Rock drillability prediction from *in situ* determined unconfined compressive strength of rock

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Synopsis

The interaction between rock and drill bit during drilling has been modeled for many years, but a complete understanding of the phenomena occurring has yet to materialize. Successful models will allow the prediction of rate of penetration in a given environment and optimal selection of drill bit and drilling parameters, thus minimizing exploration costs. In most rock-drilling models the value of the unconfined compressive strength of the rock (UCS) is used in the predictive equations, within the concept of specific energy, and the value of UCS is the percentage of the value of the stress applied on the drilling bit in order for the bit to advance. While the exact percentage depends on the model used and it is not known with certainty, good knowledge of UCS is never-theless required before any decent prediction can be made on rate of penetration. Determination of UCS, normally done via destructive testing, requires not only the availability of sound rock core samples but also expensive testing and significant time for the test, which frequently are not available for routine drillability predictions. Hence, a multitude of methods and techniques has been proposed for estimating UCS from various indirect and/or non-destructive measurements, or combination of measurements with neural networks, such as point load index, block punch index, unit weight, and apparent porosity, water absorption by weight, sonic velocity, and Schmidt hardness. The many proposed approaches are critically reviewed and the results are compared, and what becomes apparent is that after many years, not only in mining but also in oil-well drilling, accurate indirect determination of UCS is still an elusive goal. An equation to predict UCS from sonic velocity data is suggested based on several data sets reported in the literature. Use of the specific energy equation with UCS or sonic data and utilization of drilling data allows an estimation of the efficiency of energy transfer from the bit to the rock and of the friction coefficient. Analysis of data reported in the literature, both from laboratory and field studies, has shown that this approach is sound and enables the determination of energy transfer efficiencies and friction coefficients, which for the cases studied range between 15 and 30% and 0.15 and 0.30 respectively. Thus, the suggested data analysis approach allows drillers to focus on inefficiencies and optimize drilling practices in future campaigns.

Keywords
Rock drillability, unconfined compressive strength, prediction.

Introduction

The prediction of drilling time when designing a drilling campaign for any type of well, hydrocarbon, mining, geothermal, even a water well, for different subsurface conditions and using a variety of equipment could be very beneficial for estimating drilling costs and for applying safe drilling practices. This could be accomplished if a full model that takes into account drilling parameters and formation properties is available. However, this is currently not the case, and industry as well as researchers attempt to predict drilling times via the concept of specific energy (SE), defined by Teale[1] as the minimum energy required by the drilling rig to cut a unit volume of rock. Teale's model, which has been used by many researchers and practitioners[2,3] is given as,

$$SE = \frac{W}{A} + \frac{\omega * T}{R * A} \qquad [1]$$

where R is the rate of penetration, ω is rotational speed, W is the weight on bit, T is the applied torque, and A is the bit face area, in any consistent system of units. Torque is normally not measured, and one can easily show that torque, T, and weight, W, are related by

$$T = \frac{\mu W D}{3} \qquad [2]$$

where D is the bit diameter and μ is the friction coefficient.

Teale went a step further and indicated that the units of specific energy were essentially units of stress and identified similarities between specific energy and unconfined compressive strength of rocks (UCS). Since one cannot expect 100% efficiency of energy transfer from the bit to the rock, one can then replace SE by the term:

$$SE = \frac{UCS}{eff} \qquad [3]$$

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Rock drillability prediction from *in situ* determined unconfined compressive strength of rock

Combining Equations [1], [2], and [3] and solving for the penetration rate, replacing rotational speed by the normally measured revolutions per minute (RPM), yields

$$R = \frac{(\pi/30)(RPM)(\mu D/3)(W/A)}{\dfrac{UCS}{eff} - \dfrac{W}{A}} \qquad [4]$$

where (*eff*) is the efficiency of transmitting the penetraton power of the drilling rig to the rock. The value of (*eff*) is not known *a priori*, but could be estimated from existing data. Other authors[4–5] proposed to use additional rock properties besides UCS as parameters of drillability, such as tensile strength, modulus of elasticity, stiffness of the rock, brittleness of rock, while for rock cutting performance, a range of indices has also been suggested[6–7]. Rock drillability, defined as the time spent to drill one metre of rock, has been widely used as rock classification in mining[8] but it is not objective, as it does not take into account the drilling equipment. The approach of specific energy has been used also for roadheader performance prediction[9–10].

A great deal of testing has thus been undertaken via standard methods (ISRM[11], Brown[12]) to gather representative mean values of the properties of the drilled rock types. The results have indicated that rock properties are influenced by anisotropy and orientation of discontinuities related to the direction of testing or drilling, spacing of discontinuities, mineral composition and equivalent quartz content, moisture, and finally pore volume and porosity of the microfabric[13–14].

From the literature cited, UCS could be used as a rough estimate of rock drillability which, when combined with the use of Equation [4], can provide a rough penetration rate model. A critical bibliographic search has therefore been undertaken on the reported values of UCS for representative rock types that could be encountered while drilling in shallow and deep horizons for water, geothermal, mineral, and hydrocarbon exploration. In addition, there is a strong need to access such data in the field to run drillability models, and there is a continuous search for optimum methods to predict UCS from field-measured parameters with sufficient accuracy. These approaches are therefore reviewed, and the implications of the findings with respect to variability of the reported measured and predicted values of UCS on the prediction of rock drillability are discussed. Furthermore, the specific energy Equation [4] is used, by analysing laboratory and field data, in an effort to derive information about the efficiency of energy transfer from the bit to the rock and the value of the friction coefficient, which may vary according to the rock type but also according to the bit used. The aim is to provide a technique that can be used to optimize drilling procedures.

Rock unconfined compressive strength and its measurement

UCS is a property very often measured and used by engineers to design surface and underground structures and to drill wells for mineral exploration and exploitation. Standard procedures to accomplish this have been presented both by the American Society for Testing and Materials[15] and by the International Society for Rock Mechanics[11], who have classified UCS into seven grades designated by the codes R0 to R6, with R0 being the weakest rock.

The variability of the reported UCS values for different rock types from various places around the world is however, extremely high. A search for data on UCS from several different publications from the mining and the petroleum industry reveals that, for a given rock unit, there may be as many UCS values reported as probably the number of particles comprising a cubic metre of the particular rock. Variability of a parameter, defined as the standard deviation divided by the mean value and expressed as a percentage[16], could indicate the spread of data. Roxborough[16] gives a UCS variability of 20% based on 40 sandstone samples, while Zhorlu *et al.*[17] reported that the variability for 61 sandstone samples was 44%. A negative correlation between UCS and variability of the measured values has also been reported[18], stemming from the fact that stronger rocks have fewer imperfections.

It is interesting to note that the geological name of a rock is not a criterion for strength determination. Tanaino[8] categorized the data according to the maximum UCS measured from approximately 1000 samples of igneous, metamorphic, and sedimentary rocks and ores, and found that the most influential factor was weathering. UCS values for the same rock but with different weathered conditions could vary by one order of magnitude. For example, unweathered basalt could have UCS values in the range of 350–400 MPa, while weathered basalt has been reported at values of UCS ranging between 35–50 MPa.

Furthermore, one can always address the issue of weak and strong rock, i.e. can one define which is hard and which is weak rock? What are the decisive parameters for characterizing a rock mass like this? Many years of research and field work cannot really answer what constitutes hard rock, even with a ±100% margin of error. In the case of weak sandstones, the UCS is usually[12] between 0.5 and 25 MPa. Factors affecting the properties of weak rock include poor cementation, weathering, tectonic disturbance, and large pore spaces[19]. In addition, the mineral composition of the rock is also important, as well as porosity, water content, density, and particle size, the properties that are known to influence the wave velocity, compressive strength, and slake durability[20].

Confining stress is a very influential factor in the magnitudes of compressive strength values, particularly for deep strata. Several studies have shown, using triaxial testing, an increase in UCS with increasing confining pressure, typically called Confined Compressive Strength (CCS). CCS may be very important for oil well drilling but is not as significant for mining, particularly for shallow drilling. Use of CCS takes into account the change in pore volume with increasing pressure, thus mimicking better what is happening in the field during drilling[21]. Studies by Peng and Zhang[22] have shown that for CCS values up to 10% of UCS, UCS increases dramatically by almost 80% (80 to 145 MPa). Even stronger influence has been reported for oil-well drilling, as can be seen in Figure 1 for different sedimentary rocks.

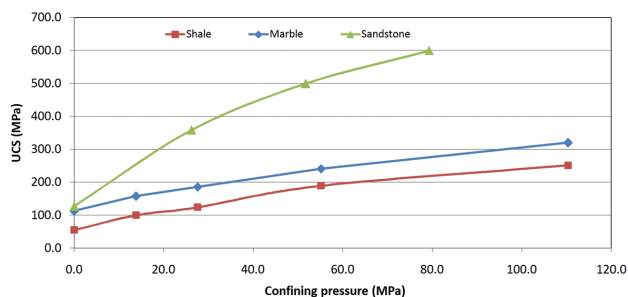# Rock drillability prediction from *in situ* determined unconfined compressive strength of rock

Figure 1—Effect of confining pressure on rock compressive strength for three different rock types (adapted from Black *et al.*[23])

UCS prediction

Measurements of UCS can be time consuming and expensive, while it is also expensive to get core data. Information about rock strength could be derived from measurements on cuttings[24], and some success has been reported. A point not addressed, though, is that the actual horizon where cuttings are generated is not known with certainty, because of the cutting slip velocity, which may hinder identification of the rock horizon. Industry has thus addressed several different ways to predict UCS, including the Schmidt hammer test, point load test, impact strength test, and sonic velocity.

Fener *et al.*[25] tried to relate UCS with the Schmidt hammer test, point load test, and impact strength test for 144 samples, but found no good correlations with any of these tests. The highest value for the regression coefficient was 0.77 for UCS versus the point load test. The reported UCS values ranged between 61 and 202 MPa for igneous, metamorphic, and sedimentary rocks. Fener *et al.*[25] also evaluated prior relationships for prediction of UCS, with more than 20 correlations regarding UCS and the point load test and more than 15 correlations regarding the Schmidt hammer test, and reported no agreement. They attributed the inability to predict UCS to the differentiation of rock types, rock micro-texture and even to test conditions, which indicates that standardization procedures are not as definite as they should have been. Kahraman[4,26] also evaluated several simple methods including those mentioned above, to assess UCS using data from 48 different rocks. The least variability was observed with the point load test. Reported regression coefficients ranged between 0.40 to 0.86.

One of the basic techniques used to estimate UCS via non-destructive testing is by using sonic data, as the velocity of elastic waves in rock depends on rock density, stiffness, and hence rock strength. It is also known that velocity depends strongly on rock mineralogy, grain size, porosity, weathering, stress level, water absorption, water content, and temperature, all of which complicate the issue, and thus no simple correlations exist or have been suggested. In oil-well drilling, UCS is also estimated from porosity logs. Khaksar *et al.*[27] have listed 26 correlations for sandstones, 11 for shales and 7 for carbonates, for estimating UCS from various logged parameters.

An extensive literature search has indicated as many correlations between UCS and sonic data as research projects undertaken. D'Andrea *et al.*[28] derived an expression for UCS using sonic velocity data, V_P from rock samples from the

USA, while McCann *et al.*[29] derived a similar relationship for British rocks, with both relationships being of the type

$$UCS = a \cdot V_p^b \qquad [5]$$

with a reported regression coefficient in the range of 0.80. Both works reported significant data scattering, especially at low porosity values, which is unexpected, because at low porosities the homogeneity of the rock mass is greater. Similar results were also reported for volcanoclastic rocks exhibiting strong UCS variation at porosities as low as 2%[30], with the authors attributing this variation to structural differences among the samples. Using data from 144 samples with porosity ranging between 0.01 to 15.7%, Entwisle *et al.*[30] have suggested the following correlation:

$$UCS = 0.783 \left(V_p \right)^{0.882} \qquad [6]$$

with a very low correlation coefficient, $R_c^2 = 0.533$. In prior work, researchers have also attempted to separate the sonic responses according to rock type. Soroush and Fahimifar[31] measured V_p and UCS, together with other properties in 2000 cylindrical specimens, with the results shown in Figure 2. For claystone, conglomerate, marl, sandstone, and slate, significant variation is seen even among similar rock types.

Similar significant variation from various data sources and different areas in the USA is also evident from the data presented by Oyler *et al.*[32] (Figure 3), with travel time being the reciprocal of p-wave velocity. The classical McNally equation[33] given as

$$UCS = 143.000 \cdot e^{-0.035/V_p} \qquad [7]$$

is also shown, where UCS is in pounds per square inch and V_p is in feet per microsecond. It can be seen that the data is widely scattered, while Equation [7] does a decent predictive job. On the contrary, Sharma and Sing[34] reported good correlation between sonic velocity and UCS for a range of rocks, one igneous, three sedimentary, and three metamorphic rocks for a total of 43 samples. They proposed a linear equation

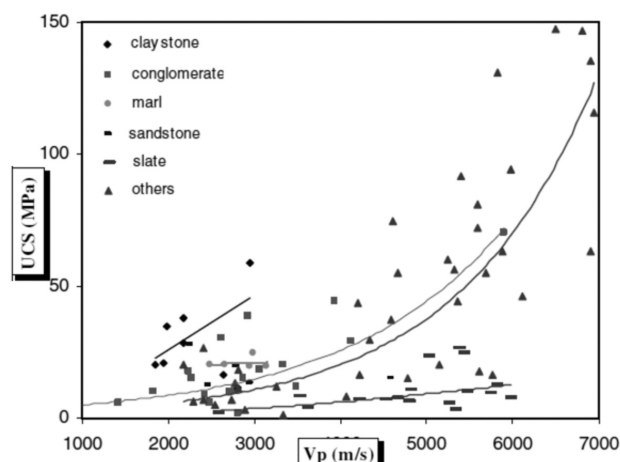$$UCS = 0.0642 \cdot V_p - 117.99 \qquad [8]$$

Figure 2—Variation of UCS with sonic velocity according to rock type (from Soroush and Fahimifar[31])

Rock drillability prediction from *in situ* determined unconfined compressive strength of rock
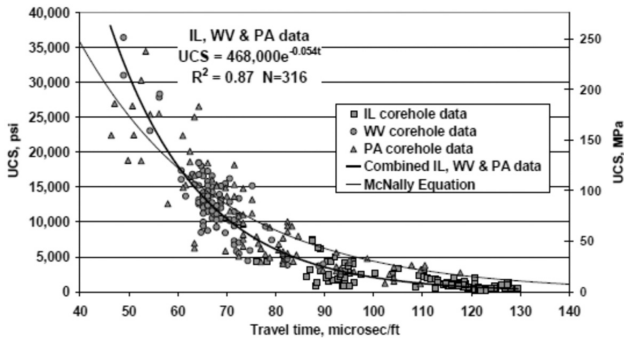

Figure 3—Variation of UCS with sonic travel time from USA data (from Oyler et al.[32])

with a regression coefficient of $R_c^2 = 0.90$, which is fairly high for the given data.

In oil-well and rock drilling, sonic and density logging is always performed, particularly in difficult to drill wells. Hence, data on sonic velocity and porosity or density is usually available. For many years, industry tried to find good correlations between UCS and sonic velocity or bulk density in order to assess *in situ* rock strength and develop the drilling strategy accordingly. What is necessary, of course, is high quality field drilling data for a first hand approximation of UCS. Onyia[35] performed several experiments and concluded that the sonic model may be used to develop a continuous rock strength model. However, extensive data using wireline logs, like that shown in Figure 4, from 10 wells from the Alberta region in Canada[36], show significant variability in the estimate of UCS derived from sonic velocity. The UCS values are estimated from,

$$A_{UCS} = \frac{K_1}{\left(\Delta t_c - 40\right)^{k_2}} \qquad [9]$$

where, A_{UCS} is the estimated apparent rock strength, Δt_c is sonic travel time, and K_1 and K_2 are constants.

Zhou *et al.*[37] attempted to obtain better results than those from only simple exponential correlations utilizing all available geophysical logs, and used two methods of data processing, SOM and RBF. Their predicted UCS results compared with UCS data from cores from three boreholes, are shown in Figure 5. The large data scatter is evident. Also, one can see that the simple McNally correlation[32] performed as well as the more elaborate approaches presented by Zhou *et al.*[37]. The authors indicated that the regression coefficients between measured and predicted values for the McNally equation and their two approaches respectively were 0.62, 0.65, and 0.72. Furthermore, the estimated relative error ranged between a minimum of 0.1% to a maximum of 157%, with averages around 30% for all three approaches. Hence, even the use of most available data to predict UCS has not been sufficient to provide a fair estimate of UCS. Thus, data is site-specific and a measurement and a calibration is probably required if decent predictions are expected.

We have attempted to gather sonic and UCS data to see whether any correlation could be developed from a variety of sources. The data from Kahraman *et al.*[38], Papanacli[39], Moradian and Behnia[40], Sharma and Singh[41], and Vogiatzi[42]

is plotted in Figure 6. The McNally equation is also shown. The results represent data from 184 samples of different rock types from various places around the world. Note that the variations are larger than ±100%. Worth noting is the narrow

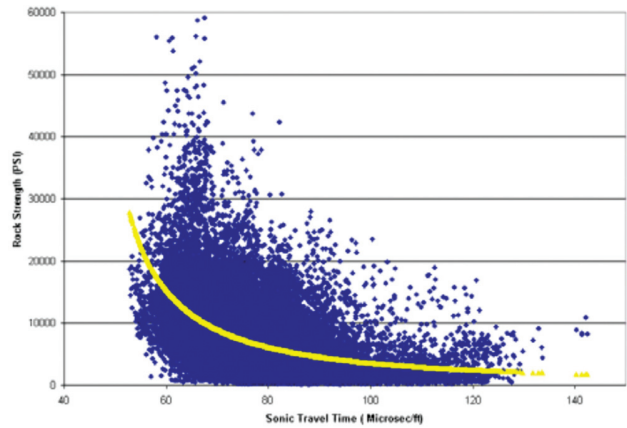**Figure 4—Data of predicted UCS values, from sonic data, from 10 wells versus sonic travel time (from Andrews et al.[36])**
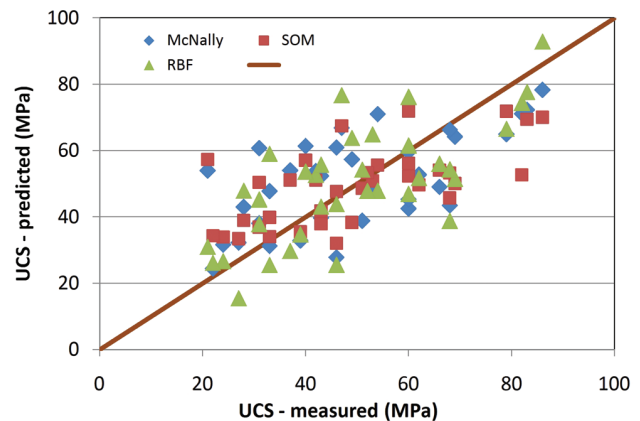

Figure 5—Predicted UCS versus measured UCS for a variety of samples from three wells (adapted from Zhou et al.[37])
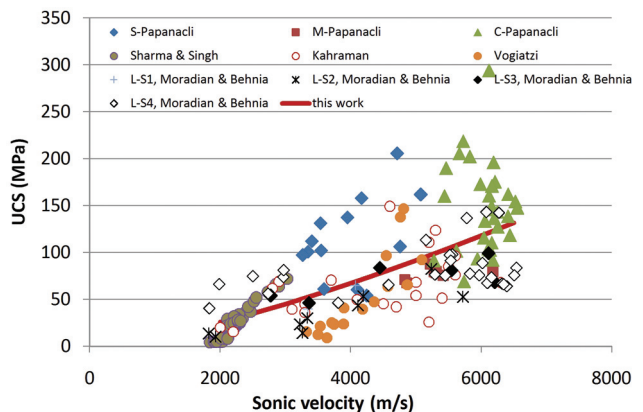

Figure 6—UCS – sonic velocity correlations for various rock types from a variety of sources. S: sandstone, M: marble, C: carbonates, L: limestone, Si: sandstone from the ith site, as per original paper; data from: Kahraman et al.[38], Papanacli[39], Moradian and Behnia[40], Sharma and Singh[34], Vogiatzi[41]

Rock drillability prediction from *in situ* determined unconfined compressive strength of rock

range of sonic velocities for carbonates, spanning a range of 50 to 200 MPa, a fairly flat response (wide variation in sonic velocity for a very narrow range of UCS) for some limestones, and a generally fairly linear trend between UCS and sonic velocity for sandstones. Attempting to get an overall general correlation from all data points, the following equation has been derived:

$$UCS = 0.00069 \cdot V_p^{1.385} \qquad [10]$$

with the units in the metric system. The regression coefficient is a fair 0.71, while the ratio of the sum of squares of errors to the variance of data is 0.48. In order to compare the predicted versus the true measurements by Equation [10] and by the McNally equation, the real data and the predicted values of UCS are presented in Figure 7. The proposed equation appears to gather the data closer to the diagonal line (perfect prediction) compared to the McNally equation. It is fair, though, to say that predictions are far from very good with this fairly low regression coefficient, but it can give a good rough estimate of UCS in the absence of any data, and since it comes from a variety of sources and different materials, it should work, within the accuracy level indicated, in any environment.

Rock drillability prediction

The variability of UCS with rock type emphasizes the importance of local calibration. But researchers have suggested a multitude of correlations, which, in the absence of other data, can give an approximate idea about rock properties from sonic data[42]. The issue is to narrow down the uncertainty in order to estimate UCS, the ever sought-after rock property, from indirect measurements, and also devise ways on how they can be combined with other available data in order to get better estimates of rock drillability.

Of course the question might be, what could be the impact of an error in estimation of UCS on the predictions of rock drillability? An answer could be given with a fair degree of accuracy if an appropriate rock–bit interaction model would be available. Fair estimates of the effect could, however, be given with the use of simulators which can be fine-tuned using real field data. Such a test case has recently been attempted using a hydrocarbon drilling simulator, Payzone, originally proposed for oil well drilling[43–44] but also

tried for shallow drilling[45]. The model used is essentially Teale's equation (Equation [4]) as it has been verified by Kelessidis and Dalamarinis[46]. The data needed to run the simulator are weight on the bit, rotation rate of the drill string, flow rate, fluid parameters, and drill bit parameters like bit type, bit make, types of nozzles, and the bit record (depth in, depth out, and wear condition at the end of the bit cycle). Formation data needed include well geometry and formation parameters, like lithology and estimations of unconfined rock strength (UCS). Use of existing well data allows for fine tuning to match the data, and hence one can predict future drilling performance in a similar field by altering mainly drilling parameters for a new well campaign. Use of the simulator with appropriate data from a well has been tried and the data was matched. Then, a scenario was run for drilling a formation with a UCS value 50% higher than the original value used when data matching. These results are presented in Figure 8, with the formations drilled being shale and soft and hard sand. One can see that a 50% error in the value of UCS could have a large effect on the prediction of drilling time for the given formations, with the error ranging between 58% and 96%, giving an overall increase in total drilling time of 82%.

Rock drillability could be predicted by using Equation [4], where UCS could be a measured value, or replaced by a sonic value derived *in situ* and using Equation [10]. A rock drilla-
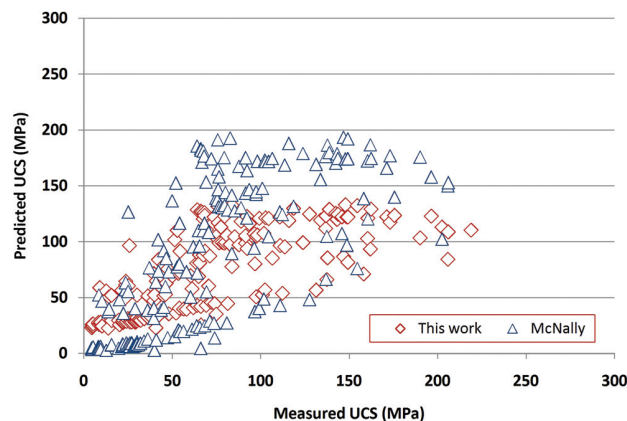

Figure 7—Comparison of predicted UCS values versus true data for the two approaches, Equation [10] and the McNally[33] equation
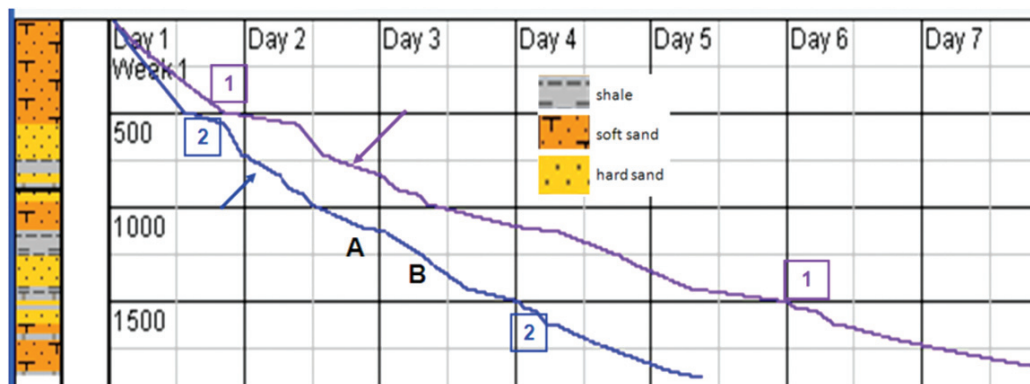

Figure 8—Normal drilling time plot [2] and simulated drilling time plot [1] when UCS for all formations encountered is estimated as increased by 50%. Depth unit is in feet

Rock drillability prediction from *in situ* determined unconfined compressive strength of rock

bility model based on the concept of specific energy then becomes available having essentially two adjustable parameters, the friction coefficient, μ, and the efficiency of energy transfer, *eff*, from the rig equipment to the rock. One then can assess available drilling data and try to match true penetration rate by adjusting these two parameters, *eff* and μ, and determine whether friction is high or low, or efficiency of energy transfer is high, so that in a following drilling campaign the optimum values can be used. We have attempted this approach using available data from the literature to gauge its applicability.

Data of Tsoutrelis[47] were analysed in the above-described manner and are presented in Figure 9. One can see that it is possible to simulate real drilling conditions using Equation [4] by adjusting (*eff*) while fixing the friction coefficient at 0.30, with the values of (*eff*) used also plotted in Figure 9. Data matching for this condition is achieved with increasing values of the energy efficiency with weight applied, from 20% to almost 60% where it levels off. Of course in reality, simultaneous adjustment of (*eff*) and (μ) will allow for the optimum conditions.

A similar analysis has been performed with the data obtained using a full size drilling machine testing full-size rock bits[48] drilling on marble at three different rotational speeds for various bit weights. The results are shown in Figure 10. It can be seen that we can replicate the drilling data well for all three rotational speeds by using the same coefficient values for the friction coefficient and for the efficiency, (*eff*), 0.25 in both cases. Good matching is observed between predictions and data at the three rotational speeds. The results also show that the increase observed with increasing rotational speed is well predicted by Equation [4]. Interestingly neither the friction coefficient nor the energy efficiency change in value, indicating that the rotational speed values used were fairly small so that they could not affect the energy efficiency values.

More extensive data from the same drilling machine and the same group (Ergin *et al.*[49]) have also been analysed with the technique proposed in this study. Here the authors have used four different bits to assess their performance for drilling rock from a copper mine, and in addition to the regular data, torque was also monitored. This of course

allows determination of the friction coefficient, which, using Equation [3] gave an average value for μ of 0.20 for bit#1, and μ of 0.17 for bit#2. In addition, the data has shown a departure from the linear increase of *R* with respect to the weight, *W*. Hence, we simulated the results by maintaining the friction coefficient at the above-listed values but changing the efficiency, (*eff*), in order to match the data. The data from the two different bits were analysed (similar results were obtained with the other two bit run data) and the results are shown in Figures 11 and 12. Good matching of predictions with the data is observed, using 'true' friction values of 0.20 and 0.17 for bit#1 and bit#2 respectively, and using the linearly varying (*eff*) with applied weight, which ranges between 15 to 30% and is similar for both bits used.

Thus, from all the considering cases, it is evident that it is possible to use, and hence predict, the drilling rate, once UCS values are known together with information on the drilling parameters, by using only two adjustable parameters, friction factor and efficiency of energy transfer. And if one uses sonic velocity data and Equation [10], then prediction is possible without the need for determining experimentally the UCS value.

Figure 10—Penetration rate data and predictions for drilling in marble using a full-size drilling machine, for three different rotational speeds, indicated on the graph as 20, 40 and 60 r/min (from Kuzu and Balci[48]). Conditions: tricone rock bit of 304.8 mm, drilling marble, UCS=50 MPa (value taken from literature as it was not given in original reference). Condition sim reflects the simulation with *eff*=0.25 and μ=0.25 for all cases

Figure 11—Penetration rate data and penetration rate predictions, together with efficiency values variation to match the data, for drilling in rocks from copper mine using a full-size drilling machine, for one rotational speed (60 r/min) for the bit#1. Conditions: tricone rock bit #2, of 150 mm, UCS=78.3 MPa Condition simulation reflects the simulation with μ=0.20 (from Ergin *et al.*[49])
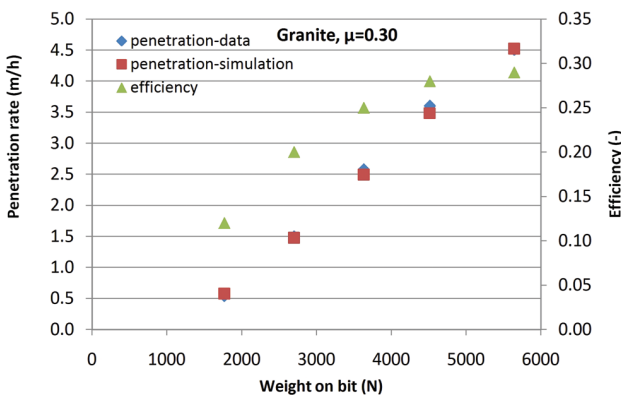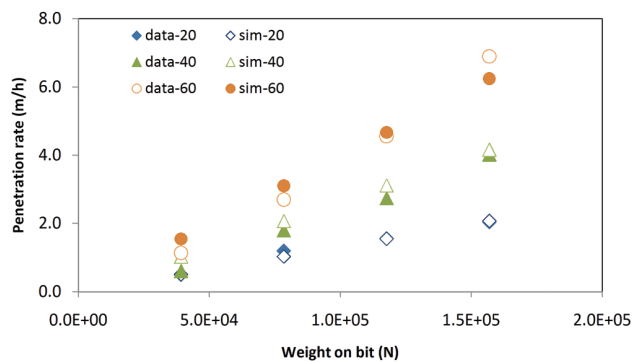

Figure 9—Penetration rate data and predictions of penetration for drilling in granite by varying the efficiency of energy transfer to match the data of Tsoutrelis[47]. Conditions: diamond bit of 36.4 mm, 260 r/min, UCS=125,6 MPa. The friction coefficient (μ) has been set to 0.30

Rock drillability prediction from *in situ* determined unconfined compressive strength of rock
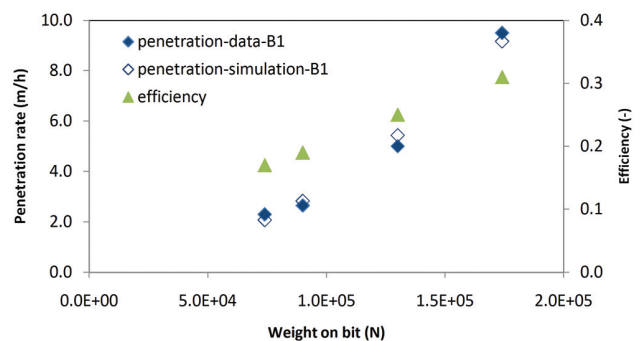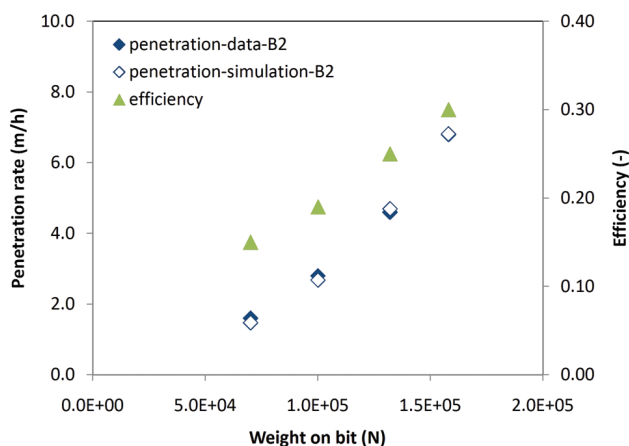
Figure 12—Penetration rate data and penetration rate predictions, together with efficiency values variation to match the data, for drilling in rocks from copper mine using a full drilling machine, for one rotational speed (60 r/min) for the bit#2. Conditions: tricone rock bit #2, of 150 mm, UCS=78.3 MPa. Condition simulation reflects the simulation with (μ=0.17) (from Ergin *et al.*[49])

Furthermore, the analysis has shown that one can identify and determine friction coefficient values and determine inefficiencies of energy transfer by matching drilling data and using Equation [4]. The results have shown that the friction factor ranges between 0.15 and 0.30, while the efficiency for energy transfer ranges between 15% and 30% (depending on the value of the friction coefficient). In two of the cases studied, efficiency increased linearly with the applied weight. What is then necessary for the design of drilling campaigns is availability of good UCS data predicted with fair accuracy, which can be accomplished to a good extent by using sonic data together with Equation [10] and the basic equation of penetration rate prediction Equation [4]. Access to drilling data then allows for estimation of the friction factor and efficiency of energy transfer from the bit to the rock, which will enable the driller to apply more optimum conditions in future drilling campaigns while alerting him at the same time to inefficiencies in the weight transfer.

Conclusions

Drilling rate models require information related to rock drilla-bility, which in the past has been approximated by Unconfined Compressive Strength. Many of the reported results on UCS for almost any rock type show wide scattering without particular trends. Measurements of UCS require rock core samples, which are not always available because they are expensive to get from drill sites and are also time-consuming and costly to obtain. Thus, researchers attempted to relate UCS to other, easier to perform measurements, with minimum to fair success.

Sonic velocity is the mostly used indirect measurement of UCS. Several works have been reviewed and the results show wide scattering, with predictions of UCS from sonic velocity with low regression coefficients ranging between 0.50 and 0.70. Attempts to integrate additional logging parameters from hydrocarbon wells did not provide any significant

improvement, thus pointing out the need for additional work to get better UCS estimates. In the absence of any more accurate data, Equation [10] is proposed, utilizing a large variety of data sets from different sources and covering different rocks, which can thus provide an order of magnitude analysis.

The drilling rate model will require a good understanding of rock-bit interaction, which currently is not within our grasp. Hence, the portion of the energy produced at the bit can be equated to the energy required to crush the rock, taken as equal to the rock unconfined compressive strength. The rock drillability model then results in two adjustable parameters, the efficiency of energy transfer and the friction coefficient. Adjustments of these parameters could allow for matching of real rock drilling data in order to extract information about the efficiency of the drilling process and provide for necessary modifications in future drilling activity. Use of experimentally obtained and field reported data allowed good matching, with energy transfer efficiency values ranging between 15% and 30%, while friction coeffi-cients ranged between 0.15 and 0.30.

Acknowledgements

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