6.1. GENERAL

SELECTING TUNNELING METHODS

In modern tunnel and underground cavern excavation, it is possible to select from many different methods. The following factors should be taken into consideration when selecting the method:

- Tunnel dimensions
- Tunnel geometry
- Length of tunnel, total volume to be excavated
- Geological and rock mechanical conditions
- Ground water level and expected water inflow
- Vibration restrictions
- Allowed ground settlements

The methods can be divided into drill & blast, and mechanical excavation. Mechanical methods can be split further to partial face (e.g. roadheaders, hammers, excavators) or full face (TBM, shield, pipe jacking, micro tunneling).

The drill & blast method is still the most typical method for medium to hard rock conditions. It can be applied to a wide range of rock conditions. Some of its features include versatile equipment, fast start-up and relatively low capital cost tied to the equipment. On the other hand, the cyclic nature of the drill & blast method requires good work site organization. Blast vibrations and noise also restrict the use of drill & blast in urban areas.

**FIGURE 6.1.-1.** Tunneling methods in different rock/soil conditions.

**FIGURE 6.1.-2.** Range of methods compared to uniaxial compressive strength.

**FIGURE 6.1.-3.** Drill and blast cycle.
Hard-rock TBMds can be used in relatively soft to hard rock conditions, and best when rock fracturing & weakness zones are predictable. The TBM is most economical method for longer tunnel lengths, in which its high investment cost and timely build-up can be utilized by the high advance rate of excavation. TBM excavation produces a smooth tunnel with low rock reinforcement cost, and is optimal in terms of flow resistance in long ventilation or water tunnels.

Shielded TMBs or shield machines are used in loose soil and mixed ground, and in conditions where high water ingress is expected. The mechanical and/or pressurized shield prevents ground settlement and ground water inflow. Because of continuous ground control and no blast vibrations, this method is commonly used in urban tunneling. Pipe-jacking is a special application, in which the tunnel lining is continuously pushed by heavy hydraulic jacks as the tunnel advances. Microtunneling is a special application of pipe-jacking in no-man-entry sized tunnels.

Roadheaders can be used for tunneling in stable rock conditions of low-to-medium hardness. Where it is applied, the roadheader combines the versatility of drill & blast for producing various tunnel geometries, and the continuity of full-face mechanical excavation. As it lacks blast vibration, this method can be used in sensitive urban areas. In harder rock conditions, use of roadheaders is limited by a shorter lifetime of tools and increasing cutting tool cost.

Hammer tunneling evolved in the late 1980’s and combines a continuous method with low equipment costs. It has gained popularity mainly in the Mediterranean countries and Japan. The tunnel face geometry is unlimited, and the method is effective in rocks of low-to-medium compressive strength, when the rock mass is relatively fractured. In hard and compact ground, application is limited by low production rate.

6.2. METHODS

6.2.1 Drilling and blasting

DRILLING PATTERN DESIGN

The drilling pattern ensures the distribution of the explosive in the rock and desired blasting result. Several factors must be taken into account when designing the drilling pattern: rock drillability and blastability, the type of explosives, blast vibration restrictions and accuracy requirements of the blasted wall etc. The basic drilling & blasting factors, and drilling pattern design are discussed below. Since every mining and construction site has its own characteristics, the given drilling patterns should be considered merely as guidelines.

DRIFTING AND TUNNELING

Many mines and excavation sites still plan their drilling patterns manually, but advanced computer programs are available and widely used. Computer programs make it easier to modify the patterns and fairly accurately predict the effects of changes in drilling, charging, loading and production. Computer programs are based on the same design information used in preparing patterns manually.

Basic design factors

The tunnel of drift face can be roughly divided into four sections (FIGURE 6.2.-1).

Drilling pattern design in tunneling and drifting is based on the following factors:
- Tunnel dimensions
- Tunnel geometry
- Hole size
- Final quality requirements
- Geological and rock mechanical conditions
- Explosives availability and means of detonation
- Expected water leaks
- Vibration restrictions
- Drilling equipment

Depending on site conditions, all or some of the above factors are considered important enough to determine the tunnel drilling pattern. Construction sites typically have several variations of drilling patterns to take into account the changing conditions in each tunnel. Drifting in mines is carried out with 5 to 10 drilling patterns for different tunnel sizes (production drifters, haulage drifters, drawpoints, ramps etc.) The pattern is finalized at the drilling site. Tunnel blasting differs from bench blasting in that tunnels have only one free surface available when blasting starts. This restricts round length, and the volume of rock
that can be blasted at one time. Similarly, it means that specific drilling and charging increases as the tunnel face area decreases. When designing a drilling pattern in tunneling, the main goal is to ensure the optimum number of correctly placed and accurately drilled holes. This helps to ensure successful charging and blasting, as well as produce accurate and smooth tunnel walls, roof and floor. A drilling pattern optimized in this way is also the most economical and efficient for the given conditions.

**Hole size**

Hole sizes under 38mm in diameter are often considered small, holes between 41mm - 64mm intermediate, and those over 64mm large. Most tunneling operations today are based on hole sizes between 38 - 51mm in diameter. Only cut holes are larger than 51mm. Rock drills and mechanized drilling equipment used in tunneling and drifting are designed to give optimum performance in this hole range. Drilling rods are designed to match hole sizes and needs of horizontal drilling. Typical applications use tunneling rods and 1 1/4" and 1 1/2" drill steel sizes. Drill steels between 1" and 1 1/8" are used for hole sizes less than 38mm.

The number of holes needed per tunnel face area decreases as hole size increases. The difference is not much in small tunnels, but becomes more significant in large tunnel face areas. Small hole sizes require smaller steels, but these bend more easily, giving rise to inaccurate holes and poor blasting.

**Cut types**

The blasting sequence in a tunnel or drift always starts from the “cut”, a pattern of holes at or close to the center of the face, designed to provide the ideal line of deformation. The placement, arrangement and drilling accuracy of the cut is crucial for successful blasting in tunneling. A wide variety of cut types have been used in mining and construction, but basically they fall into two categories: cuts based on parallel holes, and cuts that use holes drilled at certain angles. The most common types of cut today is the parallel and V cut (FIGURE 6.2.-2). The V cut is the older of the two and is still widely used in construction. It is an effective type of cut for tunnels with a fairly large cross-section and requires fewer holes than a parallel cut. The parallel cut was introduced when the first mechanized drilling machines came on the market making accurate parallel drilling possible.

**Parallel cut**

The parallel cut has a large number of minor variations, however the basic layout always involves one or several uncharged holes drilled at or very near the center of the cut, providing empty space for the adjacent blasted holes to swell into. Uncharged cut holes are typically large, 76 - 127mm in diameter. A less common alternative is to use “small hole” openings (several small holes instead of one or two large holes). Small hole opening make it possible to use the same bit size throughout the whole drilling pattern. Experience proves that big hole openings give more reliable results than small hole openings.

To successfully blast a full round, the cut must be drilled, charged and blasted correctly. Cut holes are drilled very near to each other, as parallel as possible, as shown in FIGURE 6.2.-3. Specific drilling in the cut section may rise above 10drm/m³. Apart from the large cut holes, other holes in the cut are the same size as the stope (face) holes. Large cut holes are normally drilled by reaming. First, a smaller, for example, 45mm diameter hole is drilled then reamed to the final size using a pilot adapter and a reaming bit.

Drilling holes several meters long as close together as possible demands great accuracy, but the advanced boom design and automated functions of modern drill jumbos make this quite easy. The parallel cut is especially suitable for modern mechanized tunneling equipment. This cut type has also made long rounds common in small tunnels. An earlier version of the parallel cut is the “burn cut” which does not use uncharged holes, relying instead on a very strong charge to burn the rock. Today, the parallel cut has replaced the burn cut.

**Purpose of cut holes**

In the parallel cut, the cut holes provide enough expansion space for the remaining blasted rock around it. The face area of a typical parallel cut varies from 1.6m x 1.6m to 2.5m x 2.5m. The right size is determined according to area of the tunnel face.

Big, uncharged cut holes (76 - 127mm dia.) provide an opening for the blasted, expanding rock from the surrounding cut holes. All holes are drilled very close to each other and detonated each with its own detonation number (FIGURE 6.2.-3). The main idea is for each hole to loosen the rock in the front of it, allowing it to expand and fill the available open space. Cut holes are quite heavily charged and the blasted cut becomes a square opening. Basically, only drilling errors limit the gained advance per hole length.
Therefore, the position of the blastholes in the 1st square is expressed as:

\[ a = 1.5\varnothing \]

Where:
- \( a \) = \( C - C \) distance between large hole and blasthole
- \( \varnothing \) = Diameter of large hole

In the cases of several large holes, the relation is expressed as:

\[ a = 1.5D \]

where:
- \( a \) = \( C - C \) distance between the center point of the large holes and the blasthole
- \( D \) = Fictitious diameter

**Charging of the holes in the 1st square**

The holes closest to the empty hole(s) must be charged carefully. An insufficient charge concentration in the hole may not break the rock, while an excess charge concentration may throw the rock against the opposite wall of the large hole with such high velocity that the broken rock will be re-compacted and not blown out through the large hole. In this case, full advance is not obtained.

The required charge concentration for different \( C - C \) distances between the large hole and nearest blasthole(s) can be found in **Figure 6.2.-4**. The normal relation for the distance is \( a = 1.5\varnothing \). An increase in the \( C - C \) distance between holes causes subsequent increment of the charge concentration.

**Figure 6.2.-3.** Typical 2m x 2m cut hole arrangement

When designing the cut, the following parameters are important for a good result:

- Diameter of large hole
- Burden
- Charge conditions

Additionally, drilling precision is of utmost importance, especially for the blast holes closest to the large hole (holes). The slightest deviation can cause the blasthole to meet the large hole or make the burden too big. An exceedingly big burden causes breakage or plastic deformation in the cut, resulting in a short advance. A parameter for good advance of the blasted round is the diameter of the large empty hole. The larger the diameter, the deeper the round can be drilled and a greater advance expected.

One of the most common causes of short advance is an overly small hole in relation to the hole depth. An advance of approx. 90% can be expected for a hole depth of 4m and one empty hole 102mm in diameter. If several empty holes are used, a fictitious diameter must be calculated. The fictitious diameter of the opening may be calculated by the following formula:

\[ D = \frac{d}{n} \]

where:
- \( D \) = Fictitious empty large hole diameter
- \( d \) = Diameter of empty large holes
- \( n \) = Number of holes

In order to calculate the burden in the first square, the diameter of the large hole is used in one large hole and fictitious diameter in several large holes.

**Calculation of the 1st square**

The distance between the blasthole and the large empty hole should not be greater than 1.5\( \varnothing \) for the opening to be clean blasted. If longer, there is merely breakage and if shorter, there is a great risk that the blasthole and empty hole will meet.

The cut is often somewhat overcharged to compensate for drilling errors which may cause insufficient breakage angle. However, excess charge concentration causes re-compaction in the cut.

**Figure 6.2.-4.** Minimum required charge concentration (kg/m) and maximum \( C - C \) distance (m) for different large hole diameters.
Calculating the remaining squares of the cut

The calculation method for the remaining squares of the cut is essentially the same as for the 1st square, but differs in that breakage is towards a rectangular opening instead of a circular opening.

As is the case of the 1st square, the breakage angle must not be too acute as small angles of breakage can only be compensated to a certain extent with higher charge concentration. Normally, the burden (B) for the remaining squares of the cut is equal to the width (W) of the opening, B = W.

Contour holes

Floor holes have approximately the same spacing as stope holes, but the burden is somewhat smaller; from 0.7m to 1.1m. Inaccurate or incorrect drilling and charging of the floor holes can leave unblasted bumps, which are difficult to remove later. The contour holes lie in the perimeter of the drilling pattern. In smooth blasting, contour holes are drilled closer to each other and are specially charged for smooth blasting purposes. Spacing is typically from 0.5m to 0.7m and burden varies between 1 and 1.25 times the space. This type of layout makes it possible to use special smooth blasting explosives, which limits the width and depth of the fracture zone in the walls and roof caused by blasting. In special circumstances, two or more smooth blasting rows can be used.

In tunneling, however, contour holes are blasted with stope holes, but timed to detonate last. The result in smooth contour excavation mostly depends on drilling accuracy. The required amount of shotcreting and concrete casting can be significantly reduced by using smooth blasting, particularly in poor rock conditions. Smooth blasting increases the number of holes needed for the drilling pattern by roughly 10 - 15%.

Rock hardness is occasionally incorrectly considered to be the only dominant factor when optimizing the drilling pattern. The change from very hard rock to soft rock therefore causes a change in the drilling pattern. Rocks that are hard but abrasive are fairly easily blasted, whereas the blastability of rocks such as some limestone, although relatively soft, is poor. However, it is beneficial to redesign and optimize the drilling pattern long before this stage is reached and, more important still, to take rock blastability into account. In a 10-km long tunnel project, each extra hole means about 11,000 unnecessary drilled and blasted meters.

Diagram (FIGURE 6.2.-5.) shows specific charge and drilling for different tunnel areas.

Stoping

The holes surrounding the cut are called stopeholes. The diameter of a stopehole is typically between 41 - 51mm. Holes smaller than 41mm may require drilling an excessive number of holes to ensure successful blasting. Holes bigger than 51mm can result in excessive charging and an uncontrolled blast.

Holes are placed around the cut section in an evenly distributed pattern using a space/burden ratio of 1:1.1. If hole size is between 45 - 51mm, typical spacing and burden are both between 1.0m - 1.3m. Actual rock conditions and ability to drill in the required positions are factors that can reduce or add to the number of holes needed. The design of the drilling pattern can now be carried out and the cut located in the cross section in a suitable way.
The firing pattern

The firing pattern must be designed so that each hole has free breakage. The angle of breakage is smallest in the cut area where it is around 50°. In the stoping area the firing pattern should be designed so that the angle of breakage does not fall below 90° (FIGURE 6.2.-9).

It is important in tunnel blasting to have a long enough time delay between the holes. In the cut area, it must be long enough to allow time for breakage and rock throw through the narrow empty hole. It has been proven that the rock moves with a velocity of 40 - 70 meters per second. A cut drilled to a depth of 4 - 5 m would therefore require a delay time of 60 - 100 ms to be clean blasted. Normally delay times of 75 - 100 ms are used.

In the first two squares of the cut, only one detonator for each delay should be used. In the following 2 squares, two detonators may be used. In the stoping area, the delay must be long enough for the rock movement. Normally, the delay time is 100 - 500 milliseconds. For contour holes, the scatter in delay between the holes should be as little as possible to obtain a good smooth blasting effect. Therefore, the roof should be blasted with same interval number, normally the second highest of the series. The walls are also blasted with the same period number but with one delay lower than that of the roof.

Detonators for tunneling can be electric or non-electric. Contour holes should be initiating with detonating cord or with electronic detonators to obtain the best smooth blasting effect.

V cut

The V cut is a traditional cut based on symmetrically drilled, angled holes. It has lost some of its popularity with the widespread adoption of the parallel cut and longer rounds. However, it is still commonly used in wide tunnels where tunnel width sets no limitations on drilling. The working principle of the V cut is similar to surface excavation applications. The V cut requires slightly fewer hole meters than the parallel cut, which gives it an advantage in large tunnels. The V cut is based on surface blasting principles in which the angle for rock expansion equals or exceeds 90 degrees. The angle at the bottom of the cut holes should not be less than 60 degrees. Maintaining the right angle is the main difficulty in V-cut drilling; and, the correct drilling angle limits round length in narrow tunnels (FIGURE 6.2.-9a).

Tunnel width limits the use of the V cut. In narrow tunnels, the advance per round can be less than one third of the tunnel width, which increases the number of rounds and the amount of drilled meters when excavating small tunnels. V cuts are easily drilled with mechanized rigs in large tunnels where tunnel width sets no limitations. The cut normally consists of two Vs but in deeper rounds the cut may consist of triple or quadruple Vs.

Each V in the cut should be fired with the same interval number by MS detonators to ensure coordination between the blastholes in regard to breakage. As each V is blasted as an entity...
one after the other, the delay between the different Vs should be in the order of 50 ms to allow time for displacement and swelling.

**The fan cut**

The fan cut (FIGURE 6.2.-9b) is another example of angled cuts. Like the V cut, a certain tunnel width is required to accommodate the drilling equipment to attain acceptable advance per round.

The principle of the fan is to make a trench-like opening across the tunnel and the charge calculations are similar to those in opening the bench. Due to the geometrical design of the cut, the hole construction is not large, making the cut easy to blast. Hole drilling and charging is similar to that of cut holes in the V cut.

![FIGURE 6.2.-10. Feed set-up and drilling limitations in V cut.](image)

**Other design features**

The design of the drilling pattern for tunnels should correlate with tunnel shape and size. The cut is normally placed vertically in the middle or side section, and horizontally on or slightly under the center line of the tunnel. The exact place is often left or right of the tunnel’s center point and varies with each round (FIGURE 6.2.-11.). Sometimes the tunnel is excavated in several sections, such as a top heading, followed by benching with lifters. The top is excavated as described above, but benching with lifters only requires stope holes since the excavated top heading acts as the "cut". It is also possible that the opening for the blast or the cut section has been produced earlier by other means such as the full profile method (tunnel boring). In such cases, cuts are not required and the remaining excavation holes are drilled as stope holes. It is recommended that ditches and drains be excavated at the same time as the tunnel face but sometimes their design is more complicated and they must be excavated separately.

**Look-out angle**

The drilling pattern also includes information on the look-out angle needed at different points on the tunnel face. The look-out angle is the angle between the practical (drilled) and the theoretical tunnel profile (FIGURE 6.2.-12.). If the contour holes are drilled parallel to the theoretical line of the tunnel, the tunnel face gets smaller and smaller after each round. To ensure that the correct tunnel profile is maintained, each contour hole is drilled at slight angle into the tunnel wall, the look-out angle, which of course can not be smaller than that permitted by the profile of the rock drill.

Adjusting the look-out angle by eye requires an experienced and skillful operator. Modern drilling rigs have electronic or automatic look-out angle indicators that enable correct adjustment of the look-out angle relative to standards alignment. Computerized drilling jumbos make setting, adjustment and monitoring of the look-out angle even easier. An incorrect look-out angle produces over- or underbreak, both of which give uneconomical results. Other aspects such as curve and tunnel inclination also need to be considered when the drilling pattern is designed. Any excavation later on is both costly and time-consuming.
6. Tunneling

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- Smooth blasting (contour blasting) procedure
- Correct rig set-up
- Correct hole alignment and look-out angle, with special consideration for the walls, roof and floor
- Cut placement; inclined and curved tunnels are especially prone to under- and overbreak in the walls and roof and “bumps” in the tunnel floor
- Accurate charging, the correct detonators and drilling pattern
- Continuous follow-up procedures

Advance and yield

The parameter used to describe the advance of the excavation work in tunneling and drifting is called “pull” or advance per round, or yield per round. In tunneling, the length to which the holes are drilled and charged is called the round length. It is one of the most important parameters when planning excavation since excavation depends on selecting the optimal round length.

The mechanization and automation of drilling equipment has led to longer rounds, typically 3-5 meters. Experiments have shown that round up to 8 meters long can be drilled and blasted successfully with special care and equipment (special explosives, rock conditions, special drilling equipment).
Round length must be optimized, bearing in mind several important aspects (Figure 6.2.-14).

- Stability
- Rock geological and mechanical conditions
- Drilling, charging, mucking and rock support equipment and related size, reach, maneuverability and efficiency
- Allocation of time within and between each round
- General working arrangements, work layout, distance between working places, support works needed, general regulations and legal questions (inspection needs, ground vibration restrictions etc.)
- Amount of equipment and labor, if restricted

A successfully blasted round still leaves some 20cm of unloosened drilled hole length. The excavated portion of the blasted round is called “pull” or the advance per round. Drilling accuracy, accurate hole placement and correct blasting methods are the most important factors affecting pull. In the drilling pattern layout, the choice of cut and cut hole placement also affects the final advance.

The introduction of computerized drilling equipment has greatly improved hole and profile accuracy and extended the advance per round due to 97%. Computerization has proven especially efficient when drilling long rounds where poor accuracy with conventional drilling equipment leads to uneven hole bottoms. The preplanned optimal drilling patterns are described in three dimensional form and up-loaded into the drill jumbo’s on-board computer. The pattern includes information on the starting and ending point of the holes as well as hole length and look-out angle. Even when manual changes are made to the drilling pattern during operation, the program will adjust the new hole to finish at the same hole bottom as the other holes.

The effect of pull on the final result is easily seen when excavating a 5,000 meter long tunnel. If pull of a 5.1 meter long round is 90% instead of 95%, due to poor drilling or blasting accuracy, a total of 59 extra rounds must be drilled, blasted and mucked to complete the job. The cost of these extra rounds will depend on tunnel size, labor, equipment, time penalties and other site-related factors.

**UNDERGROUND CHAMBER**

As for rock blasting techniques, the construction of underground chambers does not differ from that of tunnels of the same magnitude. The width of underground chambers can not be too great due to the inability of the rock to support the roof with its own strength. For oil storage chambers and machine halls for hydro-electric power-plants, widths of 20 - 24 m have been constructed with no required heavy reinforcement. The height of the chambers may be up to 40m.

The construction of underground chambers is based on qualitative sound rock. Some economic aspects must be considered. If the chamber is located at too shallow a level, the cost of reinforcing the rock may be high because the quality of surface rock is normally poorer than rock at deeper levels. However, a deep location results in long access roads, which may cause problem during construction and when the chambers come into use.

Small underground chambers, with a height of less than 8 m are blasted as tunnels. In larger chambers, the operation is divided into several drilling and blasting stages (Figure 6.2.-15.) in which different methods are used:

- Pilot tunnel with side stoping
- Horizontal benching
- Vertical benching

Example of a chamber excavation procedure plan.
Blasting a 31.5 m high x 21.1 wide rock cavern can be divided into three or four stages.
The transient strain in the rock due to blasting depends upon the liner charge concentration per drill hole length, explosive strength and distance from the charge. For example, granite may fail in dynamic tension at a stress of approx. 30 Mpa or around a peak particle velocity of 1000 - 2000 mm/s depending on the wave type. Assuming that damage would occur around $v = 1000$ mm/s, it is possible to establish a proper blast pattern. Attention is paid also to rows adjacent to the perimeter row in order to minimize unwanted fracturing. In the stopping stage, an 8m-high bench was removed by horizontal stoping (FIGURE 6.2.-18) and finally a vertical bench (FIGURE 6.2.-19) or possibly two 8m horizontal benches are excavated.

The reinforcement methods are bolting and shotcrete lining. Systematic roofbolting is later carried out with a bolt density of 1 bolt/4 m². Bolt lengths in the arch part of the caverns range typically from 2.0 - 4.0 m, which is 0.15 - 0.30 times the width of the span. In walls, the corresponding lengths vary from 2.4 m - 6.0 m. The need for grouting has been limited.

When calculating the largest instantaneous charge permitted for different distances from buildings, the formula below is currently very commonly used when blasting large rock caverns.

$$v = k \left( \frac{R}{\sqrt{Q}} \right)^n$$

where ($v$) is the maximum particle velocity (mm/s); $Q$ the cooperating charge and $R$ the distance. The constants $k$ and $n$ vary with foundation conditions, blasting geometry and type of explosives.
Often, mining problems with limited rock coverage and the need of reinforcement usually appear during initial blasting work on tunnels. The following measures are advised when carrying out initial blasting work on tunnels in built-up areas:

- Cautious blasting with limited hole depth, charges and holes per round
- Millisecond firing
- Suspended covering material.
- Ground vibration and air shock wave measurement (Chapter 3.10.).

In the opening up of tunnels, large hole cuts, preferably with two large holes, function well. Drilling is performed with a limited hole depth between 1.0 - 2.0 m depending on the location of the blasting site and the technical conditions of the rock. The first round consists of one cut hole, after which normally two cut holes per round are fired. In due course, the number of “cut spreader” holes and stoping holes per round increase depending on the weight of the covering and its capacity to remain in position during blasting. It is not advised to increase the number of drill holes per round to a great extent because in sensitive locations just a few too many holes can lift the covering material. Care is exercised even after the first advance so that the covering material used is able to block throw and reduce air shock waves.

Millisecond firing is the safest method to use. When using half-second firing, there is risk of the first delay lifting the covering material resulting in throw. Covering material should be used for each round until the tunnel has extended so far that air shock waves no longer have an influence. In straight tunnels, this can imply considerable distances. If vibration and air shock wave measurements are performed, blasting can be adapted to the values obtained. Since the air shock wave causes vibrations in the surrounding buildings, the horizontal shock wave component can be of the greatest interest in blasting of this type.

Air shock wave magnitude can be theoretically calculated based on charge amounts, delay sub-divisions and distance. The most difficult estimate is the charge enclosure factor which must be included when the explosive is charged in a drill hole. As more and more measuring material becomes available from air shock wave measurements, the accuracy of this type of calculation can be improved.

**FIGURE 6.2.-20.** shows the principle for opening a tunnel within a built-up area where buildings are located very close by.
In ground vibration problems, it is often necessary to drill closely spaced holes and limit advance in order to reduce the instantaneously detonating charge. Based on permissible simultaneously detonating charge, hole location, drilling depth, charge per hole and firing pattern are adapted so that ground vibrations fulfill requirements.

Normally in tunnel blasting, the drilling pattern can be adapted so that the cooperating charge is not larger than the charge in an individual drill hole. A spread of the delay numbers distributes the ground vibrations throughout the surrounding rock.

Certain cuts, for example plough cuts, are unsuitable in ground vibration problems when there is a risk of coordinating a large number of holes in the cut. “Burn” cuts of various types are also unsuitable. The fan cut can be used in this connection primarily in wide tunnels. In narrower tunnels where it is difficult to drill holes at an angle, large hole cuts can very well be used. It is preferable to drill at least two large holes when carrying out particularly cautious blasting. This reduces constriction and the risk of unsuccessful breakage. There is also the possibility to reduce the charge per meter.

**VARIOUS CHARGING METHODS**

**Charging and blasting in tunnels and drifts**

In tunnel excavation, blasting works outward from the first hole around the uncharged holes in the cut. Each blast provides more space for the following ring of blast holes. Successful blasting of the cut section is critical to the success of the whole round. Because the cut holes initially have only one direction in which to expand, the specific charge in the cut is considerably higher than in the rest of the tunnel and can even exceed 10kg/m³. Most stoping holes (especially in large tunnels) have a large expansion area. These holes are considered close to surface blasting holes for charging calculations. The same explosive, normally ANFO, is used for stope hole charging as in the cut area. Development of explosives has moved in the direction of products with better fumes such as emulsion explosives. Lightened explosives or special smooth blasting explosives are used for smooth blasting.

Initiating systems like NONEL decrease charging time and add further safety to the blasting operation because it is insensitive to electrical hazards.

Contour holes should be blasted almost last with detonating cord or with the same detonating number. It is important to blast each smooth blasting section (walls or roof) simultaneously to achieve a smooth and even surface.

Electronic detonators will perhaps become the detonators of future in tunneling, too, due to increased timing precision.

Bottom holes are blasted last right before the bottom corner holes. This lifts the loosened rock pile a little, which makes mucking easier. The specific charge and specific drilling can become quite high in small tunnels due to the restricted free space available (Figure 6.2-6. and 6.2-7.).

**Charging with tamping rod**

Tamping rod is used to tamp explosives cartridges in holes of small to medium diameters. The tamping rod should be made of wood or plastic. Any metallic fitting or pike should be of copper or brass. The diameter of the rod should be approx. 10 mm smaller than that of the blasthole thus giving space for legwires, NONEL tube, safety fuse or detonating cord.

**Charging with pneumatic machines**

Principal two types of pneumatic charging machines are available:

- Semi-automatic charging machines for cartridge explosives
- Pressure-ejector vessels for ANFO.

Semi-automatic charging machines are useful for upward holes, underwater blasting and fissured rocks where cartridges tend to jam but where a semi-ridged plastic hose could be introduced to the bottom of the hole.

Pressure-ejector vessels for ANFO are mostly used in tunneling. Free flowing ANFO is normally poured into blastholes which are vertical or close to vertical.

For horizontal and upward blastholes, the principal method of charging is via pneumatic charging devices. Such devices are also used for the charging downward blastholes where higher charging density is required. The principle of the charging machine is that the ANFO is transported from the container through a plastic hose, into the blasthole by pneumatic pressure.

Two main types of pneumatic charging machines for the charging of ANFO are available:

- Pressure vessel machines which use high pressure in the container. The ANFO is pumped through the hose into the blasthole.
- Ejector units where the ANFO is sucked from the container and blown through the hose into the blasthole.

Combined pressure/ejector machines are also available.
ANOL is a pressure vessel device for charging ANFO in all kinds of applications. Prilled ANFO can be charged in upward blastholes with an inclination of up to $35^\circ$ without running out. The flow of ANFO is remotely controlled via a charger. As ANFO is highly corrosive, all machine parts that come in contact with ANFO are made of stainless steel. ANOL is manufactured in sizes of 100, 150, 300 and 500 liters. The charging machine is a combined pressure/ejector unit for the charging of prilled ANFO in upward blastholes with diameters between 32 - 51 mm and a depth of up to 45 m. The ANFO is transported by the ejector at such a high velocity into the blasthole that the prills are crushed and stay in the blasthole. The flow of ANFO as well as the velocity of the ANFO through the hose are remotely controlled by the charger. The charging hose is anti-static as the ANFO is transported through the hose at high velocity causing a risk of static electricity accumulation. Due to this risk, all ANFO charging units must be grounded during charging operations.

**Charging with pump trucks**

In tunnel blasting operations, the explosive or blasting agent may be charged into the hole by a pump truck. An explosive or blasting agent, such as emulsion, can be manufactured at an on-site plant and pumped directly from the plant into the pump truck.

Care must be taken when charging holes containing water. The charging hose must be introduced below water level to the bottom and lifted at the same pace as the hole is filled to avoid separation of the explosive column by water pockets.

**EQUIPMENT FOR DRILLING**

**Underground drilling**

Today in underground drill&blast excavation, drilling is mostly performed with multi-boom, hydraulic drill jumbos. Pneumatic jumbos, and hand-held drilling is being replaced by modern hydraulic units which offer efficiency, lower overall cost and occupational health & safety factors.

The equipment used in construction projects must typically be able to perform multiple duties in addition to face drilling. It must be compatible with other machines and systems at the site, in maintenance as well as service arrangements.

The payback time for most equipment is quite short, so the selection process is demanding. Detailed calculations and comparisons are necessary to determine which equipment is the most economical, efficient and technically suitable for each project.

**Equipment selection**

Drilling is governed by numerous rules and regulations. All drilling units must therefore conform to global and local requirements which in turn affect the construction and manufacturing methods, manuals and labels on the units.

The equipment itself must be able to efficiently execute the drilling tasks, and adapt to different and often changing conditions, such as different face areas, rock conditions and hole lengths. In most cases, drilling equipment must perform several different tasks during each project, especially during the unit's effective life time and during different projects.

Conditions can change, for example:
- Changing face areas and geometries of tunnels
- Tunnel curvature and cross-cuts
- Design and scheduling of the work cycle
- Different rock conditions
- Conditions of the terrain
- Gradient of the tunnel
- Length of tunnel and tramming length to the face
- Different hole size and hole length
- Drilling long holes for exploration or grouting purposes
- Drilling bolt holes
- Electric supply network

Machine and component selection has a fundamental effect on performance in different conditions.

**Carrier selection**

In mechanized drilling units, the carrier's task is to move the unit around the worksite and provide a mounting frame for necessary components on the machine. Its main characteristics are typically trammig speed, trammig capability on various terrain and slopes and stability of the unit.

Three basic carrier models are available: rail-mounted, crawler-mounted and wheel-mounted. Each model can be used in drilling units for underground excavation.

Rail-mounted carriers are the traditional in face drilling units. Today they are used less frequently because all other equipment must also operate on rails or within the limitations set by the rails in the tunnel.

Rail-mounted equipment can be justified in long, horizontal tunnels because they can be built small in dimensions. In greater tunnel lengths, the drilling unit can be quickly transported to and from the face with the locomotive used in rock hauling (FIGURE 6.2.-21).
Portal drilling rigs have a passage through the machine frame for letting trucks, loaders and other traffic through. They are mostly built on rail carriers and are used in large tunnels.

The disadvantages of rail carries are the necessity to build the rail system, poor ability to tram up and down slopes, and poor ability to operate in tight curves, cross-cuts and access tunnels.

The crawler-mounted carrier is built on crawler tracks, typical in surface excavation. Due to its massive size (needed to provide sufficient stability for multi-boom jumbos) and slow tramming speed, it has been mostly replaced by wheel-mounted units.

The crawler carrier works best on rough pavement and steep tunnels, and is handy when tramming speed is not an essential criteria.

Wheel-mounted carriers are presently preferred in tunneling and are suitable in many situations from horizontal tunnels, up to 20 degrees slopes. The biggest advantages are mobility and versatility in most tunneling conditions (FIGURE 6.2.-22).

The carrier can be dimensioned to give adequate stability for the machine according to its number of booms and total weight. Typically, carriers are center-articulated or rear wheel-steered.

Selecting booms

Earlier tunneling booms were specially designed for face drilling. It was not possible to change the boom angle for vertical drilling during operation. Requirements for modern drilling units include multiple-task performance, fast and accurate boom movements and automatic parallel holding in all directions. This has led to development of so-called “universal” or roll-over booms.

The roll-over boom’s rotation unit is located at front end of the boom arm, as the boom arm can be moved in vertical and horizontal directions. This boom type provides optimum-shaped drilling coverage, which enables the unit to drill curves, bolt hole rings, benches and cross-cuts as well as ordinary face holes.

Boom size depends on the required coverage of the drilling unit, number of booms on the machine and mounting distance and height of the booms on the carrier (FIGURE 6.2.-23).
Bolt-hole drilling in small section tunnels sometimes requires a telescopic feed that allows the same feed to handle longer drill rods for face drilling, and when retracted shorter rods for bolt hole drilling.

Number of booms

In theory, more booms proportionately increase the drilling capacity, but in practice this depends also on utilizing all booms during drilling.

Most hydraulic drilling units have up to three mounted drilling booms that can drill simultaneously. Large portal-type rigs can have even more booms on the unit.

Drilling with a multi-boom jumbo normally involves some overlapping or a waiting period (few minutes), that can be reduced by the boom coverage of the rig, which should be appropriate for the tunnel face area, and the experience of the operators. Computerized rigs can minimize the waiting period because they use a pre-programmed drilling pattern. Boom movements and drilling functions are also automatic and can be programmed to give optimum performance.

Selecting the feed

The feeding system keeps the shank in contact with the rock drill and the drill bit in contact with the rock during drilling. The optimum feeding system is balanced with the percussion dynamics of the rock drill and drill string, and meets the requirements for various drilling applications.

Typical feeding systems used in mechanized drilling units are operated, for example, by a feeding screw, hydraulic motor and chain or hydraulic cylinder and steel wire.

In modern hydraulic units, the cylinder feed is mostly used because it provides a constant, stable feed force to the rock drill during drilling. Feed length, which determines the maximum length of the hole, and the round, is mostly determined by geological factors and vibration restrictions. It is typically defined as being the length of the drill rods. Typical rod length in tunneling varies between 12 - 20 feet, allowing a net drilled length of hole from 3.4 - 5.8 meters.

Rock drills

Correctly matched rock drills are critical components for ensuring drilling performance, a long life time for drilling accessories and good overall drilling economy. The rock drill performs the toughest job so it should be reliable and easy to maintain. A reliable rock drill ensures trouble-free drilling rig operation.

In various rock conditions, the rock drill requires adequate adjustments for the highest drilling efficiency. The percussion method can handle a wide range of drilling tasks from fairly soft ground to very hard rock, and from poor to good rock mechanical conditions. Most changes in geological conditions do not require special modifications to the drilling system. When rock conditions vary, it is usually sufficient to monitor the drilling and adjust it according to the basic parameters: percussion and feed pressures, rotation speed or flushing pressure or bit type change. For cases in which poor rock conditions occur frequently or drill steels get stuck, alternative flushing methods such as air-water mist (occasionally with foam or other chemical additives) may provide a solution.

Tunneling accuracy

The demand for quality is continuously increasing in underground excavation work. It is one of the most important factors for overall economy, and it also greatly affects safety and the environment.

Face drilling is just one of the many stages in tunneling, but it has a strong effect on the quality and cost of the total excavation process. The main purpose of instrumentation in face drilling is to improve drilling accuracy and allow tools to optimize the drill and blast cycle. The instrumentation available on modern drilling units can be defined as three different technological levels: Angle indicators, angle and position indicators and fully computerized systems.
Angle indicators are simple instrumentation tools that show the look-out angle of the drill feed. Simple versions show the direction in reference to machine direction and gravity field. Sophisticated versions can be navigated to the direction of the round, providing the hole’s true look-out angles in the round. The system shows the horizontal and vertical feed angle either numerically or graphically. Other basic drilling information is also provided by the measuring system such as hole depth, drilling speed etc.

Computer Aided Drilling System can show graphically both the angle and position of the feed rails. The drilling pattern is preprogrammed, and the operator can use the display as an aid to accurately spot the holes. Because of the pre-programmed drilling pattern and navigation to the tunnel reference line, no marking-up of the face is needed before drilling the round. The instrumentation also includes features for data logging, drilled round data capture, such as actual position and angle of the holes, amount of drill meters, drilling time, drilling parameters etc. This information is useful for optimizing the drill & blast design, work control and estimating rock conditions.

SELECTING DRILLING TOOLS IN DRIFTER DRILLING

The most important factors in drifter drilling are:
- Collaring accuracy
- Straight holes
- High productivity
- Long service life and grinding interval
- High penetration rate
Together they give the customer minimum over/underbreak, smooth tunnel profile and high rate of excavated tunnel per hour.

**Formula 1**

Formula 1 is the system that meets all requirements on the above list. Formula 1 is a unique and patented system which offers substantially lower cost per excavated tunnel meter. The features that enable Formula 1 to deliver the benefits described above are:
- A super rigid 39 mm-round rod section
- FF (Female/Female) rod threads
- A male-threaded drill bit
- Straight transition from rod section to bit head shoulder (i.e. no “gooseneck” on the rod)
- Patented impact energy path into the drill bit’s peripheral buttons
- Higher flushing velocity

Combined they offer straight holes, high collaring accuracy and a high penetration rate.

The system consists of a T38 shank adapter, T38/R32 drifter rod, and a female threaded button bit, R32 pilot adapter and reaming bit. The standard rod comes in 3.7, 4.3, 4.7, 5.1, 5.6 and 6.1 m lengths. Bit sizes are 48 and 51 mm. A wide selection of drill bit designs, carbide grades and button shapes are available depending on rock conditions.

**R38/T38 drifter drilling**

When requirements for precision and productivity are lower, or a less powerful hammer is used, a standard system might be sufficient. The standard system consists of a shank adapter, drifter rod with lose coupling sleeves or MF rods, insert or button bit, pilot adapter and reaming bit. Two thread sizes are available as standard: R38 and T38 with rod dimension H32 and H35. Larger dimensions are suitable for hammers with up to 21 kW (HL 550) output and hole dimensions between 45 and 51 mm. The larger rod dimension is also recommended when drilling holes deeper than 3.7 m.

MF rods are more expensive, but will give straighter holes and a 10% higher penetration rate. They are only recommended in good rock conditions. In poor rock conditions, rods with coupling sleeves are recommended.

As with the Formula 1, a wide selection of bits is available. To achieve optimum life and grinding interval as well as penetration rate, bit design, carbide grade and button shape must be selected depending on rock conditions.

The standard drifter system is schematically described below.

Sandvik Coromant Rock Drilling Tools for rock bolting with Tamrock HE 300, HL 300S and HL 500F
6. Tunneling

ROCK EXCAVATION HANDBOOK

SCALING

The purpose of scaling is to clear loose rock from walls and surfaces after blasting. Manually done it is hard work involving many safe hazards such as falling rock and dust, and requiring awkward working positions. Scaling is often very time consuming when done manually. Today, modern mechanized scaling equipment is used whenever possible.

Barring

Barring is a scaling method that uses a hydraulically powered tooth. It is frequently used with sedimentary rocks for scaling large roof surfaces without unduly disturbing the rock layers above. This is a hydraulic, mechanized form of the manual method in which the tip of a scaling bar is placed in a joint and twisted. This method uses a hydraulic tooth instead of an iron bar.

Scraping

It is difficult to find joints using a hydraulic tooth so barring is often replaced by a scraping action. Loose rock is scraped off the rock surface either with special pointed tools or the teeth of a loading bucket. When the teeth catch on loose rock they pull it away. This method is most effective in the initial scaling phase and for removing loose rock from surfaces. Scraping is especially used for wheel-loaders when securing the face.

H25 Integral drill steels

H25 integrals are manufactured in 3 standard chisel bit dimensions: ø 32, 35 and 38 mm on request to suit actual bolt lengths.

Rod and bit.

Various rod alternatives are possible depending on which hole size is requested. All rods must carry a R32 shank end thread to fit into the shank adapter.

The R25 bit end thread makes it possible to drill ø 35-38 mm holes with button or cross bits.

An ø 33 mm bit can be used on a special rod with R23 bit end thread.

The R28 bit end thread makes it possible to drill ø 38 mm holes.

As rod lengths depend on bolt dimensions, there may be cases where standard lengths cannot be used. Different rod lengths are therefore manufactured upon request.

Threaded integral drill steels

An interesting alternative is the threaded integral which makes it possible to drill ø 32 mm holes suitable for resin or grouted bolts.

The rod section is Hex25 and lengths are available up to 4.5 m, suitable for 4.0 m bolts.

FIGURE 6.2.-30. Integral drill steel.

FIGURE 6.2.-31. Rod and bit.

FIGURE 6.2.-32. Threaded integral drill steel.

FIGURE 6.2.-33. Typical tools for scraping and baring.
Hammering

Impact hammers are often used for scaling hard rocks by striking the places in the rock face which are suspected of being loose. Power is adjusted to match the toughness of the rock so that excessive rock is not loosened. This method is very reliable when scaling hard rocks.

Cutting - Drag tooled cutterhead

Rotary hydraulic cutterhead tooled with conical picks are also for scaling drill and blast surfaces when the rock is from moderately soft to moderately hard as well as heavily jointed. This method is mainly used for roof scaling to reduce overbreak. Hydraulics come to the cutterhead from a backhoe excavator.

Scaling devices based on hammering

A diesel-hydraulic unit is generally chosen, since it gives the greatest independence for mechanized scaling equipment. It can constantly move freely and does not require external power cables. Modern scaling equipment has a safe and comfortable cabin to protect the operator from falling rock and dust, and a dozerblade to push aside fallen rock. Dust is also suppressed with water. Scalers that are designed for very large construction sites may have a charging basket for utility works.

VENTILATION

General

In tunnel excavation, a ventilation system is required to provide an acceptable working environment for the people in the tunnel. The environment is affected by the concentration of impurities in the tunnel air. The impurities are mostly created by blasting and traffic in the tunnel. Limit values for gas and particle concentrations are set by the authorities, thus the design and dimension of the ventilation system must achieve the defined limit values. On the other hand, ventilation system efficiency has a considerable effect on the performance of the whole excavation cycle.

Harmful concentrations

The concentration of harmful substances in air is defined as:

- For gases as parts per million:
  1 ppm = 1 cm³ gas per 1 m³ air

- For dust particles as amount in mg / m³ air

Gases:

NO₂, nitrogen dioxide, is a very toxic gas. It is created during blasting and by diesel engines. Part of NO (nitrogen oxide) becomes NO₂ in the tunnel environment. Health risks from NO₂ start with very low concentrations; a typical limit value for NO₂ is two ppm. As much as 2 - 5 ppm may cause chronic bronchitis, and even short exposure to high concentrations may cause breathing difficulty or death. NO₂ has a reddish brown color and carries a distinctive smell. It is water-soluble, and therefore water-spraying the muckpile is very important after blasting before beginning other work at face.

NO, nitrogen oxide, is a colorless toxic gas, and is not soluble to water. The typical concentration limit is 25 ppm. When exposed to oxygen, it slowly transforms into NO₂.

Simultaneous concentrations of NO and CO (carbon monoxide) can cause health risks, but in general, NO is not considered to be among the most dangerous gases.

Aldehydes give off a distinctive smell of diesel fumes. An 0.5 ppm limit value is typically given to formaldehyde (HCHO). Concentrations above 1 ppm cause eye irritation and respiration difficulties.

CO, carbon monoxide, is created by both blasting and diesel engines. It may be especially dangerous in closed or inadequately ventilated tunnel areas. CO is more easily absorbed into blood hemoglobin than O₂, resulting in reduced oxygen access to the blood. CO concentrations above 35 ppm may cause symptoms such as weariness, headaches, chest aches and, in the worst case, death.

CO₂, carbon dioxide, is found in exhaust fumes. Alone it is not highly toxic, but a high CO₂ concentration reduces the oxygen content in the air.

NH₃, ammonia, is a corrosive gas. It can be the result of a chemical reaction between ammonium nitrate and basic components of cement. Ammonia is easily water soluble, and therefore it is important to carefully spray the muckpile with water. The normal limit concentration for NH₃ is 25 ppm.

O₂, oxygen. Air is normally made up of 21% oxygen. Too little O₂ content causes respiration difficulties, brain damage and death. In underground projects, the O₂ content should not be lower than 19%.

Other air impurities

Dust is solid particles contained in the air. Health risks pertaining to dust depend on the chemical composition of particles, particle size and the concentration mg/m³. Long-time exposure to dust causes lung disease. The most dangerous dust particles are, for example, quartz (silicoses) and fiber-formed particles (asbestos). Dust created during concrete spraying, especially with the dry-mix method, is also harmful. Administrative norms usually give maximum total concentrations of dust particles as a function of quartz content in dust.
**Ventilation principles - Explosion gases**

An air/toxic blast fume combination is created when blasting a round. This gas has a high NO₂ and CO, content so that even a short stay in the area is dangerous.

The toxic gases concentration depends on the type of explosives used and on how charging is performed. Carbon monoxide (CO) and nitrogen oxide (NOX) content may increase as a result of poor cartridge tamping, water in the blast hole and poor ignition. When using ANFO (ammonium nitrate mixed with oil), the oil content affects the creation of CO in blast fumes. If ANFO is exposed to cement or concrete, it creates also ammonia (NH₃).

Ventilation of explosion gases can be divided into two main categories: Blowing ventilation and two-way ventilation. The main purpose is to dilute the explosion gas plug so that toxic gas concentration is acceptable, and get the next stages in the drill & blast cycle started.

**Blowing ventilation:**

This is the easiest and most used method in tunneling. Fresh air from the outside is blown through a duct into the tunnel, relatively close to the face.

![Blowing ventilation diagram](image)

The fresh air dilutes the gas plug and starts to move it backwards out of the tunnel. Other works such as loading and hauling can start at the face when toxic concentrations in the gas plug have been brought down to an acceptable level. Further ventilation can be dimensioned according to the loading and hauling equipment, and further impurities from the muckpile.

**Two-way ventilation:**

Especially in longer tunnels with larger cross-section areas, blowing ventilation is not adequate, or requires too long a ventilation time before the cycle can continue. Therefore, two-way ventilation is becoming a common method in tunnels that are longer than 1000 m. Two-way ventilation removes the explosion gas plug from the tunnel fast, providing an improved working environment in the tunnel.

In two-directional ventilation, the explosion gases are sucked from the tunnel through a duct to the outside of the tunnel. Substitutive air is led to the tunnel through a blowing duct (two-duct system), or through the tunnel (one-duct system).
which controls the ventilation according to the stage in the drill & blast cycle. During drilling, charging, loading & hauling, the system is used for conventional blowing ventilation. After blasting, a transverse fan is used to remove explosion gases through the duct while the other fan blows fresh air towards the face to ensure that all explosive gases are mixed and removed. The one-duct system removes explosion gases fast and effectively, and is more cost-effective than the two-duct system. The one-duct system also requires good duct quality and tightness to prevent impurities from leaking back into the tunnel (FIGURE 6.2.-36).

**Diesel engine exhaust gas**

In the ventilation system and required fresh air flow in the tunnel, loading and transportation diesel equipment is usually the determining factor. Exhaust gas from diesel engines contains N₂, CO₂, H₂O, O₂ and some harmful solid particles. In most countries, engines must be approved for underground use, and the engine manufacturer is required to provide documents for approved concentrations of toxic gas or impurities in exhaust gas. However, the most important factor affecting these harmful contents is the service and maintenance of mobile equipment. Engine adjustments are important as well as the condition of the exhaust purifier. The most typical purifiers are catalytic, water scrubbers, exhaust gas ejectors and solid particle filters.

Ventilation requirements for diesel exhaust are usually estimated as the amount of fresh air per kW engine power or per kg of diesel fuel that is used. Typical values are approximately 3 - 3.5 m³/min per engine kW, or 1.400 - 1.600 m³ per kg used diesel fuel. Ventilation requirements also depend on road quality (tramming speed, creation of dust, rolling resistance) and tunnel inclination.

Some explosive gas is bound in the muckpile after blasting so adequate ventilation and water spraying during loading work is important and should be stressed. Released gases during loading work must be diluted and removed. The NO₂ concentration is removed and dust is minimized by spraying water onto the muckpile.

**6.2.2. Mechanical tunneling**

**A) PART FACE**

**ROADHEADERS**

The first roadheaders were used for tunneling in the 1960s. By the early 1970s, approximately 150-200 roadheaders were used for underground civil construction. It was during this early phase that boom-type cutting equipment in shields or on other hauling structures such as excavators also became popular.

**Basic design and operating features**

The standard roadheader features the following functions:
- Rock excavation (rock cutting)
- Gathering of excavated muck
- Muck transfer to secondary conveying equipment
- Machine transfer

**Cutter boom**

The cutter boom comprises the roadheader’s actual rock disintegration tool. (FIGURE 6.2.-38.) The cutter boom has the following components: its base, motor, coupling between the motor and gear, and the head.

**FIGURE 6.2.-38. Cutter boom components.**
Cutter heads

Two main design principles are applied:
- Longitudinal or milling type cutter heads rotating parallel to the cutter boom axis
- Transversal or milling type cutter heads with rotation perpendicular to boom axis.

Both cutter heads have several advantages and disadvantages.

Some main features important to tunneling are mentioned here:
- Transversal cutter heads cut in the direction of the face. Therefore, they are more stable than roadheaders with longitudinal heads of comparable weight and cutter head power.
- At transversal heads majority of reactive force resulting from the cutting process is directed towards the main body of the machine.
- On longitudinal cutter heads, pick array is easier because both cutting and slewing motions go in the same direction.
- Roadheaders with transversal-type cutter heads are less affected by changing rock conditions and harder rock portions. The cutting process can make better use of parting planes especially in bedded sedimentary rock.
- If the cutter boom’s turning point is located more or less in the axis of the tunnel, a cutter head on longitudinal booms can be adapted to cut with minimum overbreak. For example, cutter booms in shields where the demand can be perfectly met are often equipped with the same type of cutter head. Transverse cutter heads always cause a certain overbreak regardless of machine position.
- Most longitudinal heads show lower figures for pick consumption, which is primarily a result of lower cutting speed.
- The transverse cutter head offers greater versatility, and with the proper layout and tool selection, has a wider range of applications. Its performance is not substantially reduced in rock that presents difficult cutting (for example, due to the high strength or ductile behaviour).
- Additionally, the reserves inherent in the concept offer more opportunities for tailoring the equipment to existing rock conditions.

Cutter picks

Since its first application on a roadheader cutter boom in 1972, the conical pick equipped with tungsten-carbide tips (also called point-attack picks) has become more important and is today the most commonly used pick. (FIGURE 6.2.40.).
Vertical movement is performed by various swivel cylinders; the reactive forces are again transferred into the turret. If necessary, an extra profiling step minimizes the tunnel’s ribs and brings it closer to its theoretical shape. This excavation process is fundamental to roadheader versatility regarding the shape and size of the tunnel section.

A roadheader can, within its design dependent geometrical limits (defining minimum and maximum cross sections etc.) cut practically any required shape and size. It can also follow all necessary transitions and alterations and is highly adaptive to differing excavation processes. By using cutter booms with telescopic or special design, this important feature can be enhanced even further.
Classification of roadheaders, performance

Main classification features:

Two interrelated features form the main figures for classification:
- Machine weight
- Power of cutter motor

Machines with two types of cutting range are featured in the table: Machines with standard and extended cutting range. Table 6.2.-1. indicates the range of the defined classes with regard to their main features and limit of operation.

The max. section in the table represents the position max. area which the roadheader can cut according to its design parameters.

Capacity and performance:

Technical capacity, such as the highest cuttable rock strength, is also shown in Table 6.2.-1. This represents the highest strengths that can be handled according to the weight and power of a machine equipped with certain features.

The above-mentioned limitations regarding rock strength must be seen as the first indication of capacity and performance. In practice operating limits and performance are influenced by other rock parameters and also depend on the actual layout of the machine and actual site conditions (FIGURE 6.2.-44).

FIGURE 6.2.-45. shows the involved parameters. It also outlines the practical way to determine the most important parameters of roadheader operation:
- Cutting rate
- Pick consumption

Loading and transferring muck:

Mucking can be performed during the excavation process. Relevant loading and hauling devices are an integral part of the roadheader. A loading apron in front of the machine’s main body consists of:
- Gathering arms, which are considered best suited to handle coarse, blocky muck. This application is also well suited for tunnel operations.
- Wear-resistant spinner loaders that can handle high muck volumes when used for mineral production, such as in coal mines.
- Swinging loading beams which form a very simple and rugged solution, but offer a somewhat restricted loading capacity.

Various loading devices can be used. The most common are shown in FIGURE 6.2.-43.

Tramming facilities

Roadheader weight, together with the high loads and vibrations of the cutting process, makes crawler tracks the only reliable solution.

In tunneling, roller-type crawler tracks are considered generally advantageous because they offer better maneuverability and higher tramming speeds (up to 35 m/min.). Nevertheless, sledge type crawler tracks offer superior resistance against shock loads and are used in hard rock applications.

FIGURE 6.2.-42. Examples of telescopic and articulated cutter booms

The excavation of short roof sections and consecutive benching from one machine position can be effected, making properly equipped roadheaders the perfect tool for coping with the demands of the NATM in ground conditions with poor stability.
### Table 6.2.-1. Classification of roadheaders.

<table>
<thead>
<tr>
<th>Roadheader class</th>
<th>Range of weight (to)</th>
<th>Range of cutter head power (kW)</th>
<th>Range of operation with standard cutting range</th>
<th>Range of operation with extended cutting range</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(m²)</td>
<td>(MPa)</td>
<td>max. section</td>
<td>max. section</td>
</tr>
<tr>
<td>Light</td>
<td>8 - 40</td>
<td>50 - 170</td>
<td>~ 25</td>
<td>60 - 80</td>
</tr>
<tr>
<td>Medium</td>
<td>40 - 70</td>
<td>160 - 230</td>
<td>~ 30</td>
<td>80 - 100</td>
</tr>
<tr>
<td>Heavy</td>
<td>70 - 110</td>
<td>250 - 300</td>
<td>~ 40</td>
<td>100 - 120</td>
</tr>
<tr>
<td>Extra heavy</td>
<td>&gt; 100</td>
<td>350 - 400</td>
<td>~ 45</td>
<td>120 - 140</td>
</tr>
</tbody>
</table>

**FIGURE 6.2.-44.** Relation between weight and cutter head power of roadheaders. This table also provides an introduction to machine selection for various project conditions.

**FIGURE 6.2.-44B.** Indicative diagram for roadheader selection. This diagram can be used for first selection of an appropriate machine for certain project conditions. It indicates the maximum weight installed power to be used on this machine and maximum rock strength, which can be tackled. Smaller machines with lower powering can be also used, if they cope with the demands of rock and project.

**FIGURE 6.2.-45.** Assessment of cutting rate and pick consumption for roadheader operation.
This diagram is valid for standard operating conditions. Additionally, it is based on results achieved by skilled personal and is not influenced by rock mass properties. It also provides a good picture of roadheader potential in various operating conditions.

Recent developments that improve performance and cost effectiveness:
Since 1990, advanced-design roadheaders have operated in rock formations that are considered not only difficult but also where the economic application of roadheaders is not attainable.

One important limiting factor was insufficient power; the machine’s inability to transfer the installed power into the face.
Two important developments, which were effected or became efficacious in tunneling during this period shall be presented here:
- Roadheaders with switch gear, which allows the application of the fully installed cutter head power at a reduced cutting speed.
- Improved pick technology pertaining to the quality of tungsten carbide and support offered by high-pressure flushing systems.

Switch gears on roadheaders were added during the development of the ALPINE MINER AM 105. Via the switch gears, the advantages of a variable cutting speed, previously achieved only through pole changing motors and thus only at reduced power available at a lower speed, can be now utilized without drop of available power.

Special advantages of roadheaders for tunneling applications

General:
Primarily, roadheaders offer the same advantages as other equipment for mechanized hard rock tunneling. The fact that roadheaders are limited in regard to rock strength and abrasion at lower values compared to the TBM has been mentioned earlier in the text.
A decrease in performance in higher rock strength is also more pronounced than in machines equipped with roller cutters.

Within its range of application, the roadheader offers advantages that are exclusive to this type of equipment:

Versatility and mobility:
While a TBM is practically fixed to a circular section and a certain diameter, roadheaders can handle a great variety of sections within their layout parameters.
The face remains accessible. By retracting a roadheader from the face, all required measures for rock protection can be performed without space restrictions up to the face without significant slowdown.

Therefore, it is no problem for the roadheader to adapt to changing rock mass conditions. Larger sections can be subdivided and excavated in progressive steps enabling the excavation of large sections that require perfect tuning of the excavation sequence.
Free space and accessibility are also key if the need for auxiliary measures, such as draining or advanced grouting, are necessary.

Low investment:
Compared to the TBM, the similar size of cross section investment costs for a roadheader amounts to approx. 0.15 (large sections) to 0.3 (small sections).
Roadheaders are also commonly rented.
Therefore, roadheader application is also attractive in short projects if the conditions fit.

Quick and easy mobility:
Comprehensive assembly equipment and chambers are not required. Roadheaders can be operated immediately upon arrival.
Although they are not sold off the shelf, roadheaders require much shorter mobilization periods. Depending on the site location, a new machine can be delivered and be ready for operation in 3 - 6 months.
Delivery time is often considerably less for used and refurbished machines.

HAMMER TUNNELING

Hammer tunneling has proven to be economic mainly in the Mediterranean countries and Asia. Hammer tunneling is successful compared to drilling and blasting when the fractured rock structure makes controlled blasting hard to achieve. Additionally, hammer tunneling involves only a few work phases and there is less need for skilled work force than in drilling and blasting.

Compared to a TBM (Tunnel Boring Machine), hammer tunneling investment costs are much lower and tunnel profile is not restricted to a particular shape. Hammer tunneling economics are governed by many factors including rock type, tunnel area, tunnel length, tunnel location, schedules, and availability of equipment and skilled work force. Usually a suitable hammer would be in the weight class of over 2000 kg; preferably over 3500 kg. However, even significantly smaller hammers are used in special cases. The soft-rock chisel tool is usually recommended for tunneling.

In a typical hammer tunneling case, the main advantages over other methods are lower investment costs, lower work force costs, safer job-site conditions (because explosives are not used) and little or no over-excavation with costly refills.
Rock types

For hammer tunneling to be economic, a reasonable productivity rate is required. This can be achieved in different rock types. Rock to be excavated has relatively incoherent structure. Distance between cracks, joints and other discontinuities should not be more than 30 - 50 cm. The rock to be excavated is compact but soft enough to allow a reasonable productivity rate by tool penetration (best case: an excavator bucket is barely insufficient).

Rock strength, abrasion level and general toughness also influence productivity to some extent. Rock is seldom homogenous in long tunnels. If extremely compact rock is encountered, auxiliary blasting is recommended. It is often sufficient to fracture the rock, enabling further excavation with a hammer. Auxiliary blasting is applied at the lower middle part of the tunnel where excavation normally would start. This way hammer excavation is best enhanced and the negative effects of blasting (such as overbreak) are minimized.

Ground vibrations

Considerably less ground vibration is associated with hammer excavating than with the drilling and blasting method. The vibration level caused by hammer excavation is 5 - 10% the level of blasting. This can be a decisive factor when excavating rock in the vicinity of structures that require vibration limitations.

Working methods

The working method is dictated by the section area and length of the tunnel.

Areas 30 - 70 m²:

Hammer tunneling is suitable for tunnels with a cross-section greater than 30 m². With smaller areas, an excavator suitable to carry a 2000 kg hammer will have difficulties fitting or operating properly.

In a small and narrow width (less then 8m) tunnel profile, only one excavator-hammer combination can work at the front of the tunnel. This divides work into 5 phases:
- Excavating
- Transportation of muck
- Scaling
- Transportation of scaling muck
- Reinforcement and support of tunnel walls

In an 8-hour shift, excavating and transporting muck takes about 2 hours each. Scaling and transportation of scaling muck takes approximately an hour, and the rest of the time is used for reinforcement of the walls.

Area more than 70 m²:

A larger tunnel profile allows hammer excavating and muck transportation to be done simultaneously. This reduces the actual amount of work phases into two:
- Excavating (and scaling) + transportation of muck.
- Reinforcement and support of tunnel walls.

Broken rock can be removed during excavation of a 70 m² tunnel face, which can accommodate an excavator equipped with a hydraulic hammer, and a loader and truck. The excavating and transportation work phases actually complement one another. When material has been excavated from one side and instantly taken away, the hammer can immediately be transferred to the opposite side. Immediate muck removal also improves visibility to the material to be broken.

Tunnel height more than 7 m:

When tunnel height becomes too high, the reach of the hammer is insufficient for excavation in one stage. Excavation is then done in two stages (FIGURE 6.2.-46):
- Tunnel excavation with suitable height for hammer and excavator.
- Another excavator-hammer combination starts approx. 100 - 150m behind the initial tunnel front to deepen the existing tunnel with the trenching method (FIGURE 6.2.-46.)

When a hydraulic hammer is used, the work force requirement becomes smaller in comparison to traditional drilling and blasting excavation. This is largely because the drilling and blasting method calls for more highly trained personnel. Drilling and blasting operations also mean regular interruptions and disturbances to the tunneling process as a whole, while hammer excavating is a continuous process.
**Long tunnels**

If the tunnel is sufficiently long, it is advantageous to start at both ends and in the middle to cope with tight schedules. Starting in the middle improves equipment and operator availability. The hammer excavates at one side, while the other side is reinforced. When each working phase is completed, the excavation group and the reinforcement group trade places.

When starting in the middle of the tunnel, hammer and wheel-loader trade places with the stabilization team, as support is erected and concrete spraying completed.

**The hammer work cycle**

Excavation starts at the center of the tunnel at a height of 1.0 - 1.5m. A hole with the depth of 1.5 - 2.0m is excavated. Tunneling then continues from the sides of the hole as close as possible to the final sides of the tunnel. Once this stage is reached, work continues in the same way from the floor up until the roof of the tunnel has been formed (FIGURE 6.2.-47).

If the rock is jointed, excavating follows the shear planes in the normal manner from floor to roof, using the rock’s natural weak points and planes to maximum the effect (FIGURE 6.2.-48).

**Technical considerations**

Tunnel work is among the toughest jobs a hammer can do. During tunneling, hammer availability is extremely high (60 - 80% of excavator time compared to 30 - 50% in primary breaking). The contact force applied by the excavator to the tool is much higher in a horizontal position than in a vertical position. Due to extreme circumstances, frequent preventative and regular maintenance is essential in effective and productive hammer tunneling. This is best handled with service contracts.

When uninterrupted production is critical, a system utilizing two hammers and one on stand-by is the perfect solution.

**FIGURE 6.2.-47.** Hammer working sequence from floor to roof.

**FIGURE 6.2.-48.** Hammer working sequence when rock layers are inclined.

**FIGURE 6.2.-49.** G 100 hydraulic hammers productivity, in open pit quarrying.


**Equipment selection**

- Choose the biggest possible hammer type
- Choose the CITY model for lower noise and dust protection.
- Choose the Water Jet version for optimum dust prevention and good visibility
- Choose Ramlube automatic lubrication for maximum tool and bushing life

If the tunnel job is extensive (over 1000 m), use extension carriage or front shovel boom to carry the hammer.

In tunneling, the best productivity is achieved with long chisel tools, as excavating frequently must be done near a wall. One should, however, be aware that bending stress on the chisel is hard to avoid in a tunnel. This makes it hard for an inexperienced operator to avoid tool failure. If tool failure becomes a serious problem, using shorter tools is a solution.

**EXCAVATORS IN TUNNEL EXCAVATION**

Cross-section excavators have generally been used for loading due to their high capacity. However, these rigs are gaining more popularity as

- Carriers for rock breakers
- Carriers for cutterbooms
- Excavators with shovel, special kinematics for tunnel excavation

When using an excavator as a carrier for a cutterboom, the following issue must be taken into consideration:

- Can the excavator withstand the loads from the cutting process, taking into account its stability as well as design?

The following approx. operating weights are necessary to apply cutterbooms on excavators:

<table>
<thead>
<tr>
<th>Cutter motor power (kW)</th>
<th>Min. operational weight of excavator (t)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>35-40</td>
</tr>
<tr>
<td>200</td>
<td>55-60</td>
</tr>
<tr>
<td>300</td>
<td>80-90</td>
</tr>
</tbody>
</table>

- The cutting process requires higher swivel forces than the loading process. As a consequence, it is highly recommended to use hydraulic jacks linked to the excavator’s undercarriage to assist the swivel motion of the excavator.

Main application of excavators with cutterbooms are large-section tunnels (extension of section, removal of destroyed lining) and drill and blast tunneling for achieving a smooth contour and minimize rock fracture close to the tunnel’s roof and wall. Figure 6.2.-50 shows an excavator with a Tamrock VAB 100 kW cutterboom.

While A.M. applications are based on standard excavator types, special tunnel excavators were developed in the eighties mainly for operation in soil-like ground conditions. Through special digging kinematics design options and short-advanced roof sections, comparably deep invert arches can be excavated and loaded, making these excavators well suited for urban tunneling where fast closure of the lining ring is required. Additionally, shovels with roll-over kinematics allow the perfect contour shaping of the opening.

The success of this relatively cheap and versatile equipment has led to the development of equipment with even more flexibility.

Increasing structural strength and quick interchangeable tooling is a common feature that covers:
- Various shovel types
- Cutterbooms
- Hammers

Drill rigs have also been mounted on-board for blasthole drilling and bolting. Consequently, such tunnel excavators are frequently used in small sections where standard-sized equipment is too big or can not get through the restricted available space.

**B) FULL FACE**

**HARD ROCK**

Contrary to soft-ground tunneling where the main objective is to control and support the ground, the goal of hard-rock tunneling is to cut the rock as fast as possible. Daily advance rates of 170 m (diameter 3.4 m) have been reported. The application range is extensive and compressive strengths up to 300 MPa can be handled. The diameter range of available TBMs extend from 1.6 m - 12 m.

The tunnel length should take into consideration the investment costs including as to whether a new or refurbished TBM should be used. A TBM’s life time (including some overhauls) is up to 25 km. Full depreciation of the investment on one project is an exception.

Long and small tunnels can be driven effectively by Tunnel Boring Machines, TBMs; short and large tunnels (such as highway tunnels) often are more suited to D&B, where permitted.

The cutting tool used on TBMs are important. Starting with relatively small discs (< 14" dia)

...it required more and more power and one solution was to increase the cutter discs diameter. Large disc diameters require higher loads to achieve reasonable penetration rates and levels off at approx. 19”. There is a tendency today to focus on 17” high performance discs which provide sufficient service life and which keep the design of the TBM in feasible limits.

**Basic operation of a TBM**

The cutting process is performed by disc cutters. These cutters - generally steel rings - are pressed against the face. The contact pressure between the disc and rock pulverizes the rock on contact and induces lateral cracking towards the neighboring kerf - and rock chipping. To achieve the best performance, kerf spacing (distance between two adjacent tracking cutters) and cutterload must have suitable values for each rock type. Average values of 80 - 110 mm spacing and 250 kN cutter load for 17" (= 430 mm) discs are sufficient in most cases.

**FIGURE 6.2.-51.** Example open hard-rock TBM.

**FIGURE 6.2.-52.** Cutting process TBM.
**TBM design**

Two basic TBM design principles are available:

- Single-gripper machines
- Double-gripper machines

Both principles have advantages and disadvantages, single-gripper machines are used more frequently in standard tunneling projects.

**The single-gripper TBM**

The basic concept comprises a main frame with a main drive, a floating support at the front end and a gripper at the rear end, required for transferring induced forces into the tunnel wall. A rotating cutterhead is attached to the main gear and rotates at approx. 2.5 m/s peripheral speed. The cutterhead is thrust forward by advance jacks. After a stroke of 1.5 - 1.8, the machine must regrip for a new stroke. The front support is provided by a dust shield, which is a steel structure with expendable plates in the upper area and a rigid support in the lower area. It seals off the working area and makes dust collection easier. This front support is kept in frictional contact with the tunnel wall and overthrusted by the installed thrust force.

The machine is steered by adjusting the rear end of the frame and turning the machine around the front support. A single-gripper machine can be steered continuously during the boring operation which results a smooth surface in the tunnel. Careful steering only while the head is rotating is essential so as to avoid gage cutter and main bearing damage. The curve radius of the TBM is approximately >150 m, and < 100 m in special designs. A belt conveyor handles muck discharge. It is installed in the main frame and loaded by buckets on the cutterhead via a hopper in the center of the cutterhead. For maintenance reasons and cutter change, the belt can be retracted to give access to the rear inside area of the cutterhead. The belt discharges into the main conveyor which leads through the back up and discharges into the muck train on the back-up. The operator’s cabin can be placed on the TBM or the back-up, depending on tunnel requirements, which influence the back-up design (Figure 6.2.-53).
Double-gripper TBM

Contrary to the single-gripper machine, the double-gripper TBM is supported by two sets of grippers that perform the whole guiding function of the TBM. The front dust shield only seals off the dust from the tunnel and cleans the invert.

The main frame, which is stabilized by the grippers, does not move. To advance the cutterhead, a sliding inner frame is used. Steering during boring is almost impossible; and therefore double-gripper TBM’s bore a polygonal tunnel line. Muck discharge is also done by a belt conveyor from the top of the frame to the end of the TBM.

Double grippers have the advantage of better distributing the gripper forces to the tunnel wall in weak ground. However, a disadvantage is taking up free work space for passage and consolidation projects at least in smaller diameters. Furthermore, the skewed process stresses gage cutters and main cutterhead bearing.

Main TBM assembly groups

Cutterhead:
The cutterhead is a rigid steel structure that supports the cutters and loads the muck onto a belt conveyor. Depending on machine size and site conditions, the cutterhead can be one piece or of sectional design. For sectionally designed cutterheads bolted versions are used. Replacement of worn discs on the cutterhead is performed by replacing the cutters held in special saddles by bolts or a wedge lock system. Particularly 3.5 m double-gripper machines usually have front loading systems, which means cutter change can only be performed from the front. In bad ground conditions, this procedure can be dangerous to people performing this job. Bigger machines have back-loading systems that allow cutter change from inside the head.

The buckets load the muck from the invert and discharge it into the hopper. It is very important to keep the bucket lips in good condition and as close as possible to the cut wall to reduce gauge wear on the cutters and on the cutterhead. Specially designed backloading buckets reduce the remaining fines in the tunnel invert.
Disc Cutters:
Disc cutters have an important role in tunnel boring including the layout of cutters on the cutterhead (kerf spacing) and the shape of the cutterhead itself. In special cases and if the diameter must be kept constant for as long as possible, button cutters with tungsten carbide inserts are recommended. Button cutters are commonly used on micro TBMs where access to the cutterhead is not possible.

The steel disc rings are mounted on a hub assembly which comprises the bearing and seal arrangement. The most common type of bearing is a pre-stressed pair of case-hardened conical roller bearings.

Cutter life varies extensively from approximately 30 bcm to 3000 bcm depending on the rock type and especially on its quartz content. The most popular disc shape today is the “constant section” ring, which means the disc footprint does not change significantly with wear.

Main Drive:
The main drive is integrated in the structure of the front dust shield (single gripper system). It comprises the main bearing, generally a three axis roller bearing; double conical roller bearing, the main seal arrangement and planetary drives for the main motor in smaller machines. Most of the machines are electric, with single and double speed run on pole-changing motors or frequency controlled drives in difficult geological conditions. There is a multiple-disc clutch located between the main motor and the planetary gear that protects the main drive against overload and for start-up if stalled. For cutter change and maintenance, an auxiliary drive allows the cutterhead to turn in slow motion.

Installed power is approx. 250 kW/m of diameter (only a rough indicative value depending on the cutter size and geological situation) which means a 3.5 m TBM has approx. 1000 kW installed power on the cutterhead.

Rear Gripper (single-gripper TBM):
The gripper is thrust against the tunnel wall and the TBM is propelled forward by hydraulic cylinders connected to the grippers. Gripper force is distributed via the grippers to the rock. Depending on the rock, the contact pressure is limited to approx. 350 N/cm². Studs in the gripper help in slippery conditions.

The gripper cylinder is carried in a frame which allows vertical and horizontal steering. The frame is guided by a specially designed guide along the main frame.

Consolidation, Probe drills
Consolidation Drills:
Provision for dealing with weak rock conditions provisions can be made by installing a pair of roof bolters just behind the dust shield. This allows a primary roof support in poor ground conditions. Due to restricted available space, systematic bolting should be done from the back-up.

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6.2.3. Shaft excavation

Vertical or steeply inclined tunnels called raises or shafts are usually required for ventilation, access and hoisting in hydropower projects and penstock tunnels etc. A deeply inclined or vertical tunnel is usually called a shaft. A raise is an opening underground that goes from one level to another.

Shaft and raise excavation has always been considered one of the most difficult tasks in construction. Today, however, modern equipment offers efficient and safe methods for this type of excavation.

RAISE EXCAVATION USING THE DRILL AND BLAST METHOD

Four different methods are generally used for raise excavation by the drill and blast method. Method selection depends mainly on the length of the raise:

- Raise building
- Long-hole method
- Alimak method
- Inclined tunnel method

**Raise building**

Raise building is the oldest method of raise excavation. Excavation progresses upward from a platform that must be built and dismantled before and after each blast. Drilling is performed with hand-held jackleg drills. The shielded TBM, as the name says, looks similar to a shield, but the working process is different.

A shielded TBM is a hard-rock TBM enclosed by a shielded body. The rear end of the machine has a pair of integrated grippers to stabilize the TBM in the tunnel. The front end with the cutterhead is pushed forward out of the telescopic shield via advance jacks. A ring of segments can be simultaneously erected under the shield tail cover. After completing the cutting stroke and segment lining erection simultaneously, the TBM’s rear part with the grippers is reset into the next position.

If the rock is too weak to give enough resistance for advancing the TBM, the shield mode can be used. In this case, the rear thrust jacks will push against the segment ring and advance the machine. In this event, a parallel operation is not possible which slows the advance rate.

Segment systems used together with shielded TBMs usually serve as a primary lining; and is not watertight. Honeycomb or normal lining can be used. Developments of watertight lining systems have been developed, but provide at the time only sufficient tightness of low pressure conditions. Daily advance rates of up to more than 100 m can be achieved but require excellent logistics from the jobsite organization. The backup system performs similar requirements as for open TBMs in addition with segment handling and grouting logistics.

**Long-hole method**

The long-hole method is suitable for raises with more than a 45-degree inclination (sufficient for rock removal). Maximum raise length, normally from 10 to 60 meters, depends on drilling accuracy, hole alignment and geology. For successful blasting, maximum hole deviation should not exceed 0.25 meters ($10^\circ$).

Excavation via the long-hole method starts by drilling all the holes in the drilling pattern through to the next level. After drilling, each hole’s accurate position is recorded to determine the right detonating sequence for the holes. This must be repeated after each blast, because the positions can vary in each blasting section due to hole deviations. (FIGURE 6.2.-60.)

Blasting starts from the bottom up with the center part always some rounds ahead. The last few meters can be blasted at one go.
The Jora method is similar to the Alimak method with the exception that the lift is operated by a winch. A pilot hole through to the upper level is required for operating the winch.

**Inclined tunnel method**

One application of mechanized raise excavation is the inclined tunnel method. It can be utilized on steeply inclined raises. Excavation progresses from top down similar to tunneling. Specially made drilling units, such as rail-mounted jumbos lowered by a winch, are used.

**Raise Boring**

In the past, all shafts and raises were made by drilling and blasting (methods described previously.) However, during the last decades, full-face raise boring methods have by and large surpassed drill and blast methods for making raises both in mining and civil contracting (Figure 6.2-62). In full-face raise boring, the entire cross section is bored to its final diameter. Explosives are not used. There are various alternative methods to bore the full face holes:

Boxhole boring is a special method in which the raise is made in advance from the lower level up. This must be ready when tunneling reaches the area. The rig is on the level beneath
the hole and bores up. Boring is performed either by using pre-drilled pilot holes or boring straight with the final diameter boring head.

Blind (down) boring, is another type of boring where the hole is bored downwards. The name “blind boring” comes from the early use of boring down to the final diameter in one pass. Down boring via a pre-drilled pilot hole was developed from blind boring. In small diameter holes, a normal pilot drilling diameter 9 to 13-3/4 is used; in bigger holes the pilot hole is reamed with raise boring to 3 to 8 ft in diameter.

Raise Boring is the most established full-face excavation method of shafts and raises. This method consists of first drilling a pilot hole and then reaming it to the final diameter. The pilot hole diameter is somewhat larger than the drill rods. Reaming is performed in the opposite direction (back reaming) (FIGURE 6.2.-63).

In normal raise boring, pilot drilling is performed from the upper level vertically down or inclined to the lower level. Sometimes the pilot hole is drilled up and back reaming is done downward.

FIGURE 6.2.-63. Cutter used in Raise Boring.

FIGURE 6.2.-64. Shaft excavation by Raise Borer.
Shaft dimensions are determined by shaft purpose, geological and rock mechanical conditions. Most shafts have a diameter of 5 - 8 meters, with only a few reaching 10 meters in diameter. Shafts are usually round in shape.

After exploring of geology and groundwater conditions, overburden is removed. If the overburden requires stabilizing, it is typically lined with concrete rings. Once the rock surface has been exposed, it is reinforced and grouted. The collar for the headframe is installed after excavating has progressed a short distance. The head frame includes the hoisting system for the shaft sinking equipment. At this point, the actual shaft sinking begins.

**Manual shaft sinking**

Manual shaft sinking requires several men operating hand-held rock drills and shoveling the rock manually into small buckets. All equipment must be transported up and down in buckets. The work is time consuming and progresses slowly.

The number of workers and amount of effort required for manual shaft sinking makes it impossible to excavate very long and large shafts. Shaft dimensions, restricted by the excavation method, limit hoisting capacity or any plans to expand.

**Mechanized methods**

When mechanization started to gain ground in tunneling, it was gradually applied to shaft sinking. Pneumatic shaft sinking jumbos were first introduced, later the hydraulic versions. Using hydraulics made it possible to build more complex, multi-purpose shaft sinking platforms, which in turn meant that bigger shafts could be excavated with greater accuracy and efficiency. (FIGURE 6.2.-65).

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**Main uses of raise boring in civil construction**

The main uses of raise boring in civil construction are:

- Ventilation holes for road and railway tunnels
- Various holes and raises for hydropower stations and underground storage halls (FIGURE 6.2.-64).
- Holes used as pilot holes for big diameter shaft sinking
- Raises in areas where environmental restrictions (noise, vibrations etc.) limit use of other methods. For example, urban areas, nuclear power plant or nuclear waste storage vicinities etc.

**Main benefits of raise boring**

The main benefits of the raise boring methods are:

- Always working in a safe area; no working under newly blasted roof
- Clean environment: no dust, blasting fumes, exhaust gases or oil mist
- Low noise level and minimum vibration (compared to blasting)

**Mechanised shaft sinking equipment.**

**FIGURE 6.2.-65.**

**Safety:**

**Speed, efficiency:**
- Raise boring can be typically 2 to 3 times faster than older methods
- Only one operator is required in a modern raise boring machine

**Quality:**
- Round cross section and smooth walls are optimal in terms of flow characteristics (ventilation, water flow) and require a minimum amount of additional support
- A regular, round cross-section makes it easy to assemble any pre-fabricated equipment in the hole

**Adaptability to various rock conditions:**
- The raise boring method can also be used when rock conditions are so difficult that conventional drill & blast methods are not possible.
- It does not cause any fractured zones or cracking to surrounding rock
- Optimal shape of the raise is strong against rock pressure

**SHAFT SINKING**

Shaft sinking is a method where a vertical or steeply inclined tunnel is excavated from the surface.
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Depending on rock conditions and final shaft use, rock bolting and shotcreting, or steel or concrete lining can be used as rock reinforcement. When shaft sinking gets down to the lower levels, all operations become slower. Using a multi-level platform makes the operation, service and maintenance easier and faster than in older methods.

**Benching**

Benching can be used as an alternative to full-bottom shaft sinking when rock conditions do not allow full-face excavation. Benching is an older method that is suitable for square-shaped shafts. Benching is done in halves. While one half of the cross section is being drilled and blasted, the lower half serves as a water sump and spoil dump. Work continues downward in alternately lowering benches (FIGURE 6.2.-67.)

**Spiral method**

Spiraling is a variation of the benching method. Excavation spirals downward. This method is suitable for fairly large round or oval shaped shafts, or when the full bottom is not otherwise possible. Drilling and blasting progresses with half of the face at a time. The holes in each half have the same length.

Benching and shaft-sinking rigs can be used for both the spiral and the benching methods. The drawback with any partially mechanized method is mucking and transportation difficulties. Using these methods only in small shafts increases the workload and slows progress.

---

**Full-bottom method**

In modern shaft sinking, the drilling rig is a two, three or four-boom drilling jumbo designed specifically for the dimensions of the shaft and sinking platform. To build the rig, the manufacturer requires exact shaft dimensions, sinking platform requirements and any restrictions (power arrangements, through driving dimensions etc.).

In the full-bottom method, the V cut was most commonly used. Limitations, such as available space and the feed/hole length, are the same as in tunneling. Thus the parallel cut with large cut holes is replacing the V cut in shaft sinking. This makes it possible to blast long rounds. Today holes up to 5.0 meters long are being successfully used, rock conditions permitting. The extra round length increases the speed of sinking and enhances working arrangements and use of the sinking platform.

The drilling pattern design for both the V cut and the parallel cut is similar to round tunneling with contour smooth blasting (FIGURE 6.2.-66.). Special care must be taken with charging, considering blasting direction and in case of any water problems.

Mucking is done with clam shell buckets. The skips lift the blasted rock to the surface. Even if most of the work is performed from the multi-level headframe, a certain amount of manual work is required at all stages. The headframe is lowered when the working units can no longer reach the bottom, usually after two or three rounds.

**FIGURE 6.2.-66.** Shaft drilling patterns a) V cut and b) parallel cut
6.2.4. Rock reinforcement

Rock support for tunnels and underground cavern design is a demanding and very complex task. In principle, the problem can be approached from two directions: The first way is to define the relationship between geo-mechanical properties of the rock mass and the support methods used. This is mostly based on the utilization of statistical and empirical data gathered in similar conditions. The second way is to estimate the deformation characteristics of the rock structure, and then the related effect on supporting structures. This method typically requires very good rock property and rock mass property data.

The most important factors affecting rock reinforcement method and design are:

- Geological factors, such as rock properties and rock mass structure
- Dimensions and geometry of excavated space
- Location and direction of caverns in the rock mass
- Excavation method
- Use and expected lifetime of space

Common support methods in underground construction work are:

- Bolting
- Sprayed concrete
- Steel arches
- Concrete lining
- Grouting

**BOLTING**

Rock bolting is one of the most common methods of rock reinforcement. The main principle of bolting is to reinforce loose rock or fractured in-situ rock to prevent caving or spalling, and to assist the rock mass to form its own self-supporting structure.

**Bolt types**

Bolts can be divided into three categories according to the way they behave in the rock, for example, grouted bolts, mechanically anchored bolts and friction bolts.

**Cement-grouted bolts**

Cement-grouted rebar is still the most inexpensive and widely used rock bolt, because it is simple and quick to install and can be used with or without mechanized equipment. Correctly installed, a cement-grouted bolt gives rock support for years.

The grout cement provides protection from corrosion. Special galvanized and/or epoxy coated bolts can be used in extremely severe conditions.

The major disadvantage of the cement-grouted bolt is its relatively long hardening period. The grout takes between 15 – 25 hours to harden, therefore it does not provide immediate support. When immediate support and/or pre-tensioning is needed, a grouted wedge-type or expansion-shell bolt can be used. Mixing additives in the grout can reduce the hardening time, but it also increases bolting cost.

The water/cement ratio considerably affects the quality of installed bolts. The best water/cement ration is 0.3 (w/c).

The grout density can be easily used and maintained when using mechanized bolting equipment (FIGURE 6.2.-68.).
Mechanically anchored bolts

Mechanically anchored bolts are usually wedge or expansion-shell bolts that are point-anchored at the bottom of the hole.

The bolt has an expanding anchor at its end. After insertion, the bolt is either rotated or pressed/hammered against the bottom of the hole. This expands the wedged end and anchors the bolt firmly to the sides of the hole. To install anchored bolts successfully, the hole size must be accurate and the rock must be relatively solid.

Wedge or expansion-shell bolts are typically meant for temporary rock support. Together with cement grouting, it provides both immediate and long-term support.

Friction-type bolts

Typical examples of friction-type bolts are the Split-set and Swellex bolts. Both are quick and easy to install and give instantaneous support. They cannot, however, be used for long-term reinforcement.

The Split-set bolt is hammered into the hole, which has a slightly smaller diameter than the bolt. Using the correct hole size for a specific bolt diameter is essential for successful installation. Split-set bolts are very suitable for layered formations. The Split-set bolt provides immediate support but only for a fairly short period of time. A disadvantage is that the Split-set bolt cannot be effectively protected against corrosion. The life span can somewhat be extended by using cement grouting. The Swellex bolt has a longer life span than the Split-set. It is installed by applying high-pressure water to the bolt after inserting it to the hole. The high pressure expands the bolt to its final dimensions in the hole, therefore enabling it to utilize the roughness and fractures in the bolt hole surface. As with the Split-set bolt, poor corrosion protection limits this bolt.

Equipment for bolt installation

Development of mechanized equipment began as early as the 1970s. Today there is a wide selection of fully mechanized equipment, and a wide variety of different methods for bolt installation. The main factors affecting the choice of method are usually tunnel size, amount of bolts to be installed and work cycle arrangement at the site.

Manual operation, the hand-held drilling and installation of bolts, is typically used in small drifts and tunnels where drilling is also performed by hand-held equipment, and there is a limited amount of bolting work.

Semi-mechanized installation is still typical at tunneling work sites. The drilling jumbo is used for drilling bolt holes, and bolt installation is performed from the jumbo’s basket boom or from a separate utility carrier or truck.
**Fully mechanized bolting**

With today's fully mechanized equipment, one operator can handle the entire bolting process from drilling to grouting & bolt installation. The operator is positioned away from the unbolted area under a safety canopy that protects him from falling rock.

![Tamrock Robolt fully mechanized bolting unit](image)

Although safety is a major reason for the development of mechanized bolting equipment, the superior installation technique of mechanized bolting rigs also produces consistently higher bolting quality. Thanks to powerful cement mixers, pumps and effective grouting methods, the bolts are securely fixed and grouted to their full length, providing a sound reinforcement structure, even with long bolts.

**Robolt**

The first fully mechanized bolting unit, called Robolt, was introduced by Tamrock in 1979. Mechanization initially involved cement grouted rebar bolts, but extended quickly to other bolt types. Today all most commonly used bolt types can be installed mechanized with the Robolt.

Mechanized bolting with the Robolt follows the pattern:

- Mixing the cement grout (if cement grout used)
- Stabilizing the bolting head to the desired spot
- Drilling the bolt hole
- Pushing in the grouting hose and grouting the hole, starting from the bottom, or shooting the resin cartridges to the bottom of the hole
- Inserting the bolt from the magazine into the hole
- Mixing of the resin/tightening or pre-stressing the bolt as required

The progression from drilling to grouting and installation stages is performed by accurately indexing the bolting head to the right position.

When grouting is started from the bottom of the hole, the hole is completely filled, eliminating all air pockets. Mechanized equipment also allows the use of best possible water/cement ratio in the cement grout.

**Cabolt**

Manual installation of cable bolts is time-consuming, difficult and labor intensive. Grouting manually installed bolts is normally done after bolt installation, and often leads to unsatisfactory bolt quality.

The Tamrock Cabolt is a fully mechanized cable bolting unit that handles the complete bolting process including hole drilling, feeding the cement grout and inserting the cables. Bolt length can be freely selected and all the work is performed by one operator controlling the machine.

![Tamrock Cabolt A fully mechanized cable bolting unit](image)
**SCREENING**

Screening, which is the installation of wire mesh, is most typically used in underground mining, but also at construction sites together with bolting and/or sprayed concrete. Screening is primarily performed manually by applying the wire mesh together with bolting of the tunnel. It can also be done by mechanized equipment, such as by having a screen manipulator on the bolting or shotcreting unit, or on a dedicated screening machine.

![FIGURE 6.2.-72. Robolt 320 with screen manipulator.](image)

**SPRAYED CONCRETE**

Sprayed concrete, otherwise called shotcreting, is a widely used support method in construction. It is used for temporary or long-term support, lining and backfilling. Usually shotcrete is used together with bolting to obtain the best support or reinforcement. Shotcrete can be reinforced by adding steel fiber to the concrete.

The most common forms of shotcreting are the dry-mix and wet-mix methods. In the dry-mix method, the aggregate, cement and accelerators are mixed together and propelled by compressed air. Water is added last through a control valve on spray nozzle. The dry method is suitable for manual shotcreting because the required equipment is usually inexpensive and small. On the other hand, the dry method can pose health hazards as it creates considerably more dust and rebound than the wet method. The quality also depends heavily on the shotcreting crew, and may vary widely.

In the wet mix method, the aggregate, cement, additives and water are measured and mixed before transport. Today, wet mix is more widely used because it is easy to mechanize and the capacity can easily out-do the dry method. Rebound rate is low and the quality produced is even.

Critical factors in shotcreting are:
- Water/cement ratio
- Grain size distribution of aggregate
- Rebound ratio, affected by
  - Grain size distribution
  - Mix design
  - Nozzle design
  - Nozzle distance and angle
  - Layer thickness

Manual shotcreting has been largely replaced by mechanized shotcreting machines. With mechanized equipment, multiple capacities per hour can be reached, together with consistent and even quality of the concrete layer. Safety, ergonomic and environmental conditions are other important aspects of shotcreting. These factors are efficiently improved with mechanized shotcreting units.

![FIGURE 6.2.-73. Mechanized shotcreting unit.](image)

**STEEL ARCHES**

Steel arches are a common permanent support method for weak rock formations. The preformed steel arches are usually installed in the tunnel immediately after each round, at the same time as rock bolting. Steel arches are also commonly installed during shotcreting to give temporary support before final concrete lining of e.g. traffic tunnels.
6. Tunneling

ROCK EXCAVATION HANDBOOK

Grouting after excavation (Post-grouting)

When grouting is done after excavation, grouting holes are drilled from the tunnel in a radial form. In good rock conditions with small water leakage, post-grouting is often adequate. Post-grouting enables better rock mass structure evaluation. On the other hand, water leakage blockage is more difficult because the water flow tends to flush away the grouting agent before it hardens.

Grouting agents

The grouting agents can be divided into two categories: Suspension and chemical.

Cement water or bentonite water suspension is the most typical in rock grouting because both are cost-effective and environmentally safe. The drawback is, however, a relatively large maximum grain size, which leads to poor penetration in small cracks. Penetration characteristics can, however, be improved by adding additives. Silicate-based chemicals are also used to speed up the hardening time.

Chemical agents are silicate-based, resin polymers, polyurethane-based or lignin-based chemicals that typically penetrate very small cracks and have adjustable hardening times.

6.3. CASES

6.3.1. Railway tunnel

Tamrock Data units (DataSuper, DataMaxi and DataTitan) were used by Lemminkäinen Construction Ltd. in a project in Norrala, which began in October 1996. The Norrala tunnel is a part of the Hälsingekusten project consisting of building a railway and road, E4, from Söderhamn to Enånger in Sweden.

The 3,850 m-tunnel construction schedule held. Accurate planning of the extraction of 300,000 m³ solid rock, mainly granite and gneiss, was made possible by the precision of the Data equipment. Additionally, 200,000 m³ of earth was moved and 40,000 m³ rock excavated from the surface.

The tunnel is 7.9 meters wide and 8.9 meters high. Its profile from north to south declines 35 meters and has a cross-section of 68.2 m². There are 113 holes in each face. The advance in each round is 5.3 - 5.4 m with 20 feet rods. The average drilling time per round was 3 - 4 hours and the average advance per week (120 hours) was 120 m. The record advance per one week was 138 m with two jumbos and with 8 - 9 men per shift.

Both system and random bolting was used for a total of 12,000-13,000 bolts. When needed, a total of 10,000-11,000m³ concrete was sprayed. 19 grouting holes, 21 meters long, were drilled every 3 rounds to provide water tight access to the tunnel.
A maximum of six faces developed at the same time. Safety was a major priority: emergency tunnels (33m²) in three different places, totalling 700 meters. The railway tunnel was made sufficiently wide to accommodate rescue vehicles. Evacuation tunnels will also help to equalize the air pressure due to the train’s high speed.

Lemminkäinen discovered how to best utilize Datamaxi’s properties. A 3 dimensional V cut was developed for the demanding conditions. There was not a single hole drilled parallel to the tunnel’s direction; all holes are inclined. The 3-D V cut offered considerable savings because drilling big reaming holes was not required. Pull-out was achieved even with 50 - 60 m less drilled meters per round.

**6.3.2. Oil and gas storage**

Oil and gas storage underground presents a popular and economical alternative to surface facilities. Underground construction offers better environmental protection, and deep rock caverns are ideal for pressurized storage tanks when general rock conditions are suitable.

Underground oil and gas storage facilities are among the largest underground excavation tasks and come in various shapes and sizes, depending on what is being stored. Some oil storage facilities are several hundred meters long, and one storage plant can contain several storage halls. Excavation work can be done through only horizontal benching, or both horizontal and vertical benching (Figure 6.3.-2).

**6.3.3. Hydropower stations and waterworks**

**UNDERGROUND EXCAVATION AT YELLOW RIVER, CHINA**

The Xiaolangdi project surface work was described earlier in chapter 5.3.2.

This project was designed to trap sediment at a point where it reaches a balance between the sediment’s outflow and inflow. A total of sixteen Tamrock rigs were delivered to the site: Four Maximatic HS 305 T units, six Paramatic HS 205 T PowerClass jumbos, four PowerTrak CHA 660 and two Commando track drills. The underground projects on Lot II consisted of three diversions; three free-flow and three sediment tunnels, resulting in the excavation of 1.4 million m³ of rock. The free-flow tunnels ranged from 450 - 700 m All diversion and sediment tunnels were approximately 1,100 m long. The largest tunnels were 18.5 m in diameter. All-in-all, the project consisted of 16 tunnels.

The civil jobs of Lot III consisted of an underground power house (120 m long, 23 m wide and 22 m high), a transformer chamber, a draft tube gate chamber, six power tunnels, six bus tunnels, a penstock, six draft tubes, three tailrace tunnels and an access tunnel. Three ventilation shafts, an elevator shaft, drainage tunnels and high-voltage tunnels were also excavated.
6. Tunneling

ROCK EXCAVATION HANDBOOK

Treno Alta Velocita (TAV) is a railway network construction project for high-speed trains in Italy. The project includes several tunnels, such as the Briccelle Tunnel near the town of Capua, which is located between Rome and Naples. Tunneling began in December 1995, and upon completion the total length of the tunnel will be 1033m. The tunnel is 12m high and 13m wide and a total of 135 m² was excavated. The project was executed by Condotte D’Acqua.

The project starts from the upper part of the tunnel, which is 9m high and has a cross-section of 100 m². This section was excavated with an S 86 installed on a Fiat-Hitachi 400, and an S 84 installed on Fiat Hitachi 330 machine. The lower part of the tunnel is 3 meter high with a cross-section of 35 m². A Rammer E 68 CITY hammer equipped with an automatic lubrication system and installed on a PMI 834 machine was used in this section.

6.3.5. Roadheader tunneling

NEW SOUTHERN RAILWAY TUNNEL IN SYDNEY, AUSTRALIA

The New Southern Railway (NSR) will form an additional rail link between the center of Sydney and the East Hills Railway Line, which will be met shortly west of the Sydney airport. The tunnel will provide a direct rail connection from downtown Sydney to the airport, and will be ready for operation for the Summer Olympic Games in Sydney in the year 2000.

The northern part (approximately 2.2 km) of the 10 km tunnel is excavated by roadheader - ALPINE MINER AM 105 (FIGURE 6.3.-5.).

The tunnel extends from Prince Alfred Park to the TBM exit access shaft south of Green Square, Alexandria. This section is set mostly in Hawkesbury sandstone (10 - 75 MPa, 20 - 40 MPa in average with 60 - 80 % quartz content) with some Ashfield shale and stiff clay interbedding.

Work will be performed from each end simultaneously, at the tunnel heading and bench from Prince Alfred Park and a similar operation from the TBM exit access shaft. Excavation will be carried out by the joint venture company Transfield-Bouygues. The ALPINE MINER AM 105, a powerful boom-type roadheader of the 100-ton class, has proven its unique transverse cutting technology in hard rock applications worldwide. It has an extended field of operation for mechanized roadway development in hard and abrasive rock formation.

Fine tuning and optimization of the AM 105 for the New Southern Railway Tunnel has been performed during the first period of excavation and resulted in a project-specific customized cutterhead as well as tailored operating procedures.

Lot III’s underground excavation volume is 1.2 million m³. Tamrock Maximatic HS 305 T, Minimatic HS 205 D PowerClass jumbos and Commando 100 second-hand track drill rigs operate underground. A significant amount of rock bolts were used in the tunnels for rock support.

FIGURE 6.3.-3. Underground excavations in Xiaolangdi.

FIGURE 6.3.-4. Hammer tunneling. (Note: The photo and text are not interrelated.)

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The machine achieved a maximum instantaneous cutting rate of 121.4 bcm/ch; a pick consumption of only 0.02 to 0.03 picks/bcm.

**Figure 6.3-5.** Alpine Miner AM 105.

**Figure 6.3-6.** Excavated tunnel profile in railway in Sydney, Australia.