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MODERN CONSTRUCTION OF TUNNELS AND LARGE CAVERNS IN HARD ROCK

VIDAR AARVOLD
FORMER CONSTRUCTION DIRECTOR OF THE GJØVIK OLYMPIC MOUNTAIN HALL.

NOW CHIF CONSTRUCTION MANAGER OF THE HIGH SPEED RAILWAY PROJECT NSB GARDERMOBANEN A/S, NORWAY

Abstract

Modern construction of tunnels and large caverns in hard rock involves high technology design and construction methods. The use of sofisticated construction equipment is also an important part of a succesful completion.

Since tunnels and caverns in hard rock often is situated in urban or sub-urban areas, the construction works have to be carried out under strict control as far as vibrations and other impacts on the environment is concerned.

This paper will mainly discuss modern methods and equipment for the construction of large caverns.

1 INTRODUCTION

Hard rock massives has for many years been used as building sites for a lot of civil engineering and mining purposes. Not only have tunnels been constructed in ordere to overcome topographical difficulties in roads and railway construction. The hard rock itself has more and moor been use as a very attractive building medium.

In the last 40 years or so, it has been a continoues development in the construction of sub-surface facilities in hard rock. In different countries all over the world, several installations

for a lot of purposes have been constructed. The tendency has been to extend the different use of the installations and that the sice of the installations has become larger and larger.

In the middle of this century, 10 to 15 metres were regarded to be the limits of free spans for permanent openings in hard rock. Today it has been proven by the construction of The Gjøvik Olympic Mountain Hall in Norway, that free spans of more than 60 meters are obtainable for permanent conditions. This is possible, not only from a technically point of view.

The cost of the construction can also be defined as accepttable compeared with costs for traditional on-ground buildings .

All this has been achived by a continous development of preinvestigation and design technics as well as construction methods and construction equipment.

Examples of modern use of large caverns in hard rock are found in the civil as well as in the military sector.

For civil use large caverns are constructed for

Hydropower Stations
Oil and Gas Storage
Drinking water Storage
Sewage Plants
Food Storage (Coldand Deep freeze Storage)
Sports arenas
Car parking
Dual purpose installations
Etc. etc.

In the future it is very likely that atomic power plants and atomic waste storage plants also will be constructed inside large hard rock caverns.

For military use large caverns are constructed for

- Commanding and communication Centers
- Land fortresses
- Ammunition depots
- General storage purposes.
- Shelters for air crafts
- Docking facilities for naval use
- Etc. etc.

As can be seen, there are infact very few limitations in the use of large caverns in hard rock.

2 MAIN FACTORS DETERMINING THE POSSIBILITY OF CONSTRUCTING LARGE CAVERNS

Several factors concerning the rock conditions will influence the possibility of constructing large span caverns. The most important may perhaps be:

The geological conditions i.e rock type and composition, dip and strike, orientation and properties of joints, cracks and faults, mechanical properties of rock and rock mass.

The in situ stress conditions in the rock massive. At shallow depth the existence of horizontal stresses in excess of the gravimetric stresses are particularly important.

The above mentioned factors are all important when looking for suitable sites for the construction of large caverns. The existence of virgin horizontal stresses may however be one of the most interesting factors. Optimal positioning of a planned cavern should utilaitze the existing horizontal stresses in order to increase the stability of the selfsupporting roof. In situ horizontal stresses in the order of 3 to 5 MPa is regarded as sufficient in this aspect. A major principle for design is to orientate the cavern so that its length axis is oriented normally to the direction of the major principle stresses.

The geometry of the cavern i.e span , height/ with ratio, radius of curvature are also important factors to be taken into account. The access and the escape possibilities to the cavern have also to be studied carfully regarding both the construction period and the permanent situation.

Position of planned cavern in relation to existing underground constructions or above ground structures have also to be studied. Experience is however that modern construction work easily can be carried out very near to existing structures without causing damage as long as the methods and technics applied are adopted to the actual situation.

3 MAIN ELEMENTS IN THE CONSTRUCTION PROCESS

Construction of large caverns is not very different for ordinary hard rock tunneling work. The principles of construction and the equipment and methods used for normal tunneling work can also be adopted in large cavern construction. The work has however to be carried out with much greater care and observeness than normally. Manforce and staff has to be of a very high quality.

The construction process of large span caverns can mainly be devided into three phases:

In the first phase the upper part of the cavern volume is escavated and a level is established from which the support works of the roof can be done. One or more pilot tunnels are driven into the upper part of the cavern. The arch of the roof is established by widening the span of those tunnels.This escavation process is done by ordinary drill and blast methods.
Drilling jumbos with ekstra wide range facilities are most useful. It is important that the hight of the tunnels is as large as possible. A hight of about 8 to 7 meters is suitable. At this hight the drilling of holes for the rockbolts or cables can be done under optimal conditions as far as the manouverability of the drilling jumbos is concerned.

During the excavation of the upper part, the support works in the roof normally have to be done parallel to and in sequence with the excavation works. All support works have to be finished before the rest of the cavern is constructed.

The second phase of the construction deals with the excavation of the lower part of the cavern and the necessary support works of the walls. The excavation can be done by drill and bast using tunnel drilling jumbos, but more convenient

and economic is to use bench drilling rigs. The hight of each bench is normally determined by the drilling ability of the bench rig. The ability of penetration is of less importance. It is the ability to drill straight holes which determine the optimal depth of the bench. The accuracy of the positioning and the straightness of the holes is extremely important in order to obtain a successful result as far as the stability of the walls of the cavern is concerned. A bench depth of up to 10 meters is regarded as maximum. An optimal depth will normaly be between 5 to 7 meters.
Normally we can say that for this phase it is better to accept excavation costs above what is regarded as optimal for this type of production in order to reduce the damage to the furure walls and hence reduce the cost of the support works. The risk of damaging the walls and roof is normally so great that a carful benching procedure is indeed advisable.
The supportworks in the walls have also here to be done parallel to and in sequence with the excavation of the benches.
See figure 1 and 2.

The cavern should now be excavated and sufficient secured and ready for the third phase in which the necessary interior works can take place. Those works will be very similar to any other construction works inside large above ground halls.

4 IMPORTANT FACTORS IN MODERN CONSTRUCTION OF LARGE CAVERNS IN HARD ROCK

There is of course a lot of factors influencing the results of the construction works. It is not possible to deal with all of them in this connection. However, there exists some major factors of great importants in order to obtain a successful result.
Those major factors are pointed at in the following text.

4.1 Drilling equipment

In the walls and roofs of large caverns there will normally be a redistribution and building up of high stresses during the excavation process leading to danger of rock bursting and spalling. There is therefore necessary to carry out the drilling and blasting operations with great care and accuracy in order to obtain surfaces with the heighest possible degree of smoothness and straightnesse.

To obtain this in the roof and the upper parts of the cavern it is of great advantage to use tunnel jumbos of good mechanical standard and jumbos equipped with an instrumentation system for contour control and round planning. This system consists of a large number of hardware components and software programs to suite the jumbo and the system requirements. The jumbo is moved into drilling position and with the aid of a laser beam or an electronic positioning system the on-board computer organise the drilling operation in acordance with a pre-programmed drilling pattern. See figure 3 and 4.
This system provides a more accurate tunnel profile than a conventional drilling operation. There is less damage to the surronding rock and hence less supportwork will be necessary. Longer rounds are also often a result of such systems. In addition an optimal and accurate drilling pattern will positively contribute to the vibration controle of the blasting works.

For the benching it is the same requirement as far as the straightness of the drilling holes is concerned. When using tophammer drilling equipment it is recomended to use rigid drilling tubes instead of ordinary drilling rods. Rigid drilling tubes are now availabel from 64 to 127 mm diameter. The penetration rate must be kept on a low level in order to prevent inaccuracy in the straightness of the holes. Each hole should be set out and marked and the operators must know the importance of an accurate drilling operation. Straight and correct positioned holes permit wider hole spacing and give more even fragmentation, using less explosives. Less explosives gives less damage to the surrounding rockwalls which is of great importance.
See figure 5.

4.2 Blasting technology

The blasting work is a very important factor in the construction process of large caverns. Detailed planning , skilled workforce and high technologi explosives and detonator systems are necessary elements in the process.

The need of careness of the surrounding rock massiv leeds to procedures and systems which can keep the amount of reguired explosives to a minimum and provide that the blasting energy is evenly spread out on a great number of time intervals. In addition we often will find that large caverns and tunnels are situated in urban areas or closed to existing structures which means that there exist strong limits as far as vibrations from blasting is concerned.

One of the most important elements in this process is the use of detonator systems providing a large number of time intervals. The Nonel System from Dyno Industries satiesfy this requirement. With this system is is possible to blast large rounds while keeping
the vibrations under controle. Further with the use of different types og explosives in the same round one can keep the damage to the contour (walls/roof) to a minimum.

A carful planning of the blastingwork is also necessary. An important part of this planning work is to have the possibility to record the vibration development througout a complete round. Earlier it was normal to use instruments which recorded the top peak vibration value only. Today it is normal to use instruments which record the complete vibration cyclus of one round. In this way it is possible to continually adjust the roundplans in order to keep the vibrations within the given limits. Very often one will find that there are afew holes within a complete round which are causing vibrations above the limits. By adjusting the hole pattern in that particular area or the detonator numbering for those holes only the blasting works can continue at the same rate without reduction while the vibrations are brought down to an acceptable level. See figure 6

A smooth contour of the walls and the roof is as earlier pointed out, very important. It is a known fact that the cooperation between detonating holes give an optimal result as far as the contour is concerned.
In underground blasting works we often have to use detonators with a high interval number to detonate the holes in the contour. Since detonators with high numbers have a tendency not to detonate at the exact same time, we can loose some of the cooperation effect between the contour holes.
A better timeing of the contourhole detonators gives a better result as far as the smoothness of the permanent rock surface is concerned.
During the last years a system containing electronic detonators has been developed by the Dyno Industries Company. The electronic detonator system gives indeed a very small diviation of the detonation times. The accuracy of the system is in the order of 1 : 1 million of a second. At present 250 intervals are available in the system, the shortest timegap between two intervals is 1 ms and the longest time of delay is 6.25 seconds.
The system with electronic detonators was tested on contour blasting during the excavation of The Gj°vik Olympic Mountain Hall. The conclution was that the quality of the permanent rock surface (the contour) was significantly increased. The degree of smoothness increased and the amount of necessary scaling and hence supportworks was less than when using ordinary Nonel detonators .
At present the cost of using this detonator system is significantly higher than the ordinary Nonel system and too high compared with the reduction of supportwork cost. However, for spesial blasting situations the system is an actual alternative.
Future development will probably also bring the cost of the system down and hopefully it can contributes to the development of large cavern construction.

4.3 Vibration Control

As pointed at in the previous chapter, it is essential to have the possibility to record the vibrations of the entire cyclus of the rounds. This is important in adjusting the size of the round to an optimal level.
Vibrations can also be a problem in connection with neightbouring structures, under ground as well as above ground.
There are throughout the world different standards determining levels of acceptable vibrations which can be applied to neight-bouring structures.
In Norway the tendency is to accept a vertical vibration velocity of 50 mm/sec on houses and structures in fair to good conditions and 20 mm/sec when the conditions of the structures are bad.
For spesial cases the limits can be lower. During the Gj° vik construction period a comprehensive program for recording vibrations was done. In this program applied vibrations to several objects were tested. Also computers were tested. Limit for allowed applied vibration to the hard disk of the computers was set to 20 mm/sec. The

computers were exposed for series of vibrations up to that limit without taking any damage. Even vibration velocities up to 35 mm/sec were applied to the computers without any damage.

In general we can say that vibrations from blasting works underground no longer represent major problems. Vibrations can easily be dealt with using available detonating systems and instruments for recording the vibrations. Setting reasonable limits for allowed vibrations applied to existing structures is of course also important.

4.4 Support works

The rock conditions determine to a large degree the type and amount of support works necessary. Since a large cavern construction require a fair to good rock quality, one should think that an acceptable type of support works could be systematic bolting using untensioned fully grouted bolts in combination with steelfiber reinforced shotcret. For many years now the Norwegian experience with large cavern construction is that this method of doing the support work has become a dominant one. There are several other methods, for example casting of reinforced concrete arches or shells in the roof and reinforced concrete or steel beams/walls for the walls, but those methods are not highlighted in this connection.

The length, type and spacing of rockbolts to be installed are of course varying from cavern to cavern. When dealing with large spans caverns one must however expect to use bolts with a length of up to 25 meters, may be even longer. Today there are on the marked spesial drilling rigs which can handle both the drilling operation as well as the positioning and grouting in of the bolts. The bolts will in this case mean steel cables.

Theese rigs are capable of handeling untensioned as well as tensioned cables.

More commond though is to use ordinary tunnel jumbos for the drilling of the bolts or cables. Vertical upwards hole depths of up to 12 metres is possible without doing any spesial adjustment to the jumbo. One condition is sufficient hight and space for the booms of the jumbo.
When required length of the bolt is more than 6 meters, it is recomended to use steel cable bolts. A steel cable of 12 mm diameter has a capasity of approximately 16 tonnes at yield,is easily handabel and can be installed by handforce in holes of up to 15 meters upwards depth. When there is need of higher capasity more cables can be innstalled in the same hole.
The bolts or the cables, tensioned or untensioned, have normally to be grouted in by cement. There is on the marked a lot of pumps handeling this operation. For very long holes the bolts or the cables are normally first placed in the holes and grouted in afterwards. For shorter bolts, ie up to 6 meters, the hole can be filled with grout and the bolt pressed in afterwards.

When the bolting operation is completed, there is time for a final layer of steelfiber reinforced shotcrete. The modern Norwegian practice is to use the wet mix process with a concrete quality of up 55 MPa or even up to 100 MPa, and reinforced by 25 to 40 mm long steel fibres. Normal proporsion is to use 50 to 70 kg fibre pr m^3. A layer thickness of 5 to 10 cm is normal.
Modern equipment for the applying of the shotcrete consists of compact units with remote controlled robots mounted on trucks.The units are very mobile and the capacity is at least up to 25 m^3 pr. hour using piston pumps. See figure 7.

The method is very cost effective for the application of large volumes for jobs requiring high capacities , as often is the case in large cavern construction. This is due to the advanced and expensive equipment. The equipment also calls for skilled and educated operators, both with respect to machinery and concrete technology.

4.5 Excavation and transport

This part of the process can be done by various equipments and methods. It is commond to use wheel loaders for the excavation. For the transport several types of trucks can be used.

4.6 Instrumentation of suroundlng rock masses

When dealing with the construction of large caverns it is absolutely necessary to install a comprehensive instrumentation program in the rock masses above and beside the cavern.
This program will give essential information about the progress
in settlements and stress distribution before, during and after the construction period.

4.7 Some practical advices

As a final part of this paper, some practical advices are given to those of You who have plans about constructing large caverns in hard rock.

Use only highly skilled workforce and staff.

A very close registration of the rock conditions in the cavern has to be carried out on a daily basis by a highly skilled geologist. The organisation on the site must be able to quickly respond to any demands that this registration may recall.

There must be sufficient and adequate equipment available on the site in case of an emergency situation.

Check the geometry of the cavern very often. The consequences of wrong measurements are formidable.

There must exist plans in case emergencies, dealing with alternative methods of excavation and supportworks, fire and escape routs and so on.

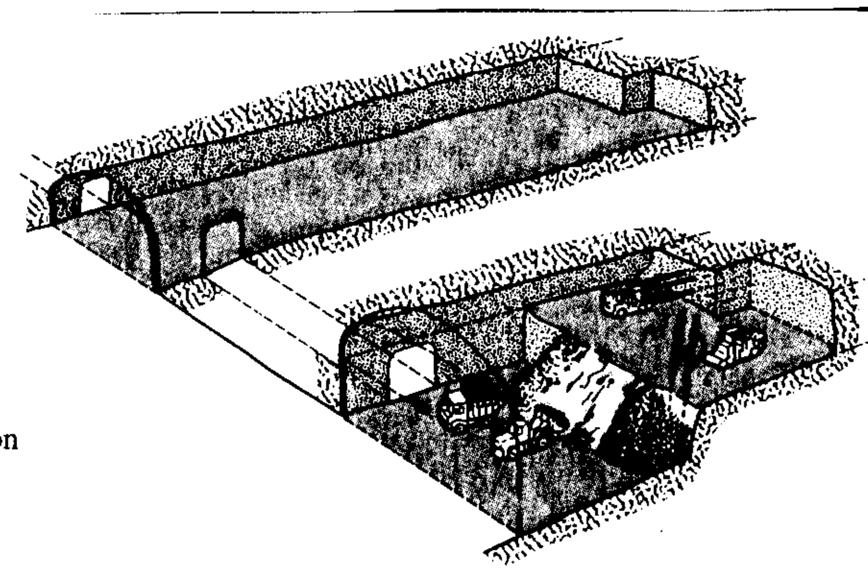


Figure 1.
First and
second phase
of construction

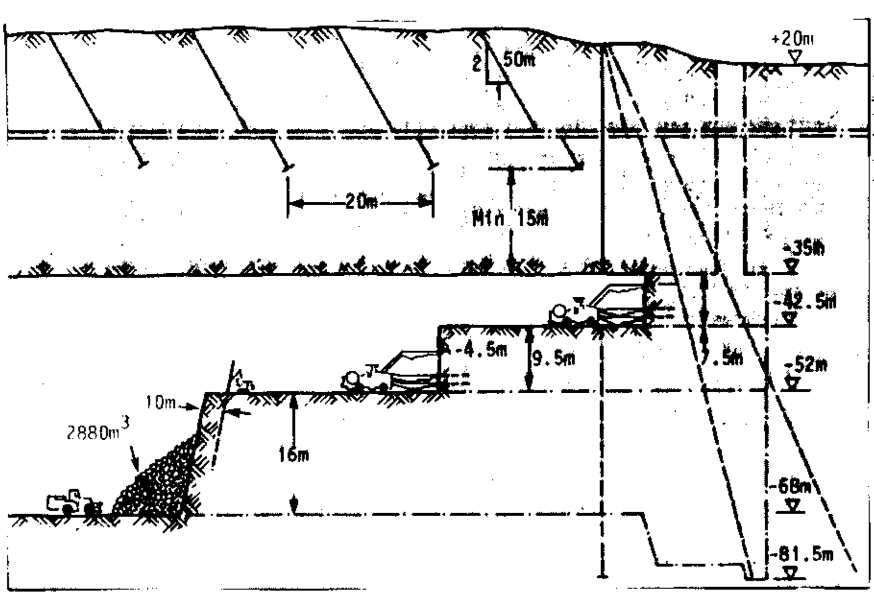


Figure 2
First and second
phase of construction.

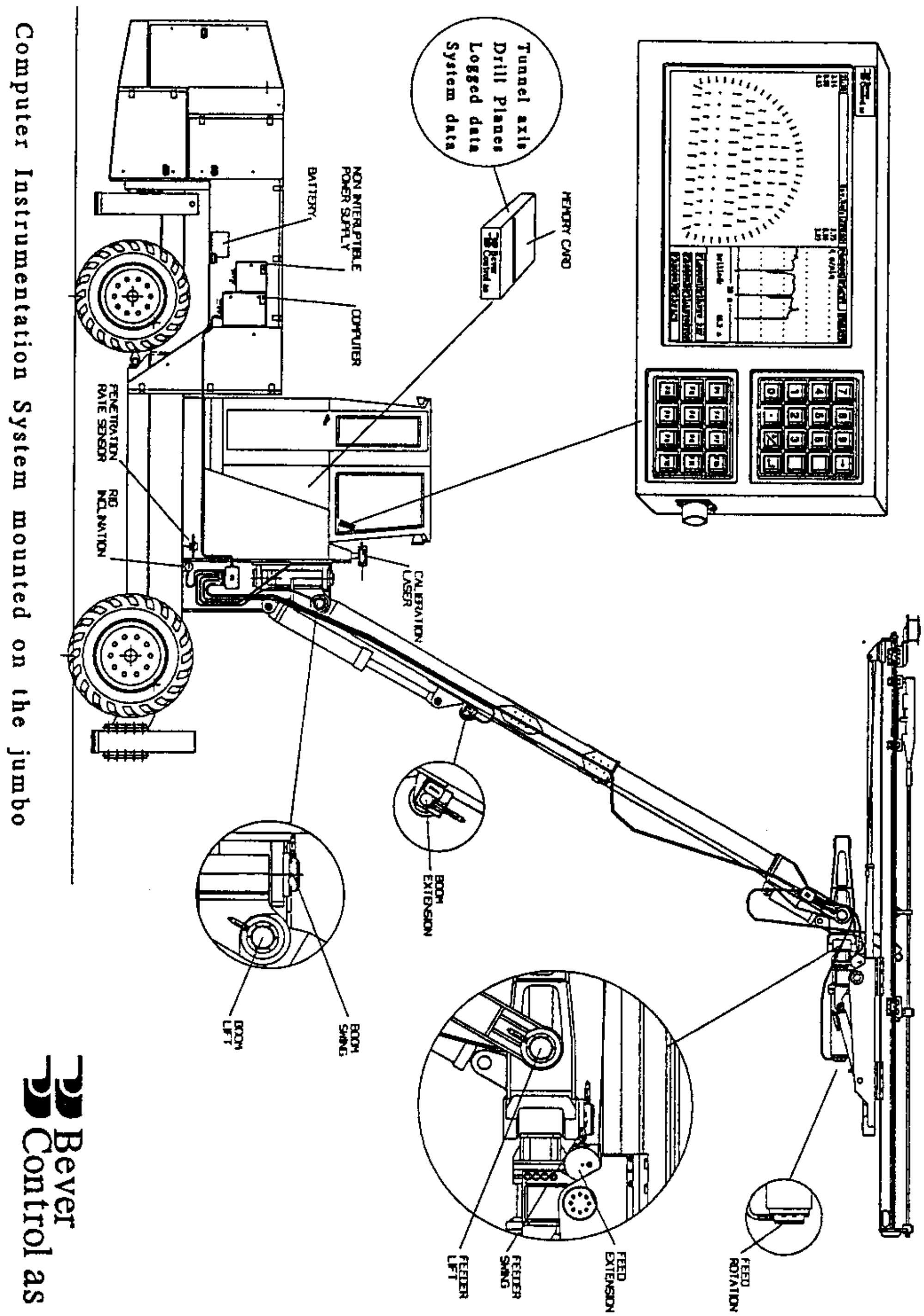

Tunnel axis
Drill Planes
Logged data
System data
MEMORY CARD
NON INTERRUPTIBLE POWER SUPPLY
BATTERY
COMPUTER
PENETRATION RATE SENSOR
RIG INCLINATION
CALIBRATION LASER
BOOM EXTENSION
BOOM SWING
BOOM LIFT
FEED ROTATION
FEED EXTENSION
FEEDER SWING
FEEDER LIFT
Computer Instrumentation System mounted on the jumbo
Bever
Control as

Figure 3

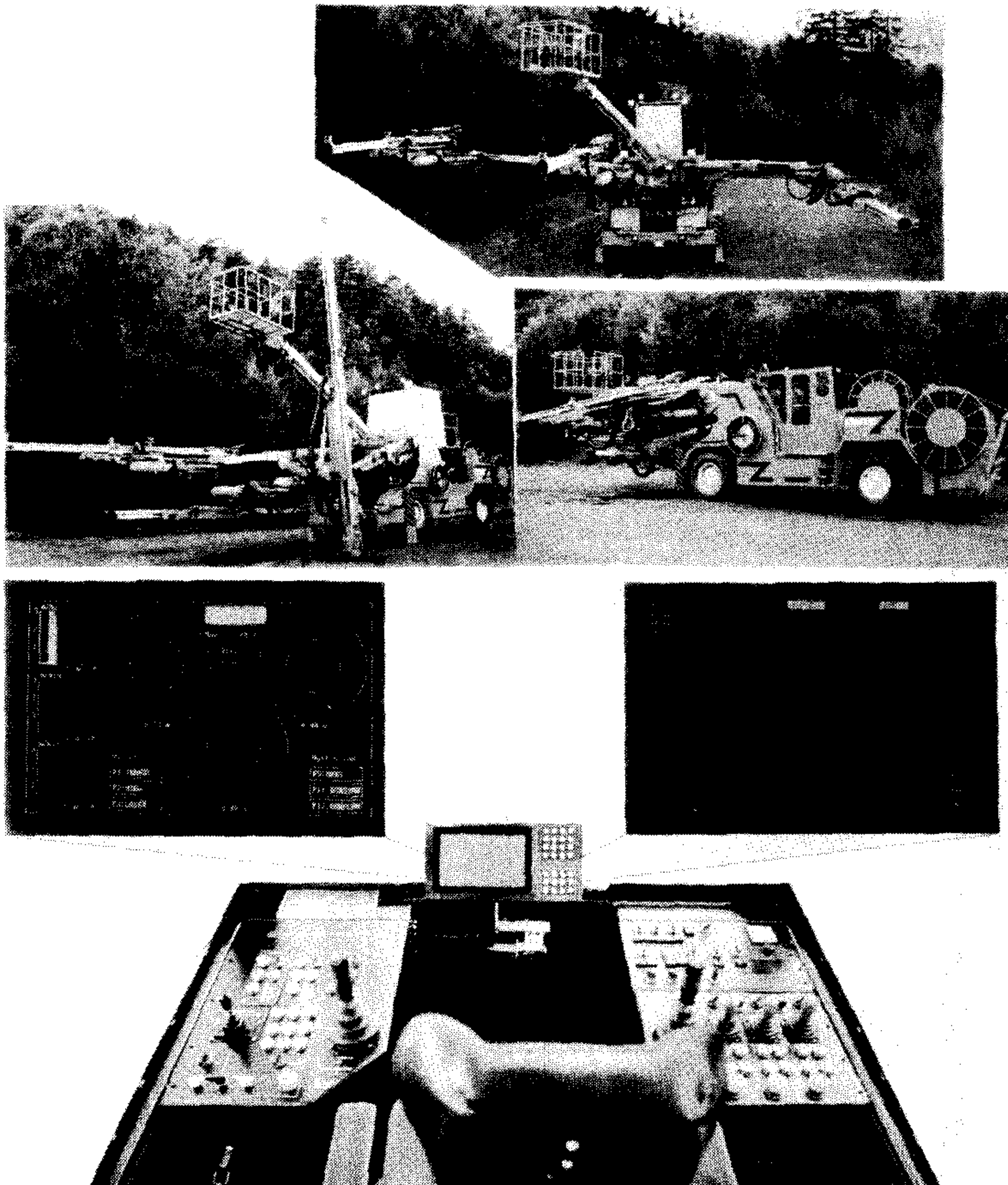
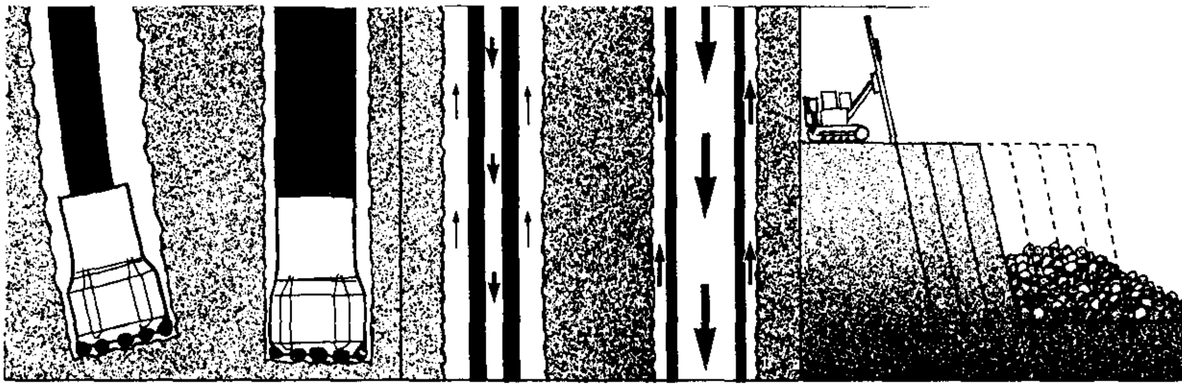


Figure 4
Modern tunnel jumbos with computerized instrumentation.



Rigid tubes give straighter holes.

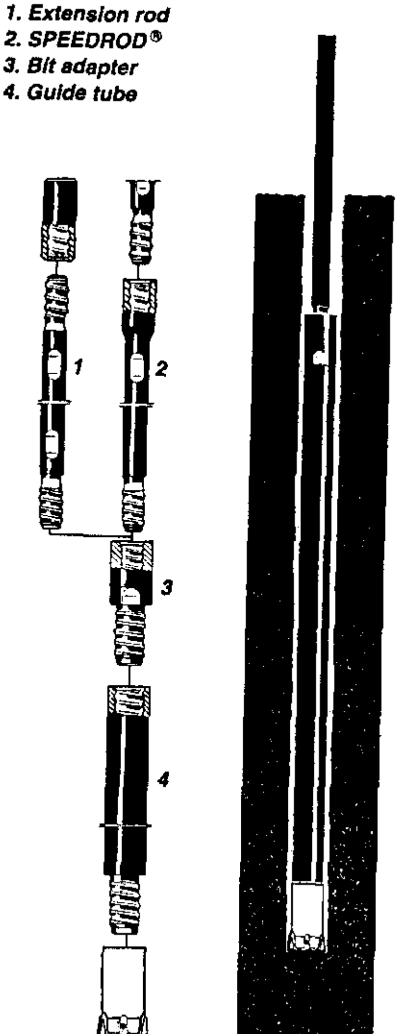
Higher flushing-air velocity gives increased penetration and reduces the risk of jamming.

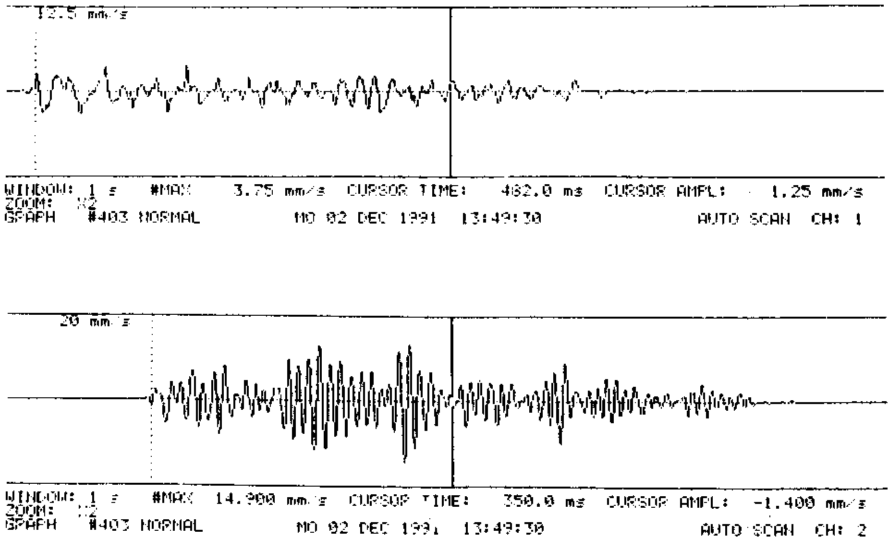
Straight holes permit wider hole spacing and give more even fragmentation, using less explosives.

Figure 5
Bench drilling equipment.

GUIDE-TUBE DRILLING
(illustration of working principle)

1. Extension rod
2. SPEEDROD®
3. Bit adapter
4. Guide tube





<u>Figure 6.</u>
Vibration record through a complete round.

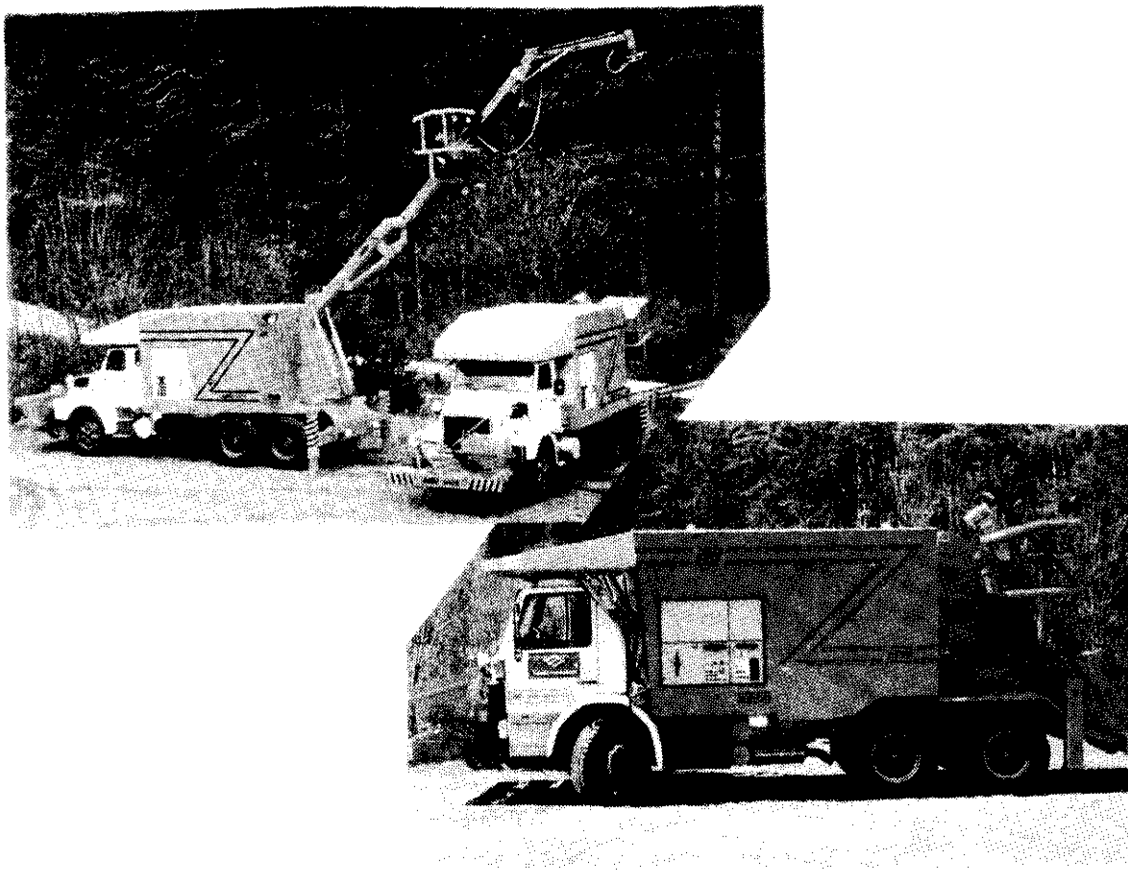


Figure 7
Modern equipment for shotcreting.