Introduction to Rock Strength Borehole Probe (RSBP) for Estimation of Rock Strength in Roofbolt Drill Holes

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ABSTRACT

Improving the safety of underground openings and optimizing ground support systems requires reliable ground characterization. This includes understanding the joints, discontinuities, and rock strength. Joint information can be obtained from borehole cameras, but measuring in-situ rock strength is very difficult. Use of borehole probes can be an ideal and efficient way to meet this requirement. This paper discusses the development of the Rock Strength Borehole Probe (RSBP) and presents the preliminary laboratory/field test. This device can be an accurate, flexible, quick, non-disruptive, and cost-effective alternative to estimate the rock strength inside boreholes in underground mines and tunnels. In addition, the scratch testing procedure in the laboratory by means of a newly developed miniature linear cutting machine is explained. Based on the results of these tests, two equations are developed to estimate the uniaxial compressive strength (UCS) and Brazilian tensile strength (BTS) of the sedimentary/metamorphic rocks. These equations, are based on testing 27 different sedimentary, igneous, and metamorphic rocks 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 rock if the depth of the scratch is known. No significant correlation was observed for igneous rocks, due to the impacts of grain size.

INTRODUCTION

Estimated rock mass properties are essential input for geomechanical studies and stability analysis for any structure constructed in or with rock. The availability of geological information is the crucial component of rock mass classification. One of the important parameters in evaluating rock mass properties is the intact rock strength. This parameter is usually measured by testing the core samples, obtained from exploration boreholes. These samples are subsequently tested in geomechanics laboratories. The test results offer limited information about the rock at the few boring locations despite all the efforts and costs. In addition, these results may not necessarily be representative of the behavior of the rock in the field as the test cannot provide the in-situ condition of the ground.

The scratch test has proven to be a promising approach to estimate the intact rock strength. The scratch test is based on the relationship between the cutting forces and mechanical properties of the rock. This relationship has been extensively studied for decades (Fowell, 2013 and Nishimatsu, 1993). Engineers at the University of Minnesota used this method to develop a rock strength measurement device in 1990s based on the initial studies of the cutting models of drag bits (Detournay and Defourny, 1992) and PDC (polycrystalline diamond compact) cutters (Almenara and Detournay, 1992). The initial work was followed by correlating the rock strength to the cutting test results (Detournay, Drescher, Defourny, and Fourmaintraux, 1995; Adachi, Detournay, and Drescher, 1996), which subsequently lead to the development of a device called the Rock Strength Device (RSD) (Detournay, Drescher, and Hultman, 1997). The scratch test has two main advantages: First, the test can be performed with a small sample and minimum to no sample preparation. Second, the strength is continuously recorded along the core sample, which partially removes the issues with representative specimen selection. These features have made this method appealing in various areas of application.

The development of RSBP at The Pennsylvania State University (Penn State) is based on the aforementioned approach. This tool can measure the in-situ strength of the rock inside narrow/upward/dry boreholes. RSBP was developed mainly because most borehole strength measurement systems available today, such as sonic or acoustic televiewers, have been primarily developed for larger downward holes that are long and filled with water. The current scratch methods (i.e., RSD) use rock core from diamond drilling to estimate the rock strength. This approach has addressed some of the issues related to rock testing. However, conventional approaches for preparing samples and getting continuous strength results still have the disadvantages of not being truly in-situ. They provide limited information from relatively scattered boreholes and are relatively costly and time consuming from the initial stage of coring and handling to setting up the samples for running the scratch test.

A scratch probe device overcomes these shortcomings by testing the rock in-situ and inside drilled boreholes in the underground opening. The system is based on using the holes that would be drilled in the normal operation cycle during the development of a tunnel, drift, mine entries, or a stope for roof bolting or blast rounds. The estimated strength values can be readily obtained on site by real-time analysis of the probing data with specialized software. Moreover, unlike the other scratch devices, which use wedge shape scribes to scratch the surface of the rock core, this study has used miniaturized disc cutters as the means to scratch the borehole wall. This will help the operator run the probe inside the borehole with much less effort in terms of pushing the probe in the borehole and its retrieval, minimizing the chance of the probe getting stuck inside the borehole.

This paper will give a brief explanation about the methodology used for performing laboratory scratch tests and the results of the preliminary tests. The results of the full-scale cutting tests were used for the design of the RSBP. The design process and the results of the laboratory and field experiments are discussed in the following sections.

LABORATORY SCRATCH TESTS

The miniature disc cutter was selected as the suitable type of scribe, which requires higher normal forces (applied against the borehole wall) and lower rolling force (parallel to the borehole axis) to penetrate the rock. Therefore, the focus of this study was on developing correlations between mechanical properties of the rock and cutting forces, while making a scratch by a tungsten carbide disc scribe. Figure 1 shows the overall picture of the linear cutting device used for testing.

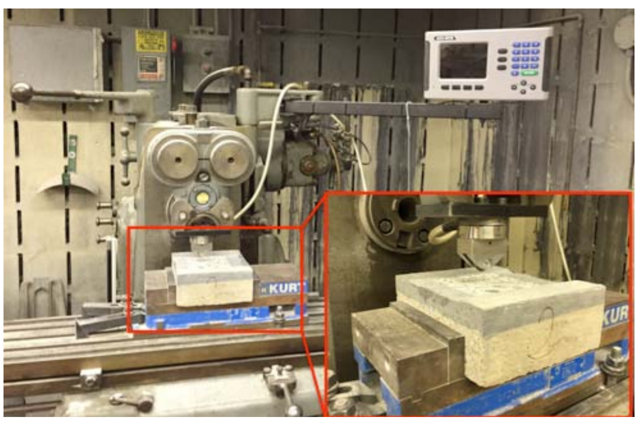

Figure 1. Linear cutting device developed to run the scratch tests.

There are various parameters involved in the scratch test, including tool velocity, scratch depth (penetration), spacing between the scratches, type/geometry of the scribe, rock type, and bit wear. During the tests, the scribing velocity was kept constant at about 2.6 m/min. The scratch depth varied between 0.2 mm and 1 mm with an interval of 0.2 mm, and each identical test was repeated at least 3 times. To minimize the effect of the adjacent scratches, a distance or cut spacing of 10 mm was used. The cutting tests were performed on various samples ranging from soft rocks such as coal, medium strength rocks such as limestone, to hard rocks such as granite. Some of the samples were collected from nearby coal/limestone mines in Pennsylvania, and the majority of samples were part of a dimension stone collection from around the world. The samples tested in this study included sedimentary, metamorphic, and igneous rocks. To eliminate the impact of bit wear on forces, the cutting edge of the disc scribe was examined by a microscope on a regular basis. In a limited study, a set of ten 1-mm-deep scratches on the surface of various hard samples were made, but negligible or no bit wear was observed by close examination under microscope. Despite this observation, disc cutters were replaced occasionally to eliminate any possibility of cutting behavior being impacted by bit tip wear.

Engineers at Penn State designed and fabricated the miniature linear cutting test device, using precise instruments and load-sensing components to meet the required high accuracy in force/position measurements. A round triaxial load cell with 14,000 N (3,000 lb) capacity measured the cutting forces in three directions, and the positioning data was collected from a triaxial readout system, with an accuracy of 0.0001 mm. All related information was monitored by a data acquisition (DAQ) system. The load cell data was collected by a NI USB-6341 X series system and recorded on a PC by a specialized MATLAB code. Rock samples were cast in concrete to provide a confining support for the specimen. The samples were then mounted and fixed on the machine table by a vice. A special flat polycrystalline diamond (PCD) bit levelled the surface of the sample by shaving it while moving the table relative to the scribe. Figure 2(a) shows the cutting tool and surface scraper assemblies, and (b) shows a typical result of the cutting test on the limestone sample with the cutting depth of 0.6 mm. It is expected that the results of scratch tests on a flat surface differ from the actual situation, which is the borehole curved surface. Under this circumstance, it is probable that the borehole wall extends the length that the chipping crack needs to propagate until it reaches the free surface, which means additional force would be needed to make this happen. The effect of surface curvature will be discussed in detail in the future papers.

A MATLAB (**mat**rix **lab**oratory) code was developed to process the data and SPSS (Statistical Package for the Social Sciences) software package was later used to examine the correlation between the normal and rolling forces and uniaxial compressive strength (UCS) or Brazilian tensile strength (BTS) values by using regression methods. Unlike the sedimentary and metamorphic rocks with a rather linear trend between forces and UCS, the igneous rocks showed no noticeable correlation. Based on the processing outcomes, normal and rolling forces both give acceptable formulas for estimation of UCS from cutting forces in sedimentary and metamorphic rocks. Figure 3 (a) and (b) show the best fit curves and related equations for estimation of UCS and BTS from cutting forces, respectively. It should be noted that, for convenience, "the average of normal and rolling forces during the cut" are simply called "normal and rolling forces" in the rest of the paper and are referred to as FN and FR, respectively.

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 during the cutting process. Statistical analysis of available data has offered the following equations to predict UCS and BTS from recorded penetration (P) and normal force (FN) data:

$$UCS = 5.84e^{(0.243\ln(FN) - 1.648\,Log(P))} \quad (1)$$

Figure 2a. Pictures of cutting tool and surface scraper assembly.

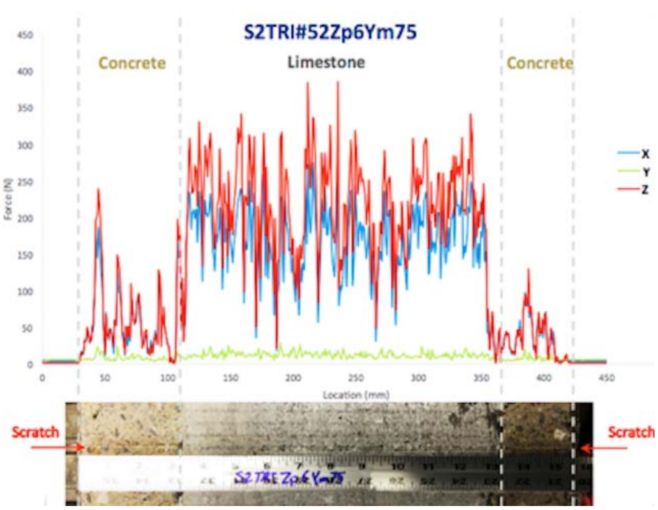

Figure 2b. Pictures of typical result of cutting test and the resulted scratch.

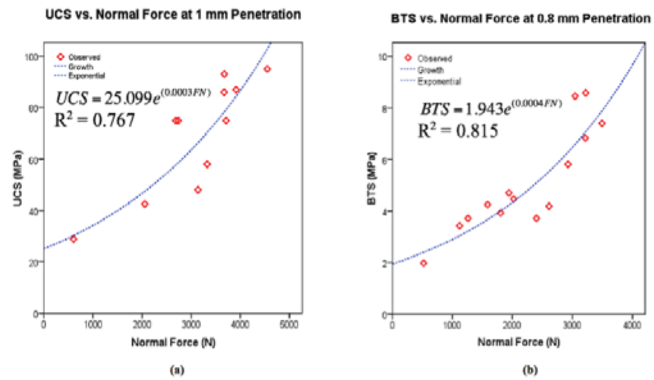

Figure 3. Best curve fits and their formulas for (a) UCS, and (b) BTS, of sedimentary and metamorphic rocks.

$$BTS = 0.26e^{(0.294\ln(FN) - 2.032Log(P))} \quad (2)$$

Although these results are from a broad range of rock types, more rock samples are yet required to be tested to verify these outcomes. Moreover, the impact of other parameters, such as rock matrix, mineralogy, and grain size, needs to be evaluated to improve the accuracy of estimated UCS and BTS in various rock types.

ROCK STRENGTH BOREHOLE PROBE DESIGN

The results of the cutting tests were used for the design of the RSBP, which was the final goal of this project. This probe is 38.1 mm in diameter, which allows it to be operated inside boreholes with 44.5 mm diameter. These boreholes can be 2–10 m long with any arbitrary orientation. The fabricated probe is light enough for an average person to operate. The RSBP measures normal and rolling forces on the scribe with a load-sensing device and monitors linear displacement using optical sensors and a micro-controller. Data is stored on a micro SD card for subsequent analysis. The RSBP is designed to be user friendly and operates by simply pressing the power button. It begins logging both position and force data once it enters the borehole. Figure 4 shows the initial conceptual design of the RSBP. The initial design involved a depth sensor for continuous recording of the depth of the scratch, as shown in Figure 4. However, during this study, no cost-effective option was found that could fit inside the RSBP and measure the depth of the scratch with the accuracy needed for subsequent analysis.

The scribe is pressed against the borehole wall by two sets of spring loaded guide wheels located on the opposite side of the scribe. In addition, two smaller wheels are attached to the ends of the cutting housing to limit and control the depth of the cut. These wheels are designed to be as wide as possible to reduce the contact stress between the rock and the wheels and as a result protect the rear rock from getting crushed. Position of these smaller wheels relative to the scribe can easily be adjusted externally by special screws. After positioning the wheels at the desired setting, they will log and regulate the depth of the cut. The combination of these four guide wheels will help to ensure that the scratch depth is constant

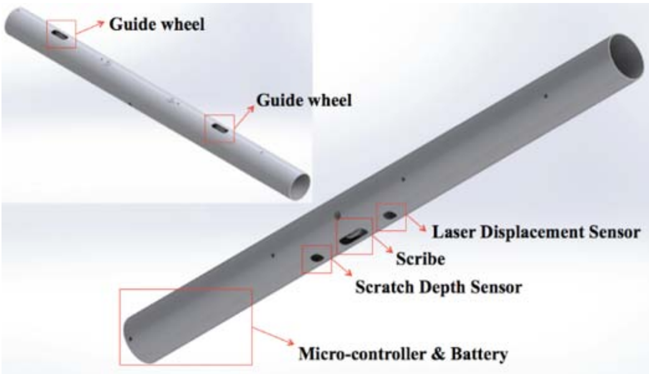

Figure 4. The conceptual design for the mechanical part of scratch probe with a disc scribe.

while the RSBP is running along the hole, without imposing unwanted pressure on the cutter housing and, therefore, the disc cutter. The operator can adjust the amount of normal force or the depth of the cutting head by control screws. This will also ensure the guide wheels will not crush the rear rock.

The mechanical parts of the probe went through many design steps and modifications. All the parts were designed by the aid of SolidWorks program. All of the parts were manufactured at a Penn State machine shop according to the drawings. In some cases, some minor modifications were made in order to facilitate the manufacturing process. The RSBP is divided into two sections: mechanical and electrical.

To develop a relatively lightweight probe, 6061 Aluminium was used to make all of the parts except the electrical housing, which is made of polycarbonate to prevent any electrical connectivity through the probe. 6061 Aluminium 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. All of the components fit inside an anodized 38.1 mm 6061 Aluminium tubing. Figure 5 (a) and (b) show the cross section of the designed probe and the final product, respectively.

For the electronic assembly of the RSBP, a circuit design was generated, where a Teensy 3.2 micro-controller is the key component and 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 an 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 storage and RAM of 256 KB and 64 KB, respectively.

The electronic components installed at the cutter housing are the strain gauges and the laser position sensor. The final design has two full-bridge strain gauge systems with eight strain gauges placed around the base of the cutter housing. The front and the rear circuits are separate to allow for measurement of normal and rolling forces.

For the 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 systems in the market for such measurements. A suitable laser sensor was selected for this purpose, which is very small, low cost, and has the right resolution and precision to fit our application. The lens can be adjusted to a maximum distance of 5 mm. 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 be more accurate, and, as such, the sensor was installed in such a way that the x direction sensor was aligned with the probe logging direction.

The probe relies heavily on an efficient software to collect the physical inputs and to produce accurate outputs in an easy-to-read format. Arduino software writes the code on a micro SD card every 500 ms.

LABORATORY EXPERIMENTS

After the full assembly of the prototype probe, various experiments were conducted on different components of the RSBP to assess the performance of each individual part, as well as the whole device. Two of the main laboratory experiments, including testing of the “sandwiched rock sample” and “mine roof simulation,” are briefly presented here. 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 parts are functional and can reliably collect and record useful data. The second experiment, however, was focused on the whole probe, assessing the performance of all of 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 make sure that all of the electronic components ran well together, and meaningful data was collected in the desired format. The main components 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 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 6 (a), (b), and (c) show the cutter housing assembly, the fabricated sample, and the test setup, respectively.

The selected rock samples for this experiment were three different rocks (from left to right in Figure 6 (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 7 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 millimeters 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.

Figure 5a. Cross section of the final design of the RSBP.

Figure 5b. Photo of the manufactured probe.

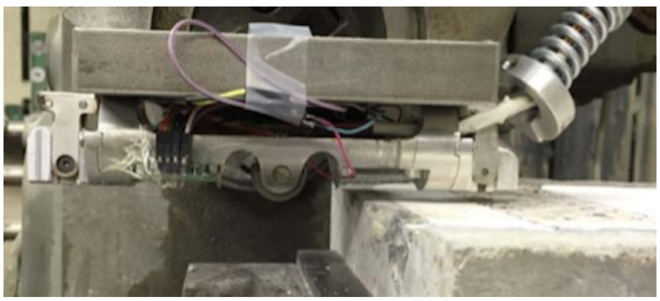

Figure 6a. Cutting housing assembly.

Figure 6b. The fabricated sample.

The initial data process 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 designed electronic system is working well. However, more analyses need to be run to calibrate the system for working conditions in the borehole. It is expected that the

Figure 6c. the test setup developed for sandwich rock sample experiment.

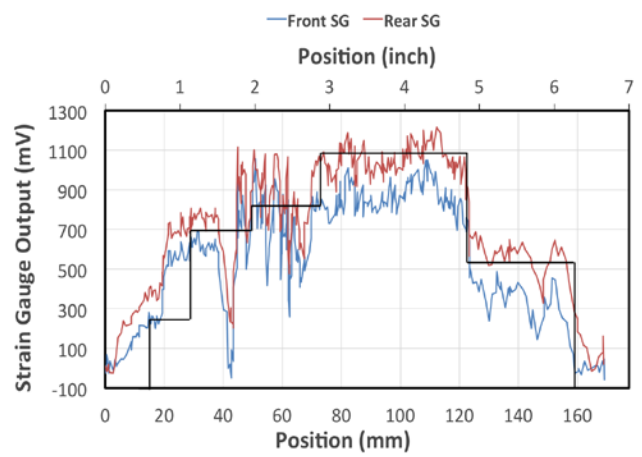

Figure 7. Typical test result from the sandwich rock sample experiment.

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 calibration of the laser sensor is needed to obtain the optimum position of the sensors for the highest accuracy.

Mine Roof Simulation at Fletcher Facility

After getting 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 the borehole local deviations. 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 graph of one of the test results. Not much analyses were done on the results since it was not possible to fully visualize the boreholes condition to interpret the RSBP results. However, the graph shows that all of the electronic systems are working well, and the mechanical part was able to scratch the surface of concrete, which means that the tool was ready for the field tests.

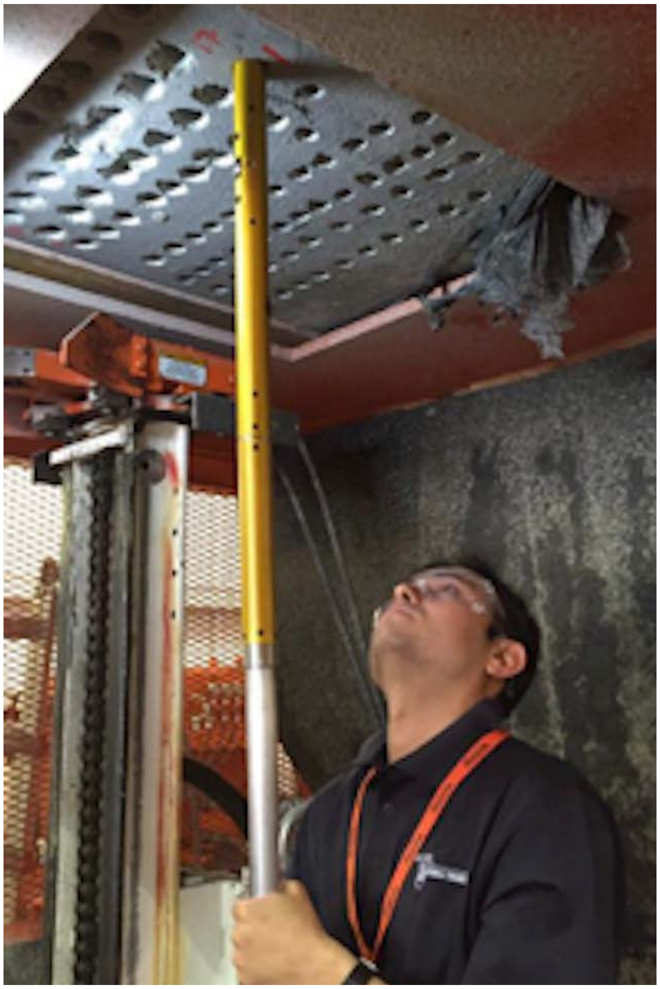

Figure 8a. Probing the holes drilled into a concrete block at J.H. Fletcher & Co. facility.

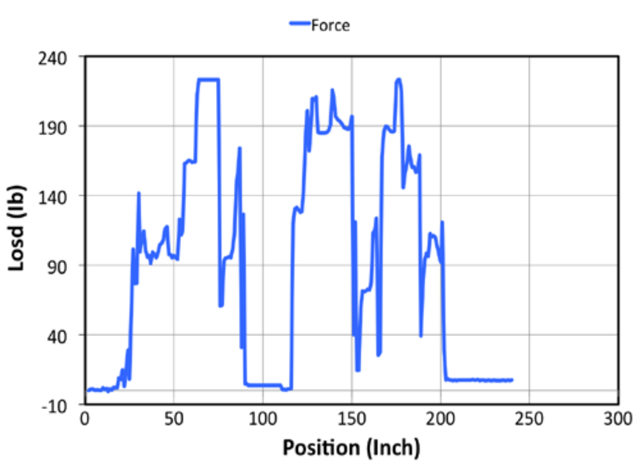

Figure 8b. Typical test result obtained from this series of probing.

FIELD EXPERIMENTS

RSBP was tested in two underground mines. In the first mine, the mechanical performance of the probe was examined in a limestone and an anthracite coal mine. Figure 9 (a) and (b) show the condition where the boreholes were tested, as well as typical scratch traces that were generated after running RSBP inside the boreholes in the limestone and coal mines, respectively. The boreholes at the limestone mine had a diameter of 2 ¼” and were drilled by rotary percussion machines. The exploration boreholes at the coal mine had a diameter of 2” as well. These photos show that RSBP can be used in any borehole with an arbitrary orientation and under varied conditions.

After implementing some modifications on the device based on the laboratory/field test experiments, the entire unit was tested at the same limestone mine. The graph in Figure 10 shows the result for one of the tested boreholes. This graph shows the strain gauge outputs from where the laser sensor started to register data up to the place where the probe reached the maximum depth, which is about 1,500 mm from the borehole collar. From this graph and the field observations, it can be concluded that both guide wheels got fully engaged at about 250 mm from the collar of the borehole. Moreover, the sudden plunge at the depth of about 750 mm might be due to a wide discontinuity, indicating the possibility of identifying open joints.

Figure 9a. Testing RSBP mechanical performance at a limestone.

Figure 9b. Testing RSBP mechanical performance at an anthracite coal mines and the image of generated scratches inside the boreholes.

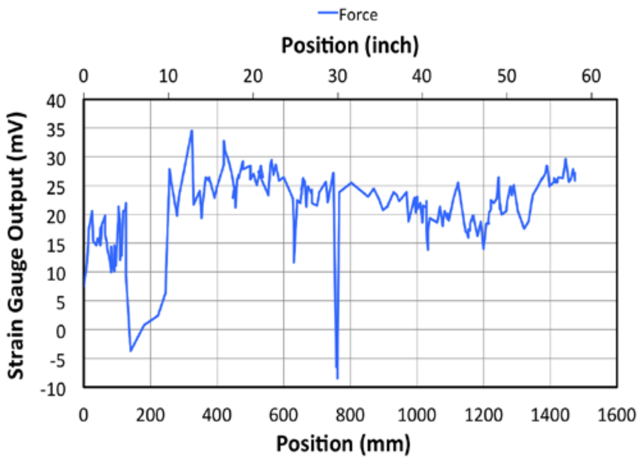

Figure 10. The result of probing a borehole by RSBP at a limestone mine.

CONCLUSION

The current studies show promising results for using RSBP in the field, which will be able to measure the intact rock strength properties, including UCS and BTS, by scratching the wall of a drillhole using a disc-shape scribe. Using RSBP a typical 10 feet borehole can be tested in few minutes and the objective is to produce an inexpensive device that can be utilized economically in almost any underground work. The laboratory and field tests proved the functionality of the electronic components of this tool. The mechanical system was also successful in making scratches on the borehole wall. The equations developed as a result of extensive testing of the various rocks at Penn State are based on correlations between rock properties and measured cutting forces. This allows for the estimation of UCS and BTS of sedimentary and metamorphic rocks from cutting forces with a reasonable accuracy. Despite the fact that broad ranges of rock types are tested to develop these formulas, more tests need to be conducted to increase the accuracy of the models, especially on typical weaker rock types present in coal mines. Moreover, additional analyses are underway to evaluate the RSBP laboratory and field test results, especially for better calibration of the load and position sensors. Finally, more studies are planned for to make the size of the probe as compact as possible, so that minimum length of a borehole is left untested and also the impact of borehole roughness on the general performance of the RSBP is minimize.

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