3.3 Rock Drillability

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Contents

- What is drilling? Drill string design.
- Classification of drilling systems. Types of rotary drill bits.
- Mechanisms of rock disintegration (sharp & blunt cutters).
- Drag bit performance.
- Drilling rate or Rate of Penetration (ROP).
**What is drilling?**

**Drilling (small hole)** is a cutting process that uses a drill bit to cut or enlarge a hole of circular cross-section in solid materials. The drill bit is often a rotary cutting tool, often multipoint. The bit is pressed against the workpiece and rotated at *rates from hundreds to thousands of revolutions per minute*. This forces the cutting edge against the workpiece, cutting off chips from the hole as it is drilled (http://en.wikipedia.org/wiki/Drilling).

**Well drilling (Mining)** is the process of drilling a hole (large) in the ground for the extraction of a natural resource such as ground water, brine, natural gas, or petroleum, for the injection of a fluid from surface to a subsurface reservoir (CO₂) or for subsurface formations evaluation or monitoring. Drilling for the exploration of the nature of the material underground (for instance in search of metallic ore) is best described as *borehole* drilling, or 'drilling'. (http://en.wikipedia.org/wiki/Well_drilling). Also Geothermal drilling.
### TABLE I. CLASSIFICATION OF DRILLING SYSTEMS

<table>
<thead>
<tr>
<th>Percussive</th>
<th>Rotary</th>
<th>Rotary-percussive</th>
<th>Jet piercing</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Churn drill</td>
<td>(a) Drag bit</td>
<td>(a) Drag-chisel bit</td>
<td>(a) Thermal bit</td>
</tr>
<tr>
<td>(b) Piston-type drill</td>
<td>(b) Roller bit</td>
<td>(b) Roller bit</td>
<td>(b) Water</td>
</tr>
<tr>
<td>(c) Hammer drill</td>
<td></td>
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</tr>
</tbody>
</table>

Fairhurst & Lacabanne (1957)
Churn drill or Spudder: it can drill loose soil or hard rock and make holes 4”-12” in diameter over a mile in depth. The hole is advanced by raising and dropping a chisel bit. The cuttings mix with water to make mud which is bailed out at intervals (ROP 2-10 feet/h).
Types of rotary drill bits (κοπτικές κεφαλές)

- PDC bit
  - PDC cutters (κοπτικά εργαλεία) that are mounted on a steel or tungsten carbide matrix body

- Tri-cone rotary bit (rolling cone bit) and cutting tools attached to it.

Teeth made from hard metal (WoC)
Examples of Polycrystalline Diamond Compact (PDC) drag bits. Various configurations of the cutters on the bit.
Drag bits with steel blades (μεταλλικά ελάσματα)
• 3 conical cutting elements
• They can rotate on roller and ball bearings
• When the bit is rotated in service, the cones rotate about their axes through contact with the rock being drilled
• This sets-up a twisting-tearing and chipping-crushing action.
• The teeth of the cones are hard faced to increase the resistance to abrasive wear.
• The rows of teeth on the inner end of each cone interfit with the grooves on the mating cones thus providing a self-cleaning action.
• Cone bits for sticky or soft formations have long, widely spaced teeth, while for harder formations have shorter and more closely spaced teeth.

( Herbert, 1955)
• Fragments or chips removed from the hole by the flushing fluid or mud circulating through the bit.
Bit sizes range from 33/4 inch to 26 inch; 77/8 and 83/4 inch are the more popular.
Rotation speeds ($\omega$) vary from 40 – 500 rpm (more frequent 100-350 rpm).

Speeds may be limited by the rotary power available or the capacity of the pump to clean out the cuttings.

Note: a harmonic vibration may occur at certain speeds which interferes with proper drilling and shortens the life of the drill string.
Response model of the drag bit

- A complete model of the drilling response of drag bits consists from the relations between the weight-on-bit WOB, the torque-on-bit T, the rate of penetration (ROP) V, and the angular velocity $\omega$.

- The logical step is to study first the mechanics of a single cutter and then compose the whole response model of the bit.
Cutters interaction and cutting profiles

Forces acting on the cutter depend on rock type, cutter geometry and wear state, position on the bit, cutter interaction with neighboring cutters, cutting speed, rock stress state, and fluid environment (Glowka, 1989a).

Cutting profiles obtained during two bit revolutions as the cutters pass through a radial plane containing the longitudinal axis of the bit. The shaded areas represent the cross-sectional cut areas for each cutter. All cutters lie on the same plane normal to the longitudinal axis of the bit.
Penetration of a cutter into the flat surface of the rock (I)

The depth to which the cutter penetrates the flat rock surface is a function of the stresses imposed on the rock by the cutter.

Fairhurst & Lacabanne (1957)
Penetration of a cutter into the flat surface of the rock (II): Influence of wedge angle (acute angle and obtuse angle)

Fig. 2. Influence of the wedge angle

Fairhurst & Lacabanne (1957)
Mechanisms of rock disintegration. I. Single sharp cutter

Cutting direction with constant velocity \( v = \omega r \)

Planning action of a rotary bit

Stavropoulou (2006)
Mechanisms of rock disintegration. I. Single sharp cutter

- Rake angle
- Clearance angle
- Positive rake angle
- Negative rake angle

\[ F = F_n + F_s \]

\[ F_n = WOB \]

\[ F_s = \frac{T}{\left(\frac{\alpha}{2}\right)} \]

\[ J = \frac{F_n}{\alpha \delta} \]

\[ E = \frac{F_s}{\alpha \delta} \]

\[ F_n = \tan(\theta + \beta) \]

\( \alpha = \) width of the cutter (or characteristic dimension)

\( E = \) ‘specific energy’ of cutting

\( J = \) ‘drilling strength’
Log-spiral form of the fracture path

Cutting direction
A cutter moves along a helical path due to weight-on-bit $W$ and torque $T$; angular velocity $\omega$ and rate of penetration (ROP) $v$.

$$p = \frac{2\pi v}{\omega}$$

$$v = ROP$$

Rotary drilling

The rotary drag bit bores into the rock along a helical path under the combined action of an axial thrust and a rotary torque, planing off the rock ahead of it.

The general inclination of the path advance is given by the relationship

$$\delta = \tan^{-1} \frac{p}{2\pi r}$$

where $\delta$ = inclination of the helix at radius $r$

$p$ = penetration per revolution

Drill bits are ground to a given back clearance angle, $c$, usually between 15 to 20 deg., the actual clearance during drilling being $c - \delta$. Hence, for small radii, i.e. close to the axis of rotation, the actual clearance is zero and the rock is compressed by the underface of the bit, where grinding occurs. It is largely for this reason that a bit with a centre gap yields higher drilling rates than one with no gap.

Fairhurst & Lacabanne (1957)
$y = \alpha + \beta e^{-x}$

Stavropoulou et al (2005)
Fig. 5—Measured penetrating forces with sharp cutters in dry, noninteracting cuts.

(Glowka, 1989a)
Fig. 11—Measured drag coefficients with sharp cutters in dry, noninteracting cuts.

(Glowka, 1989a)
In a simple analysis it turns out the ROP should be a linear function of WOB (or drilling thrust) with constant ω, and linear increasing with ω for constant WOB.

• A selected ROP can be achieved with a lower WOB and by increasing ω.
Kinematics of the failed rock: Estimation of the cutting force $F_c$ for sharp cutter

The single-cutter models predict such items as cutter forces, temperatures and wear. These predictions are independent of the cutter’s position on the bit.

Stavropoulou (2006)
Passive earth pressure on a wall in contact with a \((\gamma,c,\phi)\) rock. In this case ‘\(\alpha\)’ is the back rake angle of the sharp tool.

\[
\theta = \theta_p = -\alpha + \arctan \left( \frac{\cos(\alpha-\phi)\sin(\alpha+\phi)\cos(\alpha-\phi)}{\sin(\alpha-\phi)\sin(\alpha+\phi)\cos(\alpha-\phi) - \sin(\alpha-\phi)\cos(\alpha-\phi) + \sin(\alpha+\phi)\cos(\alpha-\phi)} \right)
\]

\[
b = \frac{2c}{\gamma h} \frac{\cos(\alpha+\beta)\cos(\alpha+\phi) - \cos(\alpha+\beta)\cos(\alpha+\phi)}{\gamma h \cos(\alpha+\beta) + \frac{2c}{\gamma h} \cos(\alpha+\phi)}
\]

\[
E_p = \frac{\gamma h^2}{2} \left[ \frac{a}{\sin(\alpha-\phi)\cos(\alpha-\phi)\sin(\alpha+\phi) - \sin(\alpha-\phi)\cos(\alpha+\phi)} \left( \cos(\alpha+\beta)\sin(\alpha+\phi) - 1 \right) \right]
\]
Kinematics of the failed rock: Estimation of the cutting force $F_c$ for the blunt cutter

Hypothesis of Fairhurst and Lacabanne (1957) and also by others, that two mechanisms are simultaneously operative: cutting of the rock and frictional contact underneath the cutter.

\[
F_n = F_n^c + F_n^f, \\
F_s = F_s^c + F_s^f
\]
The model of the drag bit & its design

The PDC bit model is a combination of rigorous geometrical relationships used to describe the kinematics of a particular bit geometry and single-cutter force and wear models.

Glowka (1989b)

Fig. 1—Schematic of the four coordinate systems used to describe PDC cutters.
Glowka (1989b)

Fig. 2—Parameters used to locate cutters on PDC bit face.

Fig. 3—Illustration of individual cutter forces and integrated bit performance parameters.

Rock drillability
Table 1—Cutter Positions in Demonstration Analysis

<table>
<thead>
<tr>
<th>Cutter</th>
<th>r (in.)</th>
<th>θ (degrees)</th>
<th>N' (in.)</th>
<th>γ (degrees)</th>
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<tr>
<td>1</td>
<td>0.950</td>
<td>0.0</td>
<td>0.825</td>
<td>-15.0</td>
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<tr>
<td>2</td>
<td>0.800</td>
<td>215.0</td>
<td>0.760</td>
<td>-10.0</td>
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<tr>
<td>3</td>
<td>1.250</td>
<td>80.0</td>
<td>0.985</td>
<td>-5.0</td>
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<tr>
<td>4</td>
<td>1.600</td>
<td>45.0</td>
<td>1.000</td>
<td>-2.0</td>
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<td>5</td>
<td>1.950</td>
<td>85.0</td>
<td>1.000</td>
<td>0.0</td>
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<td>6</td>
<td>2.300</td>
<td>155.0</td>
<td>1.000</td>
<td>2.0</td>
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<td>7</td>
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<td>0.980</td>
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<td>50.0</td>
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<td>0.104</td>
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<td>0.000</td>
<td>55.0</td>
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<tr>
<td>20</td>
<td>3.755</td>
<td>215.0</td>
<td>0.000</td>
<td>55.0</td>
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<td>21</td>
<td>3.975</td>
<td>95.0</td>
<td>0.000</td>
<td>55.0</td>
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</table>

Table 2—Bit Operating Conditions in Demonstration Analysis

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Kd, Bull/10^9F</td>
<td>1.300</td>
</tr>
<tr>
<td>h, ft/hr</td>
<td>0.033</td>
</tr>
<tr>
<td>k, ft/hr</td>
<td>0.070</td>
</tr>
<tr>
<td>k*, ft/hr</td>
<td>0.550</td>
</tr>
<tr>
<td>C1, psin^-1</td>
<td>0.750</td>
</tr>
<tr>
<td>C2, lb/in.</td>
<td>1.34 x 10^6</td>
</tr>
<tr>
<td>C2, lb/in. &amp;</td>
<td>3.26 x 10^5</td>
</tr>
<tr>
<td>C3, lb/ft</td>
<td>2.55 x 10^4</td>
</tr>
<tr>
<td>C4, in. &amp;</td>
<td>2.55 x 10^4</td>
</tr>
<tr>
<td>T, rev/min</td>
<td>6.99 x 10^-13</td>
</tr>
<tr>
<td>T, rev/min</td>
<td>100</td>
</tr>
<tr>
<td>D, ft/hr</td>
<td>80</td>
</tr>
</tbody>
</table>

*See Fig. 2 for definition of cutter position parameters.
Cutters arranged in 3-arm spiral pattern

- Bit has a relatively flat profile since it applies for hard-rock drilling

Fig. 4—Schematic of algorithm used in PDCWEAR to compute z coordinates of cutting profiles at each $x$ value.

Glowka (1989b)

Fig. 5—Schematic of 8½-in. bit design, demonstration analysis.
Bit diameter = 8.5"

Nose height = 4"

Apart of the number of cutters, placement density may be modified locally by moving cutters radially and circumferentially.

The radial placement of cutters is one of the most important parameters in bit design.

Typically increasing number of cutters towards the periphery of bit.

Glowka (1989b)

Fig. 14—Schematic of bullet-nose bit design used to illustrate effects of bit profile, modified analysis.
The radial placement of cutters is one of the most important parameters in bit design. To achieve more uniform wear, cutters can be shifted radially to provide a higher placement density in regions of excessive wear and a lower placement density in regions of low wear.

The circumferential placement of cutters is also important because it affects bit balance during drilling. Excessive side forces can be reduced by shifting cutters circumferentially in the proper directions. Circumferential placement also affects individual cutter forces and wear because it determines how the feed rate of the bit is distributed among the cutters.

**Effects of Bit Rotary Speed.** For a given wear configuration, a selected ROP can be achieved with a lower WOB by increasing the rotary speed. To investigate this effect,
References


