NOTES ON

Introduction to Drilling Technology for Surface Mining

Courtesy-

Prof. K. Pathak
Dept. of Mining Engineering,
IIT, Kharagpur-721302

Introduction to Drilling Technology for Surface Mining

1 Introduction

Drilling is the process of making a hole into a hard surface where the length of the hole is very large compared to the diameter. In the context of mining engineering drilling refers to making holes into a rock mass. Surface mining requires ***drilling for different purposes*** that include:

1. Production drilling i.e. for making holes for placement of explosives for blasting. The objective of drilling and blasting is to prepare well-fragmented loose rock amenable to excavation with better productivity from the excavation machinery. The holes drilled for this purpose are defined as blast hole.
2. Exploration drilling for sample collections to estimate the quality and quantity of a mineral reserve. The samples are collected as core and the drilling for such purposes are referred as Core drilling. As diamond bits are used for such drilling, core drilling is often called diamond drilling.
3. Technical drilling during development of a mine for drainage, slope stability and foundation testing purposes.

Opencast mining involves removal of waste rock and subsequent winning of the mineral. In case of deposits underlying hard and compact waste rock called overburden loosening of the rock mass is essential prior to excavation. Thus drilling and blasting is the important ***ground preparation*** job. Unless the rock mass is *highly weathered* and *very much unconsolidated* drilling of holes for placement of explosives and detonating them for blasting is required for any mining operation. Modern machines like continuous surface miner can however eliminate the need of drilling and blasting in certain surface mining operations.

Successful drilling under specific site conditions requires blending many technologies and services into a coherent efficient team, particularly if it is for deep exploration drilling. Blast hole drilling is comparatively simpler. However, to minimize costs and optimize the performance and post drilling operations technical managers and decision managers must understand the language and technology of drilling operations.

This lecture covers the basic elements of drilling to give you a good understanding of the drilling process and how it integrates into the 'overall mining success'. You will learn:

- ✓ *An overview of drilling technology to develop an awareness of the equipment* terminology and operations associated with the drilling process in surface mines.
- ✓ Classification of drilling methods
- ✓ Principle of rock tool interaction in drilling
- ✓ Definition and terminology
- ✓ Application of different drilling methods
- ✓ Selection of drills

- ✓ Method of measuring drilling performances
- ✓ Bailing and hole clearance
- ✓ Measure while and log while drilling
- ✓ Current safety practices
- ✓ Drilling trends and new technology
- ✓ Basic communications and supervisory skills to ensure a safe, efficient operation

2 Classification of Methods and Machines

Drilling is basically method of penetrating rock. The machine that carries out the drilling operation is called drill. Rock can be penetrated by overcoming its resistance to penetrate by providing external energy. Depending on how this energy is imparted and how the broken mass produced by drilling is removed to get new surfaces to drill, the drilling methods and the drill can be classified into several category. Table 1 illustrates how drilling and drills can be classified Figure 1 further gives the classification of drilling methods.

Table 1 Classification of drilling and drills

Sl No	Basis	Variants	Example
1	Mode of energy application.	Percussion	Churn or cable tool drill, jack hammer,
		Top Hammer	For shallow holes, the whole drill strings offer hammering
		Bottom Hammer (Down the hole hammer or DTH)	For hole larger than 150 mm and deeper holes, offers increased rod and coupling life and less noisy.
		Rotary	Auger or rotary drill, Diamond drill,
		Rotary Percussion	DTH, Top hammer drill
2	Size of Hole	Small Hole	150-200 mm for coal
		Large Hole	250-315 mm for OB
		Very Large Hole	> 315 mm for dewatering well

3	Method of mounting	Hand held	Jack Hammer
		Skid mounted	
		Wagon mounted	Typical hole size 63-150 mm (Percussion)
		Crawler mounted	Single pass drilling from 7.6 to 15.2 m, hole size 120 to 229mm(Percussion)
	Type of power	Electric	
		Pneumatic	Less costly, high noise
		Hydraulic	May be diesel or electrically powered hydraulically operated and controlled. New development, lesser noise
	Flushing	Wet drilling	Water flushed
		Dry drilling	Air flushed
	Direction	Vertical	
		Horizontal	
		Inclined	
	On board Facilities	With Measure while drilling (MWD) and automated Drill Monitoring (ADM)	
		Without measure while drilling	
		With automation	
		Semi automatic	

		Remotely controlled	

The above methods are deployed in drilling. However, one must remember that the drilling could be carried out provided the following requirements are fulfilled (Gokhale, 2003)[1]:

1. The drilling bit meant for disintegrating the formation must be sufficiently hard so that it can disintegrates the formation for a longer period.
2. The cuttings formed in the process of formation disintegration must be taken out of the hole as soon as possible. One should avoid crushing and grinding of the drilled chips inside the hole.
3. Drilling tool must be advanced in the intended direction of the drilled hole
4. The hole walls must be competent to avoid collapsing and blinding of the hole
5. After completing the hole the drilling components and the drill should be removed from the place.
6. The dust and noise generated during the drilling should be contained as far as practicable.

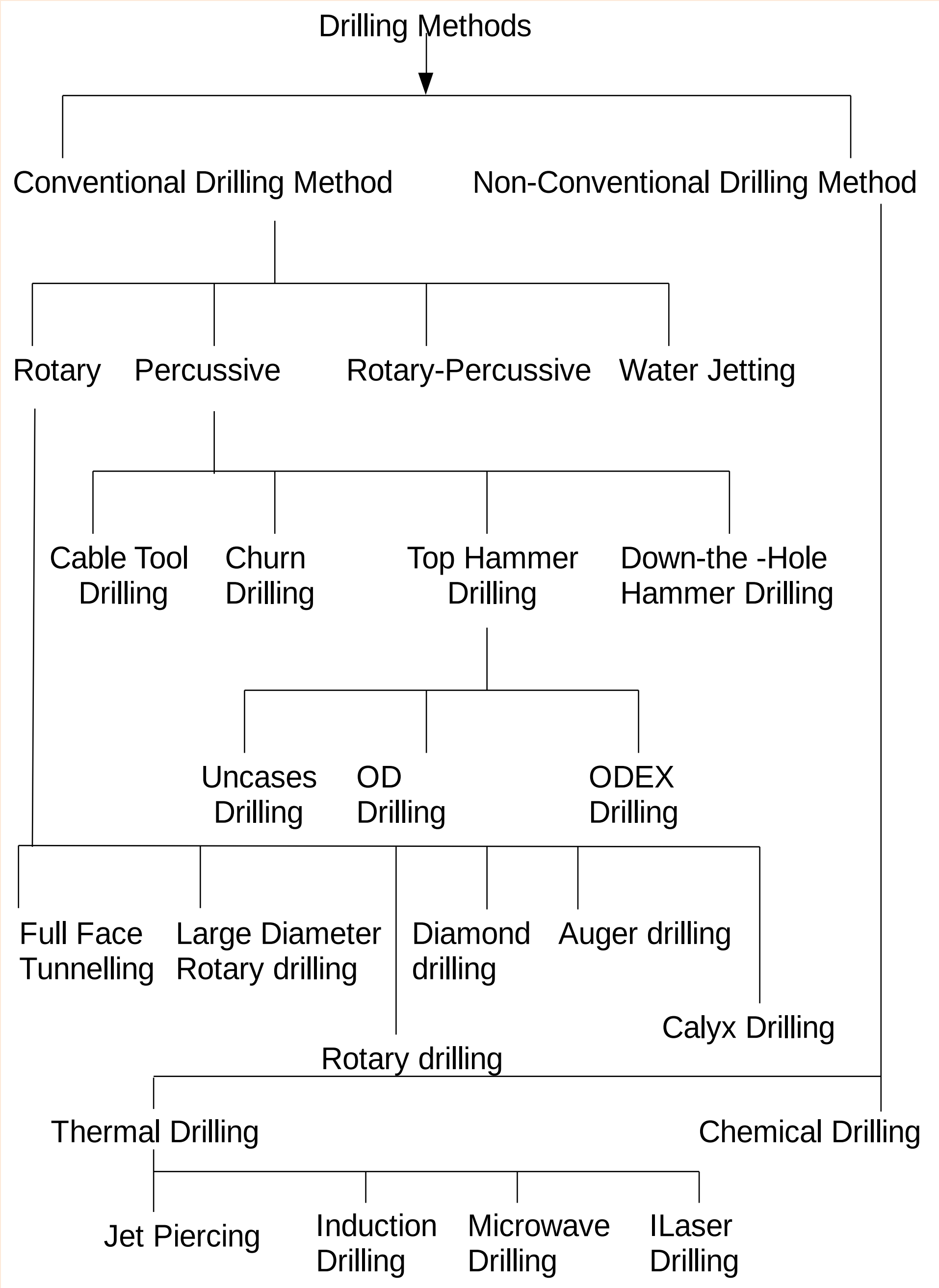


Figure 1 Classification of Drilling Methods

3 Principle of Rock tool interaction in drilling

The principle of rock drilling involves the rock tool interactions to make a penetration in rock. In the normal drilling process mechanical energy is dissipated through a bit to a rock. Based on the behaviors of drilling system and rocks the bit responds differently. The principle of rock drilling is concerned with providing a scientific basis of such responses, so that for a given job the right method can be selected.

Formation disintegration in drilling is mainly due to mechanical energy. However, there are drilling techniques in which heat energy or chemical energy is used. Water jet energy is also used in certain cases for rock disintegration.

The mechanical energy can disintegrate rock mass by crushing, impact crushing or scratching. Crushing takes place when heavy and steady force is exerted on the rock mass through hard drilling bit. The resistance to penetration of rock is called drilling strength or drillability of rock. This is different from other rock properties as it is related to number of controllable and uncontrollable parameters.

3.1 Rock Penetration in Percussion Drilling

In percussion drilling a chisel type or button type bit hammers or blows the rock mass while turning the tool in between two successive blows called blow indexing. An axial thrust is applied to keep the bit in contact with the rock when the blow is applied. The rock penetration takes place because of formation of a crater under the action of the blow. The sequence of crater formation is illustrated in Figure 2.

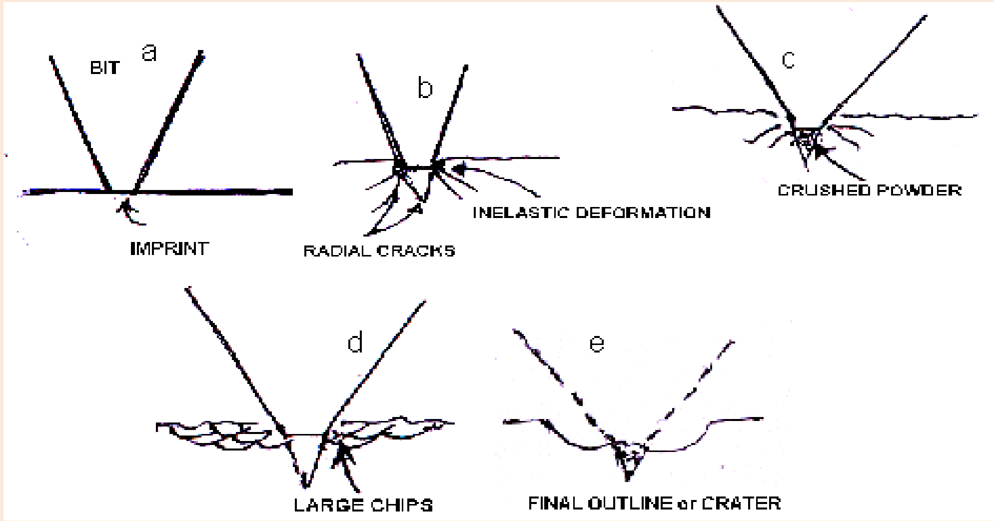


Figure2: Sequence of crater formation under percussive drill

This involves:

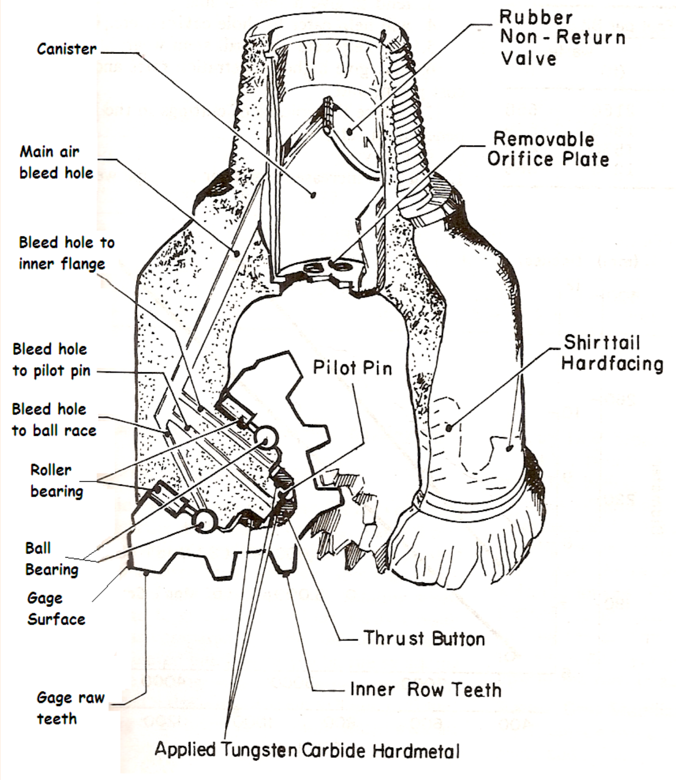
1. The rock is inelastically deformed, with crushing of surface irregularities
2. Subsurface micro cracks form from stress concentrations and confinement at the bit/rock interface enclosing a wedge of material, which is crushed
3. Secondary cracks propagate along shear trajectories to the surface, forming large fragments or chips

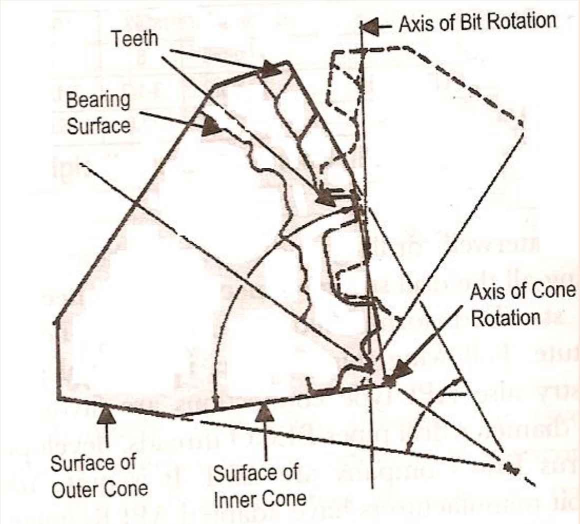
4. Broken particles are ejected by the rebound of the bit and the cleaning action of any circulation fluid, resulting in formation of crater.

This process is repeated at each blow and drilling propagates.

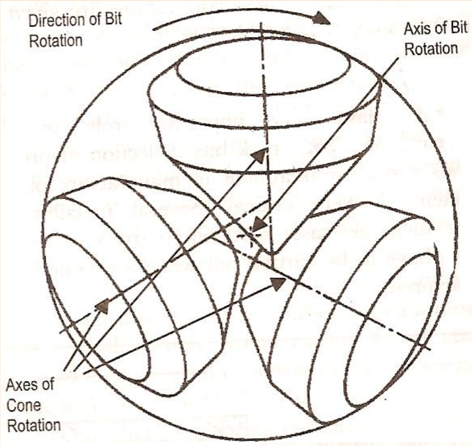
3.2 Rotary Drilling

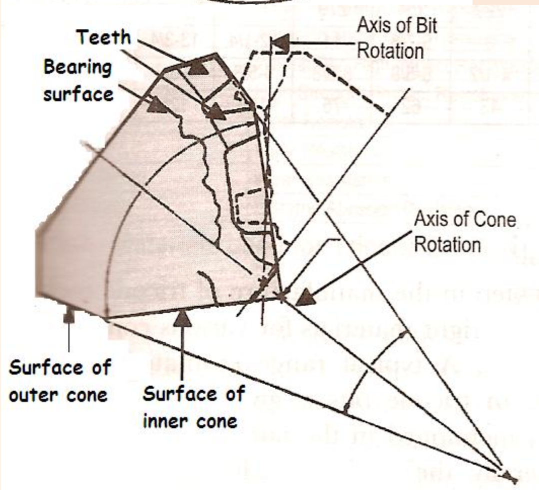
Rotary drilling uses different type of rotary bits like conventional drag bit, tricone roller bit or pollycrysta-lline diamond (PCD) bit. **Figure 3** illustrates rotary bits and their components. The principle of the extensively used tricone roller bit is explained below.





Cones for tricone bit for hard rock





Cone for tricone bit for soft rock

Figure 3 Rotary bits

Figure 4 shows the basic designs of rotary bits for different rock formations.

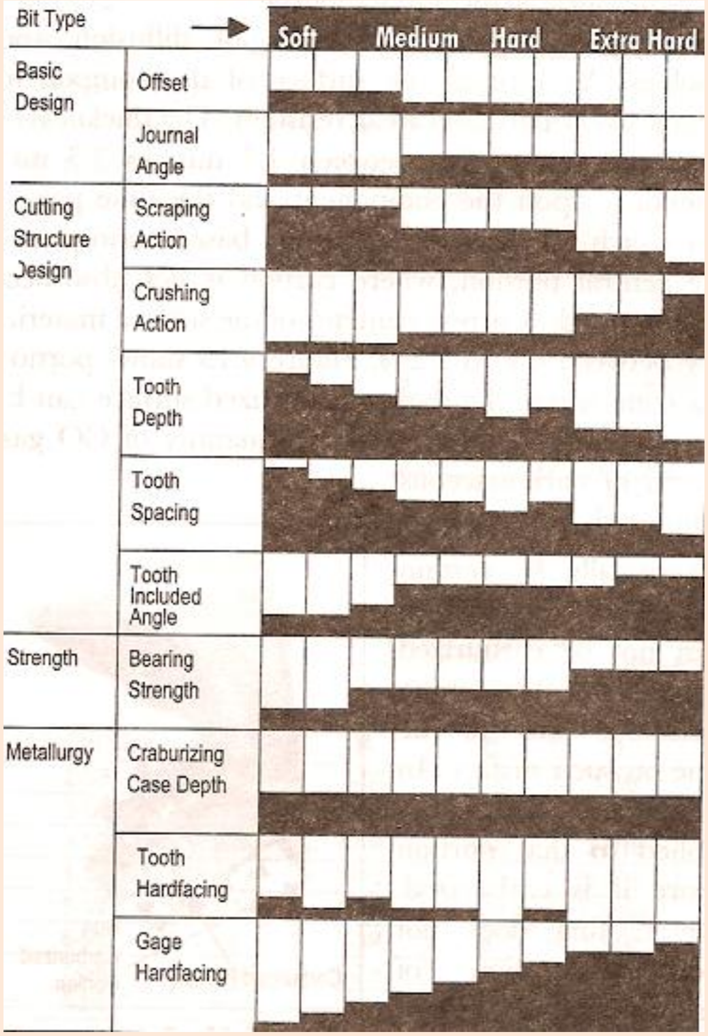


Figure 4 Selection of rotary bit design

Biggs and Cheatham (1969) [1] considered an idealized drill bit as two dimensional wheel and chipping action was illustrated as shown in Figure 5 Cheatham and Gnirk (1966) [2] determined that for producing chips some initial penetration D must be there. As shown in the figure D_c is the thickness of the chip. For chipping to occur the maximum bit penetration must exceed both D and D_c. The chipping occurs between a penetrating tooth and the adjacent withdrawing tooth shown as tooth 5 and 6 respectively in the figure. Further frictional forces on the withdrawing tooth cause tensile stress and leads to a horizontal fracture at depth D_c between the two teeth. Fracturing occurs when

1. the penetrating tooth reaches a depth equal to or greater than both D and D_c.
2. The withdrawing tooth has risen to a depth D_c or less.

Thus the chipping is result of rotation of roller under axial thrust.

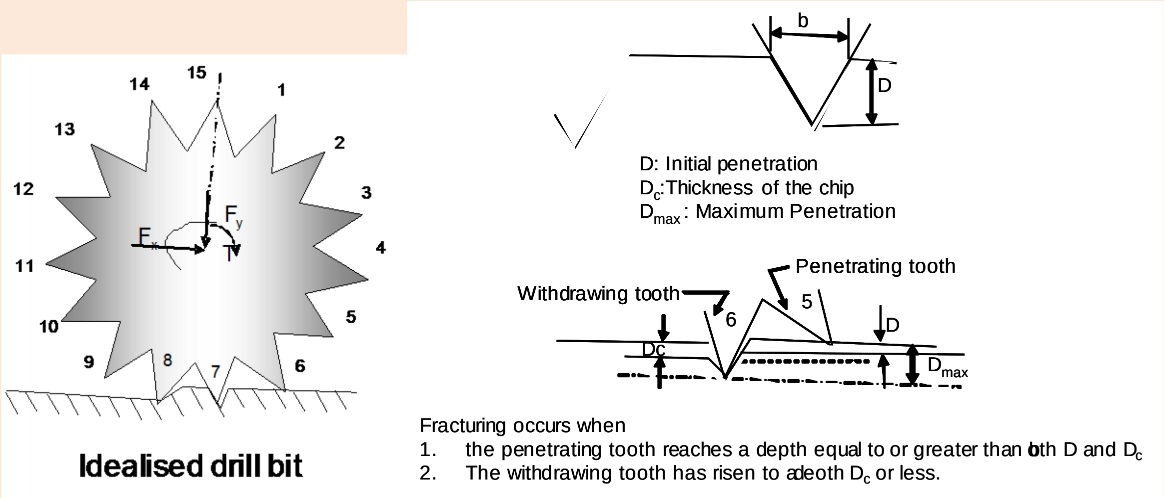


Figure 5 Rock tool interaction in rotary drilling

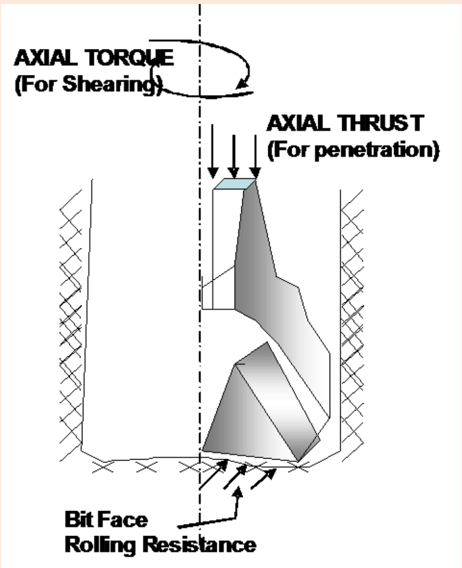


Figure 6: Forces on a roller bit

The torque applied to the bit makes the bit to interact with the rock mass to overcome the bit face rolling resistance as shown in Figure 6. The total torque required to rotate the bit under an axial thrust to get a penetration depends on the rock type.

The bit performance depends on use of drill, bit design and rock properties. It was observed (Pathak, 1989)[3] the life of bit was unpredictable, though Smith Gruner bit used to give longer life

Table 2 Life of different types of Bit at Jayant OCP

Sl. No.	Make	Bit Number	Size mm	Drill Machine	Total meter drilled
1	HK	317	311	60-R-BE	5271
2	IIA		250	IDM-V	2388
3	WIDIA	V872182	250	IDM-V	1505
4	IIA		250	IDM-VI	1414
5	WIDIA	V872181	250	IDM-IV	1071
6	Smith Gruner	BJ44802	250		9625
7	Smith Gruner	158 KK	311	60R-BE	11141
8	Smith Gruner	BJ44859	250		10695

One of the factors that influence the performance of drill bit is the size and type of bearings. The latter have to withstand various forces-longitudinal, radial, tangential, shock and vibration. The longer the bearing, the more capable for withstanding these forces. Large diameter bits have larger bearings.

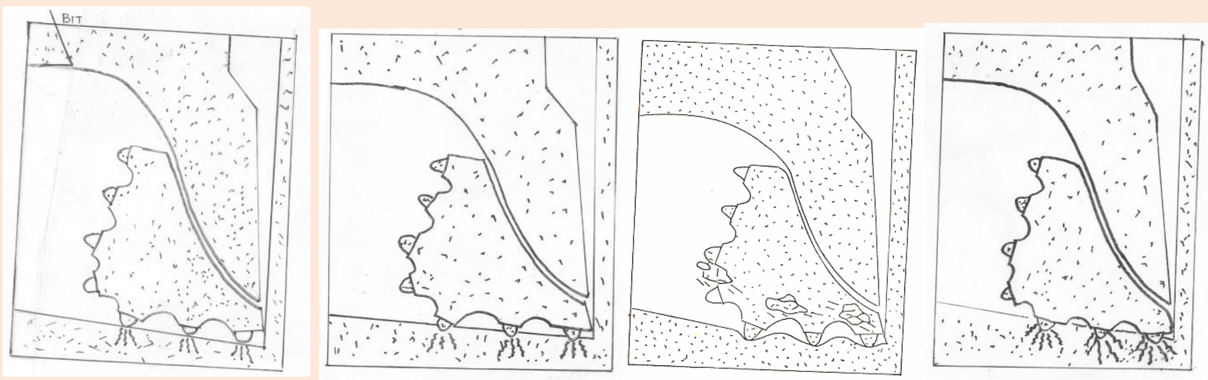
Bits for soft formations generally need more room for the teeth as they have less space for bearings. Bearings may fail if more weight is applied n bit. The maximum weight that can be applied on a bit varies greatly. On the basis of a study by Ingersol Rand, USA the maximum axial thrust on bit for longer bit life is shown in Table 3 below:

Table 3 Bit diameter and weight on bit

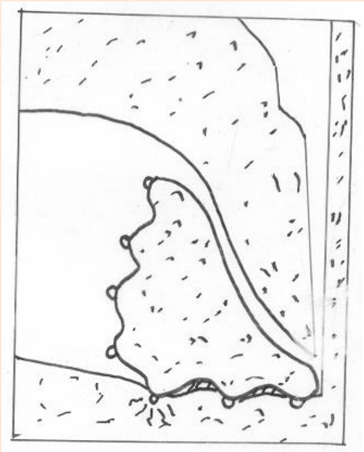
Bit Dia. mm (inches)	**Weight on Bit Kg(lb)**
169 ($6\frac{3}{4}$)	13, 600 (30,000)
184 ($7\frac{3}{8}$)	15,900 (35,000)
200 ($7\frac{7}{8}$)	20,400 (45,000)
229 (7)	25,000 (55,000)
251	27,200 (60,000)
270($10\frac{5}{8}$)	27,200 (60,000)

311 ($12\frac{1}{4}$)	40,800 (90,000)
381 (15)	49,900 (110,000)

While analyzing the performance of a bit the effect of number of teeth on the cones is also to be considered. The required number of teeth and their spacing depends on the rock formation. For stronger formation shorter teeth with higher density are used. Since the teeth are shorter the net failure moment at the base of the teeth is less. Also more teeth at hole bottom means more steel to provide resistance to wear.



a. abrasion phase b. fatigue phase c. Chipping out d. spalling phase



e. Excessive pressure

Figure 7: Rock failure under rotary drilling

Figure 7 shows the different types of rock failure under tricone bit. The first phase of rock failure under tricone roller bit is the *abrasion failure*. This is result of insufficient axial thrust on the bit. The inserts or the teeth are contacting the rock under very low axial thrust. The cuttings in this case are very fine. Thus if you are getting very fine cuttings one possible reason may be insufficient axial thrust.

In the second case the rotational speed is same as in the previous case but a higher axial thrust has been applied to the bit. The additional force causes increased penetration of the inserts into the formation without actual failure of the rock. This phase is termed as *fatigue failure* and can be inferred from the cuttings which will be a mixture of small chips and a high percentage of fines. Though rock failure can be accomplished with this type of loading and insert penetration, it may require many impacts on the formation to cause the rock to fail. The penetration rate will be considerably less than desired.

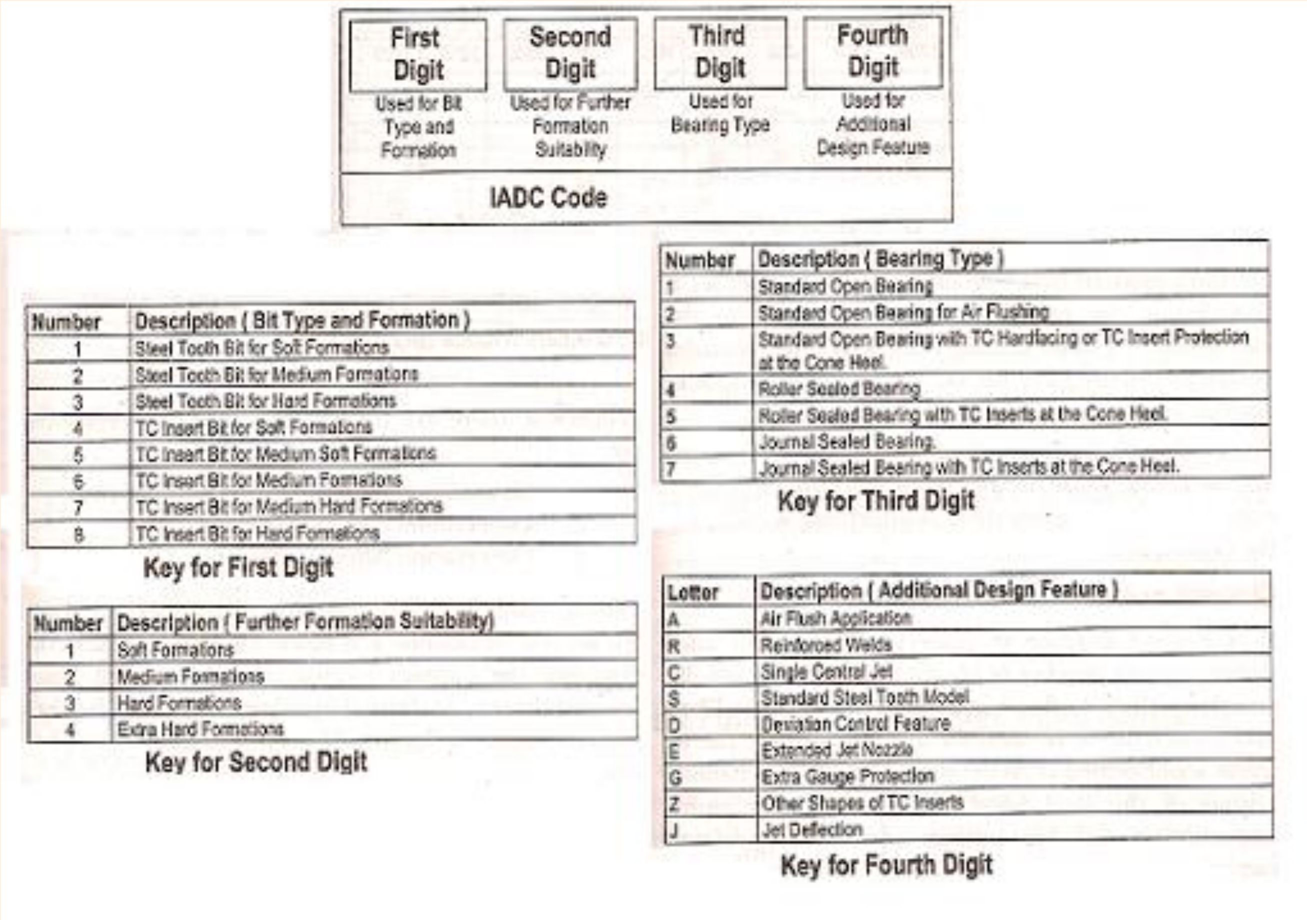
In the third case under the same rotational speed sufficient axial thrust has been applied on the bit for most effective insert penetration for the particular rock mass.

The figure for *spalling* of rock is under proper loading. Chips are removed by circulating air allowing the bit to advance. This condition will give maximum penetration rate and the cuttings will have more chips and less fines.

Under *excessive axial thrust* the bit will wear faster. These cases are described in Figure 7

3.3 IADC Code for Rotary Bit

International Association for Drilling Contractors (IADC) has formulated a four digit code for specifying the tricone rotary bit. First digit of the code represents type of bit and formation hardness for which the bit is suitable, 2nd digit indicates for which formation the bit is suitable, 3rd digit expresses the type of bearing used in the bit. All the first 3 digits are numeral whereas the 4th digit from the left is an alphabet and indicates extra features in the bit. Various numeral codes are given in Figure 8.



First Digit	Second Digit	Third Digit	Fourth Digit
Used for Bit Type and Formation	Used for Further Formation Suitability	Used for Bearing Type	Used for Additional Design Feature

IADC Code

Number	Description (Bit Type and Formation)
1	Steel Tooth Bit for Soft Formations
2	Steel Tooth Bit for Medium Formations
3	Steel Tooth Bit for Hard Formations
4	TC Insert Bit for Soft Formations
5	TC Insert Bit for Medium Soft Formations
6	TC Insert Bit for Medium Formations
7	TC Insert Bit for Medium Hard Formations
8	TC Insert Bit for Hard Formations

Key for First Digit

Number	Description (Further Formation Suitability)
1	Soft Formations
2	Medium Formations
3	Hard Formations
4	Extra Hard Formations

Key for Second Digit

Number	Description (Bearing Type)
1	Standard Open Bearing
2	Standard Open Bearing for Air Flushing
3	Standard Open Bearing with TC Hardfacing or TC Insert Protection at the Cone Heel.
4	Roller Sealed Bearing
5	Roller Sealed Bearing with TC Inserts at the Cone Heel.
6	Journal Sealed Bearing.
7	Journal Sealed Bearing with TC Inserts at the Cone Heel.

Key for Third Digit

Letter	Description (Additional Design Feature)
A	Air Flush Application
R	Reinforced Welds
C	Single Central Jet
S	Standard Steel Tooth Model
D	Deviation Control Feature
E	Extended Jet Nozzle
G	Extra Gauge Protection
Z	Other Shapes of TC Inserts
J	Jet Deflection

Key for Fourth Digit

Figure 8: IADC coding for rotary tricone bit

4 Assemblies in Rotary Blast Hole Drill

The rotary blast hole drills are consist of number of components. There are some assemblies that are directly or indirectly involved in the drilling process and some are essential for better performance. These primary assemblies and auxiliary facilities of a rotary blast hole rig are mentioned in the Table 4 below.

Table 4a Primary assemblies in a rotary drill rig

Sl No	Assembly	Purpose
1	Mast	i. To accommodate the rotary head and enable its up and down translatory motion ii. To accommodate the pipe changer iii. To support the components that move the pipe changer in desired position iv. To support the components that enable making and breaking tool

		joints
2	Rod Changer	i. To hold the drill pipes while they are not being used in the drill string ii. Accommodate the components that enable locking and unlocking of the drill pipes
3	Rotary Head	i. To accommodate all components for transmitting the rotary motion with desired torque at desired speeds to the drill pipes. ii. To accommodate the hydraulic or electric motors that generate rotary motion iii. To accommodate the components that fasten the rotary head to the pull down mechanism
4	Pull Down Mechanism	To exert the necessary downward or upward force on the rotary head in the mast
5	Air Compressor	To supply desired volume of compressed air at the desired pressure
6	Drill Pipes	To transmit the pulldown force and rotary speed and torque to the drill bit
7	Hydraulic System	To transmit energy from mechanical or electrical form to hydraulic form and thus generate desired hydraulic flow at desired hydraulic pressure
8	Dust Ducting	To prevent mixing of the dust with atmosphere by means of a hood around the blast hole and dust ducting
9	Dust suppressor	To filter the dust to the desired level from the dust laden air receiver through the dust ducting
10	Prime mover	To act as main source of power and give desired quantity of power to various components for drilling or traveling operations
11	Drill frame	
12	Operators Cab	i. To allow a driller and helper to properly sit and control the drill ii. To accommodate all the components and instrument for controlling the drilling and travel operations iii. To give desired protection to the operator from heat or cold, rain and falling objects or flyrocks iv. To properly place annunciation panel for indicating equipment condition.

Table 4b Auxiliary facilities in the rotary blast hole drill

Sl No	Assembly	Purpose
1	Piping	To allow flow of compressed air , hydraulic oil, foam or water
2	Fuel Tank	To accommodate desired quantity of fuel oil for consumption over desired time period
3	Hydraulic Tank	To accommodate desired quantity of hydraulic oil
4	Cabling	To allow flow of high voltage electric current for electric drills
5	Cable reel	To enable automatic winding and unwinding of the electric cable while the drill is moving
6	Lighting alternator	To generate low voltage electricity for the purpose of providing desired lighting in and around the drill
7	Wiring	To allow flow of low voltage current to desired points
8	Lights	To illuminate the drill and the drilling site to desired level
9	Lubricating oil Tank	To accommodate desired level of lubricating oil
10	Lube oil piping	To carry desired quantity of lubricating oil to the components that need to be lubricated
11	Machinery House	To guard the assemblies mounted on the main frame from rain, sun rays and flyrocks
12	Air conditioner	To control the temperature of the interior of the operators cab

5 Hole Cleaning and Bailing Velocities

For efficient drilling and higher penetration rate the chips are to be removed as soon they are produced. Air flushing is normally used in blast hole drilling. The return air velocity in the hole varies according to the drilling conditions i.e. weight of cuttings, hole depth, amount of moisture encountered in the hole etc. As a thumb rule it was considered that 5000 feet per min i.e. 1524 /min represents a minimum value.

For better performance of the drill when heavy cuttings result from the drilling operation, or excessive hole depth or under high moisture content, higher return velocities are required.

Bailing velocity can be determined from the following formula:

$$BV = \frac{CFM \times 144}{A}$$

Where, BV= bailing velocity in feet/min

CFM= air feed in cubic feet per min

A= area of annulus, square inch

The bailing velocity can be determined using the nomogram given in Figure 9 below.

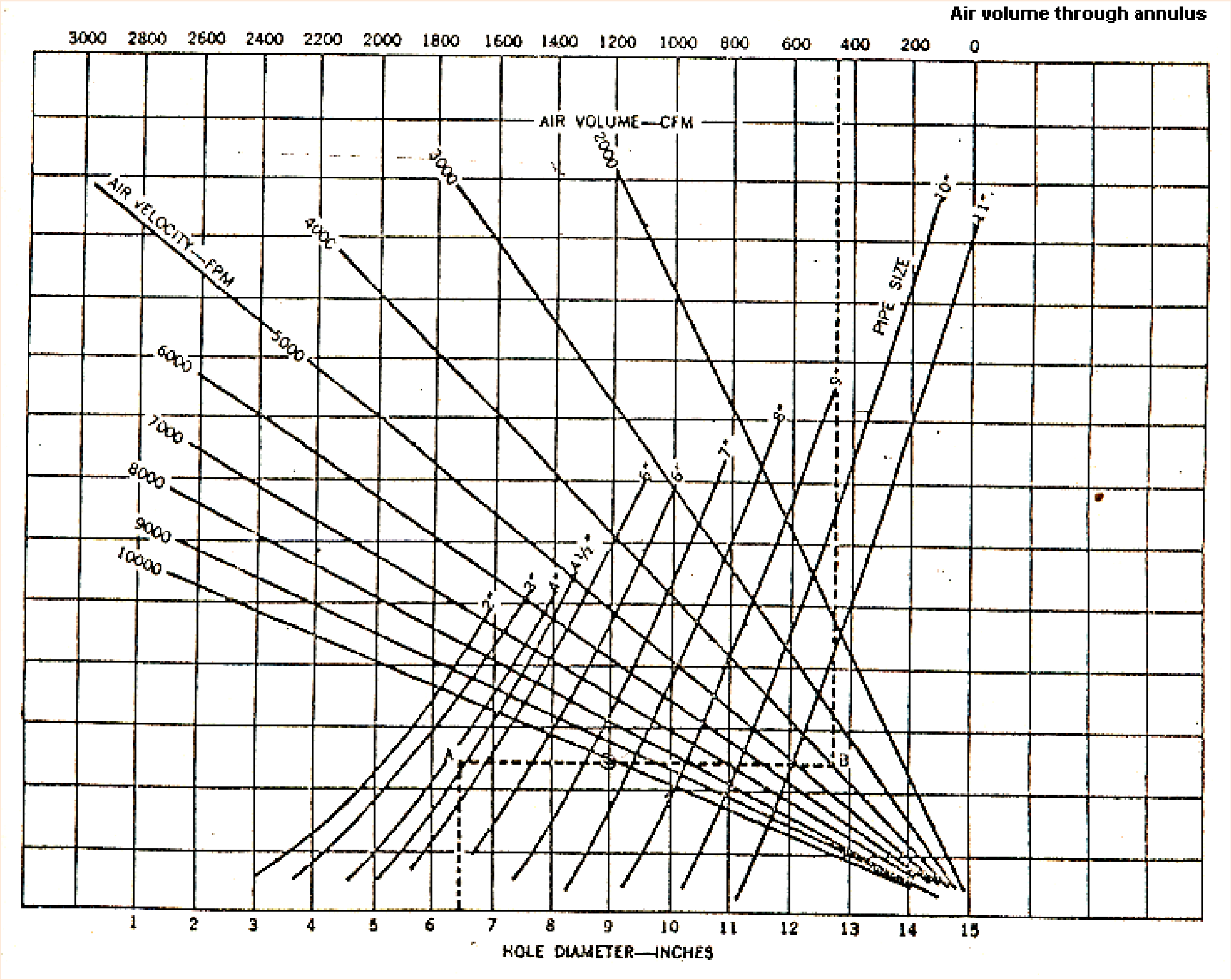


Figure 9 Determination of bailing velocity

While drilling a 6.5 inch hole using 4.5 inch drill pipe with 450 CFM air volume passing through the annulus. As shown in the dotted line, you start moving up from the hole diameter axis to meet the pipe size (as shown in A). Come down from the annulus air volume rate (top) 450 CFM. Moving horizontally from A will meet the line at B. This corresponds to bailing velocity near 4000 FPM.

The circulation air as drilling fluid medium has two primary functions

- Cooling of the bit
- Removal of the cuttings from the hole

The compressed air from the compressor is carried through the mast stand pipe, hose, swivel and tool string to the bit. There is sudden release of pressure as the air leaves the bit, this causes considerable drop of the temperature of the air around the bit.

Annular velocity is determined to calculate the air quantity for the cutting removal. The annular velocity depends on the hole diameter, drill pipe outer diameter and air quantity.

For maximizing the upward air velocity for a given quantity of air, the annular area between the hole wall and the drill pipe should be minimized. However, the linear gap between the hole wall and the drill pipe should be sufficient to permit the free upward flow of cutting chips. This clearance will depend on the chip size; however, the minimum clearance should be 7 mm. If the clearance is not sufficient to allow free flow of chips and cleaning of the hole is not effective, it may damage the drill stem. Thus it is necessary to estimate the optimal uphole air velocity for effective chip removal. It is recommended to use air velocities from 1200 m/min to 2500 m/min depending on the rock type being drilled. Lower values should be utilized for drilling through soils and soft rocks and higher values for harder rocks. The air quantity required can be calculated as:

$$Q = \frac{\pi\left(D_h^2 - D_p^2\right)V}{4 \times 10^6}$$

Where,

Q= Air quantity in the annular space, m^3/min

D_h= Hole diameter, mm

D_p= Outer diameter of drill stem, mm

V= air velocity in the annular space, m/min

Air Pressure:

For conventional rotary drilling upto depth of 80 m the air pressure is not very high. 3.5 kg/cm^2 may be sufficient. In DTH the penetration rate is proportional to the air pressure in exploratory drilling pressure upto 24 kg/cm^2 has been tried. Commonly, used DTH work at 7.5 kg/cm^2.

Selection of Compressor

The pressure rating and air volumes required for any particular drilling operation will determine the most type of compressor needed. Where the demand for compressed air is relatively small and intermittent, compressors of reciprocating type should be employed considering economy. Where demand is continuous efficient compressor like vane or screw type may be the choice though they are costly.

For the purpose of drilling blast holes rotary and rotary-percussive drilling are often used. For *very hard formations and abrasive formations the rotary-percussive drills are proved to be a better choice*. However, in *most strata conditions rotary drills are extensively used*.

Harder formations normally require special types of bits with medium and hard steel teeth or tungsten carbide inserts. In case of percussive drilling the penetration rate decreases with increase in hole diameter and increase in rock strength. The diameter of the hole in percussive drilling is kept within a limit of 228 mm or 9inches. The hammer operating pressure is normally around 0.7MPa. However, increasing it to 1.7 Mpa (250 psi) certain manufacturer has claimed to get double the penetration rate. Normally, the hydraulic percussive drill offer a 20 to 100% gain in the penetration rate.

The modern *hydraulically operated drills have number of advantages over pneumatic drills*. These are:

1. The self contained diesel powered hydraulic percussive drills do not require auxiliary compressor for drill operation.
2. Energy delivered per stroke being higher, hydraulic percussive drills offer higher penetration rate compared to the pneumatic drill.
3. Less noisy
4. Many hydraulic drill claims enenrgy saving as high as 66% than pneumatic drilling.
5. Machine wear and bit wear is less compared to the pneumatic drills.
6. The investment cost on hydraulic drill is generally higher by about 27%. However, the energy cost , drill steel cost and overall operating cost are claimed to be 24%, 86% and 76% less respectively.

Vertical blast holes are most common. However, to avoid formation of hard toes and to obtain better fragmentation and reduced vibration level inclined blast holes are more useful in many situations. A hard strata occurring at depth in the lower horizon of a high bench is better blasted by horizontal blast holes. However, horizontal drilling is not normally carried out in opencast mining due to the difficulties associated with drilling and charging.

6 Factors Affecting Drilling

The performance of drills are affected by factors related to various aspects of drilling as shown in the Table 5:

Table 5: Factors affecting drilling performance

Sl No	Category	Factors	
1	Operating Variables	Drill	1. Drill power 2. Drill Thrust 3. Drill Torque 4. Drill Rotary Speed 5. Blow energy 6. Blow frequency
		Rod	1. Rod dimensions 2. Rod Geometry 3. Material Properties

		Bit	1. Bit diameter 2. Bit geometry 3. Material Properties
		Circulation Fluid	1. Fluid flow rate 2. Fluid properties
2	Drill Hole Factor	Hole specifications	1. Size 2. Depth 3. Inclination
3	Rock factors	Material Properties	1. Resistance to penetration 2. Porosity 3. Moisture content 4. Density 5. Shore hardness 6. compressive strength 7. Coefficient of rock strength 8. Specific energy consumption for drilling
		Geologic Condition	1. Petrologic and structural bedding 2. Fractures 3. Folds 4. Faults 5. Joints 6. Rockmass composition
		State of stress	1. In situ pressures 2. Pore pressure
4	Job or service factor	Operational variables	1. Labour quality 2. supervision quality 3. Scale of Operations 4. Power availability 5. Weather conditions
		Site factors and job site conditions	1. nature and scope of task, 2. achievement targets, working conditions, 3. site lighting conditions, 4. defects on equipment, hazards and 5. coordination requirements/issues.

6

The most common diameters for blast hole adopted in Indian open cast coal mines are 150-200 mm for coal benches and 250 mm for overburden benches. For high dragline benches blast holes of diameter 315 mm are drilled. The optimal penetration rate in drilling blast holes by a particular bit size depends on appropriate pull down force necessary for the rock types being drilled. Table 6 shows approximate pull down force required for medium hard conditions. Figure 10 and 11 show the performance of drill in Indian coal measure rocks.

Table 6 Pull down force (Kg) for blast hole drilling.

Rock Type	Bit Diameter		
	200 mm	250 mm	300 mm
Shale	10800	18600	27300
Sandstone	11700	20400	29700
Limestone	12300	21500	31000

General Recommendation for better drilling performance:

1. Drill at minimum bailing velocity of 1524 m/min
2. After each hole, the bit should be inspected to ensure that all the cones are at the same temperature. One excessively hot cone usually indiates obstruction of air passage to the bearing
3. Air valve should be fully opened before rotating bit and are kept on while the bit is rotating
4. The bit and the drill steel should not be dropped to avod damamge of cones or bearings
5. The bit should never be forced into soft, loose formations faster than the cleaning of the hole by the circulating air. Operating the bit while buried under formation cuttings to lock when cuttings can cause bearings to lock when cuttings may be fixed inside the cone.

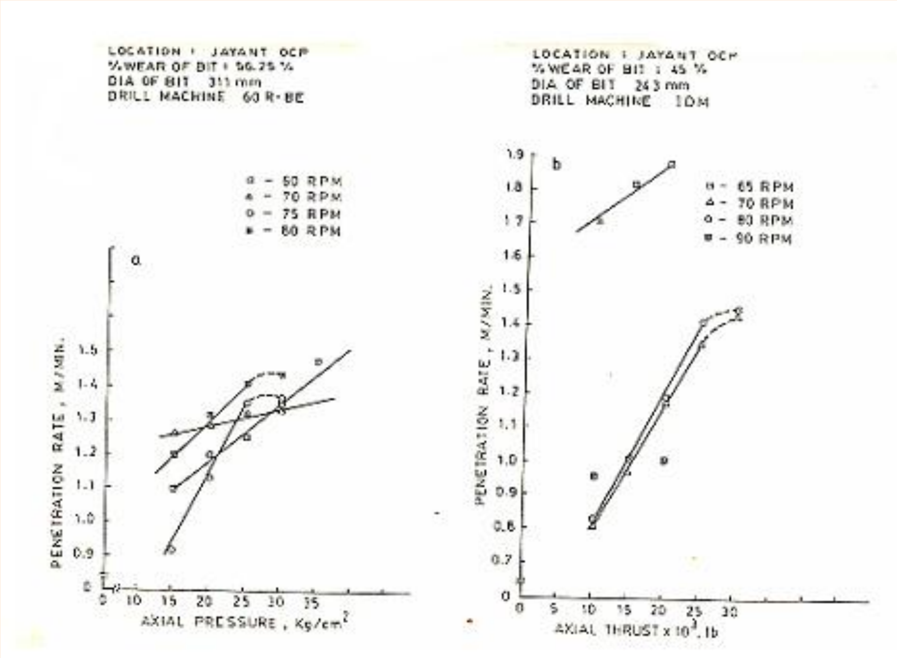


Figure 10 Performance of rotary blast hole drill (Pathak, 1989)

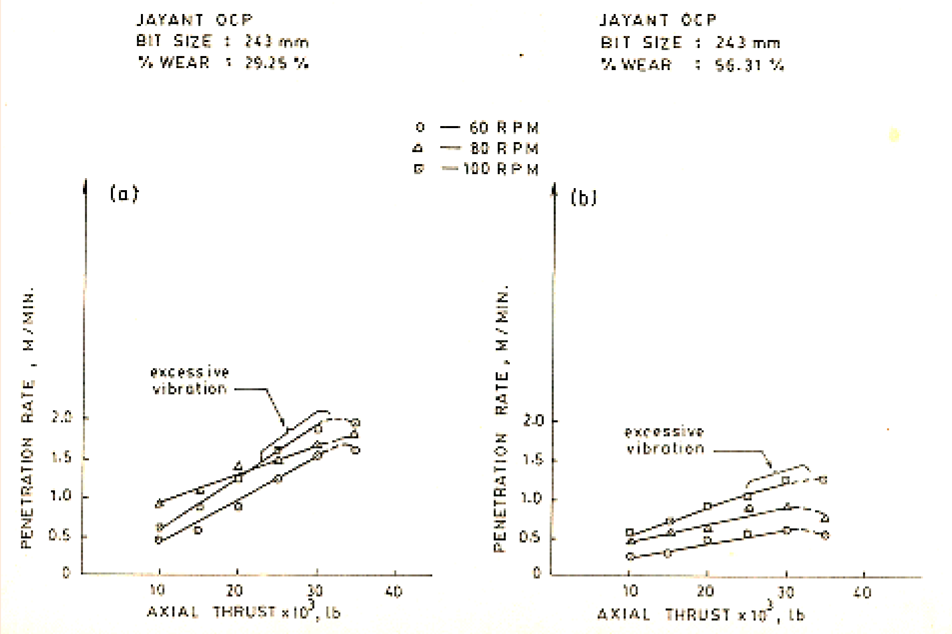


Figure 11 Performance under different initial bit wear.

It can be noted that :

1. The penetration rate generally increases with increase f axial thrust. However, beyond a certain limit the drilling is affected by excessive vibration set in. This limit is dependent on the diameter of the bit, the drill speed and the wear state of the bit as well as the formation type.

2. The penetration rate can go down by 50% for a 92% change in the initial bit wear.

6.1 Performance Measurement

Drilling performance is normally measured in terms of:

1. Energy or power requirement
2. Rate of penetration achieved
3. Bit wear per meter drilled
4. Cost of drilling

The formulae used for the measurements are shown in the following Table 7:

Table 7 Formulae for performance measurement

Sl No	System	Formulae	Reference
1	Percussive Drilling	Blow Energy: $E=1/2\ mv^2=cWL^2B^2$ Power $P= BE = cWL^2B^3$ where m: piston mass=W/g v: piston impact velocity c: constant=0.3 to $0.5x\ 10^{-6}$ W: piston weight L: piston stroke B: Blow frequency if p: gauge pressure $E\ \alpha\ p$ and $P\ \alpha\ p^{1.5}$ and $B\ \alpha\ \pi^{0.5}$ if a: area of cross section of the piston $\mathbf{P\alpha\ p^{1.5}\ a^{1.5}\ L^{0.5} / W^{0.5}}$	Wells (1950), Pfleider and Lacabanne, 1961
2	Rotary	Energy (work per revolution) $E=E_f+E_r$ where E_f = Thrust energy and E_r is rotational energy	Teale , 1965 The thrust

		$= Fh + 2\pi T$ where F: Thrust, T: Torque, h: depth of penetration per revolution =R/N, R is rate of penetration, N is rotary speed. Power $P = P_f + P_r = FR + 2\pi NT$	component being small is often neglected (Rowland, 1974).
3	Rotary Percussion	Specific energy consumption(e) per unit volume drilled. E =E/V= P/AR V is th evolume of rock, A is area of cross section of hole, V is proportional to E, energy applied	
	Percussion	1. Drilling Rate, R= BE/(Ae) $R=(V_c Bn)/A$ V_c is the volume broken per cutting edge and n is the number of bit cutting edge, e is specific energy. e and V_c are to be determined experimentally. 2. $R = \frac{BE}{Ae}$ $R = \frac{V_c Bn}{A}$	Hartman, 1959; Mauer, 1967
	Rotary	1. $R = \frac{2\pi NT}{Ae - F}$ 2.	Rotary drag bit, Mauer 1967 2. drag bit, Tandanand, 1973

$$R=\frac{2\pi N r F \cot(\phi+\alpha)}{A\, d\, F}$$

r= effective bit radius

ϕ= angle of cutting friction

α = rake angle of bit

$$R=\frac{V_c n_t N}{A}$$

3.

n_t is the number of tooth impacts per revolution, Vc is volume broken per cutting edge

Bit wear affects the performance of drilling. Pathak (1989) established that the bit wear is related to the grain size of the rock as well as other rock properties and operating parameters of the drill. The bit wear mechanism and wear rate is not precisely known. However, it is well observed that wear of percussive and rotary drills are influenced by number of factors as shown in the Ttable 8 below:

Table 8 Factors that affect the performance of drill

Type of Driling	Directly Proportional	Inversely Proportional
Percussive	1. Blow energy 2. Fluid viscosity 3. Rock hardness	1. Cutting edge angle 2. Number of edges 3. Bit hardness 4. Fluid flow rate
Rotary	1. Thrust 2. Rotary Speed 3. Rock Hardness	1. Bit cutting angle 2. Bit hardness 3. Fluid flow rate

From the bit wear study it was established that drag bit drills are useful only in soft and medium hard rock. For medium and hard rock rotary-percussive and roller cutter bit drilling are effective. While for very hard rocks only percussive drills are effective.

7 Selection of Drilling Method and Drilling Execution

Selection of machine for production drilling calls for your **value judgement.** Capp (1962) suggested the following steps as guide to select the right drill:

1. Determine the job factors:
   i. Labor and skill availability
   ii. Site conditions. From this one will specify if the site preparation for drilling will need a flat surface or inclined surface
   iii. Weather
   iv. Safety Requirements
   v. Power availability
2. Define Job Objectives of rock breakage vis a vis relationship with other production cycle operations: Clearly state:
   i. Excavation constrints and restrictions
   ii. Haulage constraints and restrictions
   iii. Pit slope stability and pit geometry
   iv. Crushing capacity for size and rate
   v. Production targets
   vi. Fragmentation demanded
   vii. Muckpile through expected
   viii. Ground vibrations restrictions
3. Design the drill hole pattern that would be use. This will be based on the blasting requirements. The pattern will consists of:
   i. Hole size
   ii. Hole depth
   iii. Hole inclination
   iv. Burden
   v. Spacing
   vi. Toe Burden
4. Determine the drillability factor and select suitable drill

An approach for selecting suitable drill is to find the drillability of the rock under different drilling method. A guideline is shown in Figure 12 below:

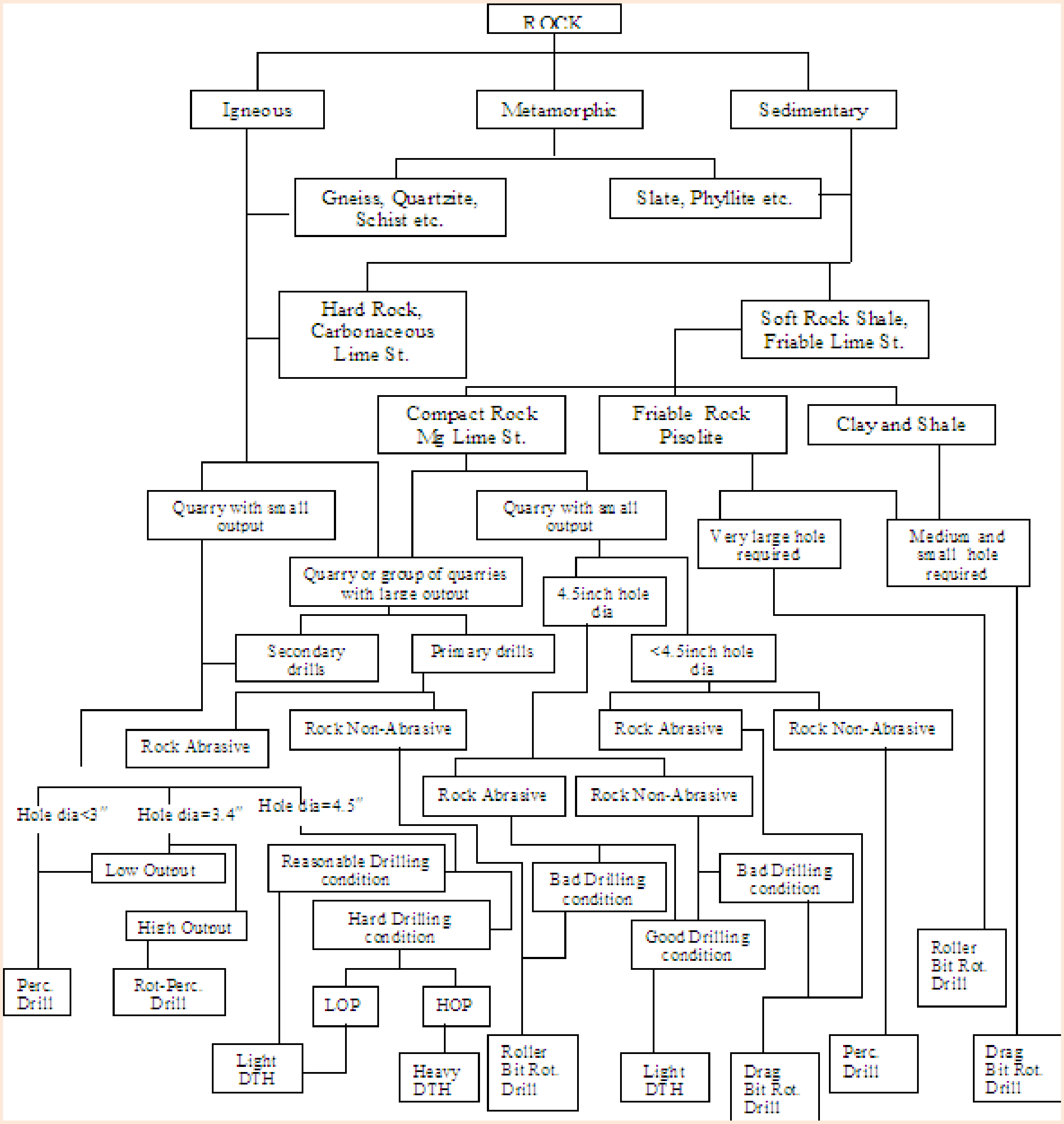


Figure 12 Selection of drill (after K. McGregor, Drilling of Rock, 1967 CR Books Ltd, London)

5. Specify Operating conditions: The drill selection should be done with the drill manufacturer and the operating variables should be properly defined considering the site conditions. For this the safety information and procedures will have to be learnt from the legislation and regulations, relevant Indian and International Standards. Management plans, manager's rules, company's policy, code of practice, equipment manufacturers

instructions and safe job procedures will have to be referred to specify the operating conditions and work instructions. The needs for positioning information through GPS, drill hole condition information through bore hole camera, hole depth measurements, dust suppression requirements should be assessed.

6. Determine Coordination Requirements: For the drilling operations it may be necessary to coordinate with the electrical department to arrange for electric supply through trailing cable. There will be necessity for site preparation equipment like dozers or grader, it may also require water truck to supply water for wet hole drilling, service vehicles, cranes and floats may also be necessary depending on the site conditions. The manager must coordinate these needs in consultation with the drilling in charge.
7. Estimate Performance parameters. This will include:
   i. Estimations of machine availability
   ii. Estimation of cost of operations
   iii. Determination of specifications of power source used
   iv. Identification of cost items like bit, oil and lubricants
   v. Determination of depreciation, labor cost, maintenance cost, power cost, bit costs, spare costs
   vi. Select a system on the basis of optimal cost, and maximum safe operation.

8. Monitoring of Operations:
   i. Drill operations monitoring includes monitoring of rotation and pull-down pressures,
   ii. Monitoring the status of the gauges, alarms and other warning devices
   iii. Inspecting the conditions of the rods, bits and associated equipment for ensuring optimal performance.

8 Small diameter blasthole drill

It is necessary for drifting in underground and for small size blasts in surface mines. This is basically a pneumatically operated percussion drill of top hammer type. DTH can also be used. Crater is formed by the blow of the drill steel and the debris formed is removed by the flushing air and new surface is impacted to make progress in drilling the required hole.

The drilling requires the drill rig and the compressor. The components of the drill rig are shown in Figure 13 below:

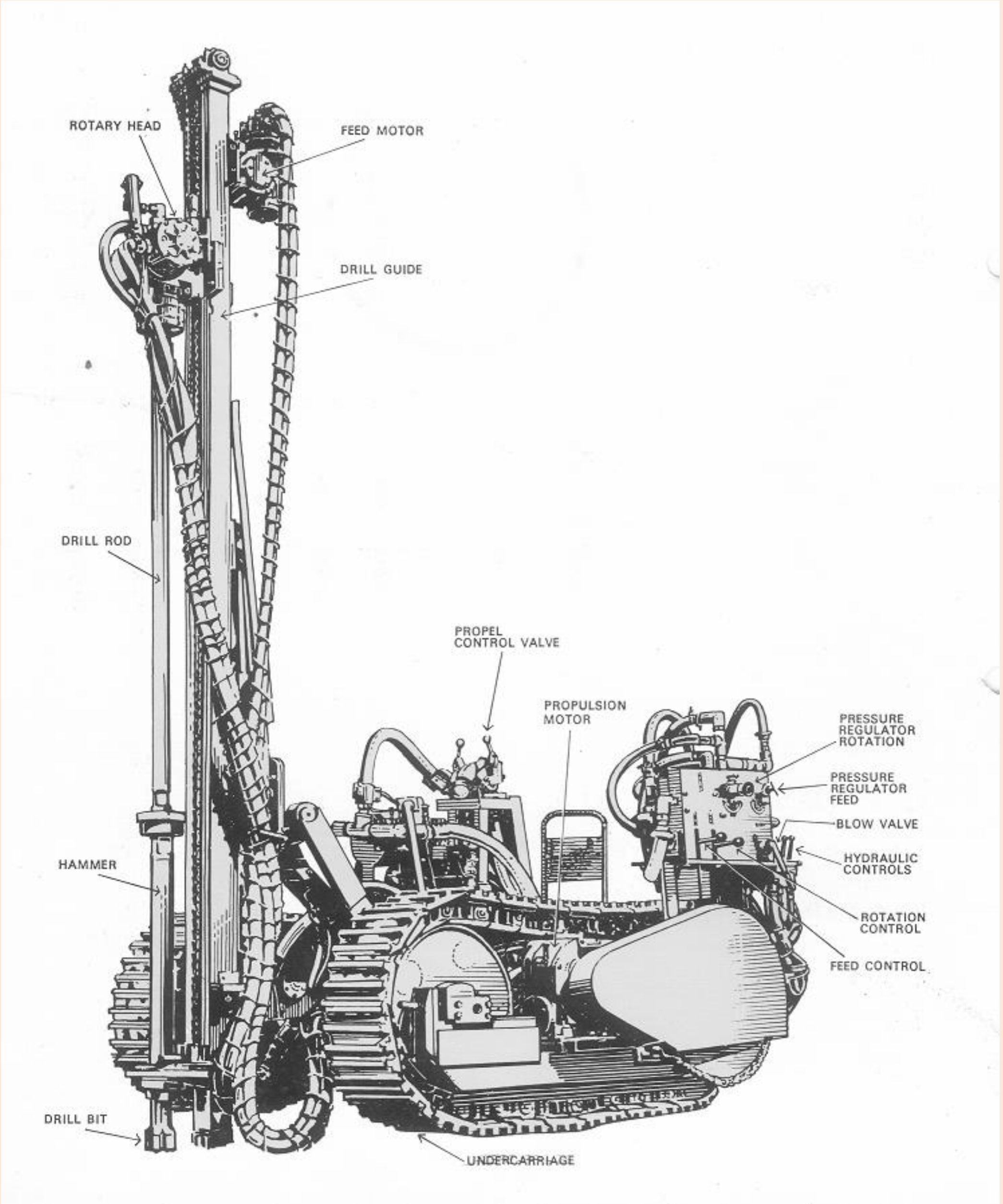


Figure 13 ICM drill

This light weight drill is easily maneuverable and easily positioned for drilling vertical, angular or horizontal holes. The operations are hydraulically controlled. It tows its own compressor for powering.

The components of this are:

1. Rotary Head: Comprises of a hydraulic motor and a suck assembly to hold the drill pipes
2. Feed motor: To apply an axial thrust on the bit through the drill rod by having a chain feed mechanism.
3. Drill guide to position the drill rod and bit at proper angle to make vertical or angular hole.

4. Drill pipe or drill rod: A tubular rod with a central hole to send compressed air and male and female ends for connecting to the next rod and to the suck of the rotary head.
5. Hammer: It is a pneumatically acting hammer. When the compressed air is entered in this valve released pressure energy to a piston to blow the bit connected to it provide the impact on the rock mass.
6. Drill bit: It is tungsten carbide button insert bit connected to the hammer.
7. Undercarriage or crawler unit which allows the drill to be propelled.
8. Propel control valve for releasing the hydraulic to power the hydraulic motor to drive the crawler.
9. Propulsion Motor is the hydraulic motor that provides the power to propel the machine.
10. Hydraulic control unit having pressure regulator for rotation of the drive head, pressure regulator for the control of the feed motor, blow valves, hydraulic control, rotation control and feed control

9 Management of Drilling Operation

What should you do while planning and preparing for the drilling job?

1. You may have to learn the work requirements from the previous shift operations. Your mine might be having prescribed form for shift briefing. In those form you may get handover details from the previous shift. In certain work culture, there may be messaging through wireless communication system or telephones. All such instructions written or verbal must be obtained, clearly interpreted and clarified before proceeding to the drilling job.
2. For the drilling job with ultimate objective of quality control of ROM, the geological and survey information should be accessible. While following the site procedure those information should be interpreted and applied.
3. Depending on the site, equipment and specific operations planned safety information and procedures may vary. The drilling operation executives must have access to these information and they must apply them throughout the work.
   i. This information may be what the noise level of the machine is and what is the safe exposure limit? For example the manager should know the permissible noise levels as shown in Table 9 below

Table 9: Permissible noise exposure (after OSHA, 1978).

Duration, Hr	SPL, dBA (Slow)
8	90
6	92
4	95
3	97
2	100
1.5	102
1	105
0.5	110

   ii. Similarly he should know how the size of blasts affects ground vibration and what are the safe vibration levels for the particular site.

4. Every mine develops their own safety information and procedures. The drilling executive must collect and apply those procedures through out his work while constantly examining if they are adequate and needs modifications
5. The drill site should be well examined and procure the required tools and man power for preparing the site for drilling.
6. The drill pattern is designed as per the technical requirements of the overall mining. The drilling personnel need to get this drill pattern and accurately mark the drilling pattern. Modern equipment and control technology can automate the drilling machine to move to subsequent holes based on the instructed pattern.

Better drilling management involves the following:

- Planning for surface blast hole drilling
- Set up and conduct of surface blast hole drilling
- Relocation of drilling equipment
- Basic maintenance of the equipment in the work site
- Maintaining safety and quality work standards in site operations

8.1 Drilling Proper

The exact drilling operation is carried out by the drill operator. Many a times he may not be aware of the technical requirement of specific drilling job. Thus it is very essential that he is properly instructed and his job is coordinated with the other operations like blending and reclamation in site. Further the drilling incharge must be careful to:

1. follow the instructions and procedures prescribed by the equipment supplier in operations like pre start, start up and shut down of the machines
2. The drill must be positioned and leveled according to pattern while taking care of the trailing cable, edge clearance, bench stability in the site etc.
3. The drill operator should be trained to use the monitoring instrumentations in the machine.
4. Based on the site conditions and the selected equipment there may be certain precautions and specific actions necessary. The drilling in-charge must know and implement those.
5. The drilling personnel must have knowledge of the hazardous and emergency situations. On such situations the drilling personnel must follow the stipulated actions laid out by the manufacturer of the machine or adopted by the mines without any panic.
6. Drilling operations should be properly logged. Whenever, there is no measure while drilling system are installed close observations of the operating parameters and recording in the logbook as much detailed as possible should be practiced. Recording requirements are normally dictated by site conditions.
7. As far as practicable the operations should be carried out as per the agreed plans without overloading the equipment in any form.

8.2 Drill Relocations

It may be essential to march the drilling machine from one location to another. Such requirement may arise in ore mining for maintaining the grade of the ROM by blending output from different zones. The relocation may be by walking, driving, towing, transporting or floating. Whenever such situation arises, the drilling crew should consider the following:

1. Properly inspect the site and collect the location and route plan from the surveyor.
2. For marching the machine site preparation work should be carried out with proper coordination with other working unit like civil construction, if available. If the drill is an electrically operated drill, it may be necessary to relocate the supply kiosk and cable handling. Depending on the location there may be requirements for construction of ramps, culverts etc. Such work should be planned beforehand and logistics should be arranged with pre-thoughts to eliminate avoidable delays.
3. There may be regulatory compliance to fulfill while handling cables, laying out ramps or roads. If so that should be given priority.
4. Overall arrangements for drilling may require services from other concerned departments like maintenance and electrical supply. For the success of operations proper coordination will be essential.
5. Prior to relocation and after relocation certain inspections of the machine may be prescribed by the manufacturers. That should be strictly followed. A check list of such inspection should be readily available to the supervisor.

8.3 Operation and Maintenance

The drilling personnel should orthodoxly follow the operating manual of the machine provided by the manufacturer. Some important points regarding operation and maintenance are:

1. The drilling personnel should have enough exposure to the manufacturer's instruction for operation and maintenance.
2. The mine might have developed certain housekeeping norm. In absence of such norms, the technical officers can take up proper faultfinding methodology whenever such need arises and should document them for future reference.
3. The manufacturers normally provide routine tests and services guideline. Such guideline should be followed without failure.
4. In case of major failure of the machine or major repair work , the manufacturer's presence may be expected for developing future procedures.
5. Depending on the size of operation, maintenance organization and system

should be preplanned.

6. Proper operational records should provide input for operation control software.
7. Proper coordination of workshop personnel, storage control etc would be necessary.

8.4 Competency Assessment

As a manager of the mines and in charge of drilling operation it is important to know how to judge competency of the persons involved in the drilling operations. The following considerations may be used to judge drilling competency:

a. Applying personal and operational safety procedures involved in drilling
b. Interpreting and communicating information on drilling operations
c. Knowledge of the requirements in drill site preparation and executing them
d. Completing drill equipment pre-start, start-up and shut-down procedures at every drilling operations
e. Operation of the drill (system)
f. Completion of drilling to pattern/specification
g. Efficient relocating and positioning of drills
h. Knowledge of maintenance needs and organizing drill maintenance
i. Capability of collecting, analyzing and organizing ideas and information.
j. Efficiency in communicating ideas and information.
k. Skill in planning and organizing activities.
l. Attitudes and ease in working with others and in teams.
m. Approach and ability to solve problems.
n. Using mathematical ideas and techniques as well as latest **technology.**

8.5 What a Drilling Operation In-charge must do

1. Plan and prepare for operations:
   i. For this the engineer should be provided with information regarding legislative requirements, site requirements based on the geo-technical and geo-mining conditions, requirements suggested by the manufacture of the deployed equipment as well as the requirements for the established procedure for the job. The officer must be able to interpret and clarify these requirements
   ii. For the satisfactory completion of the job the officer must specify the work requirements like the target to be achieved, the type of tools and worker he will require and he must understand how to allocate those requirements at proper time

and at proper location.

iii. The officer should have access to the geological and survey data and he must know how to interpret these data and apply the knowledge in field. This is important for the drilling engineer to know how his drilling pattern and drilling sequence contribute to the quality and grade control.

iv. The officer must inspect the work area and prepare it if necessary prior to mobilizing exact drilling operation.

v. The officer must identify, manage and report ***potential hazards and risks*** in accordance with ***legislative, site and manufacturer's requirements and procedures***.

vi. The drilling officer must understand the links of his job with the other operations in the mine and must coordinate his requirements with others. Resolving coordination requirements is very important for overall productivity.

vii. The drilling officer/in-charge like any other job -in charge must be very careful regarding the protective equipmnet with due consideration of the site requirements and procedural demands.

10 Safety at Drilling Operations

The hazards and risks are involved in drilling mainly due to the following:

- Noise (hearing): the drilling operations normally produce higher level of noise. The operator and helper must use personnel protective equipment as prescribed by the manufacturer of the drill or the mine management.
- Explosives material: Drilling is followed by blasting and the drilling personnel must be aware of explosive risks.
- Burst hoses: the machine comprises of hydraulic and pneumatic hose ppes. They must be properly maintained and replaced after prescribed use. Accidental bursting may cause accident.
- Air and hoses: The drilling personnel must be aware f the high pressure lines and the risks to work with them.
- Couplings: The couplings at drill rods are not supposed to break, however, poor workmanship may lead to improper coupling that get dislodged while operation may create serious injury to men or machine.
- Compressed air: All the precautions to work with compressed
- Dust: dusts can cause lung disease as well as inconvenience in working. Dust collector facilities in the drill must be well maintained.
- Loose clothing: No person with loose garment should be allowed to work with the drill.
- Pre-start checks should be conducted orthodoxy during every starting in accordance with specified requirements particularly with respect to the compressor, drill rig and the consumables. Ground area should be checked to ensure working conditions comply with specified requirements.

- At the drill work site while working inspections must be conducted to know if there is any misfires and old explosives in the site as well as the high wall stability to ensure a particular position of the drill is safe.
- All precautions prescribed by the manufacturer and norms suggested at the mine should be followed during tramming the drill to the bench, moving it into position, starting up and running to operating state, and positioning to the leveled position using the jacks.

11 Monitoring of drilling conditions

While conducting the drilling operation one must monitor the following:

- Instrument readings.
- Penetration rate.
- Replacement needs for rods.
- Adding rods.
- Dust/environmental requirements.
- Chippings quality.
- Status of water in hole.
- Cracks, faults in the rock mass.
- Conditions of the work area.
- Illumination standards (night work).

10.1 Measure while drilling

Drilling optimization is possible by controlling the operating parameters to match with the geo-mechanical and structural properties of the rock mass being drilled. Measure –While –Drilling (MWD) is the process to generate data for automatically or manually controlling the operation parameters of a drill. During the operation of a drill the operator needs to adjust pull down pressure (i.e. the axial thrust on the bit), rotary speed and bailing air pressure and velocity depending on the strata encountered.

Modern drills like BE 60R or 61 R incorporates MWD system. This system comprises of an electronic black box incorporating sophisticated transducers and current limit devices which feed back drill performance data to a central controller. The system would respond to the monitored signal when preset drilling and machine parameters were exceeded, through adjustments to down feed, rotary speed and flushing rate.

Similar systems were also developed by Gardner Denever for their GD-120/130 rotary blast hole drills and Marion for their M4 and M5 crawler rigs. The system incorporated in Marion also controls by measuring while drilling. It controls the parameters of down pressure, bailing air pressure and rotary speed. Limits for each of these are preset into the system and are determined based on ground conditions, projected rotary bit life and desired rate of penetration.

Variations in the penetration rate are due to the changing nature of the rock being drilled, but may also reflect changes in the operating skill of the drill i.e. the control of pull down pressure and rotary speed. Variations in the rotary torque indicate very clearly the presence of strong or weak rock units in a manner similar to the penetration rate. Variations may be due to change in down pressure and rotary speed, which can be confirmed by examination of the drilling records. In general, at constant or set down pressure; torque increase occurs for stronger rocks i.e sandstone whilst decrease indicates weak rocks like mudstone, coal or weathered rocks. Thus, measuring-while-drilling provides better control of the machine as well as important geotechnical information for other mining operations.

12 Problems of Drilling

The problems that may occur during drilling include:

- Bit stuck.
- Broken bit (tungsten carbide).
- Rods stuck that won't separate.
- Rods broken

Other problems associated are:

- Excessive noise
- Excessive dust generation
- Excessive bit wear rate
- Poor penetration rate
- Problem of flushing
- Wall collapse during drilling
- Water in the hole

12.1 Drilling Hazard [1]

Blast hole flushing by air renders the operators and his assistant exposed to airborne respirable crystalline silica dust. This may induce lung disease like silicosis. As the drilling process itself generated dusts and dusts are emitted at a speed from the drilled hole, it may be difficult to contain the dust at source. Normally, fixed shrouds are used to enclose the area beneath the drill deck. However, there are often significant amount of leakage due to:

1) Gaps between the shroud and ground created by raising/leveling the drill,
2) Gaps in the corner seams, and
3) Torn deck shrouds.
4) Less attention to keep it fixed.

Most deck shrouds are rectangular and constructed of four separate pieces of rubber belting attached to the deck. Because of this design, there is usually a significant amount of dust escaping from the open seams as well as the open area between the shroud and the ground. This dust can be a significant source of silica exposure to drill operators as well as other personnel downwind of the drill.

[1] (www.cdc.gov/niosh/hc27.html)

Figure 14. Dry dust collection system for blast hole drill: circular deck shroud.

Figure 15. Drill operator at the control panel.

To improve the efficiency of the dust suppression circular deck shrouds are designed. This new shroud is circular and slightly conical in design and is without any open seams. Steel banding is used to attach the shroud to the bottom of the drill deck and close the one seam. The shroud is capable of being hydraulically raised to nearly flush with the drill deck and lowered to make contact with the ground after raising and leveling the drill. A steel band is attached to the bottom of the shroud to maintain shape as well as to provide weight for lowering. Sheet rubber material, which is thinner than material typically used for deck shrouds, is used for flexibility. Operation is accomplished by guide wires attached to the bottom steel band and a hydraulic cylinder. The cylinder is controlled by a hand valve located near the other drill controls. The shroud has a small trap door which can be manually raised/lowered so that the cuttings can be shoveled from inside the shroud without losing dust capture efficiency. Such innovative designs can reduce dust emission from surface mines considerably

13 Conclusion

In this lecture various aspects of blast hole drilling technology are introduced. Basic issues for improving the drilling operations are briefly discussed. The drilling and blasting economics will have to be looked together. In the following lecture we will discuss the blasting in surface mines.

[1] Biggs, M. D. and Cheatham, J. B. 1969, Theoretical forces for prescribed motion of a roller bit, Soc. Of Petro. Engr, Jl, Dec 1969, p.473.

[2] Cheatham, J. B. Jr and Gnirk, P. F., 1966 TH mechanics of rock failure associated with drilling at depth, Proc. 8th Symp on rock mechanics, Univ of Minota.

[3] Pathak, K, 1989 Effect of operating parameters and rock formation type on rotary blast-hole drill performance, M. Tech Thesis, Dept. of Mining Engineering, ISM, Dhanbad p.37

[4] Gokhale, B. V. 2003, Blasthole Drilling Technology, Publisher: Multifields, Mumbai, p. 3