



STATE-OF-THE-ART REPORT

Water Well Construction Technology

Part 2—Rock Drillability

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Drilling technology is as old as water well drilling itself. It has been generally recognized that the art of drilling and casing was invented, perfected, and extensively practiced by the ancient Chinese. Using percussion drilling, bamboo casing, and patience, they drilled to depths rivaling those reached in modern times with steam.

However, it has only been during the last century that water well drilling, as we know it, has been perfected. Until recently, well drilling was strictly an art instead of a science. We still do not know all of the answers, but a great deal of work now has practical field application.

The need to relate drilling penetration rate and other factors to the properties of the rock is well known. Only after such a correlation has been made, can the ideal conditions be determined. Then, actual performance can be expressed as a percentage of the ideal, and various types of drilling systems can be compared against each other.

In the development of any drilling system—either rotary or cable tool—composition, properties, and behavior of the rock control the drilling process. The science of *rock mechanics* describes such rock composition, properties, and behavior. However, much of the data now available from rock mechanics studies do not apply directly to well drilling. The information must be interpreted for use by the water well industry.

Rock drillability is defined as the inverse of the resistance of a rock to be broken up. This resistance is related not only to the rock material, but to the rock environment, which includes such things as formation fluid and depth of the rock.

Under certain given conditions, the behavior of drill bits can be mathematically predicted on the

basis of compressive rock strengths, although rock drillability does not appear to depend only on compression. Basic indentation tests show, for instance, that rock compressive strength, shear strength, and impact resistance probably are the major controls on rock drillability.

Drilling Rate

In general, the rate of rock drilling is directly proportional to rock drillability. For example, when drilling an alternating sand and shale sequence, the drilling rate changes in response to rock type. The changes are directly related to the changes in drilling resistance of each rock type.

Both percussion (cable tool and down-hole hammer) bits and roller bits actually attack rock by impact. When a bit tooth hits a rock surface, the rock is elastically deformed until the crushing strength of the rock is exceeded, at which time a wedge of crushed rock is formed below the tooth.

As additional force is applied to the tooth, the crushed material is further compressed and sideways forces are exerted on the solid rock surrounding the crushed wedge. When these forces become high enough, fractures form below the bit tooth, further breaking up the rock. The process is known as *cratering*.

Most rocks have a compressive strength of no more than 40,000 to 50,000 pounds per square inch. (Compressive strength is defined as the stress or force required to break a sample that is compressed from both ends and is held at a constant cross section.)

However, a number of rocks, including some not ordinarily encountered in water well drilling, have considerable higher values. Some specific examples include:

Epidosite (quartz & epidote)	63,000 psi
Chert from Missouri	86,300 psi
Pink quartzite	68,000 psi
Hematite from Minnesota	88,100 psi
Amphibolite from India	70,000 psi

For comparison, it should be noted that mild steel has a listed compressive strength of from 60,000 to 90,000 psi.

Other rock properties, notably confining pressure and porosity, are also of interest to the water well industry. All rocks at depth are under a stress because of confining pressure. Shales, for instance, are relatively "soft" rock, but they become harder to drill at great depths because the confining pressure acts on the cutting surface to lessen cuttings-removal efficiency. At extremely high pressure, some weak rocks, such as salt, will flow plastically⁽¹⁾.

Porosity of a rock is also known to influence drilling rate. Drillers and geologists have long used "drilling breaks" as an indication of porosity changes. The reduced compressive strength, because of the fluid in these zones, explains these breaks.

Drilling Force

Special equipment (fig. 1) must be used to duplicate the conditions of pressure encountered at depth. Using such equipment, scientists have found that to produce the maximum cratering volume (that is, to remove the most rock), the length of the blow must increase with confining pressure. Or to put it another way, at greater depths the same amount of force produces a smaller crater.

As rock is buried under overlying rock, it has a tendency to become less brittle and more ductile or plastic. The effect is caused by both consolidation and a hardening caused by strain. In addition, almost all rocks have a property called *strength anisotropy*, which means that they will break easier in one direction than in another.

Strength anisotropy is one of the causes of borehole crookedness. On the basis of tests, special

bits are being designed to control the deflection in very deep boreholes.

Prediction of Core-Drilling Rates

The U. S. Bureau of Mines has attempted to determine indexes for predicting rock drillability. Drilling was done under both field and laboratory conditions, using the same rock types. The field tests used a commercially-available diamond drill; all bits were AX size, and the drilling used combinations of 600, 1000, and 1600 rpm with 1000 and 2000 pounds of thrust or pressure.

The Bureau of Mines tests produced a theoretical equation for predicting core-drilling rates:

$$d = \frac{2\pi(T - urF_v)}{SA - F_v}$$

where: d = penetration per revolution (in/rev)
 T = torque on drill bit (in/lb)
 u = coefficient of friction
 F_v = thrust (lb)
 r = bit radius (in)
 S = rock compressive strength (psi)
 A = cutting area of the bit (sq in)

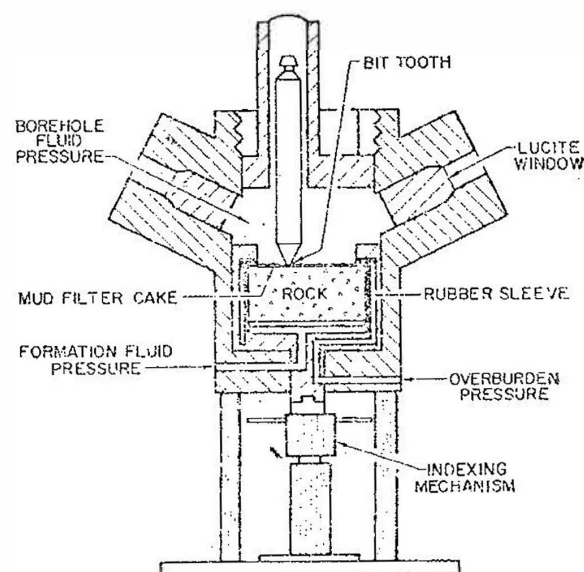


Figure 1. Typical pressure used to duplicate actual conditions in the laboratory. From reference 4.

Figure 2 shows that the theoretical and the experimental curves for drillability are in fairly close agreement. However, it was discovered that the value of the coefficient of friction (μ) was difficult to measure and apply.

This study showed that compressive strength seems to be the major factor influencing core drilling. However, another study⁽³⁾ has shown that the other factors listed earlier in this article are also important.

Roller Bit Penetration Rates

A drilling rate equation for roller-cone bits has been derived on the basis of information about rock cratering⁽⁴⁾. This equation expresses the relationship between drilling variables for the condition under which "perfect cleaning" occurs. Perfect cleaning means that all the rock debris is removed between each time a tooth strikes the rock surface. Under these conditions, which are usually found only during shallow drilling, the equation is:

$$R = k \frac{N W^2}{D^3 S^2}$$

where: R = drilling rate (ft/hr)
 k = formation drillability constant
 N = rotary speed (rpm)
 W = bit weight (lbs)
 D = bit diameter (in)
 S = rock compressive strength (psi)

The equation relates four factors to drilling rate. Drilling rate is calculated to be related inversely to the *square* of the rock compressive strength. Rotary speed, weight, and bit diameter can all be measured. The drillability constant (k) is a mathematical "fudge factor" to account for such things as pressure conditions, drilling fluid properties, and bit design that may affect drilling rate.

When the bit tooth strikes a rock surface, it forms a crater at or near the bottom of the wedge beneath the tooth. The mechanism is shown in figure 3. If the tooth hits at right angles to the rock face, the shattered material will have a tendency to remain in the crater.

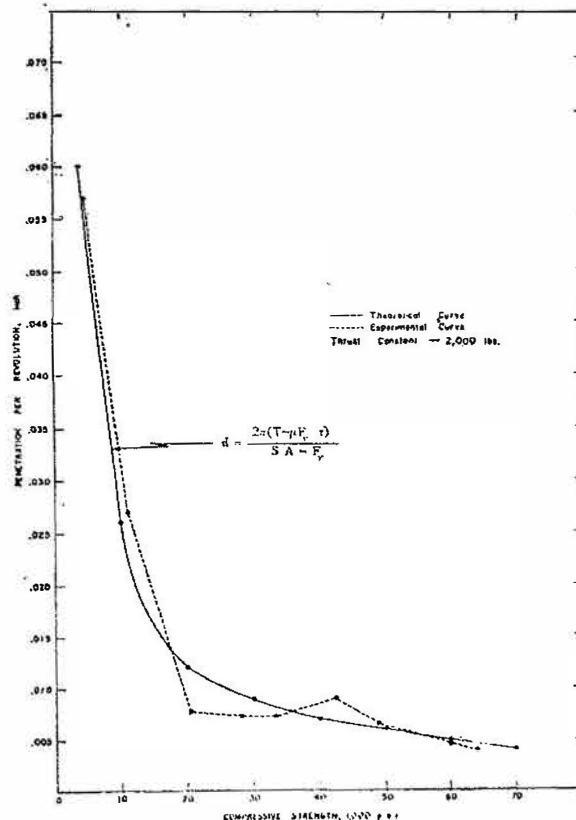


Figure 2. Relationship of theoretical and experimental curves for drillability. From reference 2.

But if the bit tooth is skewed, the tooth (or other teeth) will drag through the cuttings and aid in removal. The increase in drilling rate produced by this dragging action is due largely to better cleaning and not to additional rock breakage. Thus, the angle of the bit tooth does not enter into the above equation.

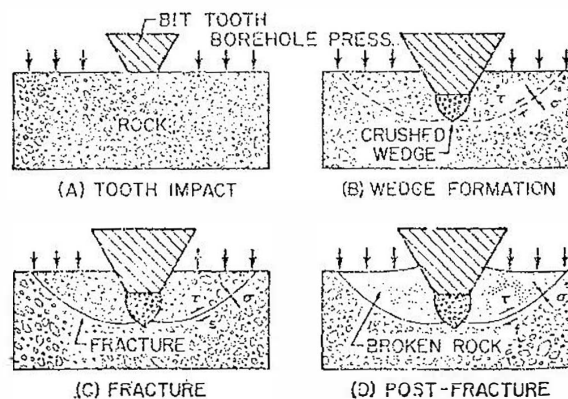


Figure 3. Four steps in the cratering mechanism. From reference 5.

Another study has also taken into account the *mechanical properties* of the rock, which include hardness and disintegration factors. Rocks were tested in the laboratory, under conditions that resembled field conditions, by increasing the weight on the rock face until breakage occurred.

These factors can be used in an equation that relates mechanical rock properties, bit weight, rotary speed, bit diameter, and a tooth-dulling factor. The results of the study suggest that rock drillability might be predicted from sonic logs.

Sonic logging is the recording of the time required for a sound wave to travel through a specific length of the rock. The speed of the sound wave depends on the elastic properties of the rock, the porosity of the formation, and the fluid content and pressure.

Figure 4 shows how drilling strength and travel time of the sound wave are related. It is important to note that for any given rock type, such as sand or shale, all the points fall somewhere near a specific line.

A Rock Drillability Index

Although it is clear that knowledge of rock properties is growing, the exact drilling mechanisms and how they can be used most efficiently are

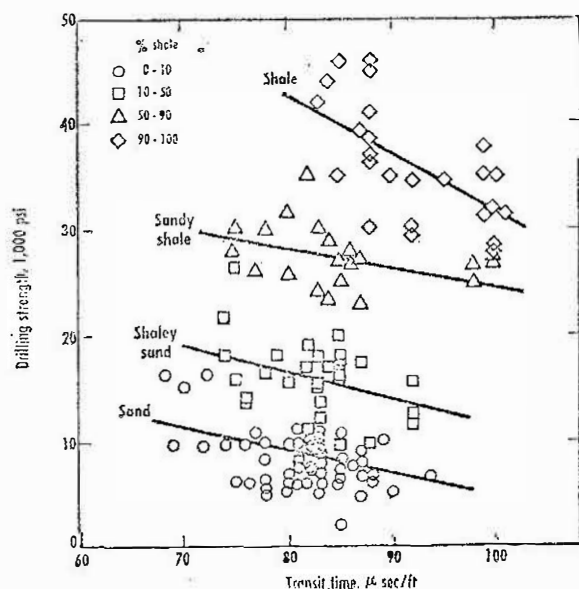


Figure 4. Rock drilling strength plotted against transit time for a sonic log. From reference 6.

still not clearly understood. In addition, although we can measure the different variables, experts do not always agree on the relative importance of each one.

Most of the studies discussed in this article consider only one drilling method and a limited range of rock hardnesses. A recently published, comprehensive rock drillability index⁽⁷⁾ attempts to incorporate the three major drilling systems—rotary, percussion (cable tool), and rotary-percussion (downhole hammer)—and also considers a wide range of rock types.

Although this index is one of the best, it is still based on the penetration rate achieved by a 3/4-inch diameter bit drilling a hole 4 inches deep. Compression strength tests on two rock types using samples from 2 to 32 inches in diameter, showed that the effect of sample size on determining mechanical properties is small.

But, it also showed that the size of the rock sample does influence the type of breakage that occurs. Thus, future tests using larger rock samples, will be required to correct drillability indexes that have been constructed over the past few years using small laboratory specimens.

In the meantime, drilling technology has evolved to the point where the limitations of the method are becoming obvious, and new approaches—some considered “far-out”—are being considered to help solve the problems of rock excavation. ■

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