td>249.00</td>
<td>8.70</td>
</tr>
<tr>
<td>CM</td>
<td>S13</td>
<td>0.57</td>
<td>115.71</td>
<td>855.35</td>
<td>1186.27</td>
<td>1943.56</td>
<td>2686.11</td>
<td>75.00</td>
<td>3.72</td>
</tr>
<tr>
<td>CM</td>
<td>S14</td>
<td>0.47</td>
<td>60.01</td>
<td>487.86</td>
<td>1068.61</td>
<td>1261.90</td>
<td>581.84</td>
<td>54.00</td>
<td>4.70</td>
</tr>
<tr>
<td>CL</td>
<td>S15</td>
<td>0.005</td>
<td>327.06</td>
<td>1113.96</td>
<td>1974.26</td>
<td>3044.40</td>
<td>3670.62</td>
<td>86.00</td>
<td>8.45</td>
</tr>
<tr>
<td>CT</td>
<td>S16</td>
<td>0.085</td>
<td>102.10</td>
<td>197.33</td>
<td>959.34</td>
<td>1120.04</td>
<td>834.52</td>
<td>58.00</td>
<td>3.43</td>
</tr>
<tr>
<td>CL</td>
<td>S17</td>
<td>0.067</td>
<td>201.40</td>
<td>1156.79</td>
<td>2025.54</td>
<td>3220.93</td>
<td>3915.32</td>
<td>87.00</td>
<td>7.40</td>
</tr>
<tr>
<td>CL</td>
<td>S18</td>
<td>0.005</td>
<td>401.89</td>
<td>1310.11</td>
<td>1993.22</td>
<td>3493.13</td>
<td>3674.15</td>
<td>93.00</td>
<td>8.57</td>
</tr>
<tr>
<td>CL</td>
<td>S19</td>
<td>0.074</td>
<td>306.40</td>
<td>995.33</td>
<td>2427.71</td>
<td>2926.95</td>
<td>4550.24</td>
<td>95.00</td>
<td>5.81</td>
</tr>
<tr>
<td>CM</td>
<td>S20</td>
<td>1.4</td>
<td>362.98</td>
<td>1128.13</td>
<td>1461.73</td>
<td>2401.57</td>
<td>3136.87</td>
<td>48.00</td>
<td>3.72</td>
</tr>
<tr>
<td>CM</td>
<td>S22</td>
<td>0.67</td>
<td>215.43</td>
<td>1082.52</td>
<td>2085.91</td>
<td>3215.60</td>
<td>3711.06</td>
<td>75.00</td>
<td>6.83</td>
</tr>
<tr>
<td>CT</td>
<td>S23</td>
<td>0.004</td>
<td>148.10</td>
<td>612.21</td>
<td>1061.27</td>
<td>1805.31</td>
<td>2737.28</td>
<td>75.00</td>
<td>4.47</td>
</tr>
<tr>
<td>CT</td>
<td>S24</td>
<td>0.006</td>
<td>17.04</td>
<td>358.21</td>
<td>1141.11</td>
<td>2022.14</td>
<td>2009.78</td>
<td>51.00</td>
<td>3.93</td>
</tr>
<tr>
<td>CT</td>
<td>S25</td>
<td>0.077</td>
<td>304.56</td>
<td>991.22</td>
<td>1410.33</td>
<td>2610.44</td>
<td>3325.32</td>
<td>58.00</td>
<td>4.19</td>
</tr>
<tr>
<td>MC</td>
<td>S26</td>
<td>23.14</td>
<td>138.41</td>
<td>542.40</td>
<td>1729.88</td>
<td>2735.16</td>
<td>3229.12</td>
<td>150.00</td>
<td>12.50</td>
</tr>
</tbody>
</table>

The UCS versus normal force graph in Figure 7-3, shows how much normal force is needed on average to scratch the surface of each sample, assuming that all the samples are cut at a depth of 0.8 mm. Based on this graph it can be observed that the igneous rocks show no noticeable pattern, unlike the sedimentary rocks that show a rather consistent linear trend. The details of the analyses on these results are discussed in the following.
Regression analyses

For each penetration depth, statistical analysis was used to examine the correlation between the normal and/or rolling forces and UCS or BTS values by using various regression functions. This includes linear, power, polynomial, and exponential functions. It can be concluded from Table 7-3 that UCS and BTS of sedimentary and metamorphic rocks can be generally best predicted by normal force when the scratch depth or penetration is more than 0.4 mm. This might be because at certain depth of cut, significant amount of rock relative to its mean grain size is crushed, and therefore, cutting forces would be good representatives of rock strength properties. For igneous rocks, there is no significant correlation between the normal and/or rolling forces and UCS or BTS. The best correlations found for these rocks are summarized in Table 7-4. In this table, “Significance” and “F” parameters are significance level and F-test value, respectively.
Table 7-3: Summary of the best curve fitting results for sedimentary and metamorphic rocks, at each penetration depth and by analyzing the related normal force values.

<table>
<thead>
<tr>
<th>Strength type</th>
<th>Scratch depth</th>
<th>Type of regression function</th>
<th>Model Summary</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>R Squared</td>
</tr>
<tr>
<td>UCS</td>
<td>0.2</td>
<td>Power</td>
<td>0.337</td>
</tr>
<tr>
<td></td>
<td>0.4</td>
<td>Power</td>
<td>0.512</td>
</tr>
<tr>
<td></td>
<td>0.6</td>
<td>Linear</td>
<td>0.674</td>
</tr>
<tr>
<td></td>
<td>0.8</td>
<td>Power</td>
<td>0.654</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Exponential</td>
<td>0.767</td>
</tr>
<tr>
<td>BTS</td>
<td>0.2</td>
<td>Power</td>
<td>0.331</td>
</tr>
<tr>
<td></td>
<td>0.4</td>
<td>Power</td>
<td>0.627</td>
</tr>
<tr>
<td></td>
<td>0.6</td>
<td>Power</td>
<td>0.79</td>
</tr>
<tr>
<td></td>
<td>0.8</td>
<td>Exponential</td>
<td>0.815</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>Exponential</td>
<td>0.702</td>
</tr>
</tbody>
</table>

Table 7-4 presents the models that best estimate the UCS or BTS for each rock group. Since, there are just 2 igneous samples with fine grain size, they are not analyzed in this iteration. Based on this table UCS or BTS of sedimentary samples can be predicted with a relatively high confidence and R-squared. For igneous rocks, BTS can be estimated with fairly good correlations. The UCS, however, cannot be estimated with an acceptable confidence range. This matter is worse for samples with medium size grains.

In most cases, exponential function offers the best fit and the data from 8-mm deep tests gives the highest R-squared in majority of cases. The results also show that generally BTS is more predictable with this method. Normal and rolling forces both gives acceptable formula for the sedimentary and metamorphic rocks. For igneous rocks with coarse and medium grain size, rolling and normal forces, respectively, provide more suitable formulas.
The graphs of actual UCS and BTS and the best fits calculated from these formulas are shown in Figure 7-4. In this figure, UCS or BTS best fits of sedimentary and metamorphic rocks and BTS best fits of coarse and medium grain size igneous rocks are presented in charts (a) through (d), respectively.

### Table 7-4: Summary of the best curve fitting results obtained from SPSS software.

<table>
<thead>
<tr>
<th>Rock type</th>
<th>Strength type</th>
<th>Load type</th>
<th>cut depth</th>
<th>Type of reg. function</th>
<th>Model Summary</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sedimentary and metamorphic</td>
<td>UCS</td>
<td>FN 1</td>
<td>Exp.</td>
<td>0.767 0.741 29.65 0.000 Yes</td>
<td>25.099. Exp (0.0003 FN)</td>
<td></td>
</tr>
<tr>
<td>BTS</td>
<td>FN 0.8</td>
<td>Exp.</td>
<td>0.815 0.799 52.82 0.000 Yes</td>
<td>1.943. Exp (0.0004 FN)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>FR 0.8</td>
<td>Exp.</td>
<td>0.798 0.782 47.53 0.000 Yes</td>
<td>2.007. Exp (0.003 FR)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Igneous with coarse grains</td>
<td>UCS</td>
<td>FN 0.8</td>
<td>Linear</td>
<td>0.740 0.611 5.704 0.140 No</td>
<td>226.031 -0.03 FN</td>
<td></td>
</tr>
<tr>
<td></td>
<td>FR 0.8</td>
<td>Exp.</td>
<td>0.856 0.783 11.85 0.075 No</td>
<td>232.258. Exp (-0.001 FR)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BTS</td>
<td>FN 0.8</td>
<td>Exp.</td>
<td>0.732 0.598 5.466 0.144 No</td>
<td>4.873. Exp (0.0003 FN)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>FR 0.8</td>
<td>Exp.</td>
<td>0.905 0.857 19.02 0.049 Yes</td>
<td>5.063. Exp (0.002 FR)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Igneous with medium grains</td>
<td>UCS</td>
<td>FN 0.8</td>
<td>Power</td>
<td>0.534 0.379 3.437 0.161 No</td>
<td>3.91E-05. (FN^0.96)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>FR 0.8</td>
<td>Power</td>
<td>0.444 0.258 2.394 0.220 No</td>
<td>0.152 . (FR^1.16)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BTS</td>
<td>FN 1</td>
<td>Exp.</td>
<td>0.884 0.846 22.93 0.017 Yes</td>
<td>0.013. Exp (0.002 FN)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>FR 1</td>
<td>Exp.</td>
<td>0.730 0.641 8.127 0.065 No</td>
<td>0.364. Exp (0.005 FR)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Although it is of high interest to know which depth(s) of cut gives the best estimation of the UCS and BTS, it is more practical to find a more general correlation that involves penetration as a variable. This is because for borehole probe application it is not possible to keep the depth of the scratch penetration constant. Therefore, it would be desirable to predict the UCS and/or BTS

Figure 7-4: Best curve fits for (a) UCS, and (b) BTS, of sedimentary and metamorphic rocks; (c) BTS of igneous with coarse grains, and (d) BTS of igneous rocks with medium size grains.
based on the recorded penetration depth and forces at each point. Consequently, statistical analysis was used to establish a set of linear regressions for estimation of UCS and BTS from penetration and measured cutting forces. Table 7-5 summarizes the results of these analyses for the sedimentary and metamorphic rocks.

In this table, $F_N$, $F_R$ and $P$ represent average normal and rolling forces, and penetration depth, respectively. The first two equations for UCS and BTS show that $F_N$ provides better estimates of rock strength compared to $F_R$. Also, the last two equations for each parameter are the optimum correlations between UCS or BTS, $F_N$ and $P$. As it can be noticed, all the statistical parameters, including $R^2$ and adjusted $R^2$, of each set of these equations are the same, although one is correlated to the logarithm ($\log_{10}$) of the parameter and the latter to the natural logarithm ($\ln$). However, since some equations involve smaller number of components, the suggested equations are the ones from row #5 and #10 in table 4 for UCS and BTS, respectively, which can be rewritten as follows:

$$UCS = 5.84e^{(0.243\ln(F_N) \ 1.648\log(P))}$$

$$BTS = 0.26e^{(0.294\ln(F_N) \ 2.032\log(P))}$$

Table 7-5: Best fit formulas for estimation of UCS and BTS for various penetration depths.

<table>
<thead>
<tr>
<th>#</th>
<th>Strength type</th>
<th>Equation</th>
<th>R-Squared</th>
<th>Adj. R-squared</th>
<th>Significance</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>UCS</td>
<td>$UCS = 77.748+0.021(F_N)-71.554(P)$</td>
<td>0.482</td>
<td>0.466</td>
<td>0.000</td>
<td>29.774</td>
</tr>
<tr>
<td>2</td>
<td>UCS</td>
<td>$UCS = 81.851+0.107(F_N)-64.773(P)$</td>
<td>0.365</td>
<td>0.345</td>
<td>0.000</td>
<td>18.374</td>
</tr>
<tr>
<td>3</td>
<td>UCS</td>
<td>$UCS = 37.430+0.016(F_N)+18.245\log(FN)-81.971(P)$</td>
<td>0.538</td>
<td>0.516</td>
<td>0.000</td>
<td>24.492</td>
</tr>
<tr>
<td>4</td>
<td>UCS</td>
<td>$\log(UCS) = 0.766+7.385E^{-5}(F_N)+0.105\log(FN)-0.716\log(P)$</td>
<td>0.569</td>
<td>0.548</td>
<td>0.000</td>
<td>27.694</td>
</tr>
<tr>
<td>5</td>
<td>UCS</td>
<td>$\ln(UCS) = 1.764+0.243\ln(F_N)-1.648\log(P)$</td>
<td>0.569</td>
<td>0.548</td>
<td>0.000</td>
<td>27.694</td>
</tr>
<tr>
<td>6</td>
<td>BTS</td>
<td>$BTS = 6.242+0.002(F_N)-7.064(P)$</td>
<td>0.493</td>
<td>0.477</td>
<td>0.000</td>
<td>31.077</td>
</tr>
<tr>
<td>7</td>
<td>BTS</td>
<td>$BTS = 6.646+0.011(F_N)-6.386(P)$</td>
<td>0.372</td>
<td>0.352</td>
<td>0.000</td>
<td>18.964</td>
</tr>
<tr>
<td>8</td>
<td>BTS</td>
<td>$BTS = 2.565+0.002(F_N)+0.723\ln(F_N)-8.012(P)$</td>
<td>0.542</td>
<td>0.52</td>
<td>0.000</td>
<td>24.812</td>
</tr>
<tr>
<td>9</td>
<td>BTS</td>
<td>$\log(BTS) = -0.585+9.443E^{-5}(F_N)+0.127\ln(FN)-0.883\log(P)$</td>
<td>0.636</td>
<td>0.619</td>
<td>0.000</td>
<td>36.741</td>
</tr>
<tr>
<td>10</td>
<td>BTS</td>
<td>$\ln(BTS) = -1.347+0.294\ln(F_N)-2.032\log(P)$</td>
<td>0.636</td>
<td>0.619</td>
<td>0.000</td>
<td>36.741</td>
</tr>
</tbody>
</table>
It should be mentioned that although these results are from a broad range of rock types, more rock samples are required to be tested to verify these outcomes.

The results of the analysis show that the measured forces while scratching the surface of different sedimentary and metamorphic rocks with disc shape cutter can provide good estimates of rock strength properties. The results show good correlations between the average normal and/or rolling force and the compressive and tensile strengths of the sedimentary and metamorphic rocks, meaning that UCS and BTS of the samples can be predicted from the measured cutting forces. In addition, it was concluded that for the igneous rocks, generally no significant correlation can be found. The igneous rock samples consist of different type and percentage of minerals, the mean grain size of these minerals ranges from 5 micrometers to 25 mm. Also, igneous rocks have mostly heterogeneous and anisotropic structure in the scale of cutting with the miniature disc cutter. Therefore, obtaining a significant relationship between the normal and/or rolling forces and the mechanical properties was not possible. However, in some cases the BTS of these rocks could be estimated from the measured forces. According to the test results, the formulas with R-squared in the range of 80% were offered for estimation of UCS and BTS of the sedimentary rock samples, for the tests at cutting depth of 1 and 0.8 mm, respectively. Moreover, additional equations are available to estimate UCS or BTS values of sedimentary rock from cutting forces and penetration depth.

**Evaluating the impact of Cutting Speed**

As mentioned earlier, rock samples S2, S5, S11, S15, S16, S17, and S22 were chosen to evaluate the effect of cutting speed on the cutting forces, and therefore, on the estimated rock strength. These sample were tested under five different cutting speeds of 112 through 3000 mm/min (4.5, 20, 60, 100 and 120 inches/min). The cutting speed was measured by the positioning readout
system and controlled by a knob on the control panel, as shown in Figure 7-5. The readout system displays the table speed with an accuracy of 1 mm/min. It should be noted that unlike the previous tests, in this series of the experiments the force data was recorded against the time and not the position.

Figure 7-5: Photo of the control box and the position readout system.

The chosen samples cover variety of rock types. As it is summarized in Table 7-6, the first three samples were igneous rocks with medium, coarse and fine grain sizes, respectively. The rest of the samples were from the sedimentary and metamorphic group. These samples include a marble, a travertine and two limestones. One of the limestones (S15) has a finer grain size than the other (S17). It also can be noticed from this table that the UCS values have a broad range of 58 to 249 MPa.

Table 7-6: Properties of samples chosen for testing the effect of the cutting speed.

<table>
<thead>
<tr>
<th>Rock Type</th>
<th>ID</th>
<th>UCS (MPa)</th>
<th>BTS (MPa)</th>
<th>MGS (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MM</td>
<td>S2</td>
<td>145.00</td>
<td>8.20</td>
<td>4.89</td>
</tr>
<tr>
<td>MC</td>
<td>S5</td>
<td>163.00</td>
<td>9.66</td>
<td>11.97</td>
</tr>
<tr>
<td>MF</td>
<td>S11</td>
<td>249.00</td>
<td>8.70</td>
<td>1.47</td>
</tr>
<tr>
<td>CM</td>
<td>S22</td>
<td>75.00</td>
<td>6.83</td>
<td>0.67</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rock Type</th>
<th>ID</th>
<th>UCS (MPa)</th>
<th>BTS (MPa)</th>
<th>MGS (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CL</td>
<td>S15</td>
<td>86.00</td>
<td>8.45</td>
<td>0.005</td>
</tr>
<tr>
<td>CT</td>
<td>S16</td>
<td>58.00</td>
<td>3.43</td>
<td>0.085</td>
</tr>
<tr>
<td>CL</td>
<td>S17</td>
<td>87.00</td>
<td>7.40</td>
<td>0.067</td>
</tr>
</tbody>
</table>
Results of the tests run on these samples are illustrated in Figure 7-6 (a) to (g). Based on these graphs, increase in the speed of cutting either causes increase in the magnitude of the normal force or no significant change can be observed in the results. By referring to Table 7-6, it can be deduced that increase in the cutting speed will noticeably increase the normal force needed to scratch the surface of these rocks. Also, increased speed has insignificant effect on the cutting forces in sedimentary and metamorphic rocks. Sample S16 also shows an increase in the magnitude of the forces, however, due to the significant fluctuations in measured forces, test results cannot be used with high confidence to make any conclusion. One can also observe that in general, the slope of the regression lines is similar for different scratch depths, which means that regardless of the depth of cut, the cutting speed affects the normal forces in the same way.

Since the developed equations for the scratch tests in this study are solely applicable to the sedimentary and metamorphic rocks, we can conclude that based on the aforementioned results and considering the range of the cutting speeds, cutting speed doesn’t have a significant effect on the cutting forces during the scratch test. Obviously, more tests are need for more accurate and comprehensive conclusions.
Figure 7-6: Graphs of average normal force vs cutting velocity for (a) S2, (b) S5, (c) S11, (d) S15, (e) S16, (f) S17, and (g) S22, and for the penetration depths of 0.6, 0.8 and 1 mm.
Evaluation of impacts of borehole wall curvature

As introduced earlier, another factor that might affect the cutting forces inside a borehole is the peculiar geometry of cutting surface in such conditions. The UCS estimation models and related equations discussed earlier are based on the tests run on flat surfaces, however, inside the borehole we scratch a curved surface instead. As a result, for selected samples, the scratch tests were repeated, but on surfaces with different curvatures. These scratch tests were run on curved surfaces representing boreholes with ¾”, 1” and 1.5” diameter. The curved surfaces were made by scrapping the rock surface with round PCD scribes as discussed earlier.

Due to the project time constraints, only three rock types were tested for these experiments. The rock samples tested include S5, S15 and S17, which are coarse-grain igneous rock, and limestones, respectively, as also shown in Table 7-6. Unfortunately, S17 sample broke during the test and it couldn’t be tested for ¾” and 1” curved surfaces. All the tests were conducted under a constant cutting speed of 500 mm/min (20 inch/min). The results obtained from these tests are summarized in Table 7-7 and also illustrated in Figure 7-7. In this figure the curve corresponding to borehole diameter of 100 mm, is assumed as infinite curvature diameter for the flat surface. From these graphs it can be implied that in general higher normal forces are needed for curved surfaces. This might be due to the partial support that the surrounding walls are providing. They also can increase the length that the crack needs to propagate before it can reach the rock surface. It can also be observed that by increase of curvature diameter from ¾” to 1.5”, the normal force needed to scratch the surface of the sample S5, is increased regardless of the scratch depth. This is opposite of what was expected. The expectation was that less normal force is needed for the larger curvature diameters, as it was also the case for the flat surface. In these conditions the distance between the walls of the curves are larger, and therefore, the distance of propagation for the cracks should decreased. Unlike sample S5, test results in S15 was as expected. The only interesting observation
in this case is that the cutting force for 1” inch curvature is less than both ¾” and 1.5”. Furthermore, by comparing Figure 7-7 (a) and (b), it can be deduced that by increase of scratch depth, the difference between the flat and curved surfaces becomes more significant. More extensive tests seem to be needed to allow for generalized conclusions.

Table 7-7: Summary of scratch test results on different curved surfaces.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Surface condition</th>
<th>P= 0.6 mm</th>
<th>dev.% from flat</th>
<th>P= 1 mm</th>
<th>dev.% from flat</th>
</tr>
</thead>
<tbody>
<tr>
<td>S5</td>
<td>Flat</td>
<td>266.1</td>
<td>NA</td>
<td>566.4</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>C1.5</td>
<td>382.2</td>
<td>43.6</td>
<td>1041</td>
<td>83.8</td>
</tr>
<tr>
<td></td>
<td>C1</td>
<td>369.4</td>
<td>38.8</td>
<td>1032</td>
<td>82.1</td>
</tr>
<tr>
<td></td>
<td>C3/4</td>
<td>345.2</td>
<td>29.7</td>
<td>778.5</td>
<td>37.4</td>
</tr>
<tr>
<td>S15</td>
<td>Flat</td>
<td>519.5</td>
<td>NA</td>
<td>854.3</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>C1.5</td>
<td>555.7</td>
<td>7.0</td>
<td>1179</td>
<td>38.1</td>
</tr>
<tr>
<td></td>
<td>C1</td>
<td>536.8</td>
<td>3.3</td>
<td>1117</td>
<td>30.8</td>
</tr>
<tr>
<td></td>
<td>C3/4</td>
<td>550.0</td>
<td>5.9</td>
<td>1194</td>
<td>39.8</td>
</tr>
<tr>
<td>S17</td>
<td>Flat</td>
<td>353.6</td>
<td>NA</td>
<td>697.4</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>C1.5</td>
<td>340.3</td>
<td>-3.8</td>
<td>837.2</td>
<td>20.0</td>
</tr>
</tbody>
</table>

Figure 7-7: Plots of curved surface scratch tests for the scratch depth of (a) 0.6; (b) 1 mm.
Testing Sandwich rock sample

The aim for performing this series of tests was to compare the cutting force results in a more realistic environment consisting of different layers of the rock with variable thicknesses. This composite/layered specimen is made of S6, S18 and S25 samples with the thickness of 2”, 2.5” and 1.25”, respectively. The least thickness is assigned to the weakest sample, i.e. S25. This can help us understand if the scratch test method is able to detect thin layers of such weak rocks. If successful, the method can be considered to work in the worst case scenario. Based on Table 7-8, except for the test run on S6 with scratch depth of 6 mm, all the recorded normal forces for both scratch depths of 0.6 and 1 mm are less than 15% deviated from the regular (primary) test results. In three of the cases this deviation was very close to zero. For the rolling force however, the deviation percentages are significantly higher, i.e. between about 25% to 55%. This indicates that, unlike the rolling force, the normal force is a more consistent parameter in varied experiment conditions. The difference could be due to the ratio of normal to rolling force being in the order of 10-15 times and thus FN being less sensitive to small variations.

Table 7-8: Comparison of the sandwich rock and flat surface (regular) test results for penetration depths of 0.6 (Zp6) and 1 (Z1) mm.

<table>
<thead>
<tr>
<th>ID</th>
<th>Ave_meanFN (lb)</th>
<th>Ave_meanFR (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Zp6</td>
<td>Z1</td>
</tr>
<tr>
<td></td>
<td>sandwich</td>
<td>SDev. %</td>
</tr>
<tr>
<td>S6</td>
<td>509.23</td>
<td>333.19</td>
</tr>
<tr>
<td>S18</td>
<td>515.23</td>
<td>448.09</td>
</tr>
<tr>
<td>S25</td>
<td>325.53</td>
<td>328.61</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ID</th>
<th>dev. %</th>
<th>dev. %</th>
</tr>
</thead>
<tbody>
<tr>
<td>S6</td>
<td>121.7</td>
<td>162.35</td>
</tr>
<tr>
<td>S18</td>
<td>63.66</td>
<td>151.77</td>
</tr>
<tr>
<td>S25</td>
<td>51.49</td>
<td>122.84</td>
</tr>
</tbody>
</table>
A quick review of the test results show that application of scratch testing for estimation of rock strength inside a borehole is feasible and the results are reliable for calculation of UCS and BTS. This led to development of the detailed design of a probe that could make such measurements in small boreholes, as will be discussed in the following chapter.
Chapter 8

Rock strength estimation by RSBP® tool

Introduction

As also mentioned earlier, the results of cutting tests is used for the design of Rock Strength Borehole Probe (RSBP) to accommodate quick measurement of rock strength from a small borehole, which is the final goal of this project. This probe is 1.5” (38.1 mm) in diameter, which allows it to be operated inside boreholes with 1.75” (44.5 mm) diameter. These boreholes can be 2-10 m. (7-30 ft) long at any arbitrary orientation. The manufactured probe is light enough for an average person to operate. This probe will measure normal and rolling forces on the scribe with a load sensing device, and monitors linear displacement using optical sensors and a micro controller. All the data can be stored on a SD card for subsequent analysis. The probe is designed to be user friendly, and therefore, operates by simply pressing the power button and it begins logging both position and force data once it enters the borehole. Figure 8-1 shows the initial conceptual design of the RSBP. At the initial design stage a depth sensor was considered to be employed to continuously record the depth of the generated scratch. However, the additional testing and investigations showed that this could not be done with reasonable cost and accuracy and fit inside this probe.

The scribe is pressed against the borehole wall by two sets of spring loaded guide wheels located on the opposite side of the probe relative to the scribe. In addition, two smaller wheels are attached to the ends of the cutting housing in order to limit the depth of the cut. The vertical position of the smaller wheels can easily be adjusted externally. After having the wheels at the desired position, they will be fixed during the loggings. The combination of these four guide wheels will
help ensure that the scratch depth is maintained constant while RSBP is running along the hole, without imposing excess pressure on the cutter housing and therefore the strain gauges. The operator can also adjust the amount of normal force or depth of cutting by control screws on the back of the probe.

Figure 8-1: The conceptual design for the mechanical part of scratch probe with a disc scribe [125].

The mechanical parts of the probe went through many design iterations and modifications. All parts were designed using SolidWorks and the final assembly was modeled to make sure that all the components would fit together. All the parts were manufactured at the EMS college machine shop according to the generated drawings and in some cases in order to facilitate manufacturing process, some minor modifications were made. The tube was also divided up into two sections. The first section contains the mechanical components, and the second electrical.

As one of the objectives of the project is to develop a relatively light probe, 6061 Aluminum was utilized to make all the parts except the electrical housing, which is made out of polycarbonate to prevent any electricity from impacting the electronic parts of the probe. 6061 Aluminum is corrosion resistant, relatively light and strong. However, some of the more delicate parts are heat treated to ensure that they have enough load bearing capacity under high stresses. Finally, all the components are fit inside an anodized 1.5” 6061 Aluminum tubing. Figure 8-2 (a) and (b) show the cross section of the designed probe and the final product, respectively.
For the electronic assembly of the probe, a circuit schematic was generated. In this design, the Teensy 3.2 microcontroller is the key component, which interfaces with the laser sensor, strain gauge, SD card module, and time clock module. Teensy 3.2, is the perfect size to fit inside the probe. It is rated at 72 MHz with a SPI communication bus which is needed to interface with the laser sensors and SD module. The speed matches the data acquisition rate as required by the specifications of the probe design. It also has a storage and RAM of 256 KB and 64 KB, respectively.

![Probe Design](image1)

Figure 8-2: (a) Cross section of the final design of the RSBP and [125], (b) the photo of the manufactured probe.

Two other electronic components that are installed at the cutter housing are the strain gages and the position laser sensor. The final design has two full–bridge strain gage system with eight strain gages placed around the upper surface of the cutter housing. One bridge is at the front of the disc scribe while the other is behind it. The system consisted of two legs acting as active gages (responding to applied forces) and two legs acting as dummy gages (no change in resistance due to applied forces). This system is self-adjusting for changes in temperature and will allow the probe to measure normal and rolling forces.

For measurement of the probe position inside the drillhole, ultrasonic and infrared devices were quickly ruled out because of their inaccuracy in short distance measurements. It was
concluded that laser sensors are the most accurate in the market for such measurements. The Avago ADNS 9800 laser sensor is selected for the purpose of this project, which is very small, low cost and has the right resolution and precision to fit this application. The lens can be adjusted to a maximum distance of 5mm. The resolution is also adjustable to different surfaces. This sensor measures changes in position by optically acquiring sequential surface images (frames) and mathematically determining the direction and magnitude of movement. Based on the initial test results the x-direction of the sensor is found to produce more accurate data and as a result, the sensor is installed so that movement in X direction aligns with the probe logging direction.

The probe relies heavily on an efficient software system in order to collect the physical inputs and produce accurate outputs in an easy-to-read format. The code is written by Arduino software, and is developed in a way that all the data is written on a micro SD card every 500 ms.

Design and manufacturing procedure

RSBP was designed based on some technical requirements as well as restriction imposed by the field condition. The boreholes that RSBP is meant to probe is rock-bolt drillholes, with typical specifications/conditions as listed below:

1. 25-45 mm (1- 1¾) diameter boreholes.
2. 1-6 m (320 feet) long.
3. Upward with no fluid inside.
4. The borehole might be completely dry or groundwater might drip down.
5. The surface of the borehole is not necessarily smooth at all the locations and some material might be chipped/broken/washed out.
6. The borehole may not be necessarily straight. It might have some deviation.
7. In some cases, the height of the underground space might be as high as 9 m or as low as 1 m.
8. There is a possibility that some of the weaker rocks chip off while the scratching operation is happening and that small pieces of rocks might make it either into the probe or get scratcher disc stuck.

There are also some concerns regarding the operation of the RSBP to make it a more practical and favorable device. We want the probe to be:

1. light enough for an average person to operate it in the defined boreholes several times consecutively.
2. small enough to be able to pass through the defined narrow boreholes.
3. designed not to get stuck in the borehole with undulating surface.
4. user-friendly and easy to operate with the least number of steps for one individual.

Most importantly and based on the scratch test results, RSBP needs to meet several technical requirements as summarized below:

1. Develop a borehole probe that is able to scratch the borehole wall at one or more locations simultaneously along with measuring the applied force(s) or/and the depth/geometry of the scratch.
2. Measure/record the change of probe position while other data related to scratching is recording.
3. It should be designed to be intrinsically safe and thus explosion proof for the use in coal mines.
4. It needs to either have a borehole camera or orientation sensors to check which rock layer the data is related to.
5. Should be able to stand normal force of up to 1000 – 4000 N, and the scratch should be about 1mm deep.
6. Must be equipped with electronic sensors less than 25 mm (1 inch) in height to fit in the casing.
7. Must be equipped with memory device to store data collected
8. Should have a microcontroller to interface with the sensors and memory device.
A number of patents and products, in addition to the Rock Strength Device (RSD), was considered in the design of RSBP. Some of the more relevant/important patent/products are explained in the following:

**US Patent 7921730 B2 - Downhole Rock Scratcher:**

The downhole rock scratcher is a probe which utilizes a triangular scratch tip affixed to a metal pad that can extend/contract as needed, Figure 8-3. The force applied to the cutting tool is varied to maintain the scratch depth constant. These forces will be recorded during the well logging. The system uses caliper arms to stabilize and measure the applied forces while the probe is lowered into a borehole. The product was designed for use in larger downhole boreholes, such as oil wells [126].

![Figure 8-3: Conceptual design for the downhole rock scratcher patent [126].](image-url)
Three-arm Caliper Probe:

The three arm caliper probe is a device which mainly measures the diameter of the wells and boreholes. As depicted in Figure 8-4, this tool is composed of a motor (1), and three springs (2), which extend the sensor arms (3). Three sensor arms extend from the probe casing and are continuously held against the borehole wall. Initially, the arms are retracted and as soon as the probe enters the borehole the arms are extended outwards to touch the walls. As the operator moves the probe further into the borehole the variation in borehole diameter is logged via the DC output from a potentiometer or an LVDT instrument. This output is then converted to a frequency linearly related to the borehole diameter. Measurements can be made in inches, centimeters or millimeters. These devices are commonly used in water, oil, gas, and ice drilling wells but often only require an accuracy on the scale of inches [127].

![Figure 8-4: A cross-section of a caliper tool, mainly composed of (1) a motor; (2) three springs; and (3) three legs [127].](image)

Design of Mechanical Parts

As mentioned above, the mechanical parts of the probe went through many design steps and all the parts were manufactured at the EMS machine shop according to these drawings.
Design of scratching components

A number of concepts were evaluated for the cutting mechanism from different aspects, individually and in combination with other components.

Figure 8.7 shows the result of FEA modeling of the cutter housing performed to estimate the stresses in the part for evaluation of various strain gages to be used for force measurements. Figure 8-6 shows the final design and components of the cutter housing. The screws at the top of the housing (1) are used to adjust the force on the housing. By rotating these screws, the housing can be pushed down or brought up. The springs at the bottom of the housing (2), help to retrieve the housing back to a higher position and therefore to decrease the depth of cut and hence force on the frame. For the installation of position sensors (or any other similar sensor), two sections (3) are cut on either sides of the cutter (4). The wires for these sensors can pass through a hole, that is drilled inside the housing. To ensure that the housing will just move perpendicular to the probe axis, two constraining slides are placed at either sides of the housing.

Figure 8-5: Results of the Finite Element Analysis on the cutting housing (After Michael Rissmiller).
In addition to these components, a pair of guide bearings were added to the opposite sides of the cutter wheel in order to limit the scratch depth to 1 mm and to avoid the probe shell from getting dragged against the borehole rough wall. Figure 8-7 shows a pair of guide bearings assembled on the cutter housing (on the left) and dismantled on the sides of the cutter (on the right). The forces measured by the strain gauges are a combination of normal and rolling cutting forces.

Figure 8-6: Close-up view of the cutting housing which is composed of (1) force adjustment screws; (2) floating springs; (3) laser sensor assembly areas; and (4) scribe wheel/cutter holder [125].

Figure 8-7: Pair of guide bearings to limit the scratch depth and prevent the RSBP shell to get rubbed against the rock surface.
After all the components were machined, they were assembled inside the external shell of
the Figure 8-8 shows how various components are aligned to function as they were designed. During the manufacturing some adjustment were made to make the assembly process easier. For instance, two more slots were made on the sides of each guide wheel, so that the wheels could be installed externally and their shafts have room to move up/down during the expansion/compression.

Figure 8-8: Slots and holes drilled into the probe shell for fixing the components inside, where (1) guide wheels slots; (2) force adjustment screws’ holes; (3) cutter slot [125].

Figure 8-9 (a) shows the initial and new designs for the scissor-lift structure which is designed to allow the guide wheels to push against the borehole wall and maintain a constant load on the probe and force the scribe into the opposite wall. The picture of guide wheel housing is shown in Figure 8-9 (b).
Figure 8-10 shows the guide bearings attached to the sides of the cutter housing. An individual guide wheel is shown on the right and on the left the assembly of the housing. This new guide wheel is designed in a way that the position of the wheel can be adjusted externally by means of twisting a screw with a hex wrench. This structure has the same function as the guide bearings, to limit the depth of cut and avoid dragging the probe on the rock surface.

Figure 8-10: New guide wheels on either sides of the cutting housing to control the depth of cut.
Figure 8-11 shows the newly manufactured cutting housing and its machining requirements for the laser sensors used for detecting the probe movements along the borehole. All the final components of the RSBP are shown in Figure 8-12 beside the shell right before the final assembly.

![Figure 8-11: schematic of the new cutting housing with improved laser sensor fixtures (After William Leroy Diehl).](image)

The generated model of the electrical module consisting of three main sections which are SD Module fixture, battery holder and the PCB platform, are illustrated in Figure 8-13. This part is made by machining a cylindrical piece of polycarbonate that has a radius slightly smaller than inner diameter of the probe shell.

RSBP is designed to be pushed inside the long boreholes by means of extension rods with the length of 3 ft. (~0.9 m). These rods have male and female couplings to get fixed to the RSBP
or another extension rod. A female connection adaptor was made and attached to the end of the electrical housing so that the extension rods can be screwed in it.

**Figure 8-13:** Electrical housing 3D model, where (1) SD Module fixture; (2) 9V-battery holder; (3) PCB platform [125].

### Design of electrical components

The probe’s electrical system was designed to acquire three inputs of forces, depth of scratch and scribe position, in order to calculate the rock strength. Figure *8-14* shows the data flow through the initial system. The yellow boxes represent the inputs to the data stream. The blue ovals represent intermediate steps where values are either converted from one engineering unit to the other (i.e. Volts to Strain) or attached to other pieces of data. The green cylinder represents the output stage of our system. Arrows connecting steps display the units of data being transferred.

No suitable depth sensor was found during this research but the cutting depth can be estimated from the ratio between rolling and normal forces. This allows the probe system to be able to produce reliable estimates of the intact rock strength based on magnitude of forces and ratio of rolling to normal forces.
As shown in Figure 8-14, majority of the system inputs are provided by voltage signal. This signal can be used as an analog input or as a communication method (i.e. Master/Slave communication, SPI communication). The final output of the system is expected to be a JavaScript Object Notation (JSON) object. The JSON format has been chosen because of its portability, meaning its ability to be used in different environments. This will allow the collected data to be processed in any computer languages as JSON is supported by most object oriented programming languages.

There are several electronic components, which are used in this project. Most of these items are assembled on the circuit board mounted on the electrical housing. These components are:

- Teensy 3.1 Microcontroller
- MicroSD Card Module
- RTC Module
- INA125UA Instrumentation Amplifier

Figure 8-14: Probe Software Data Flow [128].
- LT4356-3 Surge Stopper
- IRLR 2908 N-Channel MOSFET
- Mom. Power switch
- ACS712 Current Sensing Module
- LED Indicator
- Various resistors, electronic potentiometers and capacitors

There are two other electronic components that are installed on the cutter housing, i.e. strain gauges and the position sensor. Following is a brief overview of the key components.

**Teensy 3.2 Microcontroller**

Teensy 3.2 microcontroller, Figure 8-15 (a), is the key component of electronic system, which works as the brain part of RSBP. This item interfaces with the laser sensor, strain gauge, SD card module, and time clock module. The data interrogation speed can match the data acquisition rate based on the required specifications by the user.

**MicroSD Card Module**

The SD card module will record the received data from the microcontroller on a MicroSD card. This module is compatible with cards that have up to 16 GB of memory, and transfer data at the rate of 50 MB/sec with 4 parallel data lines. The SPI communication bus feature allows it to be easily integrated with the Teensy microcontroller. Figure 8-15 (b), shows this SD module along with a typical MicroSD card and its adaptor.
INA125UA: Instrumentation Amplifier

This is a high-quality IC with 16 pin dual-inline package, which provides excitation voltage and ground to the system while obtaining the needed voltage difference measurement and applying a gain to this measurement. The final design uses the ‘UA’ package, i.e. INA125UA, which is the 16 pin IC package. This IC is relatively inexpensive and is a small amplifier. This switch saves a significant amount of space on the circuit board. In addition to the package change, another INA125 IC was added to the electrical system for monitoring two separate strain gauge bridges that each have their own amplifier.

LT4356-3: Surge Stopper with Fault Latch Off

This Linear Technologies IC was chosen to protect the strain gage system from in-rush current as well as accidental short circuits. It will act as a switch that will disconnect the strain gauge system from the power supply if it senses unusually high current entering the system. The advantage of this IC is that it is effective, small, cheap, and contains a fault output pin. The fault pin will be used in combination with an LED to indicate the status of the strain gage system.
IRLR 2908: N-Channel MOSFET

IRLR 2908 IC is the MOSFET that will be used, as recommended, in combination with the LT4356-3 IC to implement current protection for the strain gage system. This IC was chosen due to its large voltage operating range. The IC was ordered in a D-pack package, which physically allows the IC to lay flat, and not vertically, on the Printed Circuit Board (PCB). This way it will be assured that the assembled PCB will fit into the probe.

Mom. Power switch

This button uses a digital interrupt to turn off and on the components from the microcontroller. The downside of this system compared to the conventional mechanical switches, is that while the components are off, there is still a small amount of power consumption, which might drain the battery faster.

Strain gauge

The cutter housing contains two electronic components: the strain gage system and the mouse sensor. The original system was a full-bridge strain gage system with eight strain gages placed around the entire cutter housing (Figure 8-16). The system consisted of two legs acting as active gages (responding to applied forces) and two legs acting as dummy gages (no change in resistance due to applied forces) to compensate for the temperature changes. This system can measure the normal force imposed on the scribe and by differential measurement of the front and the back, can estimate the rolling forces.
In the final design, includes two full–bridge circuits (Figure 8-17 (a)). One bridge is at the front of the scribe while the other is behind the cutter (Figure 8-17 (b)). This system will allow the probe to obtain normal forces as well as rolling forces.

**ADNS9800 laser sensor**

For the measurement of the probe position inside the drillhole laser sensors were deemed to be the most accurate. The Avago ADNS 9800 laser sensor is selected for this project, which is very small, low cost and has the right resolution and precision to fit the application. The lens can be adjusted to a maximum distance of 5mm. The resolution is also adjustable to different surfaces.
This sensor measures changes in position by optically acquiring sequential surface images (frames) and mathematically determining the direction and magnitude of movement.

Figure 8-18 (a) and (b) illustrate the laser sensor assembly.

As shown in Figure 8-19 the ADNS 9800 sensor is directly attached to its breakout PCB and the PCB is fixed to the housing by two Allen screws.
Microcontroller program components

The probe relies heavily on an efficient software system in order to collect the physical inputs and produce accurate outputs in an easy-to-read format. The code is written in Arduino software environment, and is developed in a way that all the data is transferred to a micro SD card at the desired interval (500 ms is recommended to maximize the battery life). This code has been progressively improved and optimized so that the sensors are reliably interfaced with the Teensy microcontroller. This procedure involved rigorous programming and debugging of the sensors.

The final code consists of a main program, namely “fullsystem.ino”, and a supplemental program titled “sdModule.ino”. The sdModule.ino uses the SD.h (or SD-fat.h) library to implement methods to save data into a MicroSD card. These programs take advantage of several libraries, and a number of custom functions.

Electrical System Schematic & Printed Circuit Board Design

The schematic of the electrical system and therefore, the Printed Circuit Board went through several revisions to optimize the electrical performance of the probe. So far, three versions of the schematics and PCB/breadboards are developed, the final version is described below.
Figure 8-20 shows the schematic of the final PCB design. In this figure, each electronic component has a separate terminal so that its relevant wires are all solder besides each other in a certain location. Moreover, new terminals are added to the system, which are for the installation of a camera, a second laser sensor, LED lights, an electronic potentiometer and a current sensing module.

The new design of the PCB, as illustrated in Figure 8-21. The camera system can help us monitor/record the exact area that is tested before and after the scratching and could generate the image for analysis of joints and rock structure in an integrated tool.

As it can be seen in Figure 8-21, the RTC module is located as far as possible from the strain gauge bridges. Moreover, other connections and SD module are also located away from the bridge wiring. All the connections and components are also tried to be concentrated in the middle of the PCB so that they are furthest to the probe shell and therefore the maximum height, to accommodate all the parts neatly and easily without risking damaging the wires and losing the connections.
Figure 8-20: schematic of the third version of the electrical system (after John Sopczynski, 2016).

Figure 8-21: Third version of the PCB (after John Sopczynski, 2016).
**Electrical Housing Cover and Pushbutton Switch**

The Electrical Housing Cover is designed to protect the electrical components of the system as well as provide an easy access to commonly used aspects (ON/OFF switch and SD card). Adding this new feature requires developing a Push Button Extender to be able to reach the Mom. Power Switch. For the design of these new components three main factors were considered, which are conductivity of the material, weight, cost, and ease of fabrication. Figure 8-22 illustrates the designed Electrical Housing Cover and Push Button Extender. In this figure, Push Button Extender (6), will be fit to the hole (1) on the cover, that is centered relative to the top of the Mom. Switch Power. LED indicators will be at location (2) and the MicroSD card can be accessed through the designated notch (3). To fix the cover on the electrical housing, a notch (4) is added at the top of the cover to integrate it with the housing. In addition, a screw hole is drilled into the cover so that the cover can be fully secured by a screw to the housing to make them as a one whole piece. The final assembly is shown in Figure 8-23. This design and dimensions of the components are based on the initial SolidWorks drawings for the Electrical Housing model.

![Figure 8-22: Electrical Housing Cover – Isometric View [128].](image-url)
Figure 8-23: (a) Assembled Electric Housing where the letters denote (A) Electrical Housing, (B) Electrical Housing Cover, (C) LED mockups, (D) Push Button Extender, and (E) SD Card Module mockup; and (b) Exploded View of Electric Housing [128].
Chapter 9

Testing RSBP® in the laboratory and the field

Introduction

This chapter covers the laboratory and field tests that are run on RSBP® and the results are discussed. Although these experiments are the major tests run on the probe, an extensive time has been spent on the probe to make all the parts suitable for field application to perform as expected. As discussed in the last section, RSBP® has gone through many changes along this process. In this chapter, the laboratory tests and then the field tests are explained. More field tests are still needed to be done to evaluate RSBP® performance in field applications and more laboratory tests is required to calibrate the force measurement system of the tool.

Laboratory experiments

After full assembly of the prototype probe and, various experiments were done on different components of RSBP® to assess the performance of each individual part as well as the whole device. Two of the main laboratory experiments, “Sandwiched rock sample” and “mine roof simulation”, are presented below. The objective of the first series of tests, was to evaluate the interaction between sensory components and their outcomes in order to ensure that the electronic components work properly and can reliably collect/record useful data. The second experiment, however, was focused on the whole probe and to assess the performance of all the RSBP® parts in an underground simulated environment.
Sandwiched rock sample

The main goal of the experiment in a composite sample (sandwich sample) was to verify the functionality of the Components and the RSBP system as a whole. through full scale testing and collection of relevant and meaningful data. The main components of RSBP included strain gauges, laser position sensor, Teensy micro-controller, and the SD module. To have a more realistic series of tests, the actual cutter housing was mounted on the miniature linear cutting machine that was used for the performance of the scratch tests. Tests involved cutting of a sandwich of selected rock samples fabricated to simulate the rock layers inside a borehole. The test procedure was similar to scratch tests, except that the data was recorded on the micro SD card, and the testing area was covered with a black plastic sheet to simulate the darkness of the borehole. Figure 9-1 (a), (b), and (c) show the cutter housing assembly, the fabricated sample, and the test setup, respectively.

Figure 9-1: (a) cutting housing assembly, (b) the fabricated sample, and (c) the test setup developed for sandwich rock sample experiment.
The selected rock samples for this experiment were discussed before and included (from left to right in Figure 9-1 (b)) S25 - travertine, S6 - pegmatite, and S18 - limestone. UCS values of the samples were measured at 58, 134, and 93 MPa, respectively. The tests were performed for the penetration depths of 0.6 and 1 mm with three repetitions for each test. Figure 9-2 shows a typical result for the test with a scratch depth of 1 mm. The plot shows both front and rear strain gauge bridge outcomes in mV, as well as the position of the scribe in millimetres and inches. Moreover, the plot is divided into five sections, which shows the location/span of each rock sample or concrete, and the black lines in each window approximate the transition between rocks. As expected, S18 shows the highest mean value, and the S25 has the lowest force reading. Although S6 has the highest strength from the scratch test results, a medium intensity of measured forces due to the texture of the rock and its dependence to mineral grain size was observed.

The initial analysis of data shows acceptable performance of both strain gauges and the laser sensor. Moreover, all the experimental data were successfully recorded on the micro SD card, which also shows that the selected movement sensory system is working well. However, more tests need to be run to calibrate the system for working conditions in different rock measures that could be encountered in a borehole. It is expected that the difference between the rear and front strain gauge sets would allow for the calculation of rolling forces. These readouts will subsequently be compared with the similar scratch test outputs to verify the accuracy of rolling force estimates for further analysis of cutting depth. Moreover, additional testing of the laser sensor is needed to select the optimum position of the sensors for the highest accuracy.
Measurements in a drilled borehole at Fletcher facility

After observation of acceptable results from the sensory parts, the RSBP was fully assembled to be tested at J.H. Fletcher & Co. For these experiments, a cast concrete block was fixed at the top of the drilling rig platform, and several upward holes were drilled into the designated block, as shown in Figure 8 (a). The tests proved that the RSBP® operation can be considerably affected by local deviations in the borehole. A deviation with a relatively acute curvature angle can prevent proper measurement of pertinent parameters by RSBP® inside the borehole. Despite the considerable undulation of the walls along the holes, some successful tests were run inside some holes. Figure 8 (b) presents the plot of measured forces in one of the boreholes. Not much analyses were done on the results since it was not possible to fully visualize the borehole condition to interpret the RSBP results. However, the graph shows that all of the electronic sub-systems were working well, and the mechanical parts was able to scratch the surface of borehole, which means

Figure 9-2: Typical test result from the sandwich rock sample experiment
that the tool was ready for field testing.

Sensor Calibration

Position Sensor

Calibration of the position or laser sensor for detection of probe movements was one of the challenges for application of RSBP® tool. This is due to the fact that many factors influence the results, including the light and surface condition, and the motion speed. Before the start of calibration, the resolution of the sensor was adjusted based on the specifications in its datasheet to obtain the most accurate measurement on different surfaces. The sensor was tested on various surfaces, i.e. a normal mouse pad, a wooden table, and white paper, and then the results were confirmed with the pertinent details inside the sensor datasheet.
The next step was testing of the sensor on rock samples under different conditions. The results of some of these experiments are summarized in Table 9-1. The parameters tested for their impact on laser sensor performance and accuracy, can be noted as below:

- Sensor motion velocity (V, mm/min)
- Different rock surfaces and colors (light or dark).
- Direction of motion (forward, backward)
- Distance of the sensor from the surface (mm)
- Light condition (on, fully covered)

By comparing the results of tests number 2 and 4 it can be noted that when the lights are on, the motion velocity does not affect the results significantly. However, under dark conditions, the conversion factor generally increases by the increasing in sensor velocity. This can be observed in test number 8, 10, 12, 14, 16 or 9, 11, 13, 15 and 17. One exception was the results at speed of 1500 mm/min where the conversion factor was decreased. Tests 18 and 19 are the results from two of the sandwich sample scratch tests, where the depth of scratches are 0.6 and 1 mm, respectively. Although all the other conditions are the same, the variation in measured speed in different rocks was relatively high. This might be due to the difference in the intensity of vibration caused by cutting operation. It is clear that the intensity of vibration is higher when the depth of cut is larger.

The accuracy of the laser sensor can be considered independent from the direction of motion. Under dark condition, the difference between forward and backward tests were less than %10 while it seems like when the lights are on, there is no difference.

The impact of the sensor distance from the target surface is very crucial. Tests 1-4 that have a distance of less than 4 mm, show similar results while at a distance of 8 mm from the surface, the difference in sensor accuracy is very remarkable. It should also be noted that at distance larger than 10 cm, the sensor does not work.

Higher ambient light can slightly affect the sensor outputs within a range of %10-%15. The color of the rock, however, can make a very significant impact on the sensor performance. The
sandwich rock sample is composed of rocks with light colors while S11 has a dark colored mineral. Comparison of test number 6 and 7 with 2 and 3 or 8 and 9, shows a difference at the range of 60%.

Finally, it has been noticed that other changes on the circuit board such as the sampling rate can affect the results. This was clearly obvious after the field test at Graymont mine. As a result, the disc cutter position was calibrated by recording the total length of the rod. This means the while the motion sensors can identify the movement of the probe and active the data recording, their accuracy is not sufficient for recording the depth or distance of the movement. Hence, it is advisable to record the depth of probing for calibration or perhaps for further analysis. The depth of borehole logged is equal to one half of the distance that is logged by the laser sensor would indicate in related recorded data file.

Table 9-1: Comparison of position sensor results on varied surface conditions.

<table>
<thead>
<tr>
<th>#</th>
<th>V (mm/min)</th>
<th>Rock Type</th>
<th>direction</th>
<th>Length of Rock (cm)</th>
<th>Distance from Surface (mm)</th>
<th>Conversion Factor</th>
<th>Deviation from the mean</th>
<th>LIGHT</th>
<th>Rock Color</th>
</tr>
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<tbody>
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<td>1</td>
<td>460</td>
<td>Sandwich</td>
<td>forward</td>
<td>18.161</td>
<td>2</td>
<td>1.524</td>
<td>-13.36%</td>
<td>Lights on</td>
<td>Light</td>
</tr>
<tr>
<td>2</td>
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<td>Sandwich</td>
<td>backward</td>
<td>18.161</td>
<td>4</td>
<td>1.517</td>
<td>-14.00%</td>
<td>Lights on</td>
<td>Light</td>
</tr>
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<td>3</td>
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<td>Sandwich</td>
<td>forward</td>
<td>18.161</td>
<td>4</td>
<td>1.517</td>
<td>-14.00%</td>
<td>Lights on</td>
<td>Light</td>
</tr>
<tr>
<td>4</td>
<td>1570</td>
<td>Sandwich</td>
<td>backward</td>
<td>18.161</td>
<td>4</td>
<td>1.633</td>
<td>-2.40%</td>
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<td>Light</td>
</tr>
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<td>forward</td>
<td>18.161</td>
<td>8</td>
<td>7.294</td>
<td>563.64%</td>
<td>Lights on</td>
<td>Light</td>
</tr>
<tr>
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<td>S11</td>
<td>forward</td>
<td>17.462</td>
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<td>0.861</td>
<td>-79.57%</td>
<td>Lights off</td>
<td>Dark</td>
</tr>
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<td>S11</td>
<td>backward</td>
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<td>0.888</td>
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<td>Dark</td>
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<td>forward</td>
<td>18.161</td>
<td>4</td>
<td>1.654</td>
<td>-0.32%</td>
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<td>Light</td>
</tr>
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<td>Light</td>
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<td>Light</td>
</tr>
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<td>Light</td>
</tr>
<tr>
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<td>Light</td>
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<td>14.45%</td>
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<td>Light</td>
</tr>
<tr>
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<td>forward</td>
<td>18.161</td>
<td>4</td>
<td>1.156</td>
<td>-50.12%</td>
<td>Lights off</td>
<td>Light</td>
</tr>
<tr>
<td>17</td>
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<td>Sandwich</td>
<td>backward</td>
<td>18.161</td>
<td>4</td>
<td>1.743</td>
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<td>Lights off</td>
<td>Light</td>
</tr>
<tr>
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<td>18.161</td>
<td>4</td>
<td>2.667</td>
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<td>Light</td>
</tr>
<tr>
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<td>backward</td>
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<td>4</td>
<td>2.444</td>
<td>78.71%</td>
<td>Lights on</td>
<td>Light</td>
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</table>
Force Measurement Sensor Using Strain Gauges

Similar to the load cell, the strain gauge bridges are also calibrated using a hydraulic jack system. The only difference is that instead of the scratch test assembly, the cutter housing was directly mounted on the miniature linear cutting device, as shown in Figure 9-4. The calibration has been done in two settings, one when the jack was in the front and rear of the housing, as shown in Figure 9-4.

Figure 9-4: RSBP calibration by a hydraulic jack system.

The results of calibrations are plotted in Figure 9-5 (a)-(d). Figure 9-5 (a) and (b) show the results when the jack is located in front of the cutting housing and Figure 9-5 (c) and (d) show the results when it was located behind it. These graphs show some hysteresis in the responses. This might be also due to the inaccuracy of the jacking system. By replacing the pressure gauge with a calibrated load cell fixed to the tip of the jack, the accuracy of the calibration was dramatically increased.
For calculation of the calibration coefficient, the method developed by Lam (1989) [131]. In this procedure, the first-order calibration equations can be written as below:

$$R_F = C_{1,1}F_N + C_{1,2}F_R$$

$$R_R = C_{2,1}F_N + C_{2,2}F_R$$
Where the R is the ratio of the output voltage of the front (F) or rear (R) bridge divided by the pertinent input voltage. Furthermore, Cs are the calibration coefficients and \( F_N \) and \( F_R \) are the normal and the rolling forces, respectively. In this approach, the calibration coefficients are calculated by minimizing the sum of the squares of the differences between the measured strain-gauge output voltage ratios and those obtained from a calibration equation.

**Field experiments**

**Evaluating Performance of Mechanical Subsystems**

Some field tests were performed at Graymont mine and while some problems in electrical components prevented the measurement of forces, the mechanical subsystems were examined. This was done by verifying the traces of the scratching within the borehole by using a borescope. Multiple scratches were observed when the probe was inserted into the borehole in ceiling and side walls. Our probe proved that it can scratch the inside surface of the borehole. Also, the guide wheels proved their importance in preventing the probe from getting stuck inside and kept the cutter head in constant contact with the wall.

RSBP was tested in two stages at two underground mines. In the first stage, the mechanical performance of the probe was examined at a limestone and an anthracite coal mine. Figure 9-6 (a) and (b) shows the condition of boreholes after the testing and typical scratch traces that were generated by running RSBP inside the borehole in the limestone and coal mine, respectively.
Total performance Assessment

At the second stage of testing after some modifications was conducted at the same limestone mine. Following graphs in Figure 9-7 shows the result for one of the tested boreholes. This graph shows the strain gauge outputs from where the laser sensor has started to register data up to where the probe reached the maximum depth, which is about 1500 mm (60 inches). From this graph and the field observations, it can be said that both guide wheels got fully engaged at about 250 mm (10 inches) from the collar of the borehole. Moreover, the sudden plunge at the depth of
about 750 mm (30 inches) might be due to a significantly wide discontinuity. Variation of forces shows the application of the probe in a borehole without variable rock type (same limestone formation along the hole).

Figure 9-7: Experiment The result of probing a borehole by RSBP at a limestone mine.

The initial results show promising prospects for using RSBP in the field, which will be able to measure the intact rock strength properties, UCS and BTS, by scratching the wall of a drillhole using a disc-shape scribe. The laboratory and field tests proved that the electronic components of this tool can work reliably and record the pertinent force and position data. The mechanical subsystems were also successful in making scratches on the borehole wall. Additional field testing and analyses are required to evaluate the RSBP laboratory and field test results in various working conditions.
Chapter 10

Conclusions and recommendations

This research study has focused on developing new systems for quick evaluation of the ground conditions, including rock strength and joint system for assessment of rock mass classes pertinent to ground support design. The information can be obtained by applying proper probes to log the boreholes, that are used for roof bolt installation. These boreholes are small diameter, dry and upward and so far there has not been any reliable methods which can provide pertinent information on rock strength and joining. The information generated by the probe can also be used to train the instrumented or smart roof bolting systems where the recorded operational parameters of the drill can be used to assess ground or rock mass conditions based on comparison with the result of logging in selected holes. This study has looked into use of borehole cameras or optical televiewers to assess the joints and discontinuities. While some technologies exist for recording of the information, additional work was needed to translate the visual information to quantitative measures pertinent for assessment of rock mass conditions. The review of the literature and available technologies proved that there is no existing technology that can measure rock strength in small, dry boreholes. Therefore, ample amount of efforts was directed to development of such a probe.

Using the principal of scratch testing inside the borehole proved to be applicable and promising, and was considered for this application. This study is the first time that scratching of rock surface is applied to estimation of rock strength in a small borehole. Design of such probe required development of a miniature rock cutting device to be able to measure the anticipated cutting forces. An extensive testing program was implemented where over 30 different rock types were cut by various scribes and cutting forces were recorded. Statistical analysis of data allowed
for development of relationships between cutting forces and depth of penetration and rock strength. These equations allow for estimating rock strength from recorded forces and of penetration. The results were also used in design of a borehole strength probe, which was subsequently tested in the lab and in the field.

In the course of this study and analysis of the result of testing in the laboratory and field, various topics were covered and following is the summary of Conclusions of this study. Some recommendations are also offered for the follow up work to complement and complete the current study.

**Conclusions**

- There is strong evidence of promising potential for developing a reliable instrumented drilling machine. However, the full potential of instrumented drills and their field applications is essentially dependent upon conducting an extensive number of field tests in various ground conditions. The accuracy/performance of the developed algorithms for detection/estimation of geological features needs to be evaluated and compared with the real geological condition inside the drilled boreholes.
- Verifying the ground condition is best done by means of borehole probing/logging. Borehole logging is cost effective and offers continuous information about the in-situ condition of the ground surrounding the drillholes. However, not much efforts have been made to utilize these approaches for acquiring the geological information from inside the holes drilled by a roofbolter.
- This study has gone through an extensive evaluation of various methods for identification and selection of proper borehole tools for rock mass classification based on the CMRR system. In this ground characterization system, the intact rock Uniaxial
Compressive Strength (UCS) and the discontinuity conditions are the most important/influential factors.

- Optical TVs in general and Slim Borehole Scanner (SBS), manufactured by DMT GmbH & Co. KG, in particular, are found to be the best tools available to-date for evaluation of the discontinuity/joint conditions along the borehole. This device is light and is designed for upward probing applications inside the coal mines. This tool, similar to the other OPTVs, generates a 360° image of the drilled holes and records their orientation information for further structural analyses.

- Our field experiments showed that QL40OBI OPTV, which is conventionally used for down-hole probing, is not suitable for performance of upward logging due to difficulties in the operation. Especially, the relatively high weight of the tool makes it very difficult to have a smooth operation beside the point that the logging procedure is very tedious under this condition.

- This study showed that for estimation of rock strength (UCS), the conventional Full wave-form sonic and acoustic TV logging methods are not suitable for small/upward/dry boreholes, which are located at the roof and ribs of the underground spaces. As a result, a mechanical approach needed to be employed to estimate this parameter.

- Scratch test technique is deemed to be a suitable alternative for the estimation of the intact rock strength. By adapting this concept, a new probe called Rock Strength Borehole Probe or RSBP®, was designed and manufactured. This probe is able to measure the normal and rolling forces imposed on its miniature cutting wheel along with its position relative to the borehole collar. Two pre-tensioned guide wheels located behind the disc scribe generate the normal force needed to press the scribe into
the rock surface and scratch the rock while two adjustable/smaller guide wheels on the sides of the scribe restrict the penetration depth to the specified amount, e.g. 1 mm.

- An extensive number of scratch tests has been carried out on 27 different types of rocks by means of a newly developed miniature linear cutting machine, in order to investigate the correlation between the forces needed to scratch the surface of a specific rock and its Uniaxial Compressive Strength (UCS) and Brazilian Tensile Strength (BTS). The findings show that the UCS and/or BTS of the sedimentary and metamorphic rocks, are well correlated with the scratching forces. This means that the UCS of sedimentary rock can be estimated from measured scratching forces with high degree of confidence as opposed to igneous rocks, where the results were scattered and good correlations could not be found.

- In most cases, exponential function offers the best fit and the data from 0.8-mm deep cutting tests offers the highest R-square in majority of cases. Normal and rolling forces both gives acceptable formulas for estimation of strength of sedimentary and metamorphic rocks.

- UCS and BTS of sedimentary and metamorphic rocks can be well correlated to the cutting forces through the following equations:

\[
UCS = 25.099e^{(0.0003FN)} \quad R^2 = 0.767 \text{ (for 1 mm scratch depth)}
\]

\[
BTS = 1.943e^{(0.0004FN)} \quad R^2 = 0.815 \text{ (for 0.8 mm scratch depth)}
\]

- Since, in real application of the RSBP® it is not likely to have a constant penetration, the equations were modified to incorporate the variation of penetration (P) during the cutting process as following:

\[
UCS = 5.84e^{(0.243\ln(FN) - 1.648\log(P))} \quad R^2 = 0.569
\]
Based on the results of laboratory cutting experiments on the effects of cutting velocity, increase in the speed of cutting either causes increase in the magnitude of the normal force or no significant change can be observed in the results in most igneous rock samples. Also, increased speed has insignificant effect on the cutting forces in sedimentary and metamorphic rocks. Furthermore, the slope of the regression lines is similar for different scratch depths, which means that regardless of the depth of cut, the cutting speed affects the normal forces in the same way.

Since the developed equations for the scratch tests in this study are solely applicable to the sedimentary and metamorphic rocks, we can conclude that based on the aforementioned results and considering the range of the cutting speeds, cutting speed doesn’t have a significant effect on the cutting forces during the scratch test.

The experiment show that cutting the curved surface of the rock, can result in higher normal forces. This might be due to the geometry of the cutting surface and the impact of surrounding walls which confines the surface and can increase the length that the cracks needed to reach the rock surface.

The trends for the normal force needed to scratch the surface of the igneous sample (S5) on curved surfaces were inconclusive. Test results of the sedimentary / metamorphic sample was as expected and forces increased with decreasing radius of the curved surface (hole diameter). Furthermore, it can be deduced that by increasing the scratch depth, the difference between the flat and curved surfaces becomes more pronounced.

The current studies show promising results for using RSBP® in the laboratory setting when it was tested in drilled boreholes as well as field applications. The laboratory and
field tests proved the functionality of the electronic components as well as effectiveness of the mechanical system in making scratches on the borehole wall.

- The initial testing proved that by measuring the forces for scratching borehole wall one can identify transition from one rock type to another and offer a reasonable estimate of the rock strength. This data can be visualized to show 3D position of the layers and rock strata, perhaps the rock mass classes for better presentation of the outcomes from borehole logging.

**Recommendations**

- Although the results of this study and lab testing covers a broad range of rock types, more testing is required to verify the formulas and extend the outcomes broader range of geological conditions. Moreover, the impact of other parameters, such as rock matrix, mineralogy, and grain size, needs to be evaluated to improve the accuracy of the estimated UCS and BTS in various rock types.

- Additional tests are required to assess the effect of cutting velocity and surface curvature, and therefore, to allow for generalized conclusions.

- The mechanical components of the RSBP® need to be optimized to offer a more compact but more effective system of generating the load required on the cutting wheel. Additionally, further laboratory/field tests need to be done on the tool under various conditions to calibrate/optimize the performance of the electronics, especially the position sensor. The field tests can also include SBS probe, instead of borescope, to better evaluate the RSBP® results.
• A camera system can be added to the probe so that the borehole wall condition before and after scratching can be observed and examined.

• A user-friendly interface should to be developed for processing the data from both SBS and RSBP® tools. This program can be made in a way that the CMRR value, and/or other rock parameters, are calculated based on the processed data and the final outcomes are illustrated in varied 2D/3D maps.
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