

FRAGMENTATION SYSTEMS

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Summary

A survey is made of such systems used for fragmentation of in-situ rock that are in large-scale use at the present time. The survey is thus concerned with fragmentation by blasting, drilling and boring mainly by conventional methods. It gives a basis and a background for future work in the field.

The report contains the pre-print text for the English version of the "General Report, theme 5, "Fragmentation Systems" by the same authors for the 3rd ISRM Congress, Denver. Colorado 1974.

GENERAL REPORT OF THEME 5
Fragmentation Systems
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Systemes du Fragmentation
GENERALBERICHT DES THEMAS 5
Systeme der Zerkleinerung

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Introduction

This paper will be concerned primarily with fragmentation as a technical and economical problem in present day rock excavation. It is an attempt to give, as a background to future developments, an overall picture of the well-established, smoothly operating, conventional drilling and blasting or mechanical boring techniques.

Fragmentation is always a means to an end - the fragmented rock material will always be handled or used in one way or the other. The economy of the overall operation, be it a mine, a dam, or a construction site will nearly always be influenced considerably by the condition of the muck pile, its block size distribution, the amount of secondary blasting necessary (if at all), and the ease of mucking that depends on the way in which the material is packed together in the pile.

When we talk in general terms about improving

fragmentation we really ought to say controlling fragmentation, because not always do we mean only decreasing block size generally and decreasing the number of large boulders specifically. Sometimes, as in dam building, there may be a need for controlling fragmentation with other goals in mind, such as to produce large numbers of regularly sized large blocks. In such cases it can be necessary to choose the machine equipment after the required size of the blocks. Most common is, however, that the fragmentation has to be adjusted to the existing shovel-loaders, trucks and rock-crushers.

Below we will first discuss the most common means to "improve fragmentation" in blasting, and then go on to treat the fields of drilling and boring. It is hoped that the stress laid on the conventional present-day methods will be helpful both in work aimed at improving these methods and in work aimed at

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replacing them with new and better techniques.

It is necessary, and sometimes to be preferred, that the authors' own experience somewhat dominates a report such as this. Undoubtedly, hard rock fragmentation therefore has come to dominate this report. It may not be necessary to apologize for this, but it should be mentioned at the outset.

Fragmentation by blasting

Specific charge and critical burden

The two most important ways to improve fragmentation in blasting consist in increasing the specific charge and reducing the burden. According to Langefors and Kihlström (1963), and Langefors (1965), the average boulder size L will decrease with the specific charge q at different burden V in the case of bench blasting, in the manner shown in Fig 1. Using this diagram, in which the hole distance is $E = 1.25 V$, one experimental point, e.g. on the curve for $V = 2$ m, is sufficient as a basis for plotting a series of curves for other V -values as well, with good reliability. The points in Fig. 1 have been observed for $V = 1.1$ m.

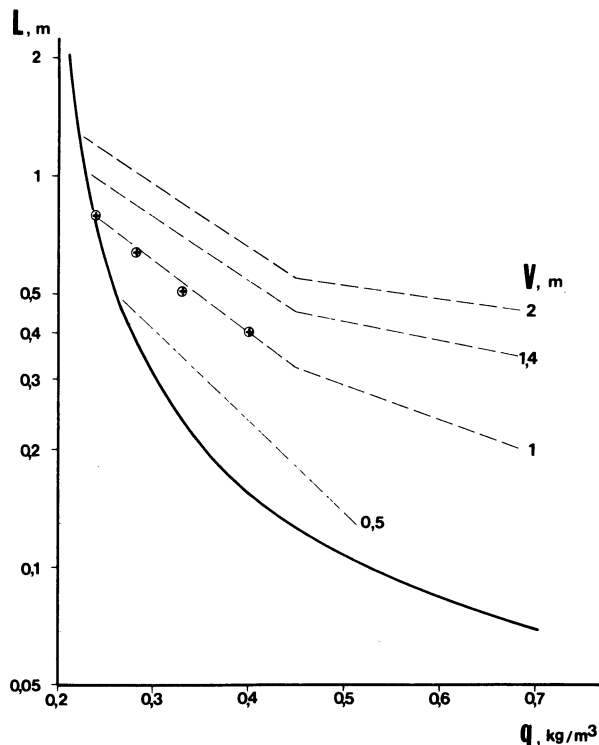


Fig. 1. Average boulder size as a function of the specific charge with the burden as parameter. L indicates the average side length of the weight average of the largest boulders including 90% of the blast rock mass.

Short delay multiple-row rounds

Short delay blasting was primarily introduced as a means of reducing ground vibrations at blasting. Before long, however, fragmentation was found to be much improved by the introduction of multiple-row

rounds, owing to, among other things, the fact that the specific charge could be increased without hazardous throw. On one hand, the short delay time between the rows is long enough to allow the rock of one row to move away, and the free face of the following row to be uncovered prior to the detonation of its charges. On the other hand, the short delay time is so short that the rock from the previous rows will still be hanging in the air, and thus will curtain blocks from the subsequent rows moving with a speed above the average. Besides that, collisions between blocks moving with different velocities will very much contribute to the fragmentation.

The optimal delay time τ , that is the delay time at which the best fragmentation is achieved, is a function of the burden V . According to Langefors and Kihlström (1963), for burden between 0.5 and 8 m,

$$\tau = k \cdot V \quad \dots\dots\dots (1)$$

where k is 3 to 5 ms/m.

The wide-space blasting method in short delay multiple-row rounds

If the hole spacings E in the rows are increased keeping the product $E \cdot V$ constant, the fragmentation in short delay multiple-row rounds will become improved. This method, proposed by Langefors and investigated in model scale (1965), has now been worked out and tested in full scale by Persson and Ladegaard-Pedersen (1970). The ratio of spacing E to burden V has previously been kept in the range of 1 - 1.3. Through systematic investigations using model tests with the product $E \cdot V$ constant, the fragmentation was found to increase with E/V up to $E/V = 8$. The causal connection is principally simple. Fig 2 a-c shows schematically one-row rounds with E/V from 0.25 to 4. At $E/V = 0.25$ the burden is a layer, the thickness of which is four times the spacing or distance between the holes. It is easily seen that it will be thrown out as a whole, divided in a few blocks. At $E/V = 1$ the course of events is similar, but the cracks from each charge assert themselves more and the fragmentation will improve. At $E/V = 4$ there will be little co-operation between the charges in the one row round. Using multiple-row rounds, however, the sections between the holes in each row will be loosened and fragmented by the charges in the following rows. At high values of the ratio E/V , for instance $E/V = 8$, a satisfactory

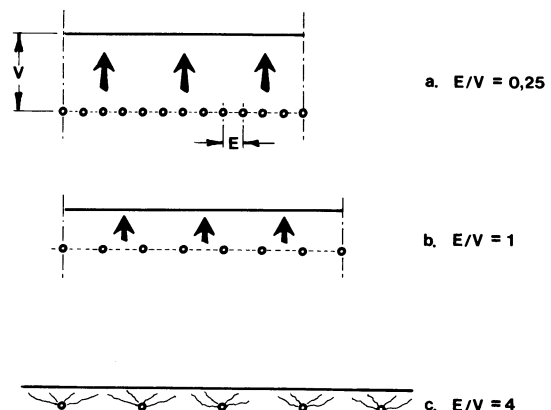


Fig. 2. One-row rounds.

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fragmentation is achieved when every second row is displaced sideways half the distance between the holes. Table I gives some comparative results for granite (Umeå) and limestone (Stora Vika). At both places the bench height was 20 m and the hole diameter 78 mm (3 in). Fig 3a shows the drilling and ignition delay pattern for a round of 66 holes in 7 rows with $E/V = 6$, and Fig 3b gives a picture of the pile of rock after the round. To the left, where the mucking has started the remaining boulders can be seen. According to table I the total number of boulders in limestone was 47 per 1000 m³ of rock as compared with 121 for $E/V = 1.25$ and in granite 90-112 in 5 rounds with $E/V = 4$ as compared with 171-219 for $E/V = 1.25$. The mucking capacity increased from 1500 to 2000 ton/day, and the total costs for drilling, blasting and mucking dropped from 1.50 to 1.30 \$ per cubic m. It should be emphasized that the results of the tests carried out in plexiglass models have been the necessary basis for the work in full scale. Without the thorough

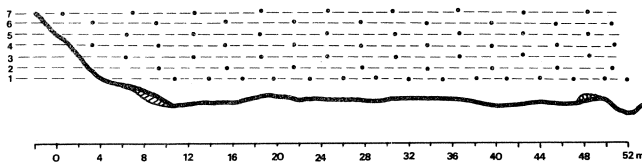


Fig. 3a. Drilling and ignition pattern of a seven-row round with $E/V = 6$



Fig. 3b. Photo of the round in fig. 3a after blasting. The mucking has started to the left.

knowledge of the influence of the different factors thus achieved, it would have been impossible to propose testing in full scale. The wide-space blasting method is now used in production blasting at Umeå and many other sites in Sweden and abroad. This is also the case in the mining of sulphide ore by cut-and-fill stoping at several Boliden mines. In this case the holes are 35 mm in diameter, 4 m deep and the ratio $E/V = 3.5$.

The superior fragmentation associated with the wide-space blasting method may also be obtained with a "square" drilling pattern by suitably choosing the ignition delay pattern. Fig 4 shows the drilling and ignition pattern in which the rock is thrown at an angle of 25-30 degrees to the rows of boreholes. This method is particularly attractive where the blasting and drilling operations are carried out separately at widely different times.

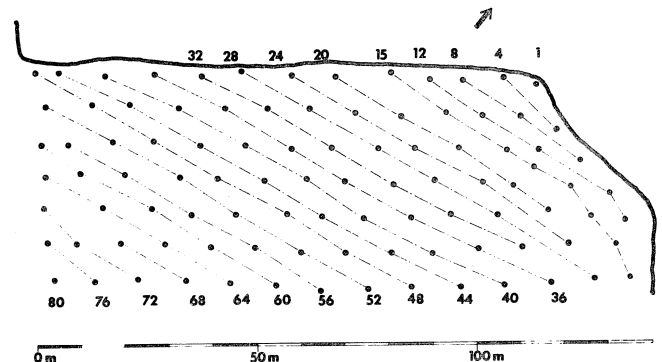


Fig. 4. How to use the short interval delay pattern to produce a blast with wide hole spacing from a nearly square drill pattern. Numbers indicate the cap number used in each row of holes connected by a dot dash line. Time interval between rows is 100 msec.

Bench blasting with auxiliary holes between the main holes

In bench blasting with large bore hole diameters a large part of the upper part of the holes must often be left unloaded in order to prevent fly rock from the hole openings. This, however, often results in the production of large boulders from the upper unloaded part of the bench. By the addition of short auxiliary holes of smaller diameter between the main holes it is possible to achieve a more satisfactory result. Fig 5 gives an example of a bench round where the maximum throw forward had to be kept within 15 m (50 ft). (Langefors and Kihlström, 1963, p 61). The holes were inclined. The main holes, 50 mm in diameter (2 in), were drilled to full depth and charged only to induce breakage and swelling, including the necessary technical margin. The auxiliary holes, 32 mm in diameter (1 1/4 in) were drilled to about half the depth and charged near the limit for full breakage of the rock in front of them, but with no throw. With this

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Table 1. Comparison between conventional rounds using E/V = 1.25 and 1.5 with wide-spacing rounds using E/V values between 4 and 5.

	Granite (Umeå, Sweden)		Limestone (Stora Vika, Sweden)			
	1.25	4.0	1.5	4.3	6	8
E/V	4	5	8	1	1	1
Rounds	4	5	8	1	1	1
Holes/round	10-44	41-68	39-69	67	66	45
Rock volume 1000 m ³ /round	1.3-5.9	4.0-7.4	4.7-8.3	11.1	7.9	5.8
V m ²	2.0-2.3	1.3	2	1.4	1	0.9
EV m ²	5-7	6.7	6	8.4	6	6.5
Hole diam. mm	76	76	76	76	76	76
Spec. charge kg/m ³	0.43	0.67	0.53	0.44	0.51	0.49
Spec. drilling m/m ³	0.15	0.19	0.17	0.12	0.17	0.16
Boulders/1000 m ³	171-219	90-112	121	57	47	86
Mucking ton/day	1500	2000				
Costs US\$/m ³ :						
Drilling	0.20	0.26				
Blasting	0.27	0.35				
Boulders	0.35	0.17				
Mucking	0.65	0.50				
Total	1.45	1.26				

drilling pattern, a fragmentation corresponding to the small burden of the small holes was obtained without drilling all the holes to the bottom. Perhaps because of the practical complications of operating two types of drilling equipment, this method has not been used extensively.

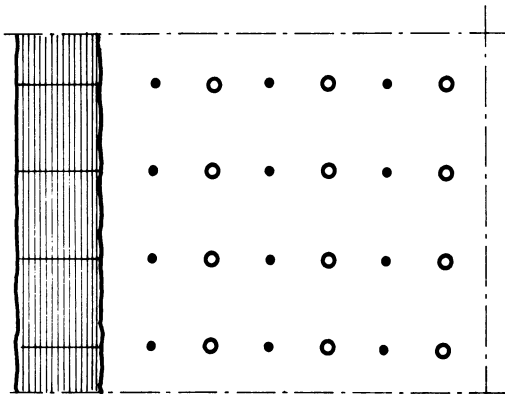
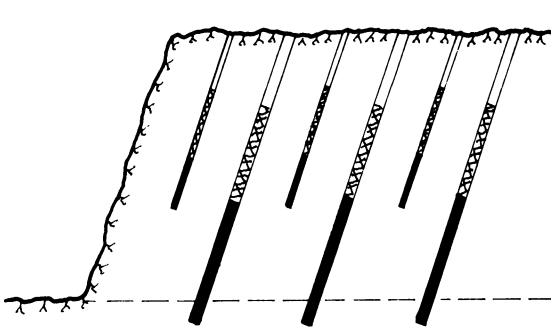


Fig. 5. A method of improving fragmentation in a blast using large borehole diameters.

Tunnel blasting

In tunnel blasting, the specific charge is much greater than in bench blasting. One reason for this is that many of the holes do not have a free angle of breakage, i.e. the angle of the free surface as seen from the charge is small, say less than 90 degrees. This is particularly the case for the cut holes.

Another reason is the dependence of the strength of rock on the lateral pressure. Fig 6 shows after Lundborg (1968) the shear strength of granite, steel, and plexiglass as a function of the lateral pressure, as determined with an experimental arrangement according to Fig. 7. The strength of granite increases considerably with the compressive stress and exceeds even the strength of steel. Shear tests carried out on fourteen kinds of Swedish rocks and four ores have given results that follow the expression

$$\tau_n = \tau_0 + \frac{\mu p_n}{1 + \mu p_n / (\tau_i - \tau_0)} \dots (2)$$

τ_0 and τ_i are the shear strength at $p_n = 0$ and $p_n \rightarrow \infty$ respectively. p_n is the normal pressure at the surface of rupture and μ is a constant of friction. Mean values for five granites are $\tau_0 = 0.5$ kbar, $\tau_i = 10.0$ kbar and $\mu = 2.2$.

The drilling scatter, i.e. the deviation from the drilling pattern at the bottom of the boreholes, exerts a stronger effect in tunnel blasting than in bench blasting operations. This is a third and very important reason for an increased specific charge. (Langefors and Kihlström, 1963, p. 188).

A statistical theory which describes in more detail than equation (2) the strength of rock at arbitrary values of each of the three principal stresses has recently been developed by Lundborg (1972).

An approximate empirical relation between specific charge and tunnel area in blasting for tunnel areas from 4 to 100 m² is

$$q = 0.8 + 14/A \dots (3)$$

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where q is the specific charge in kg explosive per cubic meter of rock and A the tunnel area in m^2 . This relation however represents a heavy overcharge to get the extra margin for full breakage in and around the cut. Due to the high specific charge in tunnel blasting the fragmentation, as a rule, is good and no special measures have to be taken in order to ensure it. At small tunnel areas the specific charge decreases rapidly with increasing area as more and more of the additional drill holes have a free angle of breakage. This is also reflected in the cost per unit volume, which is rapidly decreasing with increasing tunnel area.

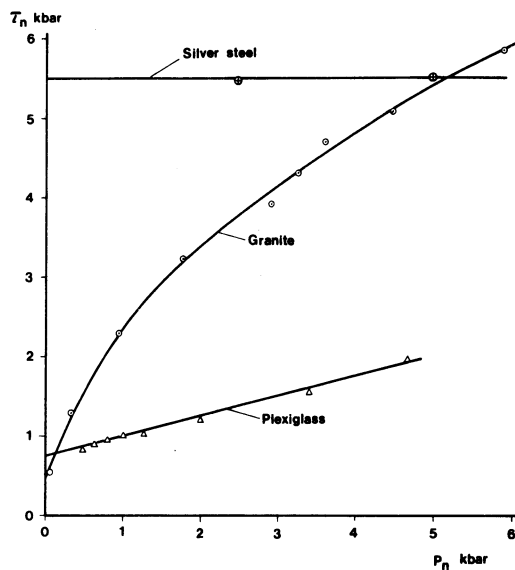


Fig. 6. Shear strength of granite, silversteel, and plexiglass as a function of normal compressive stress.

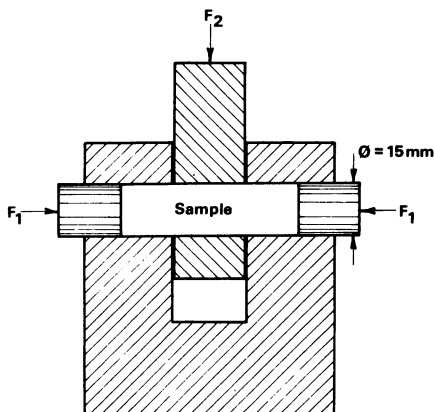


Fig. 7. The confined shear test.

Fig. 8 shows a log-log diagram according to Persson (1972), where the costs for excavating granite are plotted in dollars per litre or dollars per m^3 excavated rock, including hammer drilling of 25 to 75 mm (1 to 3 in) holes, rotary drilling of 250 mm (10 in) holes, full-face boring of a tunnel of

2.5 m (8 ft) diameter, and blasting of tunnels of 2.5 to 25 m (8 to 80 ft) diameter. Common for the different methods is the approximative relation valid for diameters from 0.025 up to 25 m (1-1000 in):

$$K = 2/d \dots\dots\dots (4)$$

where K is the cost expressed in dollars per litre of hole or tunnel volume, and d is the diameter expressed in inches.

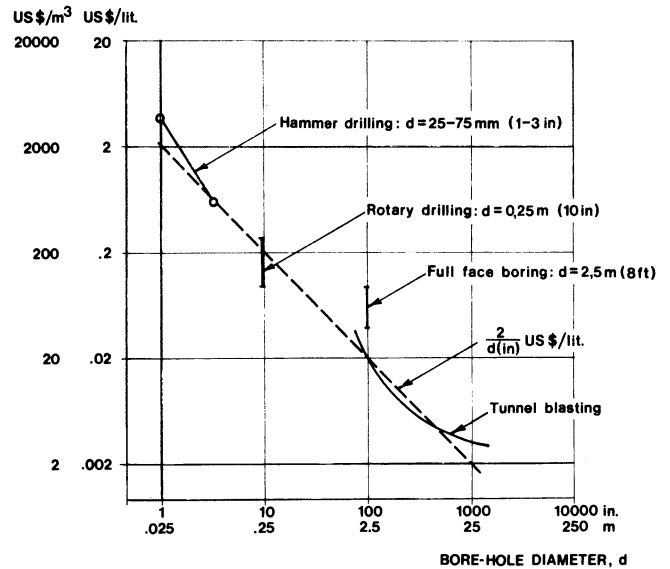


Fig. 8. Excavation cost as a function of cavity diameter in excavation of Swedish granite by hammer drilling, rotary drilling, full face boring, and tunnel blasting.

The Russian method of charges with air gaps MeInikov and Marchenko (1969, 1970), report that the Russian method of using charges separated by air gaps is now currently applied in the USSR at both open pit mines and underground mines for hard, medium hard, and soft rocks, and used by more than 100 enterprises mining ore, coal, and nonmetallic deposits. They report further that the average fragment size is reduced by a factor 1.5 to 2, the amount of boulders is reduced 2 to 10 times, the specific consumption of explosives has decreased 10 to 30%, and the productivity of mine transportation has increased 10 to 30% or even more. The optimum ratio of borehole volume to charge volume is 2 to 3. This means that the total borehole volume is increased by a factor 1.5 to 2.7.

Boreholes with empty space

In order to break loose rock at the bottom of the borehole, the bottom charge must have a greater breaking power per unit borehole length than that necessary in the column charge. If the entire borehole is filled with the same explosive, the hole will be overcharged. To avoid this, only 40% of the upper part of the hole volume should be filled. To achieve a satisfactory distribution of the explosive, one can resort to the old method of spacing or separating the cartridges with wooden sticks. As a rule the area of the cartridges as well as the sticks is much smaller than the hole area, therefore the empty space is usually quite considerable.

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The process of the initial gas expansion when a part of the hole is filled with air, is complicated, but, as a limit, it may be assumed to be isothermal and involve no borehole expansion. The subsequent isentropic expansion will then start with undiminished energy content of the gas but a lower pressure (Johansson and Persson, 1970, p. 64). The energy losses through the shock wave will become smaller than for a hole filled with explosive, and the useful external work per unit weight of the expanding gas will be larger.

Investigations have been carried out by Persson, Kihlström, and Ladegaard-Pedersen (1969) at bench blasting in a slab of granite, thickness 1-2 m, and free from the layer underneath through a horizontal fissure. These studies show that the above-mentioned effect can also be obtained with long narrow charges which do not fill out the entire hole volume. The burden was found to have a maximum for a given charge when the diameter of the borehole was twice that of the charge, giving a ratio of borehole volume to charge volume about 4.

Fragmentation by shock and stress waves

When the charge detonates in the borehole, the detonation wave will propagate along the hole with a velocity of 2000 to 7000 m/sec, or normally between 4000 and 6000 m/sec. At the front of the detonation wave, the pressure is between 5 and 500 kbar, or normally about 100 kbar, for a hole filled with a high velocity detonating explosive. If the borehole is packed full with the explosive, a pressure only about half the front pressure will initially act on the borehole wall due to the acceleration of the wall. If the charge does not fill the hole, the gas will expand radially and upon reaching the wall will exert a much smaller pressure. In either case the pressure will propagate out from the borehole into the rock as a shock wave with a conical front co-axial with the hole. A numerical calculation (Persson, Lundborg and Johansson, 1970) of the shock wave and stress field around a borehole indicates that radial cracks will first appear due to the tangential or hoop stress becoming tensional at a distance of 3-4 hole radii from the centre.

In a region extending to one or two borehole radii from the borehole wall, plastic flow due to the high radial and axial stresses appears to be likely. In an intermediate region, the preferred fracture mode might well be shear with open cracks having a direction at an angle to the radial direction.

This result of the numerical calculation agrees with results from model scale blasting in glass and plexiglass, where radial cracks always appear not at the borehole wall but some distance out into the medium. In cases where a high specific charge is used, the fragmentation is caused by the tension stress waves which are formed when the outgoing shock waves are reflected at the free surfaces. Through the co-operation of tension stress waves from different free surfaces, many spectacular effects appear. This has been beautifully demonstrated in plexiglass by Kolsky (1953) and in metals by Rinehart and Persson (1954). In rock blasting, the loosening and fragmentation of rock due to the action of shock- and stress waves, has been demonstrated in crater blasting by Obert and Duvall (1950), Hino (1959), and Duvall and Atchinson (1959).

The discussion whether the loosening and fragmentation of rock by blasting are due to the shock waves or depends on the external work of the detonation gases at their semi-static expansion at thermo-chemical equilibrium can now be considered to be completed (Langefors and Kihlström 1963, Persson, Lundborg and Johansson 1970, and Laroque and Favreau 1970). A necessary condition for the shock wave alternative, is the use of a high explosive, and - in hard rock - a specific charge not less than 1 kg/m³. In other cases no spalling due to reflected tension waves will occur. Instead the cracks will grow from the region of the borehole because of the thermo-chemical pressure of the detonation gases. Nevertheless, the influence of the reflected tension stress waves may determine which fractures will develop, and in which directions they will propagate (Field and Ladegaard-Pedersen, 1971, 1972). For concentrated charges at the bottom of a borehole with the depth equal to the burden, the theoretically calculated angle of the loosened part stands in good agreement with observed values: 90-100° in granite, and 135-140° in plexiglass. The difference is due to the difference in Poisson's ratio: 0.22 for granite, and 0.4 for plexiglass. For extended charges, the theoretical estimation gives 150-180° in granite, which is also in good agreement with observed values (Persson, Kihlström, Ladegaard-Pedersen, 1969).

The growth of cracks

The radial cracks around the boreholes, created by the transient stress from the outgoing shock wave, will grow under the influence of the semi-static stress field caused by the gas pressure in the boreholes. During this process, the hole volume will increase, and the gas pressure will drop accordingly.

A natural criterion for crack growth is that the energy released by the stress field at the crack tip as the crack grows an infinitesimal distance must equal (or exceed) the energy lost at the crack tip in the same process. The critical factor is thus the derivative of the elastic energy of the stress field with respect to crack length. The "surface energy" so defined is a material property that can be described in slightly different terms as the fracture toughness of the material. The criterion is closely similar to the Griffith criterion. Ouchterlony (1972a) has used it to determine the equilibrium length of the radial cracks at a given pressure or a given explosive loading density.

Estimates of the rate of flow of gas into the crack and the rate of crack growth indicate that the gas pressure in the major part of an extended crack is far less than it is at the borehole.

We may thus safely assume that the detonation gas pressure action will be limited to the borehole and its near surroundings. Using this assumption good agreement was found between calculated values for the maximum crack length and values observed at the abovementioned bench blasting in a granite slab of 1-2 m thickness (see page 5).

Da Gama and Nelson (1971) have investigated the initiation of crack growth around a borehole under the transient stress wave. They suggest that the radial pressure of the shock wave might weaken the material outside the near region of the borehole, by radial alignment of existing micro-cracks. It might then be easier for the subsequent tangential tension wave to initiate crack growth. Representative lengths of

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the resulting radial cracks were found to lie around 1 m. These two investigations show that models, where the cracks are taken into account in the treatment of the fragmentation process can be useful in explaining the course of events.

Some recent experimental determinations of the surface energy or fracture toughness of rocks have been carried out by, among others, Summers, Corwine and Chen (1971), and Lundborg and Almgren (1972).

An alternative formulation of the Griffith criterion for initiating growth of cracks, is found in linear fracture mechanics, where the elastic energy released at the crack tip at growth is investigated. Thus the initiation criterion in fracture mechanics is local and identical with Griffith's energy criterion which is global, but both criteria concern the relation between energy gradients with respect to crack growth.

A work by Porter and Fairhurst (1971) deals with investigations of the growth of cracks brought about by the pressure in a borehole, and the crack trajectories are shown to be in near coincidence with the main stress trajectories of the static stress field without cracks. Assuming the crack growth to be determined by the elastic energy density level present in the material at the tip of an imagined crack trajectory, the burden has a maximum at a given borehole diameter and gas pressure. Besides that, for lesser burdens the width of breakage will have a maximum.

Porter and Fairhurst are using a model where the crack growth is determined, not by the local energy gradient as in the Griffith or linear fracture mechanics criteria, but by the local energy density level. The question arises whether there exists a dualism between the two aspects since both appear to permit conclusions in agreement with reality. Kutter (1967, 1970) stands somewhere inbetween the two aspects, since he prefers to substitute equivalent circular holes, larger than the original boreholes, for his crack geometries, but still relates the critical load and the tensile strength respectively to Griffith's surface energy.

Stress analyses of crack geometries from the linear fracture mechanical point of view have been carried out by Ouchterlony (1972b). These are an extension of previous works by several workers. The quantities calculated are stress intensity factors, probable direction of crack growth and crack volume in the star crack as well as the circular hole with radial cracks of alternating lengths and also in the dihedral (V-shaped) crack. It is shown how the crack growth is affected by the number of cracks, crack lengths, and the penetration of gas into the crack system. The calculations show that irrespectively of the penetration of the expansion forces into a crack system, only a few cracks grow even when many are initiated as, for example, at the edge of a borehole, while the tips of shorter cracks close up. Closing of cracks also takes place in the dihedral crack, which can explain the existence of a minimum angle of breakage in bench blasting.

Fragmentation by drilling and boring^{1/}

Rock mechanics applied to hammer drilling

In the field of small hole drilling, the method mainly used is percussion drilling with hard metal bits. The rock mechanics at this type of drilling has been the subject of extensive research work. With experimental observations as a basis, it has been possible to work out theoretical models giving good understanding of the mechanical course of events starting from the formation of the impact wave, when the hammer hits the rod, the propagation of the wave through the drill rod and its joints, the destructive penetration of the bit into the rock and the reflected wave returning through the drill rod. These results have provided an indispensable basis for the constructive design of percussion machines with a suitable impact wave form, impact frequency, thrust force, wedge angle, etc. They have also made it possible to make use of improvements in the field of material technology immediately by increasing the loads on drill bits and drill rods. Percussive drilling is a well-established technique and practical experience during the years has been essential for the development of percussion drilling machines very close to optimal design.

Fairhurst has given a comprehensive survey of the results achieved and problems remaining in his General Report of Theme 5 on Comminution to the 2nd Congress of the International Society for Rock Mechanics in Beograd 1970. For the authors of this report there is not much to add. Hustrulid and Fairhurst (1971, 1972) have published a summing up of their investigations at the University of Minnesota. Their work is important because it emphasizes experiment and applications. During the last few years there has been a close cooperation with the Atlas Copco Research Center in Stockholm, Sweden. From this laboratory emanates a recently published work by Lundberg (1971).

His work stresses theory and basic mechanics and as he uses simplified models the work is helpful in giving an overall physical understanding of the entire drilling process including the stress wave transmission through drill rods, joints, and bit. Another valuable and important contribution of Hustrulid and Fairhurst is the study of the influence of the feed thrust.

Lundborg treats churndrilling and down-the-hole drilling and compares the effectiveness of these with that of hammerdrilling. He also studies the stress wave transmission through drill rods and joints.

Dutta (1972) has published an investigation on percussive drill bit penetration basing his work on a more detailed picture of the rock disintegration than those used by Hustrulid-Fairhurst and Lundberg.

Modern development of the drilling technique
Hardly any of the exotic drilling methods attracting great attention ten years ago constitute an economical reality today, except in the case of some limited, specialized fields of application. In the

^{1/} The authors are indebted to Mr Olav Meyer, Stockholm for valuable information regarding drilling and boring.

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foreseeable future the major part of all rock drilling most likely will still be performed by means of the mechanical action on the rock by steel or carbide tipped tools, even though several of the new concepts of tunnelling which are today on the feasibility study stage may well have more of an impact on the development than a person active in the applied work can now imagine.

The research work in the field of hammer drilling none the less would appear to have come to a certain completion. It is true that rapid progress is taking place within the field of drilling techniques, but many of the most important contributions to the development of drilling are in the region of machine design, material technology, mechanization, automation, and remote control. On these lines great progress has been made and essential improvements are on their way. The rapid development of hydraulic systems has greatly simplified the mechanization and made possible the close control over feed thrust force and impact energy necessary for today's increased drilling rates. Furthermore, the precision in collaring and directing the drill will become improved, which increases the efficiency of the entire blasting operation. One important step forward in drilling machinery consists in the development of hydraulic percussion units instead of pneumatic ones. Prototype machines of this kind are now being tested by different manufacturers. The increase in efficiency is particularly striking. It is estimated that, when applying electrically driven hydraulic percussion machines, 40-60% of the energy totally consumed will be converted into useful percussion work, as compared to around 10% in corresponding pneumatic system.

Even if this development were to be completely successful, however, there are many advantages with the pneumatic systems, and these will be used extensively for the foreseeable future.

Fragmentation by means of hammer drilling

In all the methods of fragmenting hard rock using conical or wedge shaped tools being pressed into the rock surface by impact forces, the common contention is that a part of the material becomes finely crushed, and the rest is sheared out as chips of dimensions of the order of millimeters (0.04 in). Fig. 9 shows an example of the grain size distribution in drill dust from two 76 mm (3 in) drill bits using a particular machine. As can be seen from the diagram, the average grain size was increased considerably through modifications of the flushing holes of the drill bit.

Problems of silicosis

In a series of investigations considering the risk for silicosis, K. Kihlstedt et al.^{1/} have found that all the particles with a diameter between 1 and 2 microns have a uniform negative charge which keeps the particles suspended in the air owing to mutual

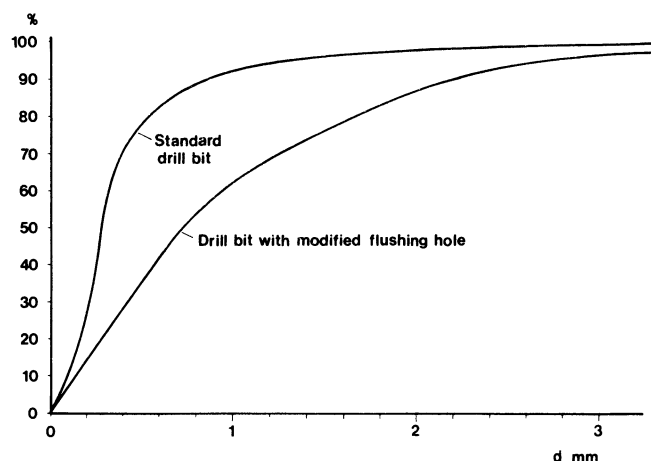


Fig. 9. Grain size distribution of drill cuttings from a 75 mm (3 in) diameter percussion drill bit.

repulsion. Fig. 10 shows an example of the distribution in a dust suspension formed during disc crushing of quartz. Different types of crushing of quartzitic minerals produce lattice distortion of variable intensity in the quartz. After rapid crushing this becomes for a time partly amorphous to x-rays (Lidström, 1968). Differential thermoanalysis indicates that large amounts of energy are stored in the distorted quartz lattice. It can further be shown that distortion of the lattice is accompanied by intense binding of water in the form of stabilized rigid water.

Experiments with rats^{2/} show that such fresh and rapidly crushed quartz from which iron impurities had been removed, gave rise to rapid development of silicosis which took up the whole thoracic cavity of the rat.

Reference quartz, which had been stored for some 10 years produced silicosis with a relatively slow rate of growth.

The conclusion would appear to be that inhalation of freshly produced quartzitic dust should be avoided especially if the quartz has been crushed by some rapid method. One possible consequence of these results may be that the idea of a permissible amount of silica dust, or hygienic limit value, expressed in grams of silica dust per cubic meter of breathing air will have to be revalued or reformulated.

It is known that the permitted dust index has been exceeded at some work sites without any incidence of silicosis while at other sites silicosis occurs in spite of the fact that all the regulations relating to the dust index have been scrupulously observed.

During the last few years, modern, convenient and efficient dust-collectors designed to be used in connection with modern bench drilling equipment have come into widespread use.

1/ Professor P.G. Kihlstedt, Royal Institute of Technology, Stockholm, Private communication.

2/ Under the supervision of Dr. Å. Svensson, assistant professor at the Occupational Medicine Clinic at Karolinska Institutet, Stockholm.

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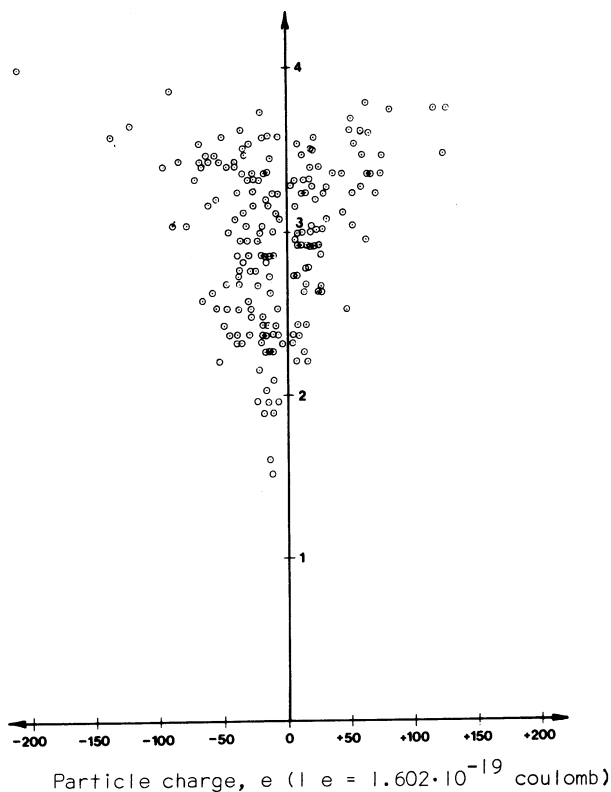


Fig. 10. Particle diameter and electric charge of Quartz dust from disc-mill.

Diamond drilling

As for diamond drilling, which is very much used in prospecting where long holes of relatively fine calibre provide the best economy, important economical improvements have been achieved through the mechanization of the process of handling and joining the drill rods and by an increased use of aluminum rods. Earlier heavy and time-consuming, this operation is now easily and rapidly performed. Progress in the techniques of bit manufacture is gradually increasing the bit life.

Full-face boring

Full-face boring machines have a rotating head that usually covers the entire tunnel area. In loose rocks, fragmentation is obtained by means of fixed drill bits or teeth cutting the rock material to pieces. In hard rocks, as a rule, the full-face boring machines are provided with rolling tools, each of them rotating around its own axis. From the point of view of rock mechanics, the fragmentation takes place in a way similar to that when chisel bits of hammer drilling machines are used. When the pegs or rolling edges of the rolling tool are pressed against the surface and penetrate into the rock, a fine crushing of the material is obtained, followed by the ejection of chips due to shearing forces.

An entirely different process of fragmentation is taking place in full-face rotary boring machines working according to the "Wohlmeyer principle" (Barendsen, 1969). The hydraulically rotated main drum is provided with several cutting heads, driven

by one electric motor each. The axes of rotation of the cutting heads form an angle with the central line of the tunnel. When the main drum rotates and is advanced forward, the cutting heads produce spiral grooves in the rock, the width of which is substantially less than the advance per revolution, and the material inbetween is broken off. In this way about 70% of the rock volume can be removed without getting into touch with the hard metal cutters.

The cubic meter cost for excavation of tunnels by blasting does not normally increase with increasing rock strength. In fact, because of the increasing cost of supports, bolts, or linings, tunnelling in soft rock is normally a great deal more expensive than in hard, competent rock.

In the case of rotary drilling and full-face boring however, there is a very strong increase of cost with increasing rock strength and/or abrasiveness, so strong in fact that there appears to exist a given range of rock materials with properties too difficult for full-face boring to be competitive. Thus we must fall back to blasting as the only practically applicable method in most hard rocks today. However, far fewer tunnels pass today and will be cut in the future through hard rocks than through soft ones. In soft and/or not too abrasive rocks full-face boring constitutes an important means for rapid and safe tunnelling operations.

Strength only is not the decisive factor for rock "borability". A highly abrasive rock (e.g. sandstone) with a compressive strength of say, only 100 bar may be as difficult to penetrate economically with a full face boring machine as will a non-abrasive but hard rock (e.g. limestone) of as much as 3000 bar compressive strength.

Even in hard rocks, in spite of high costs per unit volume for boring in the diameter range of 15-60 inches, good economy may be achieved. Such is the case for raises, the diameter of which can hardly be made less than 2 m (80") when produced by blasting, but which can be given exactly the smaller diameter desired in case large hole boring is applied.

References

- Barendsen, P. Mechanised Drifting by the Full Face Method. Annual Meeting of the Swedish Rock Blasting Committee, 1969.
- Bruce, W.E. and Morrell, R.J. Principles of rock cutting applied to mechanical boring machines. Proc. 2nd Symp. Rapid Excavation, Sacramento Oct. 1969.
- Burford, L., Cooper, H.F. Jr., Thompson, J.C. Spherical wave propagation in brittle materials. Proc. 12th Symp. Rock Mech. Univ. Missouri, Rolla 1970, p 379.
- D'Andrea, D.V. and Condon, J.L. Dye penetrant studies of fractures produced in laboratory cratering. Proc. 12th Symp. Rock Mech. Univ. Missouri, Rolla Nov. 1970 p 479.
- Dutta, P.K. A theory of percussive drill bit penetration. Int. J. Rock. Mech. Min Sci. 9 (1972) 543.
- Fairhurst, C. Comminution: Physical and mechanical bases of comminution, drilling, blasting, crushing, grinding and abrasion. General report of Theme 5, 2nd, Congr. Int. Soc. Rock Mech. Beograd Jugoslavica, 1969.

General Report of Theme 5, FRAGMENTATION SYSTEMS

- Field, J.E. and Ladegaard-Pedersen, A. The Importance of the Reflected Stress Wave in Rock Blasting. *Int. J. Rock Mech. Min. Sci.* 8(1971) 213.
- Field, J.E. and Ladegaard-Pedersen, A. Fragmentation processes in rock blasting. *Dechema-Monographien*, 69, 1972.
- da Gama, C.D. and Nelson, C.R. The formation of cracks in rock blasting analyzed in terms of the modified Griffith theory. *Proc. 12th. Symp. Rock Mech. Univ. Missouri, Rolla, Nov. 1970* p. 5117.
- Haimson, B.C. and Fairhurst, C. Some bit-penetration characteristics in pink Tennessee marble. *Proc. 12th Symp. Rock Mech. Univ. Missouri, Rolla, Nov. 1970* p. 547.
- Havir, J., Borda, S.K. and Petros, V. A simple method of determining the coefficient of loosening of rocks. *Int. J. Rock. Mech. Min. Sci.* 8(1971) 97.
- Hendricks, R.S. Raise boring, tunnelboring, pre-splitting, survey control and shotcreting at Hecla mining. *Proc. 2nd Symp. Rapid Excavation, Sacramento Oct. 1969*.
- Hino, K. "Theory and Practice of Blasting", Nippon Kayaku Co., Ltd. Japan 1959.
- Hustrulid, W.A. and Fairhurst, C. A theoretical and experimental study of the percussive drilling of rock. *Int. J. Rock Mech. Min. Sci.* I. Theory of percussive drilling 8(1971)p.311. II. Force-penetration and spec. energy determinations 8(1971) p. 335. III. Experimental verification of the mathematical theory 9(1972)p. 417. IV. Application of the model to actual percussion drilling 9(1972) p.431.
- Johansson, C.H. and Persson, P.A. "Detonics of High Explosives". Academic Press, London and New York 1970.
- Kolsky, H. "Stress waves in solids". Clarendon Press, Oxford 1953.
- Kutter, H.K. The Interaction Between Stress Wave and Gas Pressure in the Fracture Process of an Underground Explosion in Rock, with Particular Application to Presplitting. Ph. D. thesis, Univ. Minn. (1967).
- Kutter, H.K. Stress Analysis of a Pressurized Circular Hole with Radial Cracks in an Infinite Elastic Plate. *Int. J. Fracture Mech.*, 6 (1970) 233.
- Langefors, U., and Kihlström, B. "Modern Technique of Rock Blasting". Almqvist & Wiksell, Stockholm. John Wiley & Son, New York 1963.
- Langefors, U. Fragmentation in Rock Blasting. *Proc. 6th Symposium on Rock Mechanics. Penn. State Univ., 1965*. Also in *Mining and Minerals Engineering* 2 (1966) 339.
- Laroque, G.E. and Favreau, R.F. Blasting research at the mine branch. *Proc. 12th Symp. Rock Mech. Univ. Missouri, Rolla, Nov. (1970)p.* 339.
- Lundberg, B. Some basic problems in percussive rock destruction. Ph. D. Thesis at Chalmers Univ. of Technology, Gothenbourg, Sweden 1971.
- Lundberg, B. Energy transfer in percussive rock destruction. I. Comparison of percussive methods. II. Supplement on hammer drilling. III. Stress wave transmission through joints. *Int. J. Rock Mech. Min. Sci.* (In print).
- Lundborg, N. Strength of rock-like materials. *Int. J. Rock Mech. Min. Sci.* 5(1968) 427.
- Lundborg, N. A statistical theory of the polyaxial compressive strength of materials. *Int. J. Rock Mech. Min. Sci.* 9(1972) 617.
- Lidström, L. Surface and bond-forming properties of quartz and silicate minerals and their application
- Lundborg, N., and Almgren, L.Å. Determination of Fracture Toughness of Rock Materials, Swedish Detonic Research Foundation Report DS 1972:6 (In Swedish).
- Melnikov, N.V., and Marchenko, L.N. Anwendung von Sprengladungen mit Luftzwischenräumen. *Bergbautechnik* 19 (1969) 521.
- Meyer, O. Classification of rock with respect to expected drilling rate and bit wear. *Proceedings, Atlas Copco Symposium on Mining techniques, Moscow, 1-3 march 1972, Atlas Copco, Stockholm 1972*.
- Obert, L., and Duval, W.J. Generation and Propagation of strain waves in rock. U.S. Bureau Mines. R.I. 4663, 1950.
- Ouchterlony, F. Calculation of the variation of the crack length with the hole diameter at constant explosive weight per meter, Swedish Detonic Research Foundation Report DS 1971:4. (In Swedish).
- Ouchterlony, F. Analysis of the stresses in some different geometries with radially directed cracks in an infinite plane medium under the influence of expansion forces. Swedish Detonic Research Foundation Report DS 1972:11. (In Swedish).
- Pariseau, W.G. Wedge indentation of anisotropic geologic media. *Proc. 12th Symp. Rock Mech. Univ. Missouri, Rolla, Nov. 1970* p. 529.
- Persson, P.A., Lundborg, N., and Johansson, C.H. The basic mechanism in rock blasting. *Proc. 2nd Congr. Int. Soc. Rock Mech. Beograd 1970*.
- Persson, P.A. and Ladegaard-Pedersen, A. Short Delay Multiple-Row Blasting with the Ratio Hole Distance to Burden 4 to 8 Tests in Full Scale. Swedish Detonic Research Foundation Report DS 1970:14. (In Swedish).
- Persson, P.A. Boring costs in modern rock blasting. Nitro Nobel AB Report DL 1971:29. (In Swedish).
- Porter, D.D. and Fairhurst, C. A study of crack propagation produced by the sustained borehole pressure in blasting. *Proc. 12th. Symp. Rock Mech. Univ. Missouri, Rolla, Nov 1970* p. 497.
- Rinehart, J.S. and Pearson J. "Behavior of metals under explosive loads". Amer. Society for Metals, Cleveland 1954.
- Sperry, P.E., Samson, G.A., Eaglione, A.T., Finh, T. and Norman, N.E. River mountains tunnel project. *Proc. 2nd Symp. Rapid Excavation, Sacramento Oct 1969*.
- Summers, D.A., Corwine, J., and Chen, L. A Comparison of Methods available for the Determination of Surface Energy. *Dynamic Rock Mechanics, Proc. 12th Symp. Rock Mech Univ. Missouri, Rolla, 1970* p. 24.
- Thompson, R.J. Develop mining at White Pine. *Proc. 2nd Symp. Rapid Excavation, Sacramento Oct 1969*.