

FRAGMENTATION SYSTEMS

P.A. Persson and C.H. Johansson

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Summary

This paper contains the text of an oral presentation made by P.A. Persson, general reporter of theme 5, Fragmentation Systems, at the 3rd Congress of the International Society for Rock Mechanics in Denver, Colorado, September 1-7, 1974. It gives a general comparison between different conventional explosive, mechanical and unconventional methods for rock fragmentation, with the stress on the three factors, economy, energy consumption, and environmental effects, mainly for hard rock applications. Some suggestions of topics for future research are given, mainly in connection with blasting.

Included are also the summary comments made by the general reporter at the end of the plenary session.

Introduction

Earth moving has become an important requisite of our modern industrial society. As we fly over the continents we can see the foot-prints of industrialization on the surface of the earth. We see open pit mines and quarries and the dump-heaps of underground mines for metal and mineral raw materials, dams and waterways for electric energy, and roads, harbours and airfields for an increasingly complicated transportation system. We see growing towns and cities where every brick, every pavement stone, every slab of concrete and every steel frame or window pane can be traced back to one of these footprints where it all began its journey in the bucket of a big earth moving machine. Much of this earth is hard rock, and we may get an idea of the order of magnitude if I state that in my home country of Sweden during 1973, about 5 cubic meters of hard rock had to be fragmented for each and every man, woman and child in the country. The total amount of earth moved, including soft sedimentary and loose sand material is of course considerably more.

Practically all of the hard rock moved in 1973 was fragmented by the conventional drill and blast method. The borderline between "hard" and "soft" is of course somewhat diffuse, as it is not normally defined with reference to some specific tool. The major growth area for other fragmentation methods than blasting is in this borderline area, and the major steps forward are taken by mechanical fragmentation methods such as heavy impact and ripping tools, road headers, full face boring machines, and possibly water jet erosion. But a forecast for 1983, which is probably over-optimistic with respect to new methods, indicates that less than 5 percent of the world's conventional hard rock tunnel distance will be taken over by full-face boring machines, and that orders of magnitude less than one percent of the world's hard rock small diameter hole drilling will be by other than percussion drilling methods.

It may be wise to conclude from this, (at the beginning of our sessions on Fragmentation Methods), that even minor improvements in the conventional methods will reap great rewards because of the large scale of the practical application of these. But it may be equally wise to conclude that much research work remains to be done and important developments are waiting in the great fields of mechanical, exotic, or unconventional excavation methods.

The selection of papers submitted to this theme of the Congress reflects excellently the awareness on the part of the research workers of this dualism. There are interesting papers dealing with conventional techniques and equally interesting papers that report progress with technologies that belong entirely to the space-age.

Influence of rock strength

Before starting a survey of different fragmentation systems, we must remember that the character of the rock itself has a vastly different influence on the performance of different methods. Blasting is not greatly impeded by very hard rock. In fact, because of the increased need for support and careful blasting, it is usually more expensive to blast a tunnel through soft sedimentary material than through hard granite. On the other hand, a full-face boring machine may be almost stopped in its progress by a local streak of hard, or heavily wearing material. Thus, a complete survey of fragmentation systems should compare costs and performance for many different rock materials.

We have chosen, however, a different approach. The mechanical methods are rapidly growing into established techniques for soft materials. Much attention is focused on their advantages and practical problems where they are put to work. We feel there may be a danger that the hard rock side is forgotten. Therefore, we have tried to compare, in this general report, the different methods with the stress on hard rock, in the hope that others will contribute to give a good, balanced over all view.

Economy and size in excavation

The traditional criterion for choosing between different methods in engineering is economy (or efficiency which can often be referred to in terms of economy). Later in this report, and also in the discussion session, we will touch upon the increasingly important conditions of energy conservation and environment preservation.

Figure 1 shows the cost (in the 1972 value scale) of excavating a unit volume of hard rock as a function of the diameter of the excavation, be it a small or a large drillhole, a tunnel, or a large cavern. We see that the cost is strongly diameter dependent, and that the different excavation methods in large-scale use give results that fall surprisingly well on the same curve. In this diagram, mechanical full-face boring shows higher cost than other methods. This is because it deals with hard, granite type rock. For soft, sedimentary rocks we would find a similar curve with lower cost, where the full-face boring would come out more favourably.

We would like to discuss this curve against the background of a fundamental rock mechanics observation. In Fig. 2 we see the results of some experiments Lundborg /1/ made. He measured the shear strength of rock as a function of the normal stress in a triaxial compressive stress

situation. It is interesting and thought-provoking to compare the strength of granite at a confining pressure of 10 kbar with that of hard steel. When we allow a tool to work in such a geometry that it creates mainly compressive stresses, it has effectively to cut a material that is considerably stronger than steel. But not only is the strength of rock in tension practically negligible compared to that in compression. The energies of deformation are even more sensitive to lateral constraints. In fact, the energies of deformation of granite to the point of fracture for the three stress systems uniaxial tension, uniaxial compression, and uniaxial strain have the relative magnitude of 1, 100, and 10000, respectively. A geometry which produces a stress system approaching that of uniaxial strain is difficult to avoid at the circumference of the bottom surface of an extended cavity such as a drillhole or a tunnel. We may then, in the first approximation, assume the energy E required to excavate a unit length of hole or tunnel to be proportional simply to the length of the circumference of the bottom surface.

Thus, we have,

$$E \sim d$$

where d is the characteristic diameter of the excavation. It follows that the average excavation energy per unit volume, e , is inversely proportional to the diameter

$$e \sim 1/d$$

Surprisingly, it turns out that the excavation cost K is also approximately inversely proportional to the diameter. In fig. 1 the dashed line which approximates the excavation costs for widely different methods at widely different diameters has the equation

$$K = c/d$$

where c is a constant.

Thus, for practical purposes, although the cost of energy is usually small compared to the total excavation cost, the energy consumption may give an important indication of the probable excavation cost.

The constant c (in 1972 values) has to have the value 80 \$/m² to agree with the dashed curve in the figure. The cost to excavate a cubic meter of hard rock in a one meter diameter hole is 80 \$ or so and it is inversely proportional to the hole diameter. Although this is a rough average and a very simple approximation, it is a useful rule of thumb for the order of magnitude of the cost which is today acceptable for practical purposes.

Performance and cost

Table 1 gives a comparison of costs, rates of excavation and power and energy requirements for some new and some traditional methods of excavation. If we look at the three traditional methods we see that the excavation costs in hard rock are characteristically 1, 10 and 100 \$/m³ for open pit drill & blasting, tunnel drill & blasting, and full face mechanical tunnelling, respectively. The trend for the rate of excavation is the opposite, 100, 10, and 7.5 m³/hour respectively, and even more pronounced is the increase in power per unit excavated cross sectional area, 0.01, 1 and 25 kW/m².

The unconventional tunnelling methods all make claims of considerable improvements in rate of excavation over the drill and blast method, by a factor two for the thermomechanical method where a number of holes are drilled conventionally and fragmentation is achieved by applying electrical heating in each drillhole, and by as much as a factor of 10 for the projectile impact method. In both cases, the hope of such greatly improved excavation rates rests largely on the assumption that the process may be made continuous, in contrast to the drill and blast method as it is known today. It is interesting to see how energy-consuming the full-face mechanical tunnelling method is in this comparison for hard rock.

Table 2 gives a similar comparison of different methods of drilling or groove-cutting. These are all characterized by a thousandfold higher power density, a hundredfold smaller rates of excavation and, apart from the conventional rotary and percussive drilling, a thousandfold higher energy consumption than the tunnel driving methods. In compiling these tables, we have tried as much as possible to follow the authors' own estimate of future performance in order not to make the comparison unduly unfavourable for the new methods that are on the laboratory stage. The small rates of excavation and large energy consumption predicted for all of the new methods are notable. Table 3 contains some additional data not shown in tables 1 and 2.

Comparisons such as these may be useful to make particularly for the person engaged in developing a new method. They may indicate weak and strong points and initiate useful discussions. They must, however, not be trusted too far. Look, for example at the jet piercing method in comparison with the rotary drilling. In spite of its unusually high energy consumption, 20 times that of rotary drilling, jet piercing gives an excavation cost in hard rock that is nearly the same as for rotary drilling. And even at that high rate of energy consumption, the cost of fuel energy for jet piercing is probably less than 10% of the total excavation cost.

Several of the new methods indicate even higher figures for the energy consumption than jet piercing. Nonetheless, in comparison with the total

excavation cost of percussive drilling at comparable diameters, there may well be room for a reasonable margin for equipment and labor costs. The electron flash method may be of particular interest with its high rate of excavation and a reasonably low energy consumption.

Another energy-consuming method appears to be the water jet erosion method. Again, this is enhanced because we have chosen the figures for hard impermeable rock rather than those for soft porous sandstone. As with the full-face mechanical method, this is an indication that the major application area for the water jet erosion method may be in the soft sedimentary rock materials.

So, looking into the future from an economic angle alone, we may predict success for the combined thermomechanical methods, the projectile impact method and the high energy impact method if they succeed in excavating tunnels in hard rock at total excavation costs between 10 and 100 $\$/m^3$. And the various exotic drilling and groove-cutting methods to be used in combination with some other, perhaps mechanical method, may be ensured of success if they can cut hard rock at a cost between 200 and 1000 $\$/m^3$.

Energy conservation and environment preservation

Now, let us widen the perspective to include in the discussion for a moment the two factors energy conservation and environment preservation. In trying to evaluate the excavation methods of the future, we have to discuss the situation perhaps 10 years from now and even further ahead. In view of the difficulties of putting a 1984 or 1990 price on oil or of predicting the content of the 1984 laws on air pollution and permissible radiation levels, I feel there is strong reason to discuss energy requirements and possible environmental hazards as separate factors with a weight at least equal to that of the economic factor.

Let us first look at energy consumption. If all the hard rock fragmented in Sweden were to be cut in its entirety by the laser beam, we would arrive at an energy consumption about equal to the country's present home consumption of electricity. However, the laser cutting would more likely be part of some combination method, whereby the energy consumption would be one percent of that amount. So, there seems to be no need for worry. We may be able to set aside that much of the energy cake for fragmentation.

But the laser method, together with several of the other new methods, is obviously sensitive to large increases in the price of energy. For the conventional methods, the energy cost is one or two percent of the excavation cost. With the new methods this percentage is likely to be 10 or 20%, and an energy price increase by a factor of 5 or 10 might then be

very difficult to overcome.

The conventional drilling and blasting has long been known as a source of environment disturbances, and hazards. Noise from air compressors, noise and dust from percussive drills, air blast and ground vibrations from blasting, and health and accident hazards from sensitive explosives and detonators is the well-known popular picture. We all look to the new methods and hope to find safe, smooth cutting, silent and swiftmoving tools to take over. However, great strides are being taken in improving the conventional methods. Silenced air-compressors, no noisier than a private automobile, effective dust-collectors and silencers for the drilling machine, quieter hydraulically-driven drills, new and radically safer-to-handle explosives and detonators, new means and methods of predicting and controlling ground vibrations and air blast have been put on the market in the last 5 years and are beginning to spread. Through mechanization and remote control of the drilling, charging, and mucking operations, great improvements are being made in underground working conditions. The paper by Llovera and Becedoniz from Spain /2/ gives a fine example of the state-of-the art in one of these areas. The expansion of the machine-hall in the Villarino underground hydroelectric power plant was made by controlled blasting with the old part of the power plant including four 135 MW pumpturbines running continually.

It is our firm belief that research money spent on further improvements in the field of environment disturbance prevention in conventional drilling and blasting will give rich rewards in practically applicable results.

State-of-the-art and fields for further research

Let us finally look at the state of development in each of the fields of explosive, mechanical, and novel fragmentation methods.

In the research on explosive fragmentation, most of us now have resolved the age-old controversy of whether the shock wave or the slow expansion of reaction products does most of the fragmentation work. We feel we have a reasonably good qualitative understanding of the explosion and fragmentation process. We need, however, to do a great deal more work with computer programs and laboratory experiments to be able to deal quantitatively with the explosion process and with the gas expansion and rock fragmentation process. We are well on the way to be able to treat correctly the mathematics and physics of crack propagation in very simple geometries, but we need to work more with the computer to handle more realistic geometries. Parallel to the computer work we need new experimental data on crack propagation in simple geometries for different rock materials. We also need to do more experimental

work of the kind Noren and Porter /3/ describe, where a more detailed description of the explosion and gas expansion process is sought through instrumented experiments carried out in rock, both homogeneous and in real blasting work. We need some kind of simplified description of real, fissured rock to improve our understanding of the possibilities of smooth-blasting, pre-splitting, and other methods of minimizing damage to the rock adjacent to the blast.

We have evidence from large-scale production tests that there are several ways in which fragmentation can be influenced by the charge arrangement or the drillhole pattern. One such method is the wide-spacing method which has been extensively tested in Sweden, and also in Australia. At this Congress, Bhandari and Vutukuri /4/ report a large decrease, by 33%, in the number of boulders coupled with a 10% increase in production using this method in a quarry. Another method is the Russian one of air-gaps between separate parts of the charge in a bore-hole. This method, developed by Melnikov and co-workers /5/, has apparently been very useful to improve fragmentation where a concentrated charge at the bottom of an otherwise empty borehole has been the previous practice.

In both cases, the new method is based on model scale experiments. We feel that a great deal more can be learnt and developed by a more widespread intelligent use of that powerful research tool, coupled with field experiments.

As shown by the paper by Hendron & Dowding /6/, new ways of treating ground vibrations and damage criteria may develop. Work of this kind is vitally important as more and more blasting has to be made in built-up areas.

Associated with this work is the study of air blast effects and fly-rock, and methods of preventing or controlling these.

As for mechanical fragmentation, I must rely on my colleagues for a thorough evaluation of the state of the art. Let me just make a few general remarks. First, because of the general size-effect we discussed earlier, one might perhaps expect to see a gradual growth in the size of the actual cutting tool, be it a roller, a pick or a cutting tooth, within the geometrical limits set by the size of the tunnel. Some indications of this have been given in papers submitted to this congress. Secondly, we will all be interested in the further progress in the high energy impact method, where again the size effect seems to make a great deal of difference.

Thirdly, because of the sensitivity to rock strength of most of the mechanical methods, we need to devote much time to finding techniques of predicting and detail-prospecting for strength and wear-properties.

And finally we need to be aware of the rapidly growing importance of environment conservation, and to scrutinize our new developments for possible

drawbacks or advantages in this respect. It may be that the mechanical methods have their main advantages here.

It is yet too early to make general statements about the state-of-the-art in the field of novel fragmentation systems. Apart from what can be seen from the several papers presented at this congress, Fogelson /7/ has made, in his supplementary report, an excellent survey of practically everything that has been published in this field. We can only congratulate the researchers on their impressive achievements so far and wish them every success for the future.

SUMMARY BY GENERAL REPORTER

(given at end of plenary session on "Fragmentation Systems")

With these comments, together with the general and supplementary reports that are already published, I feel that this group of reporters has exhausted its capacity for summarizing. If you are left with the impression that there are different opinions among us on several subjects, this is probably correct. The subject is vast and it is developing rapidly. It is necessary for a man to believe in what he is working with, and there are several competing methods of fragmentation.

We must now turn to the substance of the present development in the form of the papers to be presented and the discussion we hope will develop during the discussion sessions. Papers have been chosen for oral presentation not necessarily by their relative brilliance as papers but rather by topic with the aim of guiding the discussion on to subjects that appear important from an overall view.

During the discussion following this morning's papers on "Explosive Fragmentation Methods" we hope that you will voice your views on such topics as the pros and cons of model scale rock blasting experiments, methods of measuring fragmentation in the field and methods of improving the fragmentation by changing the borehole pattern and methods of blasting.

We want your comments on ground vibrations, especially on the new methods of using response spectral analysis. We would like to hear the clash of opinion about the possibility and advisability of establishing universal methods for characterizing explosives with respect to blasting capacity. These are all questions of great importance, but there are others, too, that need to be discussed.

During the first part of the afternoon, we will have presented to us the latest developments in four of the many "Novel Fragmentation Methods" that show promise for the future. In this group we hope the discussion can be led into the topics of health and environment hazards and energy requirements, that we feel may have been given too little thought in connection with these novel methods. These topics, we feel, nowadays have an even greater importance than the economy and efficiency criteria that we have been used to regard in the past as all important.

The second part of the afternoon will bring to you some interesting papers on "Mechanical Fragmentation" and the "Effects of Rock Properties on Fragmentation". We feel that it would be very useful to discuss, in this context, how we can define those properties of rocks that affect the advance rate of a mechanical device. It is important that we learn to determine, by suitable prospecting, what kind of rock the tunnelling machine will encounter so that we can calculate, before we buy the machine, the cost of using it on a particular project. We feel that this is a topic of such great importance for the development of full face techniques that the whole of the time for discussion under this last group could well be spent on it alone.

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	CHARACTERISTIC DIAMETER m	POWER DENSITY kW/m ²	RATE OF EXCAVATION m ³ /hour	ENERGY CONSUMPTION kWh/m ³	EXCAVATION COST \$/m ³
OPEN PIT DRILL & BLAST	100	0.01	100	1	1
TUNNEL DRILL & BLAST	5	1	10	2	10
" THERMOMECHANICAL	5	7.5	20	7.5	
" PROJECTILE	5	12.5	100	2.5	
" HIGH ENERGY IMPACT	5	10 ?	100 ?	2	
" FULL FACE	5	10	7.5	25	100

Table 1. COMPARISON OF OPEN PIT AND TUNNEL DRIVING METHODS. HARD ROCK.

	CHARACTERISTIC DIAMETER m	POWER DENSITY kW/m ²	RATE OF EXCAVATION m ³ /hour	ENERGY CONSUMPTION kWh/m ³	EXCAVATION COST \$/m ³
DRILLING ROTARY	.25	500	.5	50	200
" JET PIERCE	.25	2500	.25	500	250
" PERCUSSIVE	.05	5000	.25	50	1000
ELECTRON FLASH	.25	2000 ?	.2	500	
WATER JET	.1	10000	.05	2000	
MELTING	.075	1000	.0025	2000	
ELECTRON BEAM	.025	50000	.01	2500	
LASER	.025	10000	.002	2500	

Table 2. COMPARISON OF DRILLING AND GROOVE-CUTTING METHODS. HARD ROCK.

	Characteristic diameter m	area m ²	Power kW	Power density kW/m ²	Rate of excavation m ³ /hour	Energy consumption kWh/m ³	Price of energy \$/kWh	Energy cost \$/m ³	total excavation cost \$/m ³
Open pit drill & blast	100	10000	10	.01	100	1	1	1	1
Tunnel drill & blast	5	20	20	1	10	2	1	2	10
" thermomechanical	5	20	150	7.5	20	7.5	.05	1 ^{x)}	
" full face	5	20	500	10	7.5	25	.05	1.25	100
Drilling rotary	.25	.05	50	500	.5	50	.05	2.5	200
" jet pierce	.25	.05	250	2500	.25	500	.02	10	200
" percussive	.05	.002	10	5000	.25	50	0.5	25	1000
High velocity projectile	5	20	250	12.5	100	2.5	2	5	
Electron flash	.25	.05	100	2000	.2	500	.05	25	
Electron beam	.025	.0005	25	50000	.01	2500	.05	125	
Laser	.025	.0005	5	10000	.002	2500	.05	125	
Melting	.075	.005	5	1000	.0025	2000	.05	100	
Water jet	.1	.01	100	10000	.05	2000	.1	200	

x) includes .5 \$/m³ for drilling conventionally.

Table 3. COMPARISON OF PERFORMANCE AND COSTS OF FRAGMENTATION METHODS IN HARD ROCK:

US \$/m³ US \$/lit.

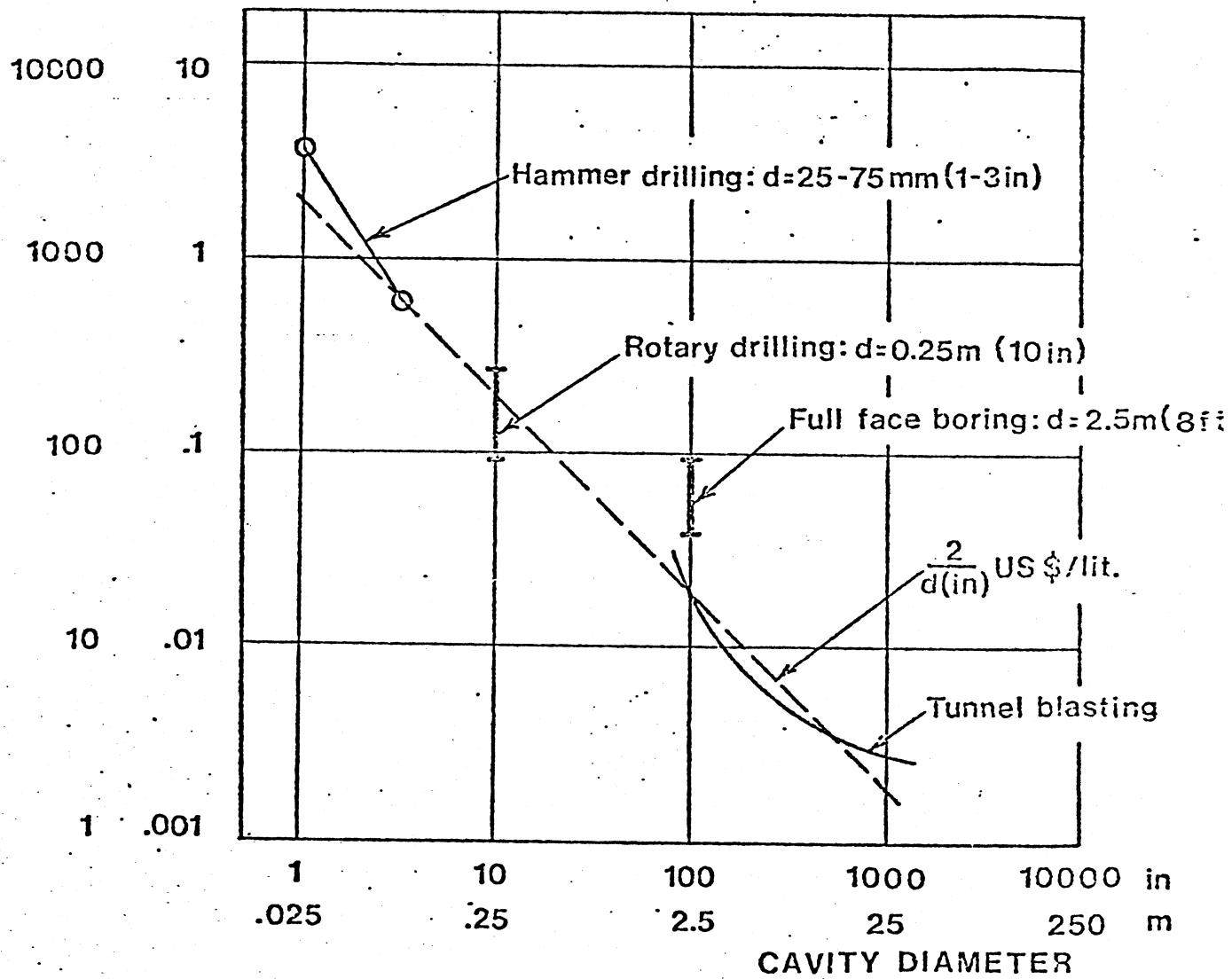


Fig. 1. The total excavation cost as a function of cavity diameter in excavation of Swedish granite by hammer drilling, rotary drilling, full face boring, and tunnel blasting

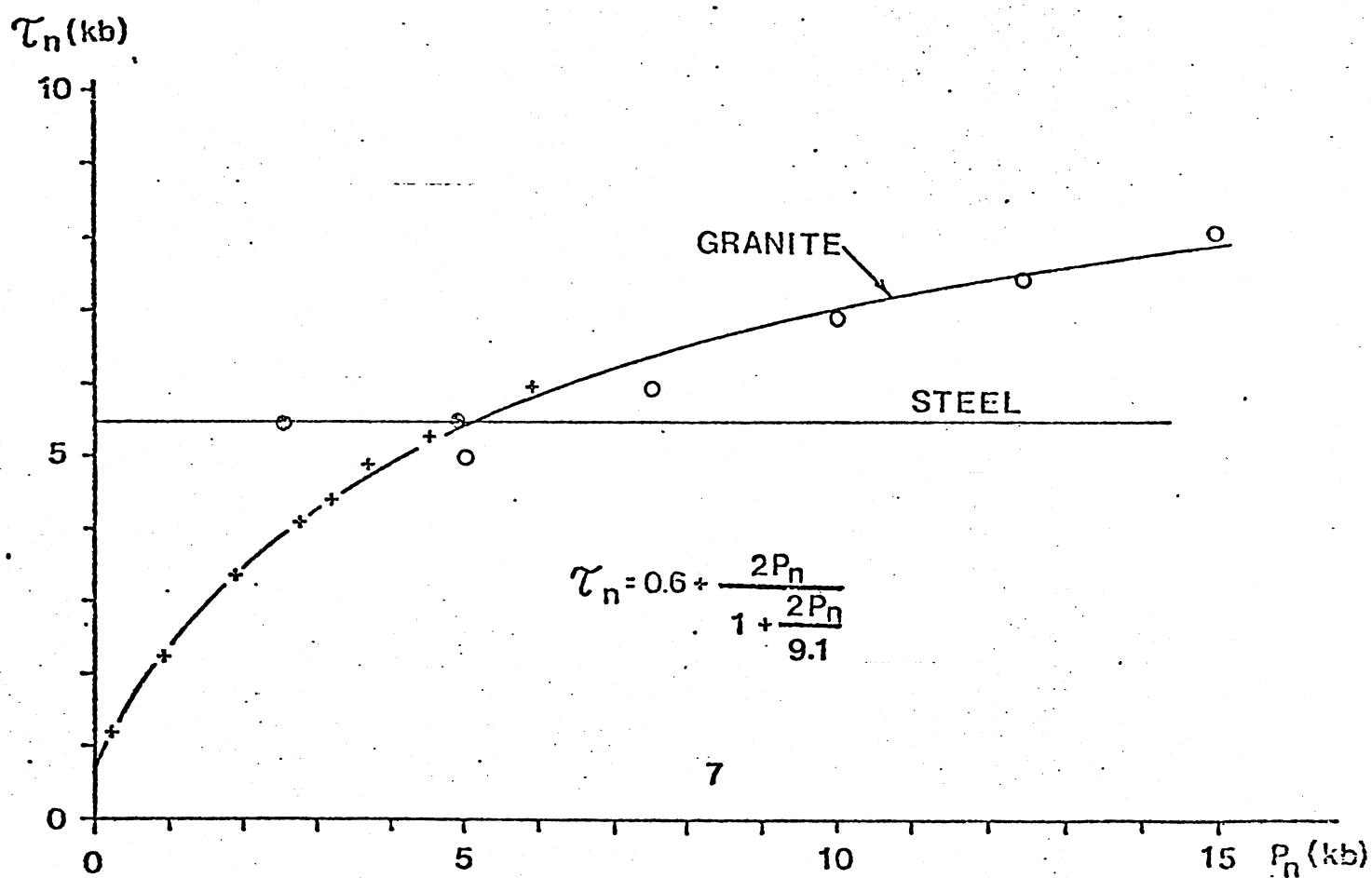
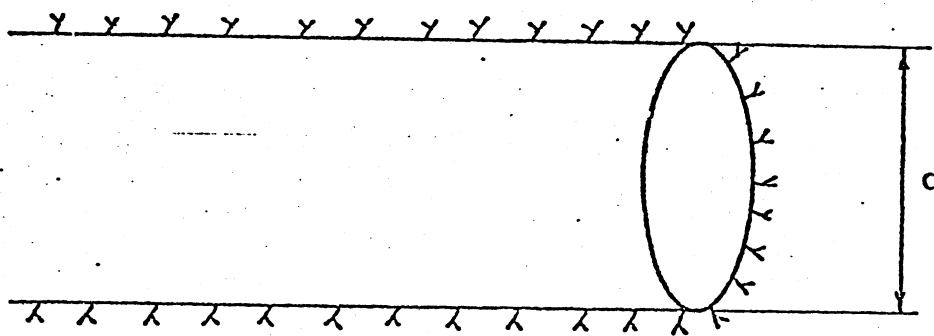


Fig. 2. The shear strength of granite and steel as a function of normal pressures.



Excavation energy per unit cavity length $E \sim d$

Excavation energy per unit volume $e \sim 1/d$

Excavation cost per unit volume $K = c/d$

Fig. 3. Cost and excavation energy in relation to the cavity diameter.