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Estimation of rock strength using scratch test by a miniature disc cutter on rock cores or inside boreholes

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ABSTRACT

Accurate estimation of rock properties is crucial for performing realistic analyses in geomechanics, especially for assessment of rock mass strength. The conventional methods for strength measurement require testing on core samples, which are not always available or are time consuming/expensive to obtain. In addition, sample preparation can be an arduous task, and finally special equipment are required to perform the tests. This process offers the strength values with a time lag and not representing the in-situ conditions. Estimation of rock strength by scratching the surface of cores has been implemented with reasonable success in recent years. The need for application of this concept for assessment of rock strength in a borehole has led to development of a special probe that can scratch the borehole wall and offer an estimate of rock strength. This is accomplished by comparing the recorded forces with the strength of the known rock samples. To develop a relationship between cutting forces and rock strength, 27 different rocks covering a wide range of strengths, grain size, and origins have been tested by a miniature disc cutter and the results are discussed in this paper. The results show a promising correlation with R-square values of around 80% between the average normal force and the compressive (UCS) and tensile strengths (BTS) of the sedimentary/metamorphic rocks. However, no significant correlation was observed for igneous rocks. This could be attributed to the impacts of rock texture, grain orientations, and grain size. General equations are also introduced to estimate the UCS and BTS of sedimentary/metamorphic rocks by using average normal force and cutting depth with reasonable accuracy. These outcomes can pave the way for field application of the borehole strength measurement probe, which is currently under development for field trials.

1. Introduction

Assessment of rock mass properties is an essential input for analysing stability of any surface or underground structure in rock. Availability of geological information including condition and frequency of discontinuities as well as rock strength are the main components of rock mass classification systems and related strength and stability analysis. 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, which are obtained from exploration borings, coring boulders collected from outcrops, or cores from within the structure. These core specimens are subsequently tested in Rock Mechanic laboratories. The test results offer limited information about the rock at the few locations along the borings for all the efforts, time, and costs allocated for such rock strength evaluation. However, despite all the efforts made to prepare and test the samples, the results may not necessarily be representative of the behaviour of the rock in the field since the test cannot provide assessment of the in-situ conditions and related impacts on rock strength in the ground. The ideal solution is to be able to estimate the rock mass properties in-situ, and inside exploration borings or other drilled holes in an underground space that is being excavated for mining or civil applications. Therefore, the objective of the current study was to develop a method for evaluating rock strength in various type and size boreholes and measure in-situ rock strength.

Scratch test method has proven to be a promising approach and offer the ability to estimate the rock strength by testing small area of the rock surface. Scratch test offers several advantages including minimum to no sample preparation, small pieces or surfaces can be tested which are for the most part easy to obtain, and finally, the test could offer a continuous measurement of strength along the length of the scratch. As such, the scratch test allows for continuous recording of rock strength

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along the core sample, which is preferred over the discrete measurement of strength along a core sample where the UCS specimen is obtained. These features have made this method appealing in various areas of application. One of the main benefits of the scratch test, which was the key reason for being considered for this study, is the adoptability to be used in the field for measuring in-situ strength of rock inside narrow/upward/dry boreholes. This is mainly due to the fact that most of the available borehole strength measurement systems have been primarily developed for larger downward holes that are filled with water or other fluids, as is often the case in petroleum and water well drilling.

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 been extensively studied for decades.[1,2] This paper will cover the background of scratch test method, followed by the description of methodology and equipment employed to run scratch test for this study. A quick review of the results of full scale cutting tests will be offered. The relationship between depth of penetration, measured forces, and rock strength which is based on a preliminary statistical analysis of the available data will be discussed. The results of this study have been used for the design of a borehole probe that can implement scratch test principals for estimating rock strength in a small hole drilled for installation of rock bolt or blast holes. The conceptual design of scratch probe is also briefly described at the end of this paper.

2. Background

Scratch test was developed in 1990's in University of Minnesota based on the initial studies on the cutting models of drag bits[3] and PDC cutters.[4] The initial work was followed by correlating the rock strength to the cutting test results,[5,6] which then resulted in development of a device called "Rock Strength Device (RSD)".[7,8] 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.[9–17] More recent studies on scratch test, is focused on estimation of fracture toughness.[18–24] Naeimipour et al. also studied estimation of UCS through scratch test using a miniature disc cutter.[25]

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. 0.1–12 mm/s).[8] Both components of the force acting on the cutter are measured. This includes the component "F_t" in the direction of motion of the cutter, and "F_n" normal to the scratched surface. From the force measurements, the specific energy "SE" can be calculated. In addition "F_n/F_t" is estimated to evaluate the wear of the cutter.[26] More than 350 different rock samples,[27] mainly sedimentary rocks, as well as construction materials, such as bricks, cement and plaster, refractories,[28,29] mortars,[30,31] and iron ore[32] were tested by this method.

In addition to the uniaxial compressive strength of the rock, Young's Modulus was estimated from scratch test.[26] Another parameter that can be estimated by this method is the internal friction angle of the rock, which can be estimated through friction coefficient by scratching the surface of the rock with a blunt cutter.[33]

Suárez-Rivera et al., 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.[34,35] Germay and Richard, also have recently evaluated the correlation between the strength and petrophysical properties.[36] 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.[35] Both cases take advantage of continuity of scratch test results. Dagrain and Germay, and Dargrain et al., employed the minimum sample preparation/requirement feature of scratch test and estimated the strength of rocks such as shale.[35,37] Attempts are also made to estimate the properties of the masonry mortars of a heritage building in Belgium, in order to stabilize its foundation,[30,31,35] and more recently scratch test was used in order to estimate the lump to fine ratio and mineralogy of iron ores through their strength.[32]

A substantial amount of studies has been conducted on cutting of rock with disc cutters and they show a good correlation between the cutting forces and rock properties. All the previous studies on the disc cutters has been in larger disc sizes that are used in tunnelling industry for TBM applications and they are in the range of ∼430–480 mm. An extensive study of the rock cutting by disc cutter has been presented by Rostami in various publications.[38–40] The range of disc diameters in previous studies include 75–483 mm and variety of rock strength. No test was conducted with smaller discs with diameter of about 20 mm, which was the selected size disc for development of a borehole probe that could fit in smaller boreholes with diameters ranging from 30 to 50 mm. The testing units for larger discs (linear cutting machine or LCM) did not have the precision for measuring forces in lower range of penetration of 0.2–1 mm, nor do they have the precision for implementing such low penetration ranges. Similarly, the reviewed scratch test machines were all using drag or wedge type tools, and not roller type cutters. Therefore, one of the steps for conducting current studies was to develop a miniature LCM that could implement high precision cuts with a small disc and measure cutting forces.

3. Theory and developed devices

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.[3] 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.[10,8,13] 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.[8]

Scratch test is based on a phenomenological model of cutter/rock interaction in the ductile regime, which was proposed by Detournay and Defourny.[3] 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, 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 (ε) 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 "ε" is indeed 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 reiterate the difference between the intrinsic specific energy "ε" and the specific energy "SE". The latter quantity, SE, 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, ε, only characterizes the energy used to fragment the rock ahead of the cutter.

Since the introduction of scratch test, scratch test devices have been evolved and some companies have developed their own devices with different names. Currently, there are three commercially available apparatus including Rock Strength Device (RSD),[7] profiler core scratch

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