Alaska Rocks 2005
40th U. S. Rock Mechanics Symposium
*Rock Mechanics for Energy, Mineral and
Infrastructure Development in the Northern Regions*
June 25-29, 2004 – Anchorage, Alaska

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ARMA/USRMS 05-795

Development of a Field Method to Evaluate Mechanical Properties of Roof Strata

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ABSTRACT: During conventional drilling in underground mining, several variables including thrust, rotational velocity, torque, and penetration rate must be simultaneously monitored in order to detect and interpret lithologic changes. This paper presents the development of a new approach to sense and characterize lithologic changes derived from the use of the Helical Drag Bit (HDB). Because of its particular geometry, the HDB can assess lithologic changes based only on measuring one drilling parameter. A theoretical relationship that correlates material unconfined compressive strength with the force of cutting is presented. Results of laboratory experiments in sedimentary rocks of various strengths confirm a torque-unconfined compressive strength relationship for the rock types drilled with the HDB. Recent underground tests have subsequently demonstrated that the geometry of the HDB can be optimized to obtain repeatable results. This method has the potential to quickly and simply detect and interpret lithologic changes within a borehole. Preliminary results indicate that a log of rock strength is possible.

1. INTRODUCTION

The underground mining industry is dependent on the ability to control the surrounding rock mass. An adequate mine design depends on the amount and quality of the information available regarding the physical properties of the rocks. A wide variety of approaches have been used in mining and underground work for collecting information that allows determination of the geotechnical characteristics of the surrounding rocks. The approaches include core collection, observational techniques (borehole camera logs, rock quality designations), in-situ testing for strength determination (hydraulic fracturing, borehole logging, borehole penetrometer), and analysis of drilling parameters. Although all of these techniques are currently used, each suffers from its own limitations. Core collection for testing is without question the most widely accepted and useful approach for determining rock properties. However, this method is expensive and time consuming. Therefore, in many underground operations, the spacing between core locations is large allowing only for sketchy geotechnical mapping. Observational techniques provide only qualitative information. In-situ testing such as hydraulic fracturing and borehole penetrometers are also time consuming and cannot be practically used to obtain enough data points for high-resolution geotechnical mapping. Analysis of drilling parameters requires simultaneous measurement of thrust, torque, rotational velocity and penetration rate to determine the mechanical characteristics of the material being drilled. To accomplish this measurement, the drill must be retrofitted with several sensors and a data collection system, all of which must be maintained in the mine environment. This is a costly procedure and could be one of the reasons, despite its potential benefits, that it is still not widely used.

This research project explores the potential for using a recently developed drill bit, the Helical Drag Bit (HDB), to perform in-situ characterization of the mechanical properties of rock. The HDB concept was developed by UTD Incorporated in the mid 1990's in response to a program of the Gas

Research Institute aimed at maintaining a portfolio of products and technologies for efficient long horizontal slim-hole drilling. HDB technology was later incorporated into the Low Reaction Force Drill (LRFD) prototype developed under NASA sponsorship for the exploration of extraterrestrial bodies. During laboratory testing, it was observed that the torque of drilling using the HDB was consistent and depended mainly on the type of rock being drilled. This observation suggested the possibility of determining rock characteristics by measuring only one parameter, torque.

2. HDB DESCRIPTION AND OPERATION

The HDB is a tool designed to efficiently enlarge a pilot borehole into a larger diameter hole by taking advantage of the rock's inherent weakness in tension. A typical HDB drilling system consists of a pilot bit and one or several HDB flights. Fig. 1 shows a model of the HDB system. The pilot bit is a drill bit with the standard features of a regular drag bit. Each HDB flight is composed of a hub and multiple cutting elements arranged in a pattern to form a helical groove or thread within the borehole. Several cutting members are typically incorporated into the HDB. Each successive cutter is designed with a longer radius arm that controls the depth of cut and to gradually increase the depth of the thread within the borehole until the desired thread diameter is attained. Fig. 2 shows a photograph of a helical "thread" cut into a limestone block.
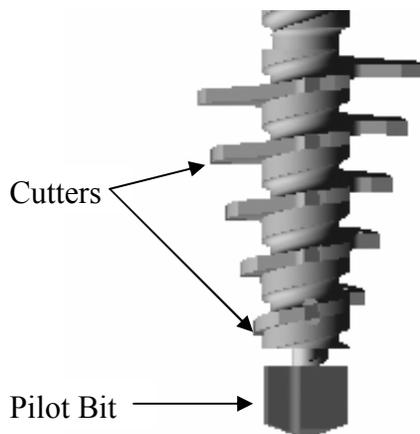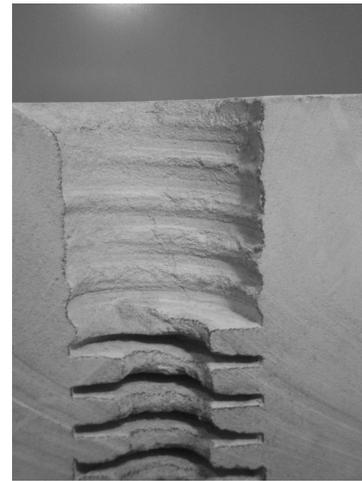

Fig. 2. "Rock Thread" cut in limestone using hardware developed for NASA's Low Reaction Force Drill.

When used for drilling, the HDB is fitted with wedge-shaped members that follow the cutting members. The wedging action on the threads takes advantage of the inherent weakness of the rock in tension, breaking the thread at its base, effectively increasing the borehole diameter, and producing large rock chips that are subsequently removed. Since the rock is weaker in tension and shear than in compression, less total power is required for drilling than with traditional methods.

Several operating variables determine the resulting geometric characteristics of the final borehole. These variables need to be optimized for each particular application. The key operating variables illustrated in Fig. 3 are:

- Pilot hole diameter (D)
- Helical pitch (P)
- "Thread" or groove depth (d)
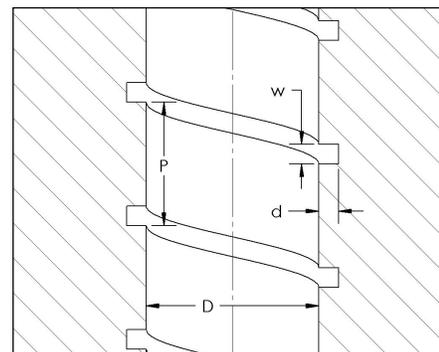- "Thread" or groove width (w)

Fig. 1. The Helical Drag Bit design is used to create grooves like those pictured in Fig. 2.

Fig. 3. Section view of resulting borehole geometry after using the HDB.

3. THEORETICAL ANALYSIS

Equations relating cutting forces and torque levels were developed to provide a means for systematic analysis and the basis for design of a HDB concept capable of interpreting lithology. The relationship for the force needed to cut a groove in the rock was derived by considering the geometry of the cut shown in Fig. 4. The work performed by the cutter to advance a unit distance is equal to the specific energy of cutting multiplied by the volume of rock displaced.

$$Fc = w \bullet \delta \bullet SE \qquad (1)$$

where
- Fc = cutting force or work performed per unit distance (N)
- w = cutter width (mm)
- δ = depth of penetration (mm)
- SE = specific energy (Mpa)

To maintain the depth of penetration, a force normal to the surface of the rock (Fn) must be applied. In the case of the HDB, this force is a reaction force that is balanced by a cutter on the opposite side of the bit. Therefore, it does not need to be controlled or monitored.
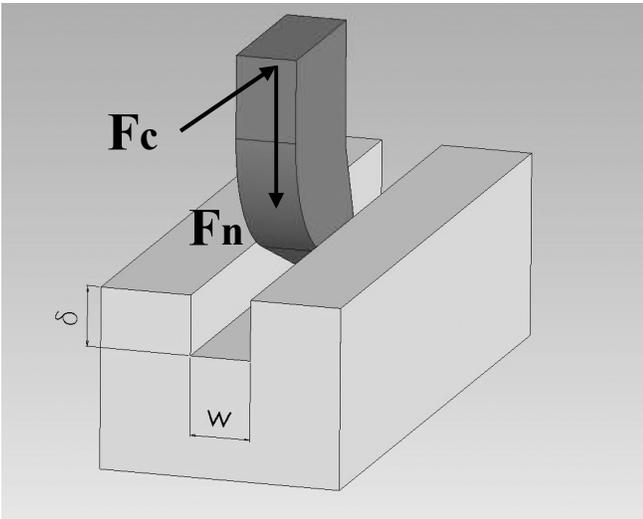

Fig. 4. Drag bit cutting action.

Experiments conducted by Richard et al. [1] indicate that the specific energy of cutting a groove in a homogeneous rock remains nearly constant when the cutter geometry is fixed. This is true up to a certain depth of cut where the mode of failure changes from ductile, where the failed rock flows ahead of the cutting face, to brittle, where cracks are initiated at the tip of the tool and propagate to the surface forming rock chips.

An important foundation of the ability of a drag bit to interpret rock properties lies in the observation that the strength of the rock is related to the specific energy. Tests carried out on sandstone and carbonate materials by Schei et al. [2] showed a good linear correlation between specific energy and unconfined compressive strength.

The proportionality between specific energy and unconfined compressive strength can be represented as follows:

$$SE = K_{SE} \bullet q_u \qquad (2)$$

where
- SE = specific energy (Mpa)
- K_{SE} = proportionality constant
- q_u = unconfined compressive strength (Mpa)

Therefore, combining Eq. (1) and Eq. (2) yields a relationship between unconfined compressive strength and the cutting force:

$$q_u = \frac{F_c}{w \bullet \delta \bullet K_{SE}} \qquad (3)$$

4. USE OF HDB TO INTERPRET LITHOLOGY

Laboratory tests have demonstrated the potential for the HDB to interpret the compressive strength of the rock being drilled for some types of rock.

Recent studies have been published reviewing advances in lithology characterization during conventional drilling [3,4,5,6,7]. Unfortunately, in conventional drilling several drilling variables must be measured simultaneously in order to interpret lithologic changes: thrust, rotational velocity, torque, percussion rate, and penetration rate. This is true because the amount of material removed with each rotation of a conventional bit is a function of all those variables. In the case of the HDB, The geometry of a helical cutter provides a balance of forces such that the normal force on each cutter is reacted by the cutter on the opposite side of the bit. Every rotation of the helical bit results in a prescribed advance into the borehole where cutting depth, and therefore the associated cutting torque, are dependent only on the initial pilot hole diameter and the geometry of the cutters. Ultimately, the HDB can interpret lithologic changes based only on measuring torque by the following equation that

correlates the measured torque to the compressive strength of the rock:

$$q_u = \frac{t_c}{K_{SE} \bullet \delta \bullet w \bullet \sum r_i}$$

(4)

where q_u = unconfined compressive strength (UCS)

       t_c = torque per cutter

       K_{SE} = coefficient of proportionality between SE and q_u

       δ = depth of cut

       w   = cutter width

       r_i = distance of tip of cutter from axis of rotation for each cutter

As the helical groove or "thread" is cut into the borehole wall, measurement of the torque of cutting allows calculation of the strength of the rock over the interval where the HDB is located.

5. LAB TESTS

Cubic blocks 610 mm on each side of four different types of rock were initially tested using the HDB with the purpose of validating the theoretical approach. The rock types and their corresponding compressive strength are shown in Table 1. This set of tests had the goal of verifying the proportionality between torque measured and unconfined compressive strength.

Table 1. Rock types tested and their compressive strength.

Rock Type	UCS (Mpa)
California Limestone	24.1
Shale	35.8
Indiana Limestone	37.9
Sandstone	68.9

Three 26 mm diameter pilot holes, each with a depth of 305 mm, were drilled into each of the rock blocks. An HDB with four cutters, a pitch of 32 mm, cutter width of 5 mm and cutting depth of 0.63 mm was used to cut a helical groove or thread in the wall of each pilot hole. The torque required to cut the thread was measured with an electronic torque sensor and the data was collected using a data acquisition system and stored on a laptop computer for analysis.

Results show that the torque required for cutting the thread has little variation for each type of rock and

that the torque values measured remain within a well-determined range for each material. Fig. 5 shows the average measured torque values for each hole grouped by rock type.
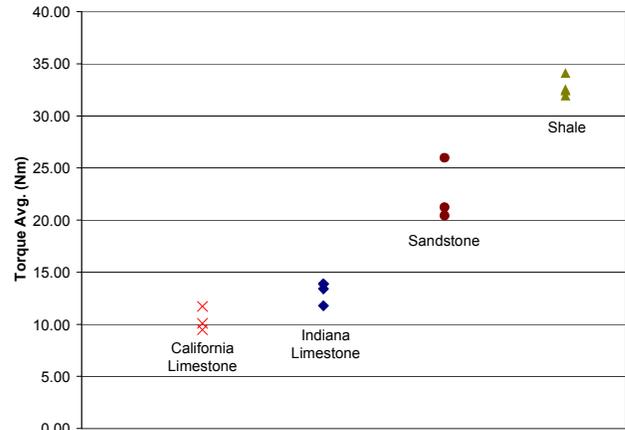

Fig. 5. Average measured torque of cutting using the HDB show consistent results for all rock types.

When torque values are averaged for each material and then plotted against compressive strength there seems to be a good degree of correlation for sandstone and limestone. Fig. 6 shows a plot of torque vs. compressive strength for all materials tested. The shale sample however, does not follow the same trend, perhaps due to its internal structure. Although all of the rocks tested are sedimentary, the shale is highly laminated. This may result in brittle failure during cutting and ultimately affect the torque needed to cut the "thread" in the rock. Fig. 7 shows a similar plot excluding shale.
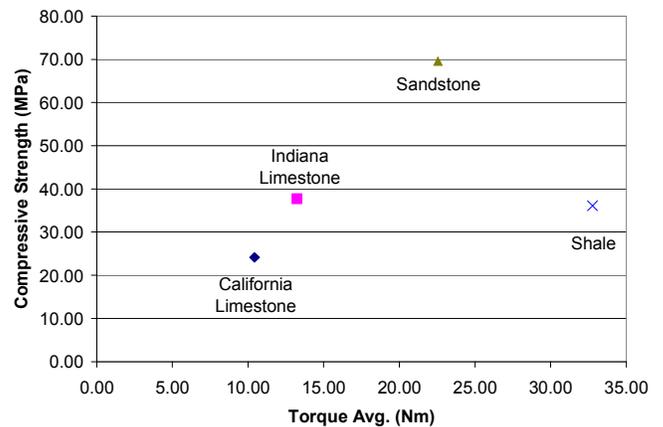

Fig. 6. Shale does not follow the average torque vs. compressive strength correlation.
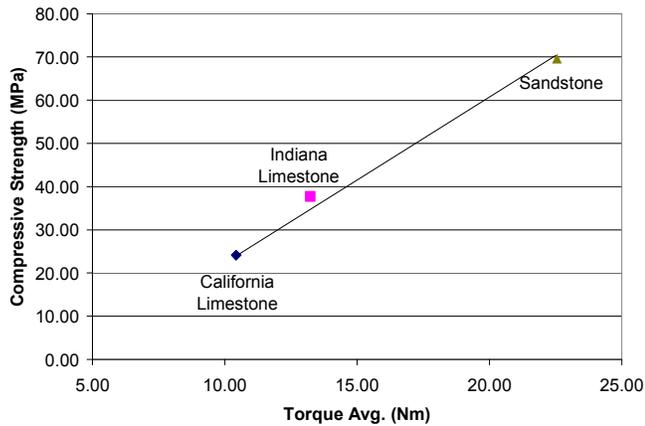
Fig. 7. An average torque-compressive strength correlation for homogeneous, fine-grained materials becomes clear after excluding the shale data.

6. FIELD TESTS

Several tests were carried out in the field. The goal was to verify that measurements taken on a particular lithology could be reproduced. This would give an indication of the reliability of the test. Another objective was to identify any additional factors that require consideration during practical application of the HDB to interpret rock properties.

The tests were conducted in two different coal mines. At each mine, pilot holes were drilled to a depth of 1,829 mm in the mine roof using standard 26.2 mm drill bits normally used for roof bolting. The diameter of the holes was measured and logged in 25.4 mm increments. The torque required to cut a thread with the HDB was measured using an electronic torque sensor. An internal encoder in the torque sensor allowed determining the position of the HDB within the borehole by performing a simple calculation involving the number of rotations of the drill string and the pitch of the helix on the HDB. All data was collected electronically using a data acquisition system and stored on a laptop computer for analysis. A core sample of the roof was obtained in a location in close proximity to where the HDB data were collected for later comparison with the torque measurements.

A typical test plot is shown in Fig. 8.   The horizontal axis represents the position of the HDB

within the borehole (depth), the vertical axis on the left represents the torque measured and the vertical axis on the right represents the diameter of the hole at each point within the hole. The plots of torque and hole diameter are simultaneously presented in the chart.   In this particular test, torque measurements were collected for the interval between 305 and 1,473 mm. The lithologic column in this interval consisted of coal to a depth of 556 mm, followed by 305 mm of carbonaceous clay stone, 254 mm of clay stone, 178 mm of carbonaceous clay stone, 127 mm of coal, 76 mm of carbonaceous clay stone, and finally fine-grained sandstone extending beyond the top of the hole. Vertical dotted lines in the chart indicate the point of transition between layers. Because of the inherent weakness of the rock in the core sample, compressive strength tests were not possible.

Two patterns can be observed in the graph. First, the torque responds to the change in hole diameter. At several points a change in diameter seems to be inversely associated with a change of torque. This is to be expected since a larger hole diameter reduces the depth of the cutters into the rock and therefore the torque that needs to be applied to the HDB. Second, over some intervals the torque shifts with the change of rock type. This is an expected and desirable result indicating the change in material. The difficulty lies in trying to de-couple the two effects. The torque cannot be normalized using the measured diameter of the hole since the magnitude of the torque contribution from change in diameter is not known.

Similar results were obtained in neighboring boreholes during testing. Since the actual diameter varies along the length of each hole, no two holes can be identical in their measured response. However, comparing results from two test holes, a trend can be appreciated.   Fig. 9 shows a comparison chart on test hole #4 located 610 mm away from hole #5 from which the test data of Fig. 8 was obtained. Both graphs show similar trends underscoring the potential for distinguishing the strength of the various roof layers, in relative terms at the very least, by using this method.
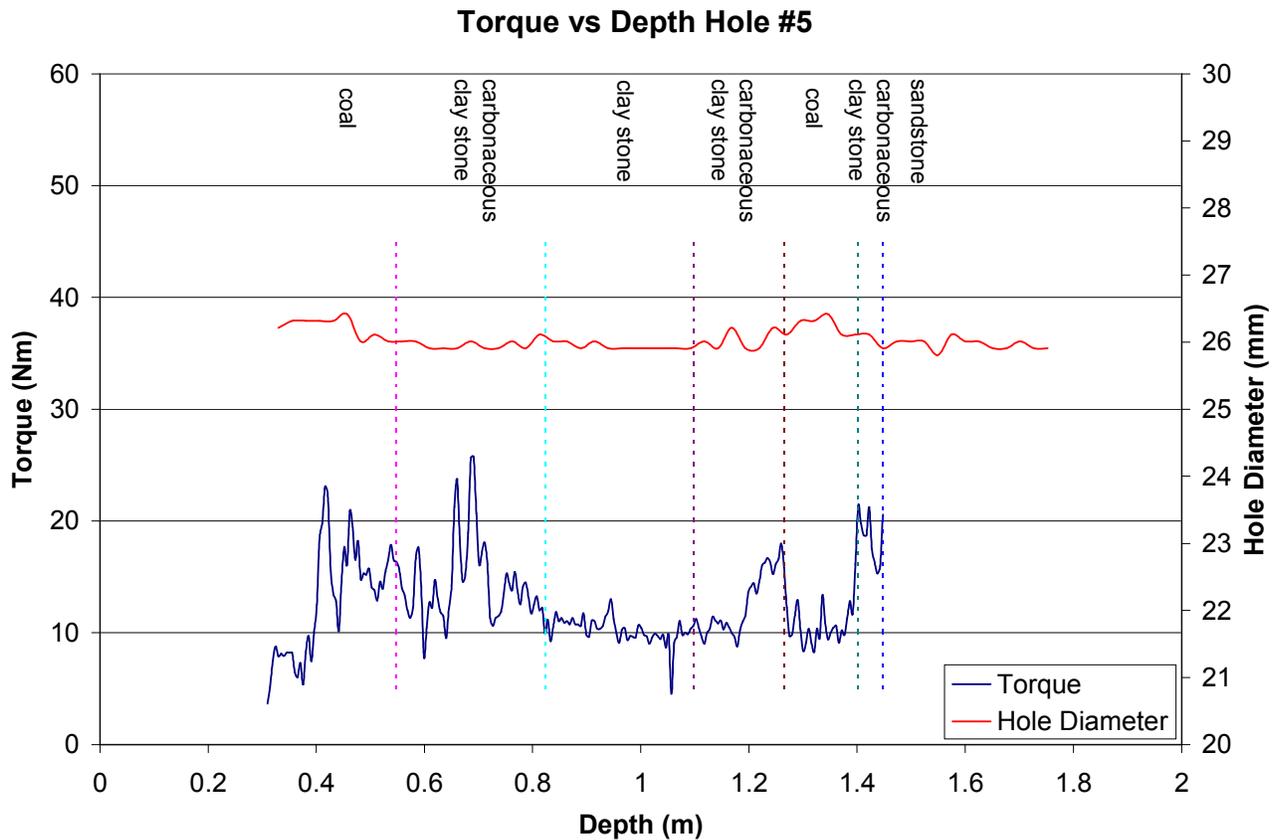
Torque vs Depth Hole #5

Fig. 8. Typical plot of torque of cutting and hole diameter versus depth. Vertical lines represent lithologic boundaries.
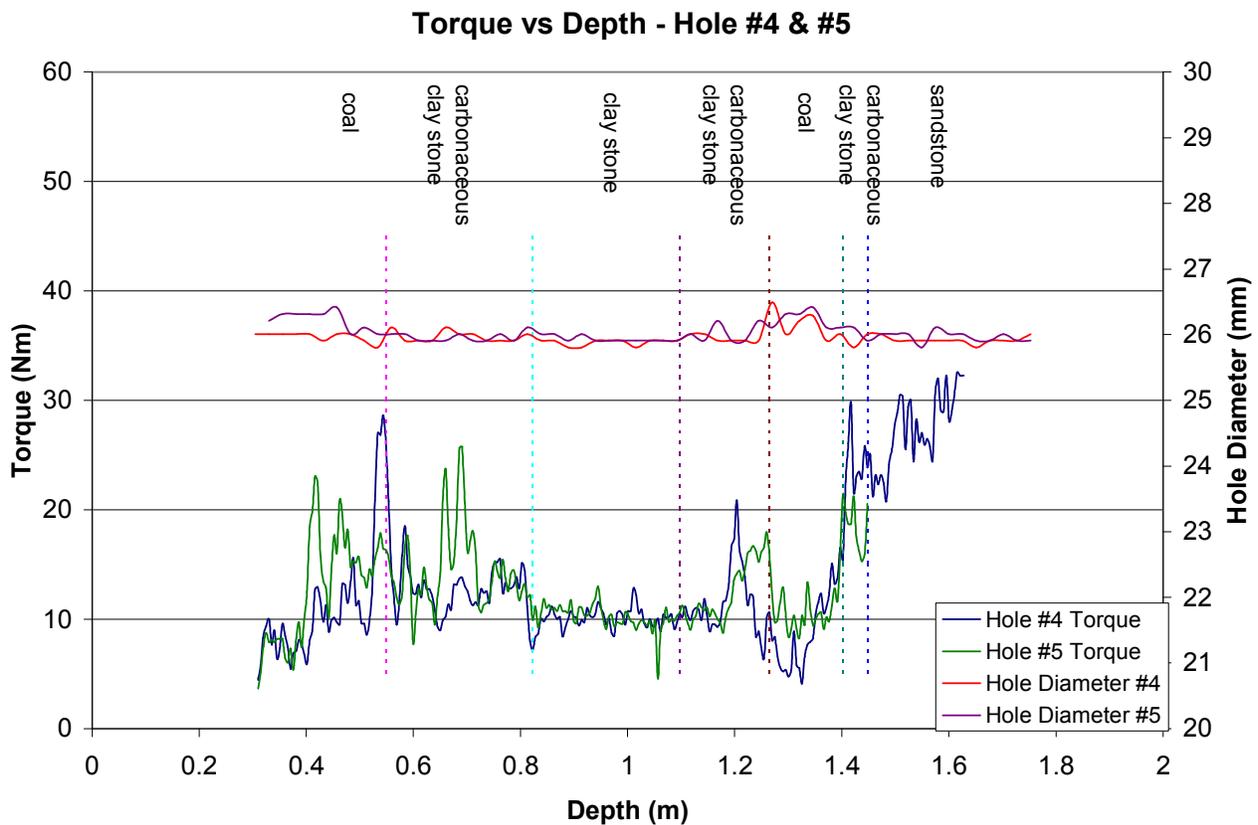
Torque vs Depth - Hole #4 & #5

Fig. 9. Comparison plot of torque of cutting and hole diameter versus depth for two tests. Vertical lines represent lithologic boundaries.

Field observations and analysis of the initial test data indicated that besides rock strength, other variables affecting torque measurements during testing included borehole geometry and friction between the body of the HDB and the wall of the borehole. Because of the spread of the cutters in the direction of the axis of the borehole, the HDB cannot accurately evaluate strength at a "point" but only over the region of the borehole where the cutters are engaged. Therefore, abrupt discontinuities in materials will be noted as transitions between two levels, not as "step" functions, and small variations that occur over the engaged length of the HDB may not be noted at all. To address these deficiencies, a modified tool and field technique was developed and additional testing was carried out.

7. METHOD IMPROVEMENTS

A new tool geometry was developed consisting of a central hub with two opposing cutters protruding radially and configured to cut axial grooves in the hole wall making it a HDB of infinite pitch (Fig. 10). Since the Axial HDB, or AHDB, tool is inserted into the hole without rotation, thrust force, not torque, is measured as the cutter advances into the borehole. The principles of operation remain the same and in this case Eq. (3) can be used to derive rock strength from the measured thrust force. The borehole is initially drilled using a standard 26 mm drill bit. To eliminate variations in hole diameter, a first pass or conditioning tool similar in geometry to the AHDB, is inserted in the hole and pushed through to create two axial grooves with a fixed distance between their bottom faces. When the AHDB is inserted, it deepens the grooves created by the conditioning tool. The depth of cut becomes fixed as it only depends on the geometry of the conditioning tool. This conditioning step eliminates changes in measured forces induced by the variation of hole diameter observed in the previous torque-based tests.

Fig. 10 also shows a section view of the geometry of the pilot hole, the grooves created with the conditioning tool, and the depth of cut of the measuring tool. Since cutters oppose each other, the forces normal to the hole wall are balanced and the hub of the AHDB can have a diameter much smaller than the borehole diameter allowing the cuttings to fall freely through the annulus between the hole wall and the tool shaft. This helps to eliminate noise in the measurements introduced by friction from rock cuttings or by contact between the hub of the tool and the borehole wall. Another potentially important benefit of using this new geometry with diametrically opposed cutters is the ability to evaluate rock strength at the particular position in the borehole where the cutters are engaged.
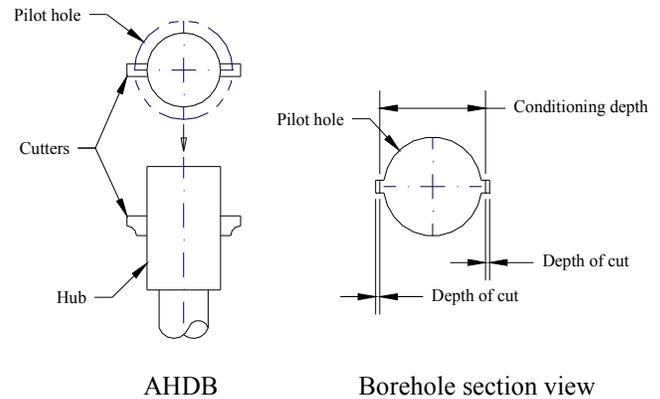

Fig. 10. Frontal and plan views of the AHDB. Also shown is the hole geometry created with the tool.

The geometry of the AHDB also allows execution of two tests in each hole simply by rotating the tool 90 degrees once the first test is completed. Test repetition provides the advantages of direct comparison between two identical experiments conducted in the same lithology and permits rapid detection of any problem in the test execution as revealed by different or conflicting observations. Additional tests can be performed in the same borehole by using an AHDB tool that cuts progressively deeper into the established groove by an additional depth identical to that cut by the previous pass of the tool.

Initial testing of the AHDB was carried out in a coal mine. Force of insertion as well as tool position was recorded for analysis. Fig. 11 shows a plot of four tests carried out in the same hole. Although there is some variation in the results, load peaks, valleys and general characteristics appear at the same depth location for all the tests. This indicates that the AHDB design is an improvement over the previous tool design.
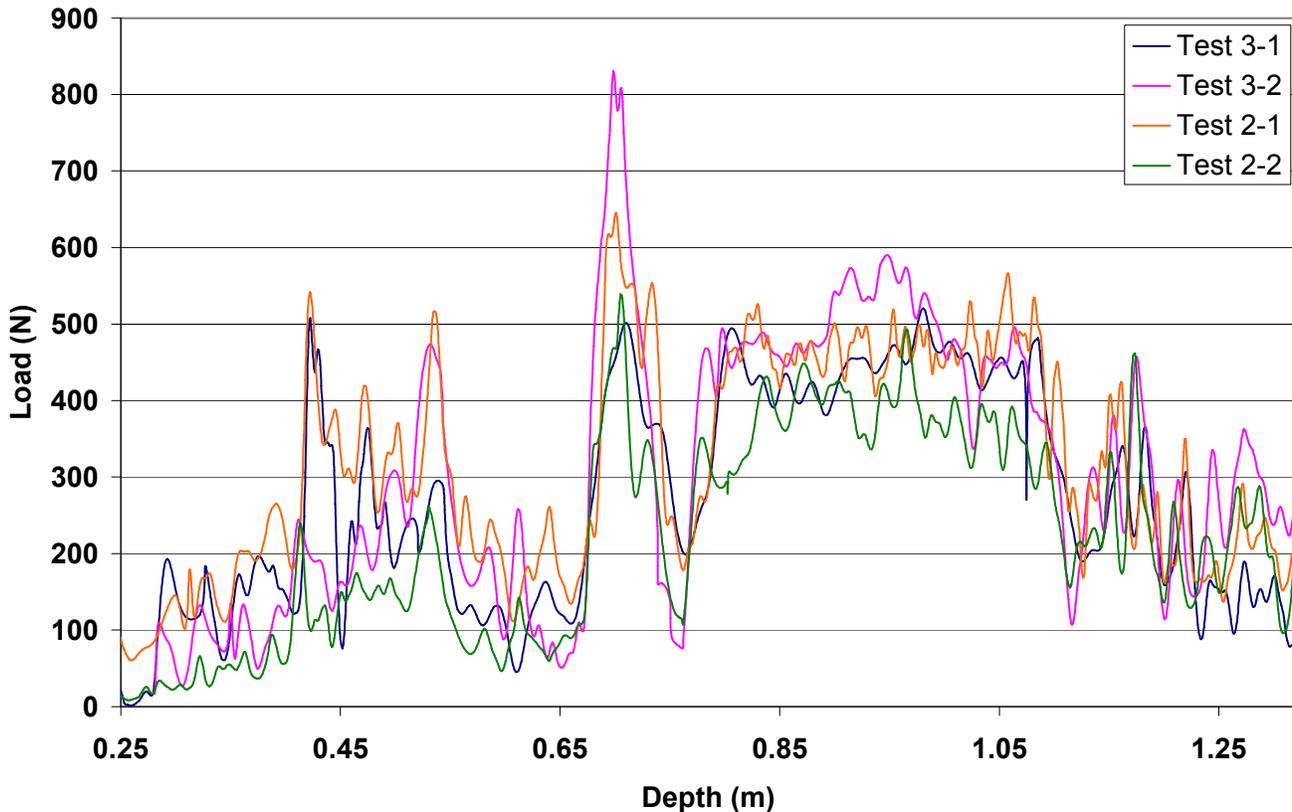
Load vs Depth - 2nd & 3rd Pass

Fig. 11. Plot of force of cutting axial grooves in the rock vs. depth obtained using new measuring tool.

The reasons for the difference between the results of the tests are not clear. One possible factor is poor tool alignment that would introduce friction and cause the load shift observed in the graph.

Although these results were obtained in a limited series of tests, they are encouraging in regards to the potential to assess relative rock strength of the layers within a lithology. Application of the AHDB has a good potential to evolve into an easily implemented index test that would provide a means to identify changes in rock type and ultimately provide a detailed borehole log of relative rock strength.

Further developments include refinement of the tool and test procedures. The tested cutter geometry is such that there is a large contact surface rubbing against the bottom of the groove. An improved cutter design should incorporate optimized rake and back angles. Measures to assure tool alignment should be implemented so

that the forces measured better reflect the cutting action of the tool and therefore the mechanical properties of the rock.

8. CONCLUSIONS

Experiments with two configurations of the Helical Drag Bit (HDB) indicate that the HDB can be used to detect and interpret lithologic changes along a borehole. Although the technique is still in the process of refinement, important milestones have been achieved. A relationship between a measured parameter of groove cutting using the HDB and an important rock engineering parameter was observed. Field tests showed not only that similar results from experiments in the same lithology are possible, but also that a change in lithology is reflected by a change of the measured parameter associated with the cutting of the groove.

ACKNOWLEGEMENT

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