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SMOOTH BLASTING FOR RELIABLE UNDERGROUND OPENINGS

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We have gained experience in Sweden and abroad during the last decades on how to excavate economically underground facilities that will function reliably for a long time. We have learnt by hard experience not to blast carelessly tunnels and storage rooms. We have come to realize that the remaining rock has to be treated as a structural material in the underground building that is in effect created when an underground facility is excavated. The blasting method has to be chosen with due respect to the predicted needs for reinforcement and support, the structural stability of the opening and the importance of undisturbed functioning of the facility. Careful smooth blasting prevents the early movement and loss of structural strength of the remaining rock, and greatly reduces the cost of the final support necessary. This paper surveys the modern tools for smooth blasting developed and extensively used in Sweden and abroad.

Grâce à l'expérience que nous avons acquise en Suède et à l'etranger au courant de ces dernières dizaines d'années nous sommes à mêmes de réaliser des installations sousterraines assurant et une bonne économie et une fonction satisfaisante pendant longtemps. L'expérience nous a appris de nous méfier de sautages non prémédités qui ne tiennent pas compte de ce que la montagne entourant la cavité ainsi créée est à considérer comme le matériel de construction pour les installations. Il faut donc choisir la méthode de sautage qui puisse satisfaire aux besoins de renforcement et de support et à la stabilité structurelle de la cavité assurant ainsi un fonctionnement sans dérangement de l'installation. La méthode de sautage de réglage empêche le déplacement initial, conserve les forces structurelles de la montagne de l'entourage et réduit la nécessité et les frais d'un renforcement final. Ce papier donne une présentation des outils modernes pour le sautage de réglage employés en Suède et à l'étranger.

Wir haben in Schweden und im Auslande in den letzten Jahrzehnten grosse Erfahrung erreicht, wie Bergräume für Untergrundanlagen ökonomisch und auf die Dauer zuverlässig zu schaffen sind. Wir haben aus teurer Erfahrung gelernt nachlässiges Sprengen, dass keine Rücksicht darauf nimmt dass der den Bergraum umgebende Berg als Baumaterial für die Untergrundanlage zu behandeln ist, zu vermeiden. Die Sprengmethode soll somit mit Rücksicht auf den Bedarf an Verstärkung und Stütze, an Stabilität des Bergraums und an der Störungsfreien Funktion der Anlage gewählt werden. Schonendes Sprengen verhindert die Initialbewegung des gebliebenen Berges und dessen Verlust an strukturaler Stärke. Es reduziert auch erheblich die Kosten für weitere Versterkungsbedürfnisse. Die vorliegende Arbeit gibt eine Präsentation der modernen Werkzeuge für schonendes Sprengen die in Schweden und im Auslande in grossem Umfang zur Verwendung kommen.

INTRODUCTION

Underground construction in rock is a Swedish speciality with its roots in the early mining industry in the 15th century. The mining tradition has been continued into our day, and LKAB's iron ore mine in Kiruna in the north of Sweden is the world's largest underground mine. In recent years, many large underground construction jobs have been completed in the competent Swedish rock for a variety of purposes, primarily for hydroelectric power plants, military and civil defence installations, and for storage (Figure 1).

The development of modern methods for such large scale excavation and construction in rock has been, and is, a continuing joint effort involving important sections of modern Swedish industry. To "build in rock" has become a normal part of our way of house building and construction for a modern industrial society.

In 1975, 21 Mm^3 of rock was excavated underground in Sweden. Out of this, no less than 5.6 Mm^3 was tunnelling and about 2 Mm^3 was underground construction other than tunnelling. The total length of tunnels excavated in 1975 was nearly 50 miles, or 6 miles per million inhabitants (Brännfors, 1977). The methods of careful blasting and particularly smooth blasting were used for more than 80% of the tunnelling and for practically all of the other underground construction. All contour blasting was done using the Nitro Nobel GURIT® and NABIT® special charge system.

It is the purpose of this paper to present the engineering background and practical experience with these methods.

The terms to describe different methods of reducing the damage effects of blasting have not become universally standardized, and one word is often used by different authors to mean different things. To avoid misunderstandings, figure 2 gives some definitions of the terms used in this paper.

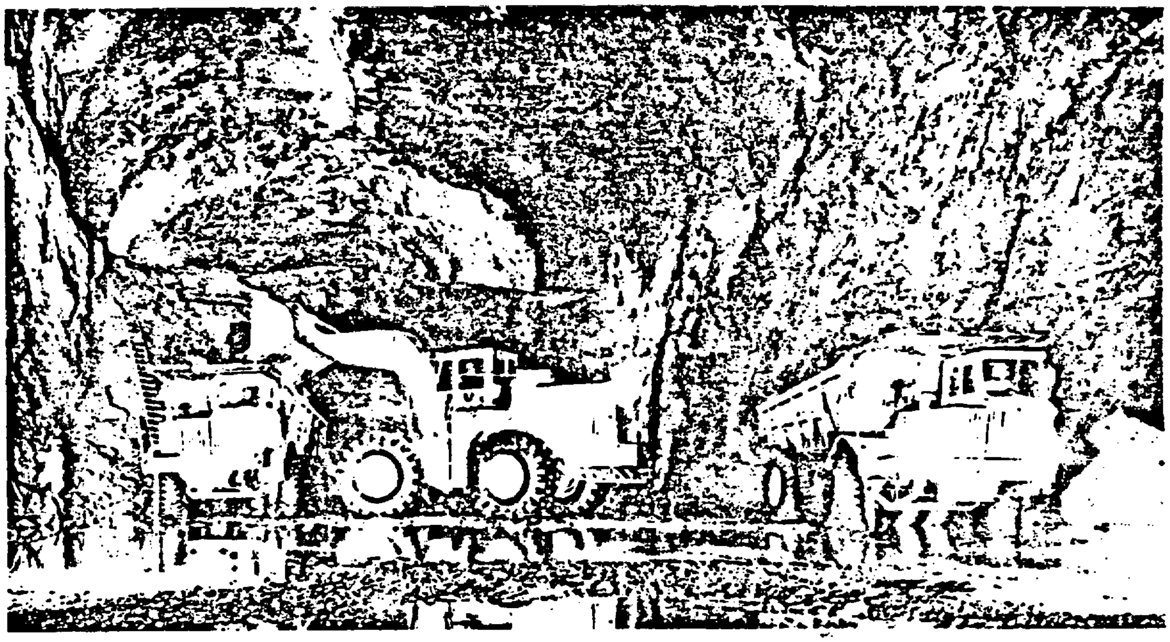

Figure 1. An oil storage chamber under construction. The gallery and part of the horizontal hole bench is excavated. Drilling of the vertical hole bench has not yet started.

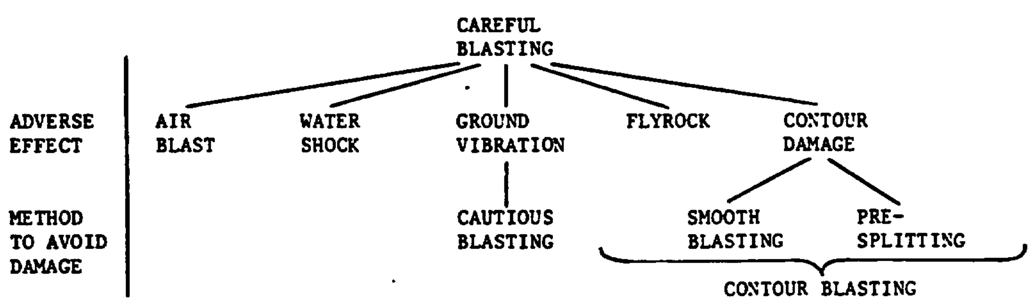

Figure 2. Methods to prevent blasting damage. The term "contour blasting" is used here not only to describe blasting that produces a geometrically clean-cut contour but also blasting that is controlled by the requirements of strength and stability of the remaining rock adjacent to the contour. It includes several methods other than smooth blasting and presplitting, but these have found limited practical use underground and are not dealt with in this paper.

THE IMPORTANCE OF DRILLING

The quality, strength, and stability of an underground cavern is determined to a large extent by the quality of drilling. The boreholes are drilled to get neither more nor less than the required weight of explosive inside the rock in such a way that the explosive energy is distributed within the rock in a precisely predetermined manner. A stable and strong cavern cannot be produced with a large random scatter in borehole positioning and hole direction.

Particularly important in this respect are the contour holes. These should be drilled with as small a look-out angle as possible and be kept as parallell with the axis of the tunnel as is possible. This produces a high strength even arch, minimizes overbreak and brings down the consumption of concrete for lining.

But the vibration and damage in the remaining rock caused by a given charge also depends on the ease with which it can break loose its burden (the fixation or constriction factor). Thus, hole deviations and positioning errors that increase the burden or the degree of fixation (constriction) always make the charge produce more damage to the remaining rock than it would otherwise have done (Langefors & Kihlström, 1963). And this is true for all holes in the blast, not only for the contour holes.

Modern drill rigs are now increasingly being equipped with devices for automatic look-out angle setting and with instruments for aiming the boreholes in the correct direction. Equally important is careful setting-out of the positions of the bore-holes. For checking the resulting tunnel profile, photo-sectioning that can now be made by a laser and a rotating prism or mirror is a useful method.

BLASTING WITHOUT DAMAGE

Blasting for underground construction purposes is a cutting tool, not a bombing operation. In the early days of cavern-building for underground oil storage it was thought that as long as the required volume of rock was removed, it would not matter greatly if some parts of the roof caved in. We now know better. The functional requirements and the presence in the cavern of pumps, tubes, and perhaps heating systems make it imperative that the cave contour is well defined and stable. The cavern also must be a safe place to work in during the time of construction. This makes it necessary to plan and carry out the entire blasting operation - gallery, first and second bench - carefully and in a controlled manner with respect to the strength and stability of the final wall and roof. This does not mean necessarily more expense. The use of the minimum required charge weights and accurate bore hole positioning often leads to considerable savings in the explosives consumption, less drilling, and better fragmentation (Gustafsson, 1973).

Ground vibrations and rock damage.

The connection between ground vibrations and blasting damage to nearby constructions has long been known and damage criteria have been established. The same basic principles are applicable for estimating and predicting damage not only to nearby already completed caverns and tunnels in rock but also to avoid damage to the remaining rock adjacent to the new contour exposed by the blast itself.

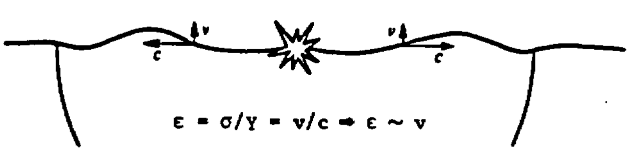

Figure 3. The interrelation between strain (ε), stress (σ), and vibration velocity (v). c is the wave propagation velocity and Y is the elastic modulus of the rock mass.

Fundamental to rock damage is stress, and stress is produced by the bending or stretching caused by the vibration of the rock. Figure 3 shows the simplest case of blasting a charge near a flat rock surface. The sudden expansion of the charge produces a stress wave that propagates over the surface like rings on the water. Downwards, the stress wave affects a semi-spherical volume as indicated in the figure. Each portion of the wave has a characteristic propagation velocity c that is some fraction of the sonic velocity which is a material property of the rock mass. As the wave passes, each particle in the rock mass runs through a vibrational motion, the peak particle velocity of which is v. In the sine-wave approximation, and for an elastic material, the strain ε and stress σ are related to v in a simple way,

$$\varepsilon = \sigma/Y = v/c; \quad \varepsilon \sim v \tag{3.1}$$

where Y is the elastic modulus of the rock mass. Thus, for each kind of rock mass and each type of wave, rock damage occurs at approximately a given critical level of particle velocity.

For predicting v, we make use of a relation between v, the charge weight Q, and the distance R to a single charge.

$$v = 700\ Q^{0.7}/R^{1.5} \tag{3.2}$$

In equation (3.2), v is in mm/sec, Q in kg, and R in m. For an extended charge, we get a first approximation of the resulting v by integrating (3.2) with respect to the position along the charge, neglecting the difference in arrival time of the elemental waves from different parts of the charge. The result is in reasonable agreement with observed velocities over a large range of distances and hole diameters (Persson, Holmberg and Persson, 1977).

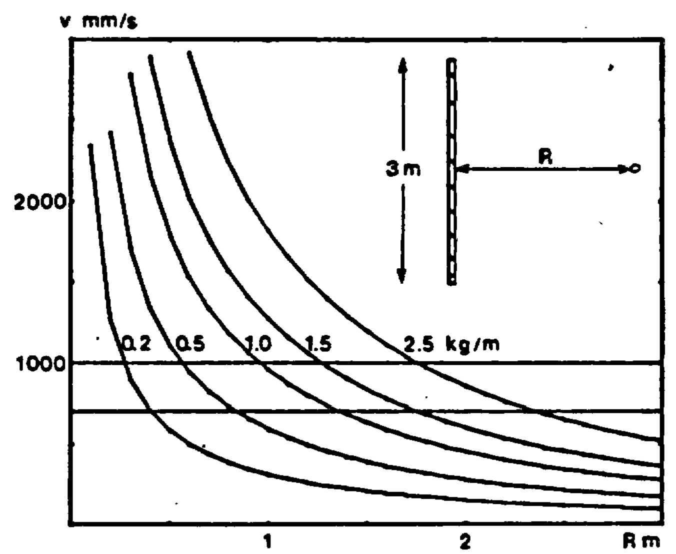

Figure 4. Estimated vibration velocity as a function of distance for different linear charge densities. Linear charge densities are given in kg Dynamex B per meter bore-hole, equivalent to 1.14 kg ANFO per meter.

Figure 4 shows a diagram of v as a function of R, the perpendicular distance to an extended charge, with the linear charge density (charge weight per unit length of borehole), ℓ, as a parameter. For a rock mass which gives incipient fracture at a vibration velocity within the range 700-1000 mm/sec, we find the radius of the zone of incipient fracture to be about 0.25-0.35 m around a 3 m long, 45 mm diameter borehole charged with a 17 mm GURIT charge. This charge has a linear charge density of 0.24 kg/m which is equivalent to

0.20 kg ANFO/m.

The fundamentals of smooth blasting and presplitting.

In smooth blasting and presplitting the linear charge density in the contour boreholes is made very low compared to that in ordinary blastholes. This gives a low initial borehole pressure. In this way the main result of the contour blast where the holes are allowed to cooperate is a crack that runs from borehole to borehole, and the damage to the remaining rock is limited within a narrow zone close to the contour.

In smooth blasting the contour charges are initiated last in the round. In presplitting, the contour charges are initiated before the rest of the charges, mostly in a separate round. The crack running from hole to hole then has to be accommodated by elastic deformation of the rock on both sides, because no rock is broken loose. Therefore, presplitting needs a closer spacing of contour holes, about 50-75% of that for smooth blasting, and presplitting thus becomes more expensive (Figure 5). Because of this, and because it is often difficult to fit in an extra blasting operation in the shiftcycle, presplitting is used very seldom underground in Sweden. Smooth blasting is the main method used, particularly in tunnelling.

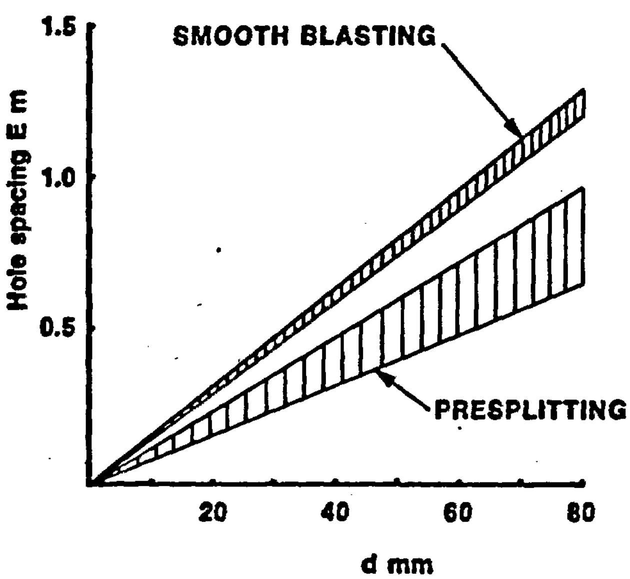

Figure 5. Recommended ranges of hole spacing as a function of hole diameter for smooth blasting and presplitting

Smooth blasting: $E = k_s d$, where k_s = 15-16.

Presplitting: $E = k_p d$, where k_p = 8-12.

Figure 6 shows a curve of the minimum required linear charge concentrations for smooth blasting and presplitting versus hole diameter, and the corresponding recommended special charge systems.

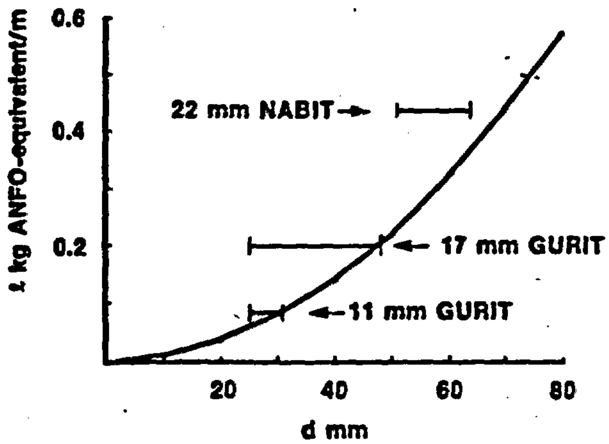

Figure 6. Empirical minimum required linear charge concentration for smooth blasting and presplitting as a function of hole diameter (full curve, $\ell = ad^2$ where $a = 90$ kg/m^3) and recommended practical hole diameter ranges for NABIT and GURIT charges.

The ratio between hole spacing E and burden V for smooth blasting should be kept well below unity. The normal recommendation is

$$E/V \leq 0.8.$$

In this way the damage to the remaining rock is minimized.

For best results in smooth blasting, the charges in the contour should be initiated simultaneously so that they can cooperate completely. However, because the extension of the crack between the holes involves the relatively slow dynamic motion of the considerable mass of material within the burden, the latitude for time scatter in the times of detonation is larger than might be expected.

Table 1 shows the factors that determine the initial borehole pressure, i.e. the pressure of the reaction products before they have done any work on the rock. For ease of understanding the table has been made for one drillhole diameter.

Ideally, in homogeneous rock, smooth blasting could be done equally easily with holes of any diameter, by choosing the charge diameter and the hole spacing proportional to the hole diameter to keep the initial borehole pressure and the resulting rock stress the same. If the borehole pressure were low enough, so that only cracks connecting the holes were created, then the large diameter holes would give no more damage to the remaining rock than the small diameter holes.

Table 1. Initial borehole pressures for different explosives and charge diameters.

Explosive	Dynamex B			ANFO	NABIT	GURIT
Hole diameter, mm	45	45	45	45	45	45
Charge diameter, mm	45	40	32	45	22	17
Explosive density, kg/dm^3	1.15	1.45	1.45	0.95	1.1	1.2
Weight strength (ANFO = 1)	1.14	1.14	1.14	1.0	1.09	0.83
Linear charge concentration						
real, kg/m	2.0	1.6	1.12	1.5	0.40	0.24
kg ANFO/m	2.3	1.82	1.28	1.5	0.44	0.20
Initial borehole pressure						
bar	55,000	32,000	13,000	21,000	3,300	900
MPa	5,500	3,200	1,300	2,100	330	90

Table 2. Recommended smooth blasting parameters using the GURIT and NABIT systems.

Drill hole diameter, mm	Charge concentration, kg ANFO/m	Charge type and size	Burden, m	Hole spacing, m
25-32	0.08	11 mm GURIT	0.30-0.45	0.25-0.35
25-48	0.20	17 mm GURIT	0.70-0.90	0.50-0.70
51-64	0.44	22 mm NABIT	1.00-1.10	0.80-0.90

In real rock, there is always a given structure of already existing cracks, weak planes, flaws, and fissures. These are more easily damaged than the homogeneous rock. In reality, therefore, the large hole diameter smooth blasting gives an inferior result and more damage to the remaining rock than the small hole diameter smooth blasting. Because of the rock structure, the large diameter charge creates damage within a large zone, whereas the small diameter charge has a very limited damage zone (Persson, 1973).

SELECTING EXPLOSIVES AND DETONATORS.

Explosives

The choice of explosives for contour blasting is determined by the required strength, stability, and lifetime of the completed construction. Even though there is an increasing demand for careful blasting of mining drifts because of labour safety requirements, the lifetime of a mining drift is limited. In a machine hall in an underground hydro-electric power plant the situation is different. There, the roof must be 100% safe against falling rock for the very long lifetime of the plant.

In the former case it can be acceptable to use a somewhat stronger charge such as the 25 mm NABIT in a borehole diameter down to 38 mm. For the roof of the machine hall it is necessary to prescribe the use of 17 mm GURIT and a hole diameter up to 48 mm. NABIT is a nitroglycerine sensitized explosive of a strength approximately equal to that of ANFO; GURIT is also a nitroglycerine explosive but with a deliberately low gas volume and explosion energy.

A great deal of effort has been put into the development of these special charges to ensure reliable functioning of such a low energy linear charge when it detonates in a borehole of a diameter considerably larger than the charge (Johansson & Persson, 1970). Table 2 shows the full range of recommended drillhole diameters, burden, and spacing for the standard range of special NABIT and GURIT charges. In the table, the charge concentration is given in equivalent weights of ANFO (Table 2).

Table 3 shows the characteristics of GURIT. This explosive system has been used for more than 20 years for a great variety of smooth blasting and presplitting applications.

It is very easy to ruin the results of a well planned smooth blasting by charging the rest of the holes in the round carelessly with a high charge concentration. We can see from figure 4 that a 48 mm drill hole fully charged with ANFO with a linear charge concentration about 1.8 kg/m gives a crack zone of more than 1.5 m. The recommended burden for a 17 mm GURIT charge in a 48 mm hole is 0.8-0.9 m (Table 2). Obviously the row of holes next to the contour row also has to be charged with a reduced charge concentration.

Table 3. Functional characteristics of GURIT

Detonation velocity	m/sec	≈ 4000	
Gas volume at NTP	m^3/kg	420	
Working factor	kJ/kg	3700	
Weight strength relative to ANFO		0.83	
Charge diameter	mm	11	17
Charge concentration	kg GURIT/m	0.11	0.24
Charge concentration	kg ANFO/m	0.08	0.20

Detonators

The time interval between detonation of adjacent contour charges is important for the result of smooth blasting and presplitting. It has been found by practical experimentation that the shorter the time interval the better the result will be. This implies that the best result should be obtained if the contour holes were initiated simultaneously. This can be done in presplitting and also in smooth blasting if the contour holes are initiated separately in a special round. Both of these methods are expensive and difficult to fit into a modern high productivity cycle of operation. More usual is to combine, as is done in many parts of the world, in tunnelling, the millisecond delay series of detonators with the half-second series. The half-second detonators will then be used for the smooth blasting row. Because the time scatter in the half-second delay series is large (100-200 milliseconds) this means that the result of the smooth blasting is not as good as it could be.

A better result is obtained by using the Nitro Nobel VA-SYSTEM® of detonators. This system has delay intervals of a length between the millisecond and the half-second series (Table 4). The considerably smaller scatter of the 100 millisecond VA-MS series gives a better smooth blasting result and also an increased advance per round than the half-second series.

Table 4. Detonators, interval numbers, and interval times.

Type of detonator	Interval No.	Interval time millisec	Scatter millisec
VA-MS	0-20	25	5-10
VA-MS	24-80[1)]	100	20-50
VA-HS	1-12	500	100-200
NONEL	3-20	25	5-10
NONEL	24-80[2)]	100-150	20-50

1) This series has the numbers 24, 28, 32,....80.

2) This series has the numbers 24, 28, 32,....44, 50, 56,....80.

The advantage of electric firing is the controlled firing sequence obtained by means of short period detonators and also the control of the instant of initiation. One disadvantage is, however, the risk of unintentional initiation through other sources of electricity. The VA-SYSTEM has a relatively high built-in degree of safety, but there are still numerous regulations to be satisfied and in some cases even the VA detonators are not allowed. Traditional non-electric firing systems do not always provide the precision required for modern blasting technique.

The new NONEL® initiating system, however, is a non-electric initiating system that is an alternative to high-energy electric detonators. It can satisfy the same demands for precision timing and controlled blast initiation and it is used more and more in underground applications. The basic feature in this system is the invention of the NONEL tube, i.e. a small plastic tube transporting a self-sustaining shock wave (Persson, 1967, 1968, 1976).

The Nitro Nobel NONEL detonators are available in any required length and the range of delays is 30 periods, comprising 25, 100 and 150 millisec intervals. The time scatter is kept within the same narrow limits as for VA millisecond delay detonators to suit tunnelling where very high quality smooth blasting is demanded (Table 4).

BLAST PLANNING, SUPERVISION AND CONTROL

Because the remaining rock is an integral and loadcarrying part of each underground construction, it is necessary that the rock is left as intact as possible after the blasting operations are completed. This necessitates careful planning, supervision, and control. Firstly, the rock surface to be exposed must be protected during the blast by a well-planned smooth blasting of the contour and by designing the charge pattern of the adjacent row so that cracks spread no longer from this row than from the contour row.

Secondly, even when the contour blasting has been successful, the result can still be spoiled by later rounds. In an oil storage chamber, for example, an originally intact roof may be damaged by blasting the lower bench without due care to the ground vibrations. A gallery roof in granite should not be exposed to a higher ground vibration velocity than 70-100 mm/sec to avoid such damage. Rock fall has occurred in the past in several cases bringing a risk of injury to personnel and damage to equipment. When the height of fall is perhaps 30 m, the consequences of such a fall could be catastrophical.

Many oil storage chambers are built today quite close to older chambers that are already full of oil. In these cases blasting must be planned and executed with an eye to the possible effects in the roofs of the older chambers due to the ground vibration. Another important factor is the accompanying air blast that could damage the concrete plugs.

Rock falling from the ceiling of an oil-filled chamber can do considerable damage to the tube system and pumps. It is no easy task to take care of securing such a failed roof in a chamber full of oil. By measuring and monitoring the ground vibration and air blast, the blasting can be controlled and the risks brought down to a minimum.

COST

The innocent rock mass often gets the blame for insufficient stability that is really due to rough and careless blasting. Where no precautions have been taken to avoid blasting damage no knowledge of the real stability of the undisturbed rock can be gained from looking at the remaining wall. What one can see are the remains of what could have been a perfectly safe and stable rock wall, had the available techniques for contour blasting been applied. The damaged ceiling and walls of an underground chamber in rock often need an amount of support and reinforcement that reflect the extent of blasting damage caused rather than the real available rock mass properties.

This can be seen particularly clearly in the case of a low strength rock mass where a tunnel can be given a sufficiently long stand-up time for safe excavation work to continue, simply by careful contour blasting followed quickly by a light shotcrete treatment to prevent the early motion that is so damaging to the long term stability of the finished tunnel.

When weighed against the very high cost of a different driving method and more extensive support, reinforcements and safety measures, the actual cost of contour blasting is often negligible.

The additional cost of contour blasting is proportional to the surface area of contour exposed by the blast, and it increases with increasing borehole diameter in the rest of the round. Several minor factors enter into this cost, such as the seemingly higher price of the special charges (compared to the same weight of a standard explosive), the cost of extra detonators, and the extra work of loading a small quantity of explosive into a large number of holes. The main cost factor, however, is the extra drilling necessary because of the relatively small burdens that the reduced charges can remove.

In the price level of 1975, this cost is of the order of 10-20 Sw.Crs./m^2 contour area depending on the borehole diameter in the main blast. The higher figure is characteristic of the large diameter boreholes that require considerable reductions of charge in one or more rows of holes adjacent to the contour row.

When we consider that a normal oil storage chamber has 0.03-0.04 square meters of ceiling area per cubic meter of volume, the additional cost for good contour blasting is a very small price to pay for obtaining a strong, stable roof with a minimum of support and reinforcement, and reliable functioning of the storage facility.

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