

Chapter 2

Rock Drilling

Drilling, in the field of rock excavation by drilling and blasting, is the first and essential operation carried out, and its purpose is to drill holes, with the adequate geometry and distribution within the rock masses, where the explosive charges will be placed along with their initiating devices. Even in the rock excavation with non-blasting method, drilling sometimes is also needed for creating some spaces to place the chemical expanding agent or insert a breaking tool or only creating a free face for rock breaking by mechanical tools.

The systems of rock drilling have been developed with various means such as mechanical methods (percussion, rotary, rotary-percussion), thermal method (flame, plasma, hot fluid, freezing), hydraulic method, sonic method, and laser ray method. Nevertheless, mechanical drilling system is always the most economic and convenient method and widely used in mining and civil engineering field at present. Therefore, in this book, only the mechanical means will be discussed.

2.1 Mechanism of Rock Breakage by Drilling and Drillability of Rock

2.1.1 *Mechanism of Rock Breakage During Drilling*

The general types of rock breakage during drilling by mechanical method, including percussion drilling, rotary drilling, and rotary-percussion drilling, are three kinds of basic mechanism: percussion-penetration, pressured roller, and cut (see Fig. 2.1).

During the process of drilling the tool (percussive drilling bit, roller-disk and studded roller-disk cutter, rotary tricone bit, or drag tools), the first action is push

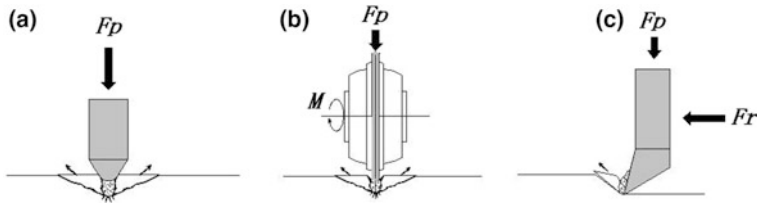


Fig. 2.1 General types of rock breakage during drilling: **a** percussive-penetration; **b** pressured roller; **c** cut

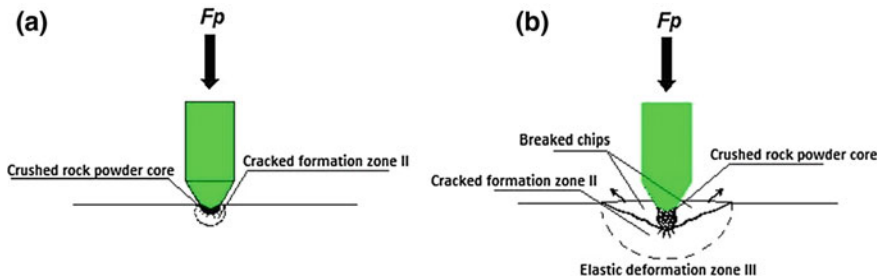


Fig. 2.2 Rock breakage by tool penetration

(or percussion), the tool penetrates into (indentation) and breaks (by F_p) the rock surface, then expands the breakage by continual percussion together with rotation of the bit, or pressured-rolling by thrust force (F_p) and torque (M) or continual cut by push force (F_r) under the thrust force (F_p). The tool penetrates and breaks the rock surface by a static (thrust) force or impact (percussion) force; this is the basic process of the rock breakage by mechanical method.

The process of tool penetrating the rock surface can be divided into four phases as follows [1] (Fig. 2.2):

- Crushed zone

As the tool tip begins to dent the rock surface, stress grows with the increasing load and the material is elastically deformed, zone III in Fig. 2.2. At the contact surface, irregularities are immediately formed and a zone of crushed rock powder core develops beneath the indenter (the bottom or insert of the tool). The crushed core comprises numerous microcracks that pulverize the rock into powder of extremely small particles. About 70–85 % of the indenter's work is consumed by the formation of the crushed zone. The crushed core transmits the main force component into the rock.

- Crack formation

As the process continues, dominant cracks begin to form in the rock, phase (a) in Fig. 2.2. This initial stage of restricted growth is described as an energy barrier to full propagation. The placement of major cracks depends on the indenter shape. Generally, the dominant placement of major cracks with blunt indenters, such as a sphere, is located just outside the contact area, pointing down and away from the surface.

- Crack propagation

After the energy barrier has been overcome, spontaneous and rapid propagation follows. At a lower depth than the contact dimension, the tensile driving force falls below that necessary to maintain growth, thus the crack again becomes stable. The crack is then said to be “well developed.”

- Chipping

When the load reaches a sufficient level, the rock breaks and one or more large chips are formed by lateral cracks propagating from beneath the tip of the indenter to the surface. This process is called surface chipping, phase (b) in Fig. 2.2. Each time a chip is formed, the force temporarily drops and must be built up to a new, higher level to achieve chipping. Figure 2.3 describes the “leapfrogging” progress of the indenter as it penetrates the rock surface [2].

During the process of loading–penetration, there are two facts mentioned by the researchers [2]:

- From Fig. 2.3, it shows that the load–penetration curves for each subrising sections have substantially the same slope. That means the increase in penetration depth is nearly a constant when unit load is increased. The dropping sections of the curves are in relation to the stiffness of the loading mechanics; it is not fully dependent on the rocks being dented;
- Secondly, the bottom angle of the crater (called “natural breaking angle”) formed by crushing and chipping are almost always within a range about 120° – 150° (see Fig. 2.4). Table 2.1 gives the values of the natural breaking angle of some rocks.

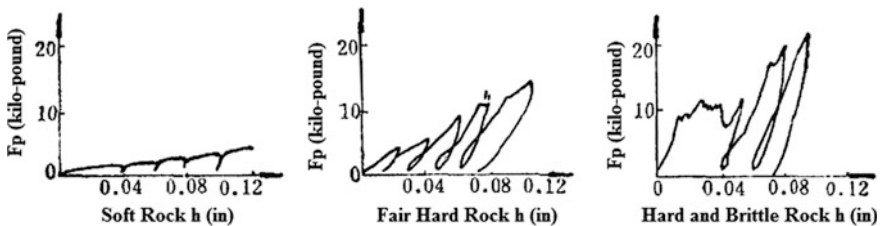
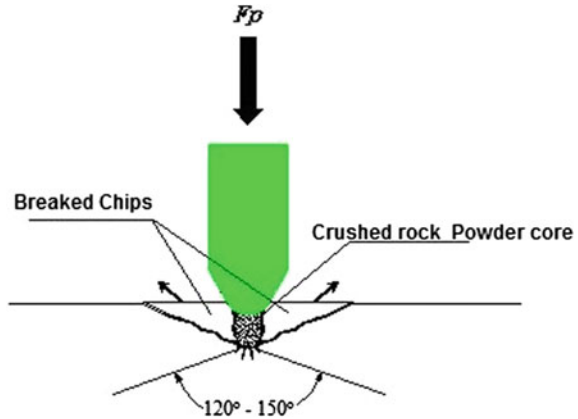


Fig. 2.3 Load (F_p)–Penetration (h) profiles of various rocks (Courtesy of Coal Industry Press, China, Ref. [2])

Fig. 2.4 Natural breakage angle



2.1.2 Drillability of Rock and Its Classification

Drillability is the resistance of rock to penetration by a drilling technique, and it is a term used to describe the influence of numbers of parameters on the drilling rate (drilling velocity) and the tools wear of the drilling machine. Penetration of rocks is influenced by rock properties as well as machine parameters.

The purpose of studying the drillability of rock is for:

- Choosing a suitable drilling method, equipment, and technology to achieve best results on project progress and economy;
- Estimation of the drilling rate and working life of the drilling tools to offer the basic data of project planning;
- Offering reliable data of rock performance for design and improvement of drilling machines.

So, studying rock drillability and its classification is a basic technical work for rock excavation, mining, and geological and petroleum exploration.

Since 1927, B.F. Tillson introduced the concept of “rock drillability,” researchers in many countries carried out lots of work on the rock drillability and its classification. In this book, the work of NTNU/SINTEF (Norway) and Northeast University (China) will be introduced.

2.1.2.1 NTNU/SINTEF Method and Classification of Rock Drillability

As a result of 30 years’ research, SINTEF Rock and Soil Mechanics and NTNU Department of Geology have developed a test procedure for evaluating rock drillability. The method includes measuring three indices:

- Drilling rate index (DRI);
- Bit wear index (BWI); and

Table 2.1 Natural breakage angles (ϕ) of some rocks courtesy of coal industry press, Ref. [2]

Rock	Soft shale	Clay shale	Dense limestone	Soft sandstone	Hard sandstone	Coarse-grained marble	Basalt	Diabase	Fine-grained granite	Hard quartzite
ϕ	116	128	116	130	144	130	146	126	140	150

- Cutter life index (CLI).

Testing on more than 3400 rock samples from all over the world provides unique and sound basis for correlation, updating, and further development. These data make it possible for us to give cost and time estimates for:

- Tunnel driving with TBM;
- Tunnel driving with conventional methods; and
- Rock quarrying.

a. Drilling Rate Index (DRI)

The DRI is assessed on the basis of two laboratory tests: the brittleness value (S_{20}) test and The Sievers' J value (S_j) miniature drill test.

The brittleness value S_{20} is an indirect measure of rock resistance to crack growth and crush. S_{20} is determined by the Swedish Stamp Test (Fig. 2.5).

The crushed and sieved aggregate, sizes ranging 16.0–11.2 mm, is placed in a mortar and then struck 20 times with a 14-kg hammer. The mortar aggregate volume corresponds to that of a 0.5-kg aggregate with a density of 2.65 tons/m³.

S_{20} equals the percentage of undersized material that passes through 11.2-mm mesh after droptest. S_{20} is presented as a mean value of three or four parallel tests.

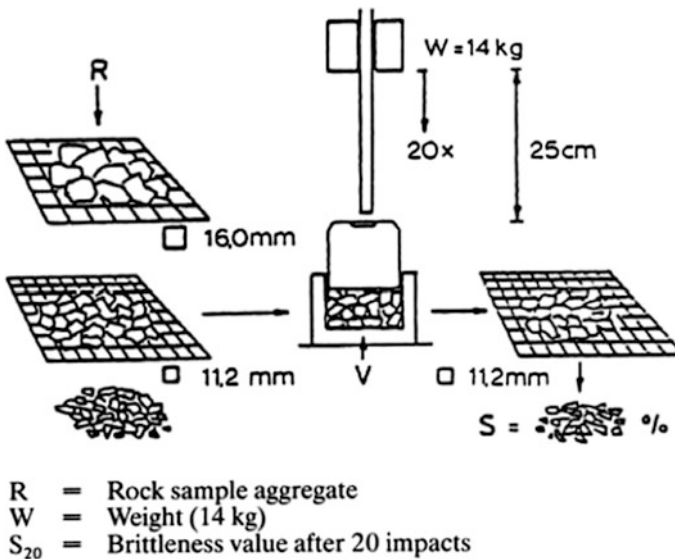
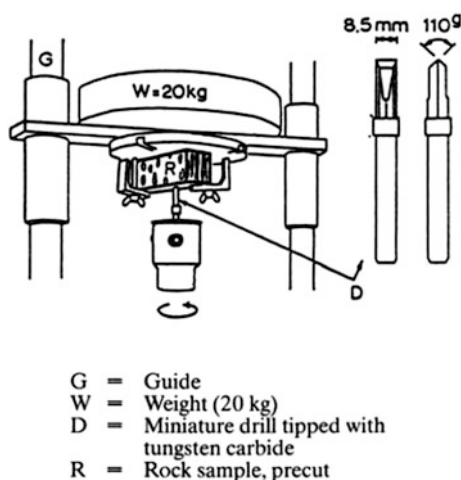


Fig. 2.5 Outline of the brittleness value by stamp test (Reproduced from Ref. [4] by permission of Sandvik)

Fig. 2.6 Sievers' miniature drill test (Reproduced from Ref. [4] with the permission of Sandvik)



The *Sj* miniature drill test is also an indirect measure of rock resistance to tool indentation (surface hardness). The apparatus of miniature drill is shown in Fig. 2.6.

The hole depth in the rock sample is measured after 200 revolutions in 1/10 mm. A mean value of four to eight test holes is used.

The orientation of the rock specimen can affect test results.

Therefore, the *Sj* value is always measured for holes parallel to rock foliation. In coarse-grained rocks, care must be taken to ensure that a representative number of holes are drilled in the different mineral grain types.

The DRI is determined by the diagram shown in Fig. 2.7 [4]. The DRI can also be seen as the brittleness value corrected for its *Sj* value.

A qualitative DRT drillability rating is shown in Table 2.2 (Tamrock, [4]).

b. Bit Wear Index (BWI)

The BWI is assessed on the basis of two laboratory tests, the abrasion value (AV) test and abrasion value cutter steel (AVS) test [3].

The AV test constitutes a measure of the rock abrasion or ability to induce wear on tungsten carbide. The development of the AVS test was based on the AV test method. The same test equipment as for the AV measures the AVS, but the latter uses a test piece of steel taking from a TBM cutter ring. The AVS constitutes a measure of rock abrasion or ability to induce wear on cutter ring steel. The abrasion powder used for both the AV and AVS is normally prepared by the use of test material from the extractions used to determine S_{20} and should hence be regarded as representative and homogenized sample material. An outline of the AV and the AVS tests is shown in Fig. 2.8.

AV is defined as the weight loss of the test piece in milligrams after 5-min testing. AVS is defined as the weight loss of the test piece in milligrams after 1 min of testing. The AV and AVS tests are normally performed on 2–4 test pieces.

Fig. 2.7 Diagram used to determine DRI (Reproduced from Ref. [4] with the permission of Sandvik)

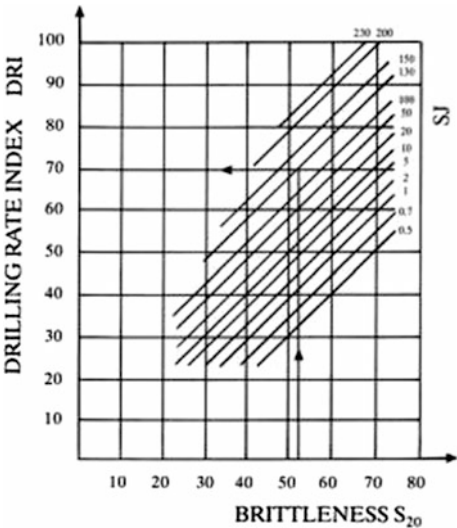


Table 2.2 Qualitative DRI drillability

Rating	DRI
Extremely low	21
Very low	28
Low	37
Medium	49
High	65
Very high	86
Extremely high	114

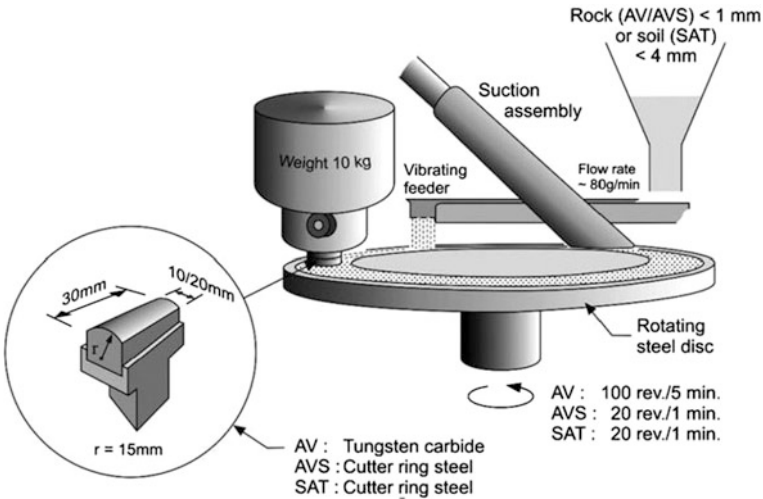


Fig. 2.8 Outline of the AV and AVS test (source [3])

Table 2.3 Classification or rock drillability by NTNU/SINTEF (quoted from [3])

Class	S_{20} value (%)	S_j value (mm/10)	AV (mg)	AVS (mg)
Extremely high	≥ 66.0	≤ 2.0	≥ 58.0	≥ 44.0
Very high	60.0–65.9	2.1–3.9	42.0–57.9	36.0–44.0
High	51.0–59.9	4.0–6.9	28.0–41.9	26.0–35.9
Medium	41.0–50.9	7.0–18.9	11.0–27.9	13.0–25.9
Low	35.0–40.9	19.0–55.9	4.0–10.9	4.0–12.9
Very low	29.1–34.9	56.0–85.9	1.1–3.9	1.1–3.9
Extremely low	≤ 29.0	≥ 86.0	≤ 1.0	≤ 1.0

c. Classification of drillability

The NTNU/SINTEF database does presently contain recorded test results for nearly 3200 samples from various rock excavation projects. NTNU/SINTEF tests show very good reproducibility and consistency. The following table shows the classification or rock drillability of NTNU/SINTEF [3] based on statistical analysis of the test values recorded in the database so far (Table 2.3).

2.1.2.2 Rock Drillability Classification Using the Method of Impact Penetrate

In 1980, Northeastern University, China (NEU), published their research result of rock drillability classification using the method of impact penetrate with two indexes of “specific impact penetrate work” and “abrasion width of bit” and developed two sets of measurement apparatus.

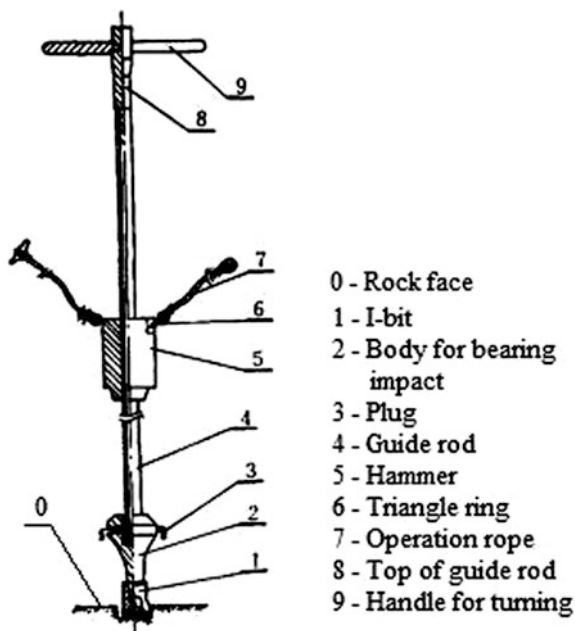
a. Concept of impact penetrate-specific work (IPSW)

The work consumed for impact penetrate on a unit volume of rock is called “impact penetrate-specific work (IPSW).” It is the basic physical quantity for the percussion (rotary-percussion) drilling of rock. During the process of impact penetrate, the relationship between the impact work applied (A) and the IPSW (a) is shown in the following Fig. 2.9 for some rocks. In the figure, it shows that there is a critical value of impact work A_c for the tested rock. When the applied impact work A is less than a certain value A_c , the value of IPSW is not stable and varies greatly as the small impact force only produces a scar and small powder cannot produce any chipping. When impact work A is greater than A_c , IPSW reach a plateau. The phenomenon tells us that the impact work as a main parameter of the test apparatus must be greater than the critical value, A_c , of any rock to be tested.

b. Test apparatus—impact penetrate apparatus (IPA)

The apparatus of the IPA is shown in Fig. 2.10. The weight of hammer (5) is 4.0 kg. The hammer free fall height along the guide rod (4) is 1.0 m. The hammer impacts the body (2) with an I-type bit connected in the bottom and the bit chisels

Fig. 2.9 Impact penetrate apparatus (Reproduced from Ref. [5] with the permission from Metallurgy Industry Press)



the rock. After every impact, the bit is turned 15° by the top handle of the rod. The diameter of the bit is 40 ± 0 and made with Type YG-11G tungsten carbide insert. Insert angle is 110° . For measuring the abrasion of the bit, a new bit (or newly grinded bit) must be used for every test. The rock face to be tested is placed horizontally, and a shallow nest is previously prepared manually for locating the tested bit. The net depth of the drilled hole, H , is measured and recorded after total 480 impacts for each rock specimen. The IPSW, a , can be calculated using the following formula:

$$a = \frac{A}{V} = \frac{nA_0}{\frac{\pi}{4}d^2H} = \frac{480 \times 39.2}{\frac{\pi}{4} \times 4.1^2 \times \frac{H}{10}} = \frac{14252}{H} \text{ J/cm}^2 \quad (2.1)$$

where:

- a impact penetrate-specific work (IPSW), J/cm^3 ;
- A total impact work of 480 freely falling of the hammer, J;
- V rock volume to be broken after 480 impacts, cm^3 ;
- N total impact times, $n = 480$;
- A_0 work of single impact, $A_0 = 39.2$ J;
- D actual hole diameter after drilling, $d = 41$ mm (bit diameter = 40 mm); and
- H net depth, mm.

After the test of IPSW, the abrasion of the bit is measured as well. The measurement is carried out using a reading microscope, expressed as “b” in mm, shown

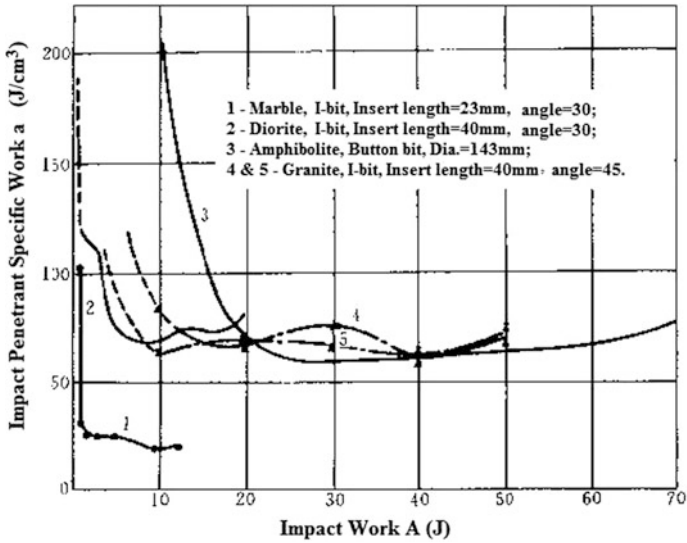
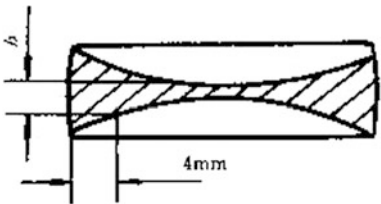


Fig. 2.10 Relationship between impact work and IPSW (Reproduced from Ref. [5] with the permission from Metallurgy Industry Press)

Fig. 2.11 Measurement of bit abrasion (Reproduced from Ref. [5] with the permission from Metallurgy Industry Press)



in Fig. 2.11. The abrasion value is the average value measured at the two ends of the bit edge after 480 impacts.

c. Classification of rock drillability

In the system of rock drillability using the method of impact penetrant, rock drillability is divided into seven classes and three categories according to both the index of impact penetrant-specific work (IPSW) “a” and the index of bit abrasion “b.” The classification is shown in Tables 2.4 and 2.5 (Courtesy of Metallurgy Industry Press, Ref. [5]).

For verifying the classification system, total 2532 samples of 96 kinds of representative rocks from more than one hundred mines and working sites were tested. These tests show very good reproducibility and consistency. The correlation study between the drillability classification and the practical drilling effects of the production equipment, such as percussive rock drill, down-the-hole drill, rotary drill with rolling tricone bit, and TBM, also was carried out.

Table 2.4 Rock drillability classification by impact penetrant-specific work index “a”

Class	I	II	III	IV	V	VI	VII
Drillability	Very easy	Easy	Fair easy	Fair difficult	Difficult	Very Difficult	Extremely difficult
IPSW “a” (kg m/cm ³)	≤19	20–29	30–39	40–49	50–59	60–69	≥70

Table 2.5 Rock drillability classification by bit abrasion index “b”

Category	1	2	3
Abrasive	Weak	Medium	Strong
Bit abrasion “b”	≤0.2	0.3–0.6	≥0.7

- The correlation between IPSW and drilling time of the rock drill 7655 and 73-200 DTH drill is shown in Fig. 2.12.
- The correlation between IPSW and the drilling time per meter borehole, *t*, of 45-R and 60-R rotary drill (rolling tricone bit) is expressed with the regressive equation:

45-R rotary drill: $t \approx 0.11a$ (the correlation coefficient of the equation is: 0.94);
60-R rotary drill: $t \approx 1 + 0.1a$ (the correlation coefficient of the equation is: 0.98).

That means the correlation between IPSW and the tested rotary drill is very good.

- The correlation of the excavation speed (*v*) of SJG-53-12 TBM with IPSW (*a*), single teeth static pressure (*K*), rock compressive strength (*R*), Protodyakonov’s smash method (*f*), and the sound velocity (*V_L*):

Fig. 2.12 Correlation between IPSW and drilling time of handheld rock drill and DTH drill (Reproduced from Ref. [5] with the permission from Metallurgy Industry Press)

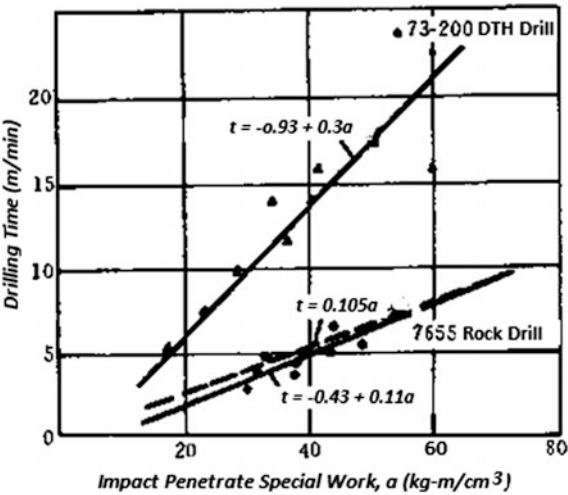


Table 2.6 Correlation between TBM boring speed, v , and different indexes of drillability

Test method	Relationship	Regressive equation	Correlation coefficient	Sample quantity
IPSW	$v-a$	$v = 41.67a^{-1.04}$	-0.885 (>0.561)	20
Single teeth static pressure	$v-K$	$v = 0.35 + 0.014K$	0.717 (>0.684)	13
Rock compressive strength	$v-R$	$v = 1.61 - 0.41R$	0.63 (\sim 0.632)	10
Smash method	$v-f$	No correlation		19
Sound velocity	$v-V_L$	No correlation		23

SJG-53-12 TBM ($\phi = 5.2$ m, thrust = 396 t, cutterhead rotation speed: 5.79 r/min, cutter disk number = 64) bored 346-m tunnel in biotite gneiss.

The correlation of the TBM boring speed v with the above-said indexes is shown in Table 2.6 (Courtesy of Metallurgy Industry Press, Ref. [5]).

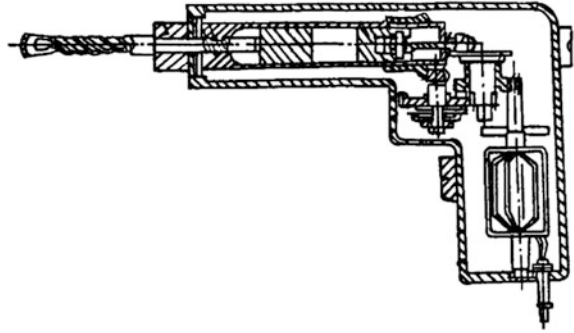
It is self-evident that the index of IPSW (a) has the best correlation with the TBM boring speed.

The sample tests also show that the index of bit abrasion (b) has a very close relationship with the consumption of drilling tools. As an example, Table 2.7 shows the test results from a large open iron mine.

Table 2.7 Rock drillability versus bit life (courtesy of Metallurgy Industry Press, Ref. [5])

Rock	Average IPSW a (J/cm ³)	Average bit abrasion b (mm)	Bit life (m)		
			DTH drill	45-R rotary drill	60-R rotary drill
Biotite quartz schist	240–280	0.1–0.2	120–150	350–450	500–600
Green clay amphibolite	200–250	0.1–0.2	120–150	350–400	400–450
Black green amphibolite	\approx 300	0.1–0.2	60–100	300–350	350–400
Dark green amphibolite	500–550	0.2–0.3	25–40	150–200	
Mixed granitic rocks	300–400	0.2–0.4	40–60	250–350	250–350
Third layer red iron ore	300–350	0.6–0.8	25–40	200–300	250–300
Third layer Iron asbestos ore	450–500	0.6–0.9	25–40	\approx 200	150–200
Third layer gray iron ore	450–550	0.5–1.0	12–16	80–100	100–140
1st and 2nd layers iron ore	550–600	0.8–1.3	8–12		\approx 100

Fig. 2.13 WZ-1 mini-drillgauge (courtesy of “Metal Mines,” China, Ref. [6])



d. Mini-drillgauge (MDG)

For convenience of test the rock drillability, the WZ-1 type of mini-drillgauge (MDG) was designed by the same research group of Northeast University in 1991 [6]. In fact the mini-drillgauge is a reformed electric mini-impact drill and a special designed drill bit. Its structure is shown in Fig. 2.13.

For testing the rock drillability, the working parameters of WK-1 MDG are determined as follows:

Working voltage: 220 V,

Motor speed: 1000 r/min,

Single impact work: 2.6 J, Impact frequency: 3800/min

I-type bit diameter: 14 ± 0.5 mm, Insert angle: 110° .

Drilling time for each test is set to 1 min. The impact penetrant-specific work measured by the WZ-1 MDG is calculated with the following formula:

$$a_w = \frac{A}{V} = \frac{n \times A_w}{\frac{\pi}{4} \times D^2 \times \frac{H}{10}} = \frac{360 \times 2.6 \times 10}{\frac{\pi}{4} \times 1.5^2 \times H} = \frac{55909}{H} \quad (2.2)$$

where

A , V same as formula (2.1);

n impact frequency, $n = 3800/\text{min}$;

A_w single impact work, $A_w = 2.6$ J

D drillhole diameter, $D = 1.5$ cm (bit diameter: 1.4 ± 0.5 cm);

H net depth of drilled hole

The measurement of bit abrasion is shown in Fig. 2.14.

The stability and reliability of the performance of WZ-1 MDG and the reproducibility and consistency of the data measured by MDG had been tested using ten apparatuses of WZ-1 MDG and different rocks. The test results are satisfied. The dispersion coefficient of the drilled depth in a same rock sample by ten apparatuses is 4.55 %. The maximum relative error of the average drilled hole depth on different rock types using 3 MDG, which have different used time, is less than 4.0 %.

Fig. 2.14 Measurement of bit abrasion for WZ-1 MDG (courtesy of “Metal Mines,” China, Ref. [6])

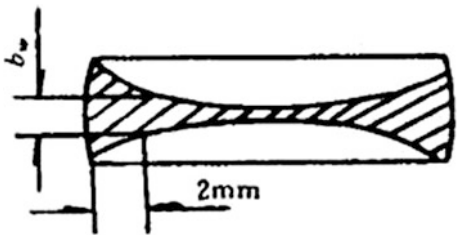


Table 2.8 Rock drillability classification by impact penetrant-specific work (IPSW) index

Class	IPSW (J/cm ³)		Drillability	Representative rock
	IPA “a”	WZ-1 MDG “a _w ”		
I	≤186	≤400	Very easy	Shale, coal, tuff
II	187–284	401–650	Easy	Limestone, sand shale, peridotite, green clay amphibolites, mica quartz schist, dolomite
III	285–382	651–900	Fair easy	Granite, limestone, olive schist, bauxite, migmatite, amphibolite
IV	383–480	901–1150	Fair Difficult	Granite, siliceous limestone, gabbro, porphyrite, pyrite, magnetite quartzite, gneiss, skarn, marble
V	481–578	1151–1350	Difficult	Martite, magnetite quartzite (Nan Fen), cangshan gneiss, in fine-grained granite, dark green amphibolite
VI	579–676	1351–1550	Very difficult	Martite (Gu Shan), lamprophyre, magnetite quartzite (Nan Fen’s 1st and 2nd layer iron ore), dense skarn
VII	≥677	≥1551	Extremely difficult	Martite (baiyunebo), magnetite quartzite (Nan Fen)

Table 2.9 Rock drillability classification by bit abrasion index

Category	Bit abrasion (mm)		Abrasion	Representative rock
	IPA “b”	WZ-1 MDG “b _w ”		
1	≤0.2	<0.2	Weak	Shale, coal, tuff, marble, amphibolite, peridotite, diabase, dolomite, bauxite, phyllite, skarn
2	0.3-0.6	0.2-0.4	Medium	Granite, diorite, gabbro, sandstone, sandshale, siliceous limestone, siliceous marble, migmatite, leptynite, gneiss, skarn
3	≥0.7	≥0.5	Strong	Pyrite, martite, magnetite quartzite, quartzite, hard gneiss

The rock drillability classification for some representative rocks using the method of IPSW and two kinds of apparatuses are shown in Tables 2.8 and 2.9 below (courtesy of “Metal Mines,” China, Ref. [6]).

2.2 Classification of Drilling Machines

2.2.1 Classification on Drilling Manner

Within the large variety of excavations using explosives, numerous machines have been developed which can be classified into two types of drilling Manners:

- Manual drilling. This is carried out with light equipment that is handheld by the drillers. It is used in small operations where, due to the size, other machinery cannot be used or its cost is not justified.

The modern handheld rock drills are developed trending to be lighter, more convenient, and more efficient. Except the widely used pneumatic handheld drill, some new energy sources, like hydraulic, electricity and internal combustion engine, are also developed (Figs. 2.15, 2.16, 2.17, 2.18).

- Mechanized drilling. The drilling equipment is mounted upon rigs with which the operator can control all drilling parameters from a comfortable position. These structures or chassis can themselves be mounted on the wheels or tracks and either be self-propelled or towable (Figs. 2.19, 2.20).

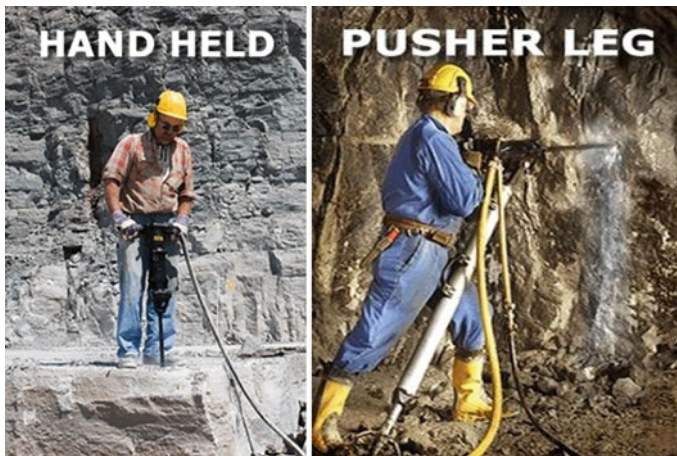


Fig. 2.15 Handheld pneumatic rock drill (Reproduced with the permission from Atlas Copco)



Fig. 2.16 Handheld hydraulic rock drill (Reproduced with the permission from Atlas Copco)



Fig. 2.17 Internal combustion rock drill (courtesy of Luoyang Bytain Trading Co., Ltd.)



Fig. 2.18 Handheld electric rock drill (courtesy of HILTI power tools)



Fig. 2.19 Crawler rig for surface drilling (Reproduced with the permission from Atlas Copco)

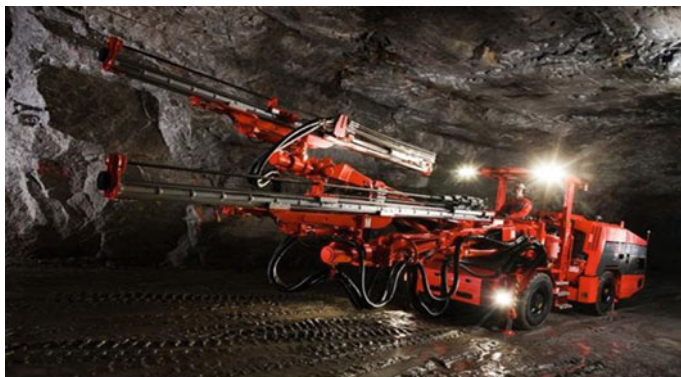


Fig. 2.20 Wheel-mounted rig for underground drilling (Reproduced with permission from Sandvik)

2.3 Classification on Drilling Methods

The two most used mechanical drilling methods are rotary-percussion and rotary.

- Rotary-percussive methods. These are the most frequently used in all type of rocks, the top hammer, as well as the down-the-hole hammer.
- Rotary methods. These are subdivided into two groups, depending upon if the penetration is carried out by crushing with tri-cones or by cutting with drag bits. The first system is used in medium-to-hard rocks, and the second in soft rocks, see Fig. 2.21.

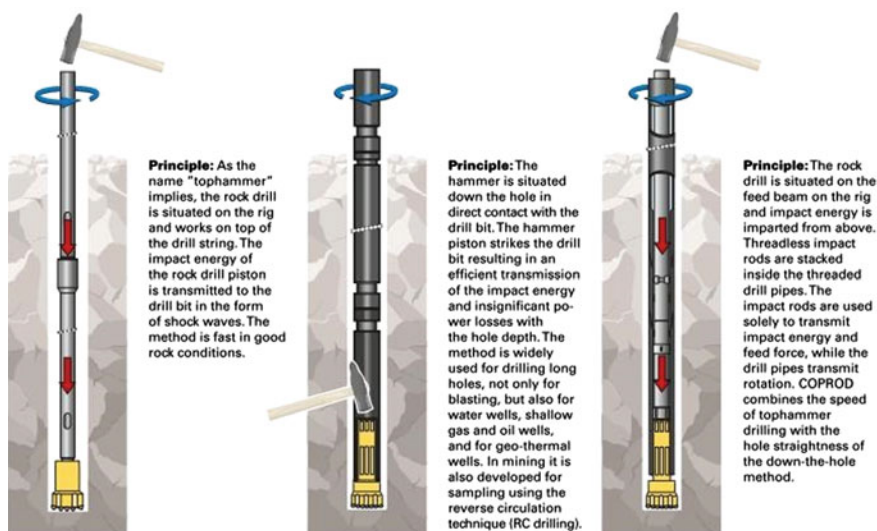


Fig. 2.21 Working methods of rotary-percussive drilling (Reproduced with the permission from Atlas Copco)

For engineering blasting, rotary-percussive drills have been used for more than 200 years from the manual drilling (excluding manual hammer drilling) to the modern hydraulic rigs. The mostly used rotary-percussive drills are the types of top hammer within the range of drillhole diameter from 38 to 127 mm. The down-the-hole drills are used for the larger holes with a diameter from 75 to 200 mm. The down-the-hole drills with a hole diameter of 150 mm were used in the blasting works for the construction of Hong Kong New Airport at Chek Lap Kok Island.

Rotary drills mostly are used in large open pit mines for drilling large diameter blastholes (127–440 mm) with the rolling cone rock bits. Other rotary drills with cutting action using the drag bits are used for soil, e.g., for installing soil nails on a slope, soft rock, like coal, or overburden drilling.

2.4 Rotary-Percussive Drilling

Rotary-percussive drilling is the most classic system for drilling blastholes and widely used in mining and civil engineering since the middle of nineteenth century starting with steam power then by compressed air. The appearance of hydraulic power in the sixties of last century has given a new boost to this method, complementing and widening its field of application.

According to the difference in the working modes of the major performances, hammer impact and rod/bit rotary, the rotary-percussive drilling are classified into two groups:

- Top hammer method including the newly developed COPOROD;
- Down-the-hole hammer method (DTH), also known as ITH (in-the-hole).

Rotary-percussive drilling is based upon the combination of the following four actions (Fig. 2.22):

- Percussion: The piston inside the rock drill strikes the tail end of the rod or bit itself and generates shock waves that are transmitted to the bit through the rod (in top hammer) or directly upon it (DTH).

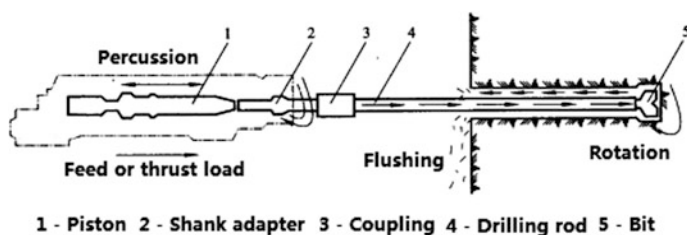


Fig. 2.22 Basic action in rotary-percussive drill

- **Rotation:** The rotary mechanism rotates the rod (in top hammer) or tube (in COPROD) or DTH hammer. With this movement, the bit is turned so that the impacts are produced on the rock in different positions.
- **Feed or thrust load:** Feed force is required to keep the shank in contact with the drill and the drill bit in contact with the rock. This ensures maximum impact energy is transferred from the piston to the rock.
- **Flushing:** Flushing is used to remove the rock cutting from the drillhole and to cool bit. The flushing medium—air, water, mist, or foam—is forced to the bottom of the drillhole through the rod's flushing hole and the hole in the drill bit.

2.4.1 Top Hammer Drilling

Top hammer drilling is the most widely used mode of rotary-percussive methods from handheld to drilling rigs. In percussive top hammer drilling, the impact energy is generated when the piston is striking the adapter (or tail end of the rod in handheld drill). This energy is transmitted from the rock drill via the shank adapter, drill rod, and drill bit to the rock, where it is used for crushing. The top hammer method is primarily used for drilling in hard rock for hole diameters up to 5 in (127 mm), and the main advantage is the high penetration rate in good solid rock conditions. Handheld pneumatic rock drill is used for small hole diameters while rig mounted hydraulic rock drill is commonly used for hole diameters above 1 5/8 in (41 mm). Heavy hydraulic rock drill with an impact power of up to 40 kW is used for large hole diameters up to 5 in.

2.4.1.1 Pneumatic Rock Drills

Pneumatic rock drill is equipped with valves (or piston itself in some handheld drills) to change the direction of compressed air into the cylinder, so that the compressed air pushes the piston with reciprocating strikes on the adapter or the tail of the drill rod through which the shock wave is transmitted to the bit where the chisel crushes rock. Along with each strike of the piston, the drill rod was rotated a certain angle (5°–15°) by a spirally fluted rifle bar or by independent rotary mechanism. The flushing system consists of a tube that allows the passage of air or water to the inside of drill steel. Figure 2.23 is a handheld rock drill, and Fig. 2.24 shows the structure of a typical handheld rock drill.

The pneumatic top hammer drill with independent rotary mechanism usually has more power even when the piston has the same size because the rifle bar is eliminated and the working surface of the piston on which the compressed air acts is increased. Another advantage of independent rotary mechanism is the percussion, and the rotation speed can be adjusted independently to suit the rock type to be

Fig. 2.23 Handheld rock drill (Reproduced with the permission from Atlas Copco)



drilled. But the independent rotary mechanism increased the weight of the drill so that it can only be used for the drill mounted in a rig.

Despite the quick development of the hydraulic hammer drill, pneumatic top hammer drill mounted on the rig has only gradually been replaced by hydraulic drills; it still occupies some market in mining and construction works due to its simplicity, reliability, easy repair, and low capital cost.

Table 2.10 gives the technical specification of some typical handheld pneumatic rock drills.

2.4.1.2 Hydraulic Rock Drill

At the end of the sixties and beginning of the seventies, a great technological advance took place in rock drilling with the development of hydraulic hammers. These new, high-power rock drills not only doubled drilling capacities but also improved the drilling environment. The introduction of hydraulics to rock drilling also led to improvements in drilling accuracy, mechanization, and automation.

The general working principle of a hydraulic percussive rock drill is presented in Fig. 2.25.

Fig. 2.24 Operational parts of handheld drill

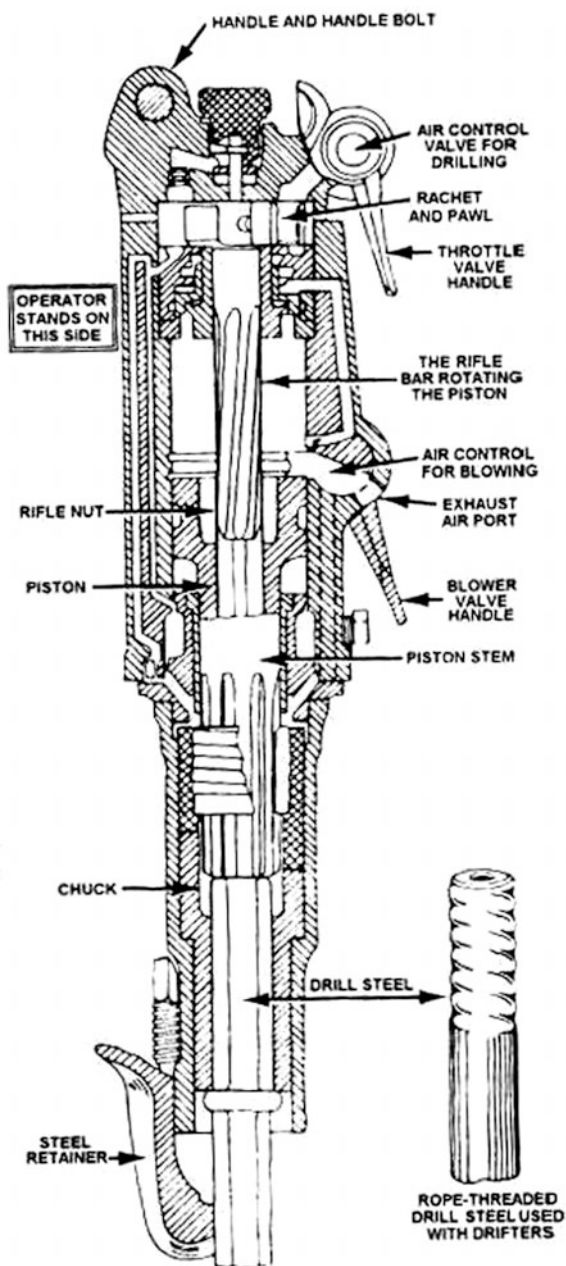


Table 2.10 Technical specification of some handheld pneumatic rock drills

Manufacture	Atlas		Sandvik		Tianshui, China	
Type	YT29A	BBC16W	RD245	RD855	YT24	YT28
Weight (kg)	27	28.5	26	27	24	26
Length overall (mm)	659	705	660	615		
Piston stroke (mm)	60	55	68	60	70	60
Piston Dia. (mm)	82	70	66.7	85	70	80
Impact energy (at 5 bar) (J)	≥70	≤70			62	63
Working pressure (bar)	3.5–5	3.5–5			4–5	4–5
Air consumption (at 5 bar) m ³ /min	≤3.9	≤4.14	2.7	3.5	3.36	3.48
Drilling diameter (mm)	32–45	32–45	32–45	32–45	34–45	34–45
Shank size	22 × 108	22 × 108	22 × 108	22 × 108	22 × 108	22 × 108

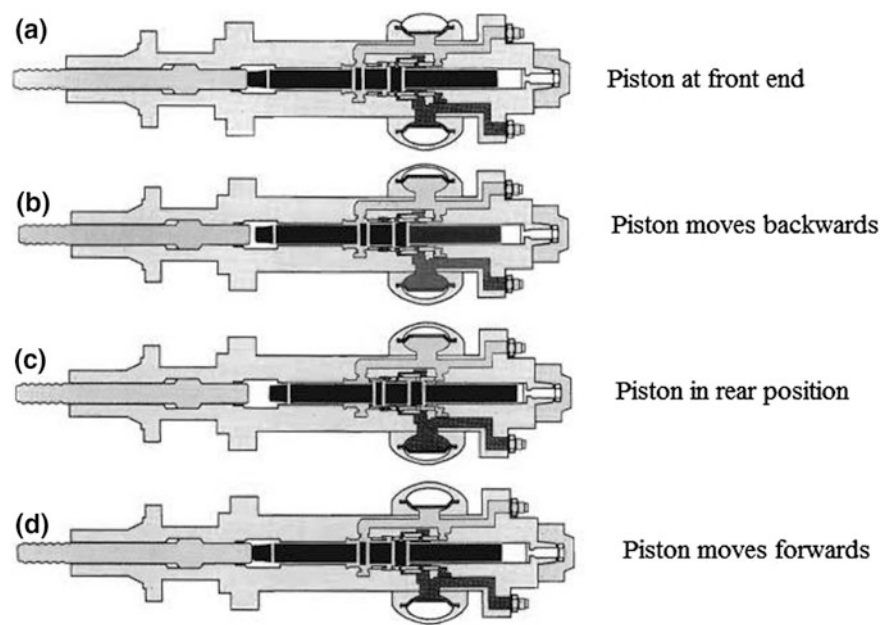


Fig. 2.25 Working principle of the hydraulic drill (Reproduced from Ref. [1] with the permission of Tamrock)

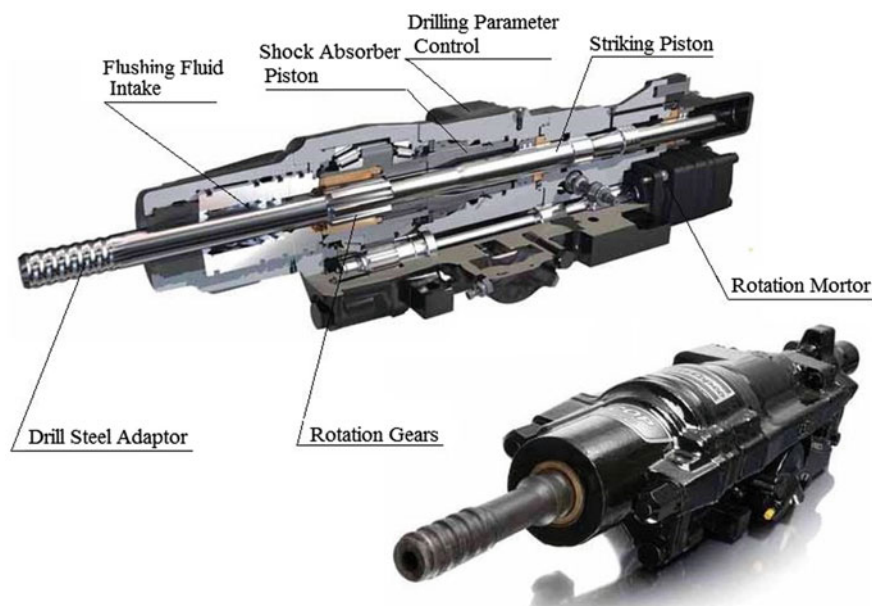


Fig. 2.26 Hydraulic rock drill and its cross section (Reproduced from Ref. [9] with the permission from Atlas Copco)

A hydraulic drill is composed basically of the same elements which are shown in Fig. 2.26.

Although in the beginning hydraulic drill rigs were mostly used in underground operation, but at present it has been widely used in both underground and surface drilling except some very small projects and places where hydraulic drill rigs cannot be used. But on the other hand, they also have some disadvantages: high initial investment, more complex, and costly repairs than those for pneumatic drills, requiring better organization and preparation of maintenance personnel. Figures 2.19 and 2.20 in Sect. 2.1 show the hydraulic drill rigs that are used in surface and underground excavation. A comparison of general working parameter range of top hammer drill rigs between pneumatic and hydraulic drills are shown in Table 2.11.

The COPROD drilling system, newly developed by Atlas Copco, combined the advantages of top hammer and DTH drilling. In this system, the inner drill rods transmit strike power to the drill bit and out tubes transfer rotation, adding stiffness to the string and improved flushing efficiency. Practices show that the COPROD system offers unique features for drilling holes straight and fast, especially suitable for the fractured rock conditions, in spite of its higher initial cost. Figure 2.27 shows the COPROD drill string, and Fig. 2.28 shows an Atlas Copco ROC F7CR equipped COPROD system in the Jackomini Quarry, Austria, drilling 89-mm diameter holes in the fractured rock.

Table 2.11 Comparison of general working parameters ranging between pneumatic and hydraulic rock drill rigs (Reproduced from Ref. [9] with permission from Atlas Copco)

Working parameter	Pneumatic rock drill (for Rig)	Hydraulic rock drill (surface/underground)
Drillhole diameter (mm)	48–102	64–127/35–89
Impact power (kW)	7.2–12	12–40/12–22
Impact rate (Hz)	33–39	36–75/40–73
Hydraulic pressure (bar)		210–230/190–250
Air consumption—excluding flushing (l/s)	175–354	
Rotation speed (rpm)	0–300	0–220/0–380
Rotation pressure (bar)		200–210/210
Drill steel torque (Nm)		1000–3500/520–1000
Flushing Air Pressure (bar)		8–12/10



Fig. 2.27 COPROD drill string (Reproduced with the permission from Atlas Copco)

2.4.1.3 Hydraulic Drilling Rigs

Since the seventies, rock drilling technique has seen rapid development following the development of the hydraulic technique. These new, high-power rock drills not only doubled drilling capacities but also improved drilling environment. The

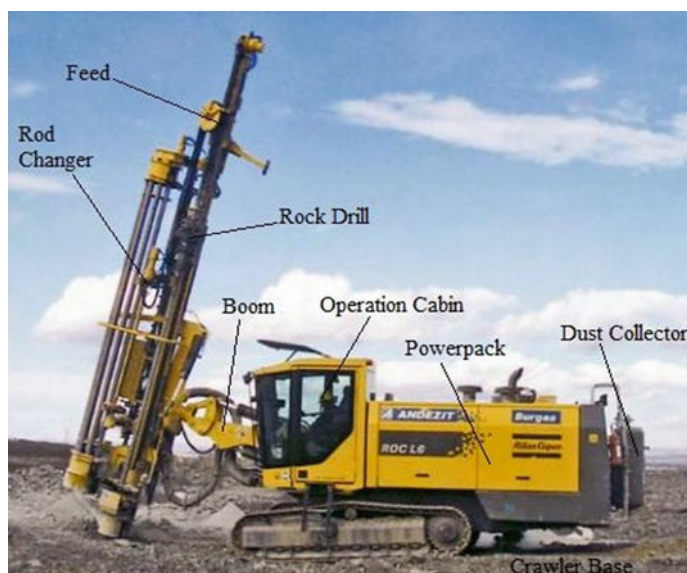


Fig. 2.28 ROC F7CR with COPROD system (Reproduced with the permission from Atlas Copco)

hydraulics to rock drilling also led to improvement in drilling accuracy, mechanization, and automation.

The following photographs (Figs. 2.29 and 2.30) show the basic components of the hydraulic rock drilling rigs working in surface and underground excavation.

For the surface drilling rigs, the power pack, including the hydraulic power supply and air compressor, is driven by a diesel engine. But for the underground drilling jumbo, it usually is driven by electric motors for reducing the air pollution of the underground working space. When a surface drilling rig works, the main source of noise is the top hammer drifter. The recently introduced silenced drill rig is for use especially in urban areas where noise levels are restricted. A soundproofing enclosure kit is designed for the drilling components, resulting in a 10 dB (A) external noise reduction. Figure 2.31 is a silenced Smart Rig, ROC D7C, manufactured by Atlas Copco, which was firstly used in 2006 in Finland and 2008 in Hong Kong (Fig. 2.31).

2.4.2 Down-the-Hole (DTH) Drilling

Down-the-hole (DTH) drilling, also known as in-the-hole (ITH) drilling, is a method in which the percussive hammer works in the hole during drilling. In this system, the hammer (piston) strikes directly on the bit, and no energy is lost through joints in the drill string (Figs. 2.21, 2.32). The piston strikes the drill bit directly,

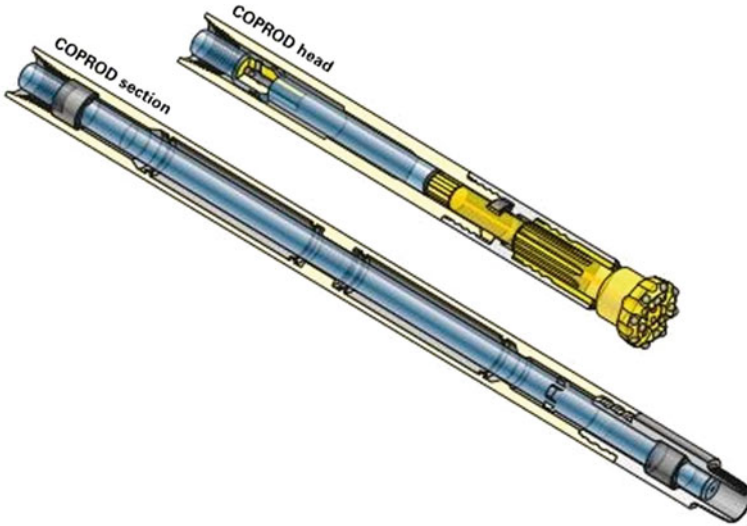


Fig. 2.29 Basic components of the surface drilling rig (Reproduced with the permission from Atlas Copco)

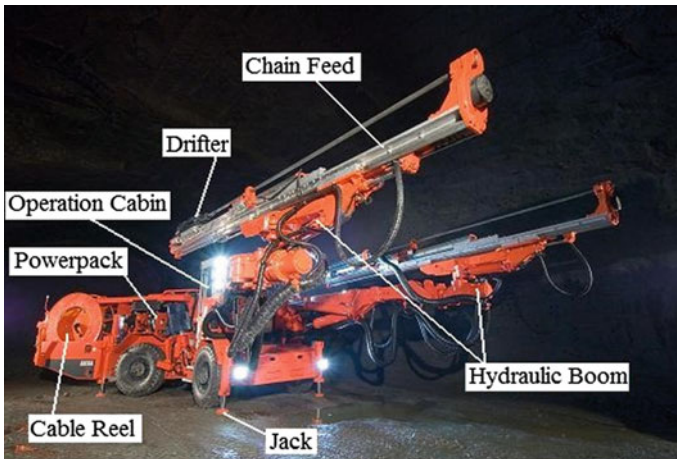


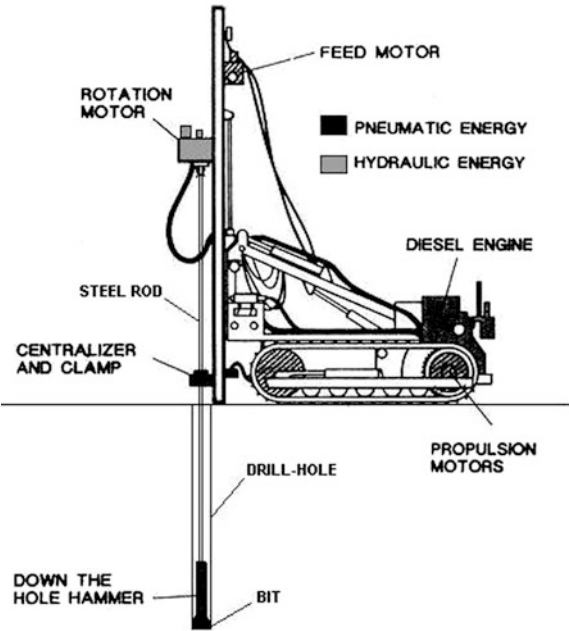
Fig. 2.30 Basic components of the underground drilling jumbo (Reproduced with the permission of Sandvik)

while the hammer casing gives straight and stable guidance of the drill bit. This results in minimal deviation and great hole wall stability, even in fissured or otherwise demanding rock. The driving fluid of the hammer is compressed air that is supplied through a tube which serves as support and makes the hammer turn. The rotation and thrust force are carried out by two separate hydraulic motors (or



Fig. 2.31 Silenced drilling rig (Reproduced with the permission from Atlas Copco)

Fig. 2.32 Down-the-hole drilling rig



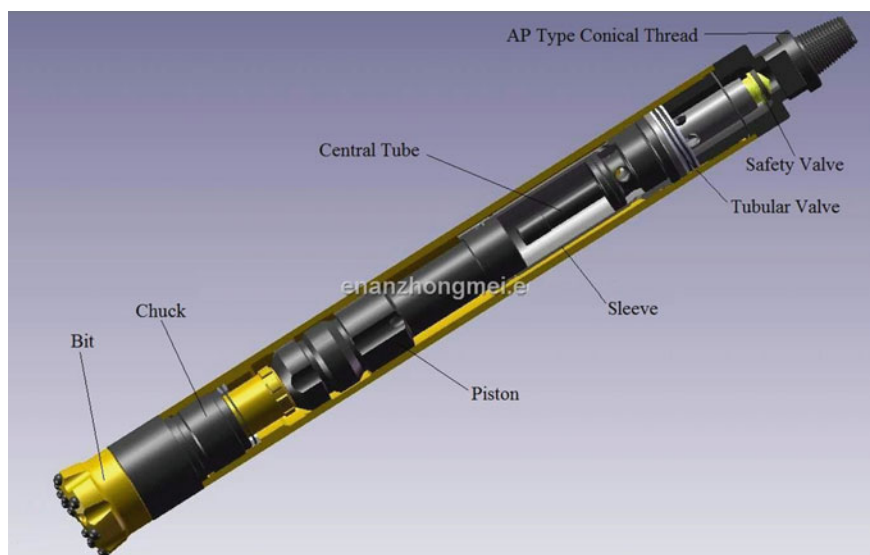


Fig. 2.33 General structure of DTH drill hammer (courtesy of Henan Zhongmei Drill Tool Co. Ltd., China)

pneumatic motors) mounted on the surface rig. Flushing is carried out with the exhaust air of the hammer through the holes in the drill bit. Since the annulus between the drill pipes and the hole wall is comparative small, a high flushing velocity is maintained, which contributes further to hole quality. DTH method is widely used to drill long holes, not only for blasting, but also for water wells, shallow gas, oil wells, and for geo-thermal wells. From an environmental point of view, as the hammer is working in the hole, the noise emission from DTH drilling is comparatively low. This is of particular advantage when drilling in densely populated areas. Figure 2.33 shows the general structure of an original DTH drill hammer. Today's DTH hammer design is much simpler than the original one which had a butterfly valve incorporated to direct the air alternately to the top part of the piston. The valveless hammers are operated through ribbings or projections of the piston itself, allowing an increase in strike frequency, lowering air consumption, and risk of dieselization. The strike frequency for down-the-hole hammer is usually between 600 and 1600 strikes per minute. The air pressure used is usually between 6 and 24 bar. Rotation speed is about 25–100 rpm, and the feeding force is varied between 6 and 20 kN. In the hole range 100–254 mm, DTH drilling is the dominant drilling method today. The main technical parameters of some DTH hammers are shown in Table 2.12.

Table 2.12 Technical parameters of some DTH drill hammers

Hammer	Drilling dia. (mm)	Hammer dia. (mm)	Hammer weight (kg)	Working pressure (bar)	Air consumption (m ³ /min)
<i>Atlas Copco</i>					
COP 34	92–105	83.5	27	12–24	6–16.8
COP 54	134–152	120	57	12–24	10.8–24
COP 64 Gold	156–178	142	96	12–28	12–36
<i>SANDVIK</i>					
EH550r, 4"	110–133	98	38	10–24	5.1–15.9
EH550r, 5"	130–152	126	73	10–24	8.64–24.21
EH550r, 6"	152–203	150	82	10–24	9.8–27.5
<i>Ingersoll Rand</i>					
DHD340A	110–125	98	32.1	10.4–24.1	
QL5/QL50	140–152	125	60.3	10.4–24.1	
<i>China</i>					
ZX-115	110–140	98	36	12–20	3.5–15
ZX-150	152–165	136	98	7–21	8.5–25

2.5 Rotary Drilling

The rotary drills include two kinds of drilling method: rotary crushing with tricone and fixed-type bits. The fixed-type bits, such as claw or drag bits, have no moving parts and cut through rock by shearing it. Thus, these bits are limited to the softest materials. The primary difference between rotary drilling and other methods is the absence of percussion.

2.5.1 Rotary Drilling with Rolling Tricone Bits

Rotary crushing is a method, which was originally used for drilling oil wells, but it is nowadays also employed for the blasthole drilling in large open pits and hard species of rocks. In most rotary applications, the preferred bit is the tricone bit. Tricone bits rely on crushing and spalling the rock. This is accomplished through transferring downforce, known as pulldown, to the bit while rotating in order to drive the carbides into the rock as the three cones rotate around their respective axis. All rotary drilling requires high feed pressure and slow rotation. The relationship between these two parameters varies with the type of rock. In soft formations, low pressure and higher rotation rate and vice versa are the logic usually followed.



Fig. 2.34 Crawler-mounted rotary drilling rig (Reproduced with the permission from Atlas Copco)

Rotation of the tricone bit is provided by a hydraulic or electric motor-driven gearbox (called a rotary head) that moves up and down the tower via a feed system and through a pipe transferring to the bit. Feed system utilizes cables, chains, or rack-and-pinion mechanisms driven by hydraulic cylinders, hydraulic motors, or electric motors. A typical rotary drilling rig with tricone bits is shown in Figs. 2.34 and 2.35 shows the typical structure of a tricone bit (Table 2.13).

2.5.2 Rotary Drilling with Drag Bits

A drag bit with no moving parts that cut by a combination of shearing (cutting action) and gouging, predominantly used in softer sedimentary rock types.

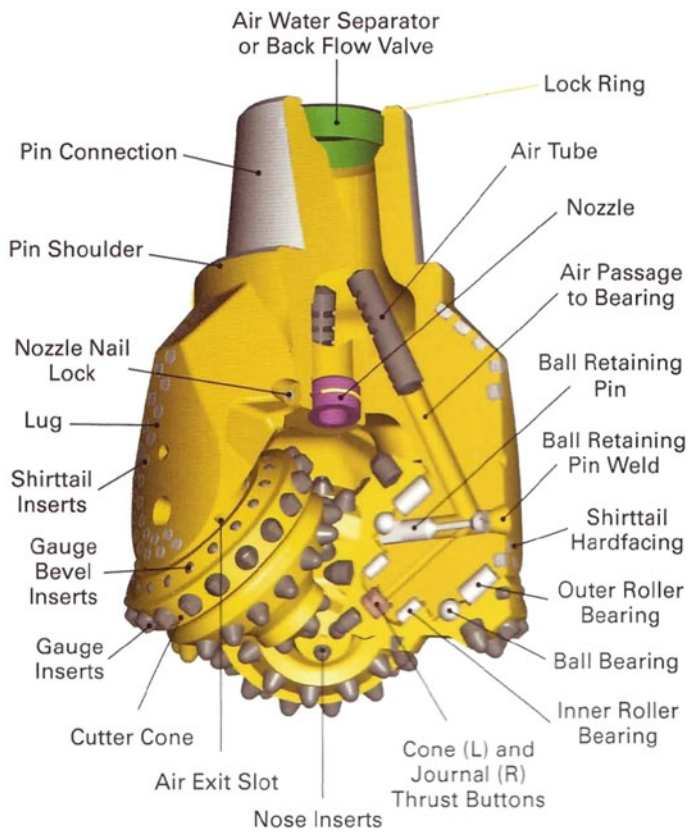


Fig. 2.35 Structure of a typical tricone bit (Reproduced with permission from Atlas Copco)

Table 2.13 The range of working parameters of rotary drilling rig with tricone bits

Nominal hole size (mm)	102–406
Hole depth (m)	12–85
Feed system	
Pulldown force (kN)	111–534
Weight on bit (kg)	11,300–56,700
Rotation torque (k Nm)	4.7–25.7
Diesel engine/electric motor (kW)	336–1230

The cutting action of a drag-type rotary drill bit is performed by a variety of tools, including blade and diamond drills as well as rope, chain, and rotary saws. Regardless of the geometry of the device, drag action at the cutting surface by two forces: thrust, a static load acting normally; and torque, the tangential force component of a rotational moment acting on the rock surface.

The mechanism of penetration in drag bit drilling is as follows (Fig. 2.36):
(a) As the cutting edge of the bit comes in contact with rock, elastic deformation

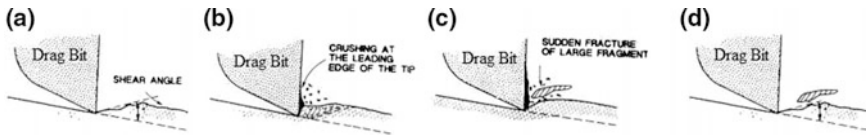


Fig. 2.36 Mechanism of penetration in drag bit drilling



Fig. 2.37 Wing rotary drag bits

occurs; (b) the rock is crushed in the high-stress zone adjacent to the bit; (c) cracks propagate along shear trajectories to the surface forming chips; and (d) the bit moves to contact solid rock again, displacing the broken fragments.

The edges of the drag bit usually are made of tungsten carbide or other materials such as synthetic diamonds or polycrystal, which vary in shape and angle. Figure 2.37 shows some drag bits.

The cuttings of drilling are eliminated with a flushing fluid that can be air, in surface operation, water, or humid air in underground operations.

The auger drag drill, in which a hollow-stem auger is rotated into the ground, needs no mud or flushing. Figure 2.38 is a two-wing auger drag drill for coal and soil drilling. The continuous-flight augers convey the cuttings continuously to the surface.

2.6 Rotary-Percussive Drilling Accessories

To drill a hole, apart from the rock drill, some drilling accessories are required. Except the integral drills, the extension drill steel is usually made up of the following elements: shank adaptor, coupling sleeves, extension rods, and drill bits (Fig. 2.39). We will discuss them in this section one by one.



Fig. 2.38 Auger drill with two-wing drag bit



Fig. 2.39 Drilling accessories of rotary-percussive drills (Reproduced with the permission from Atlas Copco)

2.6.1 Integral Drill Steels

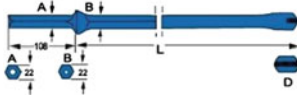
An integral drill steel as shown in Fig. 2.40 consists of a rod with a forged shank at one end and a forged bit with cemented carbide inserts at the other end. Thus, each



Fig. 2.40 Integral drill steels

drill steel is of a specific length and cannot be extended. Once the first drill steel has drilled all the way into the rock, it is withdrawn and replaced by the longer one to drill further into the rock. The integral drill steels are available in increasing lengths with reduced diameters as shown in Table 2.14. The diameter of the longest steel should be selected as per the size of explosive cartridge. The most common integral drill steel is chisel-type (I-type) and other types include multiple-insert steel, button

Table 2.14 Integral drill steel series



Shank (mm)	Length (mm)	Bits diameter, <i>D</i> (mm)	Weight (kg)
<i>11 Series</i>			
Hex 22 × 108	800	34	3
Hex 22 × 108	1600	33	5.5
Hex 22 × 108	2400	32	8
Hex 22 × 108	3200	31	10.5
Hex 22 × 108	4000	30	12.9
Hex 22 × 108	4800	29	15.4
<i>12 Series</i>			
Hex 22 × 108	800	40	3
Hex 22 × 108	1600	39	5.5
Hex 22 × 108	2400	38	8
Hex 22 × 108	3200	37	10.5
Hex 22 × 108	4000	36	12.9
Hex 22 × 108	4800	35	15.4
<i>13 Series</i>			
Hex 22 × 108	400	34	1.8
Hex 22 × 108	800	33	3.1
Hex 22 × 108	1200	32	4.3
Hex 22 × 108	1600	31	5.5
Hex 22 × 108	2000	30	6.7
<i>16 Series</i>			
Hex 22 × 108	600	35	2.4
Hex 22 × 108	1200	34	4.3
Hex 22 × 108	1800	33	6.1
Hex 22 × 108	2400	32	8
<i>17 Series</i>			
Hex 22 × 108	600	41	41
Hex 22 × 108	1200	40	40
Hex 22 × 108	1800	39	39
Hex 22 × 108	2400	38	38

steels, double chisel steels, and cross edge bit steels. The integral drill steels are usually used in handheld drills or light rigs, and the steels are manually changed.

2.6.2 Type of Threads

As shown in Fig. 2.39, the drill string, that is the shank, the drill rod, and the bit, is jointed together by threads. The string must be firmly connected to give efficient energy transmission. At the same time, the thread needs to be fairly easy to open when coupling and uncoupling rods. These features are required even when the threads are part of a long drill string.

The ease with which the thread can be tightened and loosened depends on multiple factors but mainly the thread design which includes pitch, angle between flanks, material, and surface properties.

The most common threads are the *R*, *T*, and *S* (Fig. 2.41).

The *R* thread has a small pitch and a large angle between the flanks. *R* thread is used in small blastholes with drill rods of 22–38 mm and powerful independent rotation rock drills.

The *R* thread has a small pitch and a large angle between the flanks. *R* thread is used in small blastholes with drill rods of 22–38 mm and powerful independent rotation rock drills with air flushing.

The *T* thread is used in most drilling conditions with drill rod diameters of 38–51 mm. It has a greater pitch and smaller flank angle than the *R* thread.

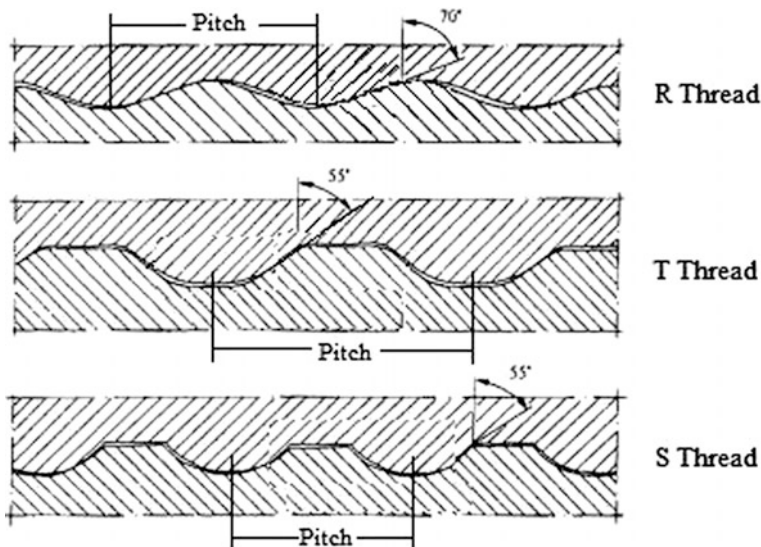


Fig. 2.41 Profiles of the *R*, *T*, and *S* threads

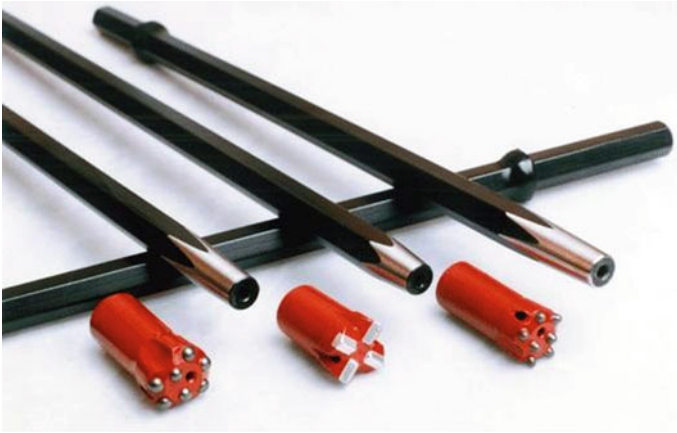


Fig. 2.42 Tapered drilling rods and bits (Reproduced with the permission of Sandvik)

The *S* thread has the same angle between the flanks as the *T* thread but a smaller pitch and used in large extension rods of 51 mm.

The tapered drill steels and bits without thread are still used at present especially in handheld drilling (Fig. 2.42).

2.6.3 Shank Adapters

The shank adapter is the component that enables percussive impact and rotation to be transmitted from the rock drill to the drill string. Shank adapter is made of high-quality special steel with excellent wear resistance. The hard surface is obtained by carburization. Shank adapters are specially designed for particular rock drills (Fig. 2.43). Where there is a separate flushing system, the flushing medium enters the shank through a side hole between the splines.



Fig. 2.43 Shank adapters (Reproduced with the permission of Sandvik)

2.6.4 Drill Rods

Drill rods can be divided roughly into five categories (Fig. 2.44):

- Shank rods
- Drifter rods
- Extension rods
- Drill tubes
- Guide rods.

The length and diameter of the rods depend on the hole/bit size and hole depth. Percussive rods have a hole inside to provide a means of flushing for the bit end.

Shank rods have an integral shank at one end and thread for the bit at the other end, similar to integral steels.

2.6.4.1 Drifter Rods

Drift rods have threads at both ends, with the shank end thread usually bigger than the bit end thread. The shank end of the rod may have a female or male thread (Figs. 2.44, 2.45). The drifter rod is designed for fast drilling of short holes, especially for the underground drilling Jumbos.

Typical Drifter rod lengths are 10, 12, 14, 16, and 20 ft. Today with modern drilling and blasting knowhow, rods shorter than 10 ft have become quite rare. There are two types of rods: hexagonal and round. The diameter of rods varies: 25, 28, 32, 35, and 39 mm.

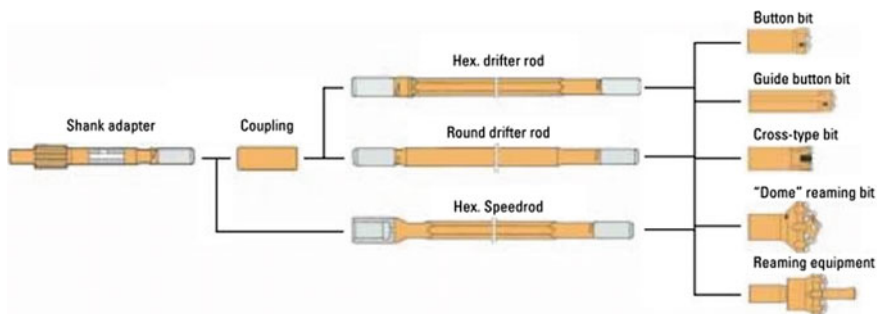


Fig. 2.44 Drilling accessories for underground drills (Reproduced with the permission from Atlas Copco)



Fig. 2.45 Drifter rods (Reproduced with the permission of Sandvik)

2.6.4.2 Extension Rods

Extension rods are made for either light or heavy drilling, although the heavy extension is more commonly used. The threads at both ends of the rod have the same dimensions. Both threads can be either male or female (Fig. 2.46). The lengths of rods vary from 10 to 20 ft for surface drilling and 3 to 6 ft for underground drilling. The diameters vary from 32 to 52 and 60 to 87 mm for heavy drilling.

2.6.4.3 Drill Tubes

With the application of top hammer hydraulic rock drills to the drilling of large diameter and long blastholes, some drill tubes have been recently used in both surface and underground drilling, which are similar to those used in down-the-hole drilling, especially when drilling in difficult rock formation with soft, broken rocks. Drill tubes have a large inner flushing hole, which provides water or air for effective



Fig. 2.46 Extension rods (Reproduced with the permission of Sandvik)



Fig. 2.47 Drill tube (Reproduced with the permission from Atlas Copco)

flushing. They have a female–male connection and do not require any couplings. The tight joints enable maximum energy transfer. As they have larger diameters and more rigidity, the deviations and irregular blasthole walls are reduced (Fig. 2.47). The diameter of the drilling tube is only slightly smaller than the recommended optimal hole size. The tube diameters are varied between 76 and 127 mm, and lengths varied between 1.5 and 6.1 m.

Drill tubes for DTH drilling usually have a diameter of 76–140 mm and lengths of 4.0–6.0 m.

There are also guide tubes, used immediately after the guide or retrace bit, which have two guiding sections to improve accuracy and hole straightness. The guide tube has a female thread at one end and a male thread at the other.

2.6.5 Couplings

Couplings are required to extend the drill string to the desired length and to join the rods together in such a way that the energy is transferred from one rod to the next all the way to the bit. The correct type of coupling promotes accurate drill steel connection and minimizes energy loss in the joint. To prevent overthreading, couplings have a stopping point in the middle. The type of coupling depends on the drilling conditions and the selected rod type (Fig. 2.48). Figure 2.49 shows the cross sections of three types of couplings.

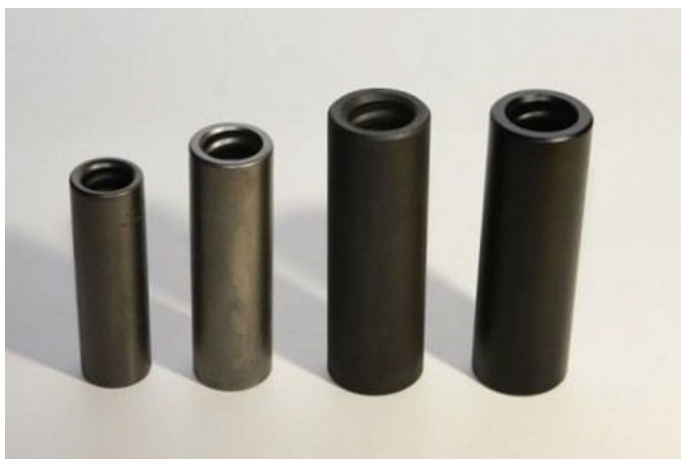


Fig. 2.48 Couplings (Reproduced with the permission of Sandvik)

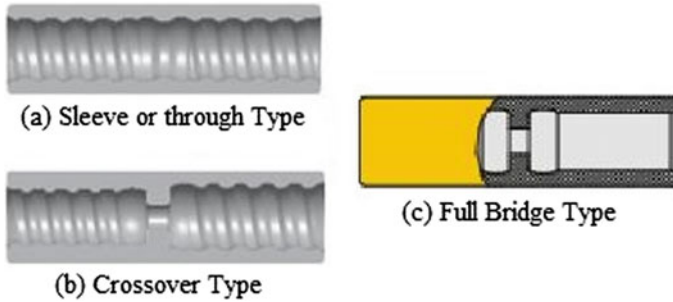


Fig. 2.49 Three types of couplings

2.6.6 Drill Bits

There are two types of drill bits for rotary-percussive drilling:

- Insert Bits, and
- Button bits.

For the two types of bits, there are some design characters in common:

- The rods are threaded to the end of the bit thread so that the transmission of impact energy is as direct as possible to the rock.
- The bits have a series of central and lateral openings through which the flushing fluid is injected and they have channels through which the rock particles produced pass upwards.
- The bits are designed to be slightly conic, with the widest part in contact with the rock so as to counteract the wear and avoid an excessive adaptation to the blasthole wall.

2.6.6.1 Insert Bits

There are three types of insert bits presently used for rock drilling (Fig. 2.50): the chisel (I-bit), cross bit, and the X-bit (shown in the right part of the figure). The chisel bits are commonly used for handheld rock drill for hard rocks. One piece of tungsten carbide is fixed in the I-bit. The cross bit consists of four tungsten carbide inserts at a 90° angle, whereas the X-bit has four inserts at 75° and 105° angles between the insert pair. The size of insert can be varied according to the drillhole size, rock type, and the abrasiveness of the rock. Insert bits are manufactured in diameters from 35 to 64 mm. Although insert bits may be less expensive to purchase, they usually have shorter regrinding intervals and life expectation, which often makes them less economical than button bits. For this reason, button bits have captured much of the market from insert bits.



Fig. 2.50 Insert bits

2.6.6.2 Button Bits

The button bit is the most popular type of bit in use today for big hole, high production, and blasthole drilling. These bits have buttons or cylindrical inserts of tungsten carbide distributed in various patterns on the face. They are manufactured in diameters that go from 50 to 251 mm. See Fig. 2.51.

The bit face is so designed that it can achieve the following important tasks:

- Allow for rock chips to clear and avoid recutting;
- Hold gauge and retain cleaning flutes;
- Present the most effective impact alignment of carbides to break and chip the rock, and
- Drill straight.



Fig. 2.51 Button bits



Fig. 2.52 Tungsten carbide

The carbide buttons have several basic shapes and are made of various materials. The carbide material normally contains 6–12 % cobalt, and it is usually classified as soft, standard, and hard, see Fig. 2.52.

- Soft material is generally used in soft, abrasive rock to allow carbide wear to move approximate bit body wear and avoid excess carbide extension.
- Standard material is used for general drilling conditions.
- Hard materials are used for very hard, abrasive formations.

Button size generally increases with bit diameter, which allows for higher rotation speeds. Bit bodies are generally of steel composition, and the various grades and styles of carbide inserts are press-fitted into the body. For some applications, the body steel may be hardened all the way through and carburized.

2.6.6.3 Special Bits

There are some specially designed bits for the particular application:

1. Retrac bits: When collaring or other problems cause tight steels, the “retrac” bit body help to ream the bit out of the hole. A typical retrac bit has a long, large diameter with edges. The large body helps it to drill straight holes, and the edges enable the drill string to be withdrawn when spalling has occurred.
2. Reaming bits: The reaming button bits are used underground to drill the large parallel cut holes. These bits usually are used with pilot rods or extension rods and reaming bit adaptors.

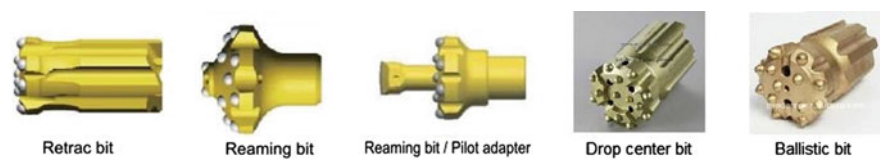


Fig. 2.53 Special drilling bits

- Drop center bits: The drop center bits have excellent flushing characteristics, as the flushing hole of the bit is in the center of the face. They are used in soft rocks that are easy to drill.
- Ballistic bits: The ballistic bits have bullet-shaped buttons which are longer than the standard and give high penetration rates and a more efficient flushing for soft rock formation (Fig. 2.53).

2.6.6.4 Down-the-Hole Hammer Bits

The bits for DTH hammers have shanks incorporated upon which the piston strikes directly. The most common diameters of these bits go from 85 to 250 mm, although larger ones exist.

Both insert (cross and X inserts) and button bits are used for DTH hammers, but button bits are the most commonly used and good for any type of rock. Figure 2.54 shows the common DTH bits designed for different rock formations. The manufacturers, like Atlas Copco, Sandvik, and Ingersoll-Rand, have similar series of bit design.

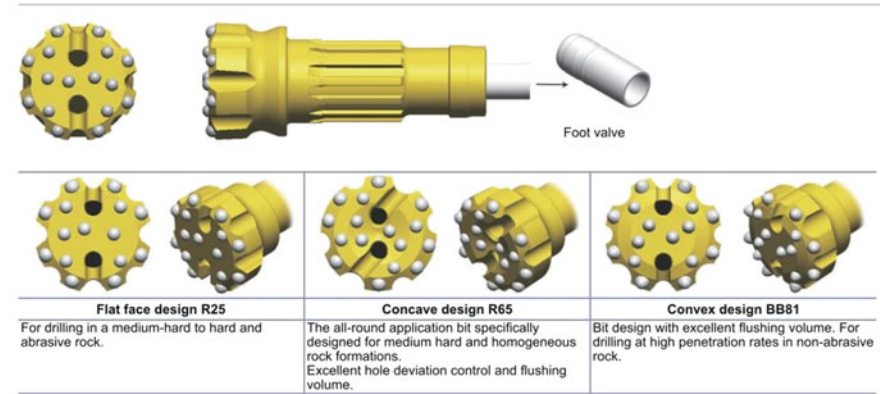


Fig. 2.54 Basic button bit face design used for DTH (courtesy of Mitsubishi, Ref. [7])

2.6.6.5 Bit Maintenance

Grinding and sharpening equipment is also required for drill bit maintenance and services for optimizing the drilling rate and to increase the bit’s service life.

There are different kinds of methods and machines to regrind different bits: button bits, insert bits, and integral drill steels. The drill equipment suppliers usually supply the services of grinding and sharpening of bits together with the maintenance service of the equipment.

2.6.7 The Service Lifetime of Drilling Accessories

The drill bit re-grinding and service lifetime depends on the geology conditions (especially rock abrasiveness), bit configuration and quality, drilling conditions (flushing, rotation, percussion, and feed), and handling. The bit lifetime can be as much as 800 drilled meters or as little as 30 drilled meters. Acceptable lifetime estimates can be based on various laboratory tests and drilling information from similar conditions.

The drill rod lifetime is measured in rod meters, a term expressing the total number of meters drilled by all the rods in a drill string for a given number of hole meters. Table 2.15 (from [4], Tamrock) can be referred to estimate the service lifetime of extension rods and tubes.

Shank adapters transmit impact, rotation torque, and feed force. Constant exposure to high impact energy levels is directly related to the shank lifetime. Abnormal drilling conditions such as too high or too low percussion pressure and too low fed pressure reduce the service life of the shank.

Table 2.15 Service lifetime for drilling bits, extension rods/tubes, and shank adapters (courtesy of Tamrock)

Component	Soft rock	Hard rock	Hard rock
	Non-abrasive	Medium-abrasive	Very-abrasive
<i>Button bits</i>			
45 mm	600–1000	250–400	100–200
51 mm	1000–1500	500–600	175–250
Rods	1200–2500	1200–2500	1200–2500
Shank adapters	2000–3000	2000–3000	2000–3000

2.7 Selection of Rock Drill and Accessories

2.7.1 Fields of Application for Different Drilling Methods

By taking into account the rock drillability and the drilling diameter, the following Fig. 2.55, as a reference, gives the fields of application for different drilling methods as the function of rock drillability and drillhole diameters.

2.7.2 Principles of Selection of Drilling Equipment for Surface Excavation

The following principles should be considered firstly for selection of drilling equipment for surface excavation:

- Scale and complexity of the project, the total amount of materials to be excavated, and the project schedule for excavation.
- Geological conditions of the project, especially the rock drillability.
- Environment conditions, including the distance from the residential area, slopes, and other sensitive receivers (structure, building, and utilities), relative laws and regulations.
- The conditions and costs of maintenance and services for the equipment.
- Initial investment for purchase of drilling equipment.

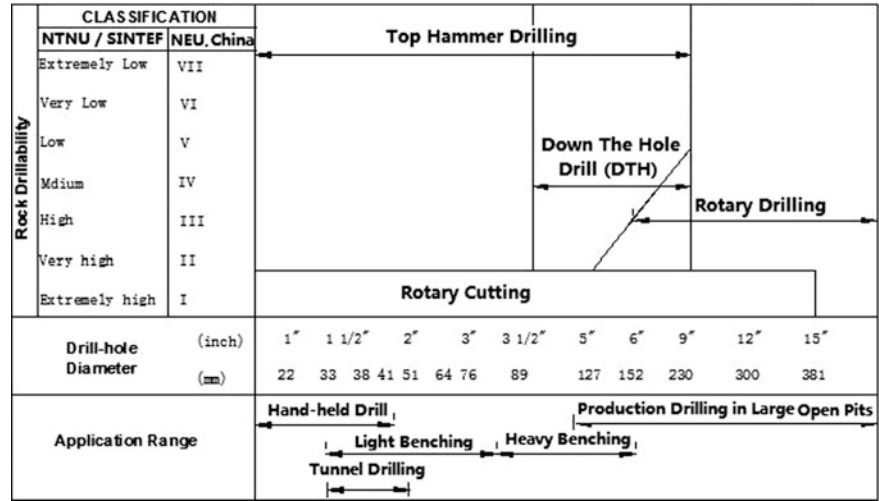


Fig. 2.55 Field of application for drilling methods as function of the rock drillability and the drillhole diameters

Under these conditions, the selection of drilling equipment can be determined step by step:

- The scale of each blasting, blasthole diameters, maximum drillhole depth;
- Total amount of drillhole length, including blastholes and other holes, such as soil nails/rock bolts, and drilling productivity are required;
- Drilling method, capacity of drilling equipment, type and modes of drilling equipment, number of drills to be used for the project; and
- Estimating the quantity of drill accessories to be used for the project.

2.7.3 Selection of Drilling Equipment for Underground Excavation

Similar to the surface excavation but more complicated, the following factors must be taken into account:

- Scale and complexity of the project. The total amount of materials to be excavated and the project schedule for excavation.
- Geological conditions of the project, especially the rock drillability.
- Environment conditions, including the distance from the residential area, slopes, other sensitive receivers (structure, building, and utilities), relative laws and regulations.
- Compatibility with other excavation equipment, like loading and hauling, for the job. The equipment must be technically advanced but compatible with existing machines and anything else being purchased. This compatibility must also extend to maintenance and servicing.
- The conditions and costs of maintenance and services for the equipment.
- Detailed calculations are necessary to determine which equipment is the most economical, efficient, practical, and technically suitable.

During the procedure of selection of drilling equipment, the following technical aspects must be considered:

- Versatility.

In general, equipment must be able to carry out drilling tasks in a variety of conditions, even it has been chosen for a particular construction target. These tasks include the following:

- Changing face areas in tunneling;
- Various hole lengths, short holes, and long holes drilling (like probe holes and grouting holes);
- Various hole directions, up-slope or down-slope, shaft sinking, and rise excavation; and
- Bolting: amount and frequency of bolting, different bolt types, length, and size.

The best possible solution in each drilling group will be able to perform efficiently while covering all major drilling tasks.

- Selection of carrier.

Three types of carrier are available: rail-mounted, crawler-mounted, and wheel-mounted, and deciding which type is suitable for a particular job depends on several factors. Table 2.16 gives the basic criteria of selection. Rail-mounted drill jumbo is very rarely used for construction projects.

- Selection of the boom

The following aspects should be taken into account:

1. Coverage. Booms have a slightly different coverage when they are mounted on a drilling rig. The effective boom coverage must be sufficient for the whole tunnel face, including the upper and lower corners of the tunnel. The coverage changes with the number of booms and when the jumbo carrier is changed, since it affects the boom mounting distance and height. Usually a drilling jumbo can be equipped with one to three booms and the coverage changes from smallest of 12 m² to largest of 230 m². Figure 2.56 shows the coverage of two manufactures' jumbos.
2. Selection of feed. The length of the feed, which decides the length of the hole and the round, is determined by the excavation timetable and any rock mechanical and geological restrictions. The drifter dimension and selected rod length also should be considered when choosing the feed.
3. Selecting a boom and rod changer for long hole drilling.
4. Selecting a boom for bolt drilling.

Table 2.17 gives the main specifications of some drilling jumbos for tunneling manufactured by Atlas Copco and Sandvik.

2.7.4 Selection of Drilling Accessories

2.7.4.1 The Features of Button Bit Design

Most percussive button bit is designed with a basic face profile and button layout similar to one of those shown in Fig. 2.57 below.

The typical shapes to be used of carbide and their characters are shown in Fig. 2.58.

With different combinations of bit face profiles, carbide shapes, and carbide materials, there are various models of drill bits to suit different rock conditions and penetration rate. The typical bit models include the following:

- * CV: convex/ballistic front bit;
- * FB: full-ballistic bit;
- * FF: flat front bit;
- * FF HD: flat front heavy duty bit;

Table 2.16 Carrier selection criteria

Tunnel length/face area	Road/floor conditions	Curves	Speed/moving frequency	Angle of slope	Carrier
Long/wide-narrow	Good	Wide	Moderate-high/moderate-often	Horizontal	Rail-mounted
Short-long/wide-narrow	Good-moderate	Tight-moderate	High/moderate-often	Moderate-horizontal	Wheel-mounted
Fairly short/wide	Rough	Wide	Slow/rare	Very steep	Crawler-mounted

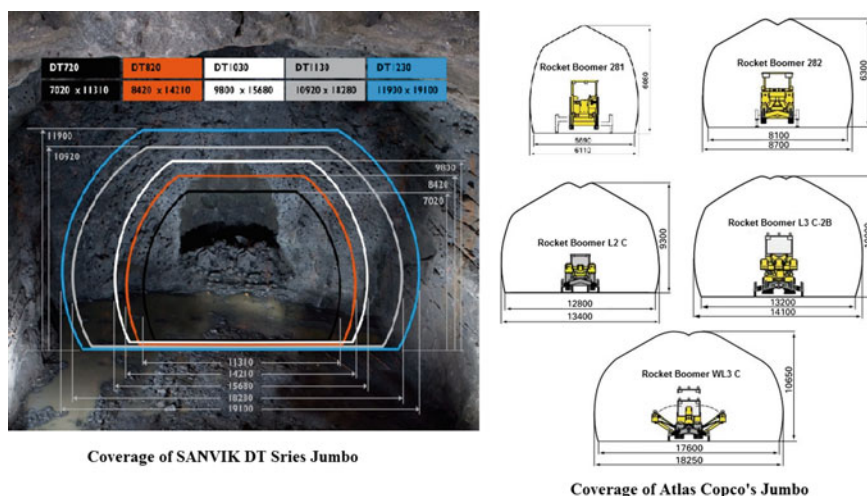


Fig. 2.56 Coverages of Sandvik's DT series and Atlas Copco's jumbos (no scale)

- * DC: drop center bit;
- * DC XHD: drop center extra heavy duty

Refer to Fig. 2.59.

2.7.4.2 Selection of Drilling Bits

The button bit is the most popular type of bit in use today for big hole, high production, and blasthole drilling. This is mainly because the button bit has a higher penetration rate and better wear resistance than the insert bit under the intensive hammering and tough rock conditions and requires less maintenance. However, when very straight holes are required to be drilled, the cross or X-type insert bit has its advantage. Figure 2.60 shows how to select the button bit under different rock conditions.

2.7.4.3 Drilling Rod Selection

Top hammer Rods Selection for Surface Drilling

For bench drilling, three types of drill rods can be chosen:

- Surface hardened rods, in which only the thread parts are hardened, are the toughest but have the lowest fatigue strength. They are the good choice when drilling in faults or folded formations, when driller is a green hand as they are the cheapest rods;

Table 2.17 Main Specifications for Some Drilling Jumbos for Tunneling

Company/model	Coverage (m ²)	Hole Dia. (mm)	Boom	Feed	Rock drill	Dimension $L \times W \times H$ (m)	Weight (kg)
<i>ATLAS COPCO</i>							
Rocket Boomer 281	Up to 31	43–76/64– 89	1 × BUT 28	1 × BMH 2831-BMH 2849	1 × COP1838ME/COP 1838HF	11.7 × 1.7 × 2.8(2.1)	9300
Rocket Boomer 282	Up to 45	64–89	2 × BUT 28	2 × BMH 2831-BMH 2849	2 × COP1838ME	11.82 × 1.98 × 3.0(2.3)	17,500
Rocket Boomer L2 C	Up to 104	43–76/64– 89	2 × BUT 35G	2 × BMH 6814-BMH 6820	2 × COP1838ME/COP 1838HF	14.17 × 2.5 × 3.01	23,600
Rocket Boomer L3 C-2B	Up to 114	43–76	3 × BUT 35G	3 × BMH6800-series	3xCOP1838ME	17.17 × 2.5 × 3.66	50,000
Rocket Boomer WL3 C	Up to 163	43–76	3 × BUT 35G	3 × BMH6800-series	3 × COP1838ME	17.22 × 3.01 × 3.66	43,000
<i>SANDVIK</i>							
DT92li	12–125	43–64	2 × SB100i	2 × TF5i 12–21 ft	2 × RD525	15.4 × 3.25 × 4.13	29,000
DT112li	20–183	43–64	2 × SB150i	2 × TF5i 12–21 ft	2 × RD525	17.78 × 3.86 × 4.69	37,700
DT113li	20–183	43–64	3 × SB150i	3 × TF5i 12–21 ft	3 × RD525	17.78 × 3.86 × 4.69	44,000
DT123li	20–211	43–64	3 × SB150i	3 × TF5i 12–21 ft	3 × RD525	17.78 × 3.86 × 4.78	45,500
DT133li	20–232	43–64	3 × SB150i	3 × TF5i 12–21 ft	3 × RD525	17.78 × 3.86 × 965	50,000

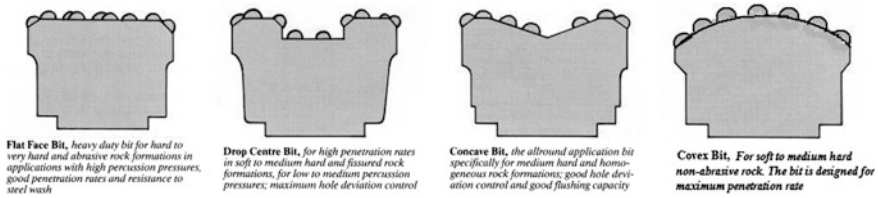


Fig. 2.57 Typical button bit face profiles (Reproduced with the permission of Sandvik)

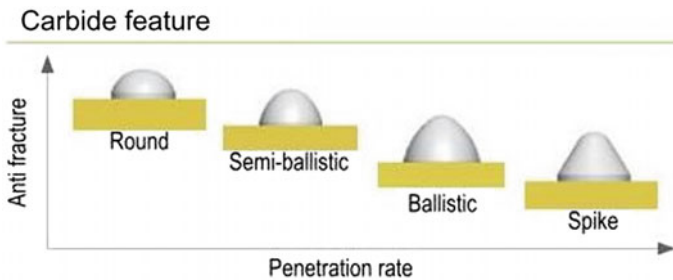


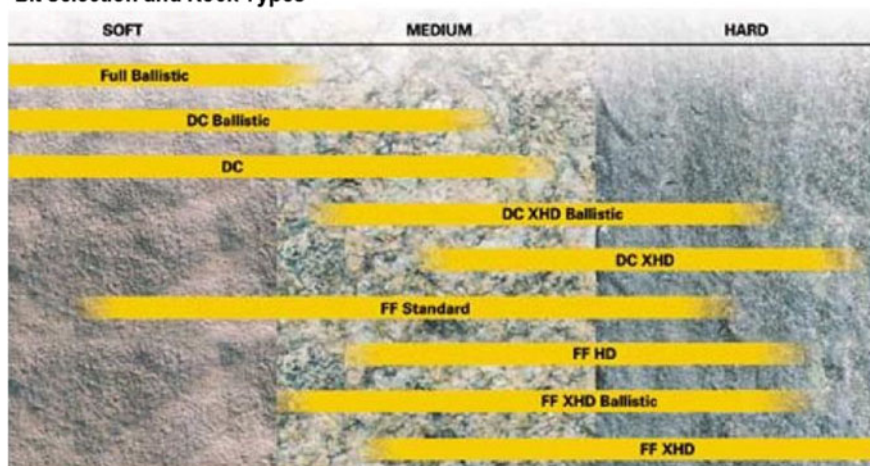
Fig. 2.58 Carbide shapes and characters (courtesy of Mitsubishi, Ref. [7])



Fig. 2.59 Typical models of button bits (Reproduced with the permission from Atlas Copco)

- Carburized rods, where all surfaces, including the inside of the flushing hole, are hardened. Carburized rod has better wear resistance and a higher fatigue life compared to surface hardened rod; and
- Carburized male/female rods (Speedrods of Atlas Copco, MF-rods of Sandvik), which have male thread in one end and a integrated female coupling in opposite end. As the integrate coupling is used, the energy loss in the joints of carburized male/female rods are about 50 % less than normal carburized rods which use the standard couplings.

Bit Selection and Rock Types



DC = Drop Centre; FF = Flat Front; HD = Heavy Duty; XHD = Extra Heavy Duty.

Fig. 2.60 Selection of drilling bits according to rock conditions (Reproduced from ref. [8] with the permission from Atlas Copco)

Rods Selection for Underground Jumbos

For tunneling, two types of drill rods can be chosen. Standard drifter rods have male threads at both ends. Male/female rods (Speedrods of Atlas Copco, MF-rods of Sandvik) have a male thread at the front end and an integrated coupling with a female thread at the shank end. Both rod types are carburized including the inside flushing hole.

Standard drifter rods, as well as male/female rods, are produced with either a hexagonal or a round rod section.

For a given hole size, the largest possible rod cross section should be chosen, commensurate with the required hole size and the rock drill. This is in order to achieve the best possible service life, hole straightness, and penetration rate. Normally, a rod with a T38 or R38 thread in the shank end will be chosen. The long middle section of the drifter rod is generally hexagonal, with a 32- or 35-mm cross section. Round 39-mm rods are getting more and more common, especially if the hole is 4 m and longer. The bit end of the rod is similar and has a smaller thread in order to fit the small bits and hole size used. Hexagonal rods are today's standard, while round rods, diameter 39 mm, have started to become of more and more common. The round rod is a stiffer rod, because of more material in the cross section. Round rods give straighter holes and are therefore recommended when hole deviation is a problem. But using the round rod the flushing properties for cleaning the cuttings out of the hole are not good as the hexagonal rod. This can result in higher risk of jamming round rods when drilling in the fractured rock formation, mainly when drilling 45-mm holes or smaller. In homogeneous rock, this is normally not a problem.

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