The Effect of Rock Properties on the Design and Results of Tunnel Blasts

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ABSTRACT

The design and results of tunnel blasts are affected by rock properties more than by any other variable. As the mean spacing between fissures (ie,natural cracks) decreases, the importance of rock substance strength decreases while that of rock mass strength increases. Because the great majority of new cracks are produced by tension, the dynamic tensile breaking strain (ϵ_t) is a very important property of massive rock. In closely fissured rock, ϵ_t is less influential than the combined effect of the spacing, orientation, persistence, aperture and infilling of fissures. Explosive charges should be designed such that the peak radial strain at the blasthole wall is equal to the dynamic compressive breaking strain of the rock. Tunnel blasting is affected most by rock strength; it is influenced to a lesser degree by the internal friction, grain size and porosity of the rock.

1. INTRODUCTION

Tunnelling is an essential feature of many civil engineering projects and virtually all underground mines. Of the total length of tunnels driven annually worldwide, the greater proportion is still produced by drilling and blasting.

In a blast, explosion gases act and the rock reacts. The action of explosion gases is well understood and can be adequately quanitified. But this certainly cannot be said of the reaction of rock to explosive attack. Our failing to understand the reaction of rock results not from an inability to characterise the rock substance but from our failing to comprehend and synthesise the numerous and complex effects of faults, joints, bedding plane partings, laminations, vughs, micropores, etc. in the rock mass.

While suffering from the handicap of its cyclic nature, drilling and blasting has a very high degree of versatility; it can be carried out satisfactorily in rocks ranging from weak thinly bedded shales to the strongest and most massive rocks. This versatility results from the contractor's ability to vary, for successive rounds, the blast design between very wide limits. Drilling and blasting is also flexible; equipment and personnel can be moved rapidly from one tunnel face to another.

Although a trend towards purely mechanical excavation methods (eg, tunnel-boring machines) exists, there are strong indications that construction and mining companies will be blasting tunnels for many years to come, especially in rock having very high substance strengths and in mixed ground conditions. In the interest of maximising both safety and cost efficiency, it is important that the effects of rock properties on tunnel blasting be documented as well as is currently possible.

2. EFFECT OF STRENGTH OF ROCK

In tunnelling, two major categories of rock strength need to be considered, viz. rock substance strength and rock mass strength.

The importance or rock substance strength increases with the mean spacing between natural cracks (hereinafter referred to as fissures) in the rock. As substance strength increases
(a) drill penetration rate decreases and, hence, the cost of drilling increases; and
(b) more explosion energy is needed to create new cracks in the rock.
When creating new cracks in a blast, it is the dynamic rather than static substance strengths which are important. More precisely, it is the dynamic breaking strains which need to be exceeded if the rock substance is to be broken.

Rock mass strength is lower than rock substance strength; it is lowered by the presence of fissures in the rock. The importance of rock mass strength increases with a decrease in the mean spacing between fissures. As rock mass strength decreases
(a) less explosion energy is needed to produce a muckpile having the required characteristics; and
(b) it is generally more difficult to control overbreak, to eliminate rockfall hazards and to minimise rock support costs.

2.1 Effect of Dynamic Breaking Strains

The dynamic breaking strains of the rock (substance) are important in that new breakage (cf. fissures) occurs only when these strains are exceeded. Because rock is weaker in tension than in either compression or shear, it is the dynamic tensile breaking strain that is most important.

2.1.1 Effect of dynamic compressive breaking strain

When an explosive charge detonates in a blasthole, the very high-pressure gases produce an intense compressive strain wave which radiates out into the surrounding rock. If the peak of this radial strain exceeds the rock's dynamic compressive breaking strain (ϵ_c), an annular zone of intensely crushed rock is formed around the charge. Pulverisation or plastic deformation occurs during a period of volume compression through collapse of the intergrain or intercrystalline structure. Beyond the crushed zone boundary, the peak compressive strain falls, due to divergence and energy absorption effects, to a value below ϵ_c. The excessive fragmentation or plastic deformation in the crushed zone is associated with a very high rate of energy dissipation. The radial thickness of the crushed zone increases with
(a) an increase in the peak blasthole pressure (P_b), and
(b) a decrease in ϵ_c.

Crushing is to be avoided, since it represents very poor utilisation of explosion energy. What contractor would knowingly convert much of a sandstone into sand when the blasted rock is to be removed using large mucking equipment?

If the mechanical efficiency of blasting is to be maximised, P_b should be equal to the value at which crushing is about to occur. If ϵ_c is known, therefore, P_b should be adjusted by varying

(a) the degree of coupling of the explosive charge (see Fig. 1), or
(b) the type of explosive.

When using cartridged explosives, crushing can be prevented by adjusting the degree of coupling by

(a) tamping the cartridges less or more, — most practical
(b) inserting spacers between cartridges (see Fig. 2),
(c) changing the cartridge diameter, or
(d) changing the blasthole diameter. — least practical

For fully coupled charges, P_b is approximately proportional to the product of the density of the explosive (ρ) and the square of its detonation velocity (D), ie,

$$P_b \propto \rho D^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

If follows that fully coupled charges of a dense, high-velocity explosive are more likely to waste some of their energy in crushing the rock. When using bulk ANFO or a pumped emulsion explosive, crushing can be prevented best by adjusting ρ. The density of ANFO or a pumped emulsion can be lowered best by adding a low-density fuel (eg, expanded polystyrene beads or an expanded cereal) to it.

2.1.2 Effect of dynamic tensile breaking strain

The importance of dynamic tensile breaking strain (ϵ_t) increases with the mean spacing between fissures in the rock. In rocks which contain very widely spaced fissures, blasts are required to create many new cracks. In closely fissured rocks, on the other hand, few new cracks are needed; most of the required fragmentation is achieved when the explosion gases jet into and wedge open the fissures.

In practice, the importance of ϵ_t increases, more particularly, with the "natural" fragmentation: required fragmentation ratio. (Natural or in-situ fragmentation is given by the size distribution of natural blocks, blocks which are bounded by fissures in the rock.) Where the spacing of fissures is very large and the mucking equipment is small, blasts are required to create large numbers of new cracks and ϵ_t is very important. If large mucking equipment were to be used in this same situation, blasts would need to create fewer new cracks and ϵ_t would be less important. Where large equipment is used to remove muck produced by blasts in highly fissured rocks, very few if any new cracks are required and ϵ_t would be least important. New fragmentation is greater where a higher percentage of natural blocks of rock contain the charged section of a blasthole and, hence, where smaller-diameter blastholes are employed.

If the degree of fragmentation of blasted rock is to remain unchanged, any increase in ϵ_t necessitates

(a) an increase in energy factor (ie, the yield of explosion energy per m^3 of rock), and
(b) a decrease in burden distance, blasthole spacing, stemming length and, in some tunnelling operations, mean advance per round.

Increases in ϵ_t also have the effect of reducing both overbreak and the probability that explosive charges will be desensitised by dynamic pressures (Ref. 1, 2).

Fresh (ie, unweathered) igneous and metamorphic rocks are usually the hardest to drill and, for a given degree of fissuring, the most difficult to blast. When blasting strong, relatively massive rocks of these types, it is usually necessary to employ small blasthole patterns, short stemming columns and correspondingly high energy factors. Equally fissured but weaker rocks can be blasted satisfactorily with fewer wider-spaced blastholes, longer stemming columns and lower energy factors.

When tunnelling in rock having a low value of ϵ_t, the detonation of one charge may laterally compress, densify and desensitise an adjacent later-firing charge, especially where the blasthole spacing is small, as is the case in burn cuts (Ref. 1, 2). This phenomenon, which can also occur in highly fissured rock, is discouraged

(a) by drilling burn cut blastholes as far apart as possible, and

(b) by positioning these blastholes so that each later-firing charge is shielded by a large-diameter relief hole (see Fig. 3).

2.2 Effect of Rock Mass Strength

Where a large-diameter tunnel is driven in a low-strength rock mass, safety may well dictate that excavation be carried out by the top heading-and-bench method (see Fig. 4b) rather than by the full-face method (see Fig. 4a). In very wide tunnels in weak rock, it may be prudent

(a) to blast a top central heading (see A in Fig. 4c) and then support the limited roof area,

(b) to side strip (see B1 and B2 in Fig. 4c) and then support the remainder of the roof, and then

(c) to bench with horizontal blastholes (see C in Fig. 4c).

Where a full-face tunnel or a top heading is driven through rock which is too weak to be self supporting or where "slips" in the roof are likely to occur, it is often necessary to limit the design advance per round; in this situation, the selected mean advance per round is commonly equal to the distance between alternate or, in very adverse conditions, consecutive supports.

3. EFFECT OF STRUCTURAL PROPERTIES OF ROCK

The structural properties of rock can affect both the design and results of a blast. When designing blasts, one needs to consider the spacing, orientation, persistence and aperture of fissures and the properties of the material (eg, air, water, clay) filling these fissures. Blasting results should be assessed in the light of these structural properties.

3.1 Effect of Structural Properties on Size of Blast

In general, the maximum practicable span of unsupported roof increases with

(a) increases in the spacing of fissures, and

(b) decreases in the persistence and aperture of fissures.

When blasting wide faces in rocks having persistent and closely spaced fissures, safety may dictate that the advance per round be limited, especially where fissures are open or filled with water or clay.

3.2 Effect of Structural Properties on Type of Cut

When selecting the type of cut, structural properties are usually a minor consideration. More important factors include the type of drilling equipment, width of tunnel, cost of explosives, and number of available delay numbers.

Well laminated and fissured rocks respond well to wedge-cut rounds, and in large-diameter tunnels (where the wedge can have a large apical angle - see Fig. 5), advances of up to about 6 m per round are possible. In massive rocks, it is sometimes desirable to drill short "stab" blastholes into the centre of the wedge to prevent oversize fragments being ejected from the cut (see Fig. 5).

Where blastholes are closely spaced and fire on different delays, and especially in burn cuts, the presence of open fissures or clay bands increases the probability of experiencing problems with

(a) sympathetic detonation (especially where gelatine dynamites are being used) or
(b) dynamic pressure desensitisation (especially where watergel or emulsion explosives and employed).

Where charges detonate sympathetically, the intended inter-charge delay time is eliminated, ground vibrations are higher and the probability of a "frozen" round is greater. Where one charge is desensitised by the dynamic pressures produced by an adjacent earlier-firing charge, the later-firing charge fails to liberate all of its potential energy and this reduces the overall efficiency of the round.

3.3 Effect of Structural Properties on Blasthole Pattern and Energy Factor

An increase in the mean spacing between fissures demands that a greater amount of new breakage be produced in the blast. For a given value of ϵ_t, therefore, an increase in mean fissure spacing encourages the use of smaller blasthole patterns, shorter stemming columns and correspondingly higher energy factors.

3.4 Effect of Structural Properties on Mean Advance Per Round

In closely fissured rock, it is easier and less costly to achieve finely fragmented muckpiles and the desired mean advance per round.

In slabby rocks, longest rounds can usually be pulled where the dominant fissures are normal to the axis of the tunnel. The effect of structure orientation on mean advance per round is pronounced in some underground metal mines; here, advance rates in drives (aligned with the strike of the orebody) are usually lower than those in crosscuts (which run normal to the strike). In wedge-cut rounds, second best results are usually obtained where the dominant discontinuities are parallel to the line joining the bottoms of wedge-cut blastholes (see Fig. 6).

3.5 Effect of Structural Properties on Overbreak

Overbreak-control techniques are more successful in strong massive rocks and in rocks in which tight fissures are essentially normal to the axis of the tunnel. But the need for overbreak control is greater in weaker rocks.

In highly fissured rocks, excessive overbreak and inadequate stability of the roof and walls of the tunnel are often experienced. The associated cost of rock support tends to increase with the number, persistence and aperture of fissures unless this potential problem is given extra consideration during both the design and implementation of blasts. But in rocks with **very** closely spaced fissures, some overbreak will occur, principally along the fissures, irrespective of the steps taken to prevent it. No blasting technique, no matter how well engineered, can produce a smoother sounder tunnel profile than the rock mass properties will permit. The very blasting technique that produces the desired effect in a strong massive . may be quite unsuitable in weak highly fissured rock. Because they need to change with roc. mass properties, the spacings and charge concentrations for perimeter blastholes are location-specific.

In closely fissured rock, continuous highly coupled charges of a powerful explosive should not be used in perimeter blastholes. Where it is important to achieve the design tunnel profile in such rocks, every perimeter blasthole should contain a discontinuous charge which consists of spaced cartridges of a water-resistant explosive (see Fig. 7) With this type of charge, the explosion energy concentration can be varied between very wide limits, simply by changing the length of air gap between cartridges. Longer air gaps are needed in weaker rocks. In the interest of reducing the time required to charge these perimeter blastholes, such charges should be preassembled at a place which is remote from the tunnel face and then transported to the face as unit charges. At the face, a detonator should be inserted into the primer cartridge and then the entire charge pushed into its blasthole.

The structural properties of rock may affect the tunnel profile obtained. Where the rock is quite massive, it is not difficult to produce a tunnel roof of the desired profile. Where the rock contains mutually orthogonal cracks which are equally pronounced, a flat roof may be unstable (especially where the span is large), and safety may dictate that an arched roof be produced. In strata having pronounced horizontal bedding plane partings, it is usually very difficult to produce an arched roof; overbreak tends to follow bedding, and the roof tends to be horizontal and the "shoulders" of the tunnel square.

When blasting full-face rounds or top headings, smoothwall blasting (ie, postsplitting) is almost invariably preferred to presplitting. Provided that the rock is either massive or has few fissures normal to the blastholes, presplitting can be used to advantage to form smooth sound rock surfaces

(a) at tunnel portals, and

(b) along the sides of horizontal benches and especially downhole benches.

Where pronounced fissures make a small angle to the desired tunnel profile, the smoothwall or presplit surface tends to follow the fissures rather than the intended inter-blasthole split. In highly fissured rock, the amount of overbreak produced by presplit charges can be surprisingly large.

When blasting tunnels through weak rock, overbreak control requires that blasts be designed by someone who can blend and apply the best engineering principles and considerable experience-based judgement. Even when this is done, an initial design will often need to be modified after the results of the first blast have been thoroughly evaluated. Our inability to predict blasting results exactly is due very largely to our incomplete understanding of overbreak mechanisms and the influence of rock properties on them. As one would expect, the design of a smoothwall or presplit blast usually needs to be changed as the tunnel is driven from the portal area (which is likely to be in weathered rock) into progressively fresher, stronger rock.

4. EFFECT OF POROSITY OF ROCK

The vughs (ie, macropores) which usually result from dissolution of rock by groundwater are much larger and less uniformly distributed than the micropores which are present in rocks such as sandstones. Some limestones contain vughs with volumes up to several cubic metres.

4.1 Effect of Vughs

Where they are intersected by a blasthole, vughs (ie, macropores) are likely to cause charging problems. It may be difficult to push cartridges past a vugh into the base of a blasthole.

Where a bulk explosive (eg, ANFO) is being charged so as to give a predetermined stemming length, intersected vughs allow blastholes to contain abnormally heavy charges, with consequential risk of intense ground vibrations, excessive overbreak, the dislocation of adjacent later-firing charges, etc.

If a sizeable vugh is located near the charged section of a blasthole, the cost efficiency of blasting is reduced as a result of

(a) the premature termination of outward-propagating radial cracks at the vugh (see Fig. 8a), and

(b) the more rapid decrease in blasthole pressure as explosion gases jet into the vugh via fissures and strain wave-generated fractures (see Fig. 8b).

Once gases start to jet into a nearby vugh, they cease to fully pressurise and, hence, stop extending radial cracks which are propagating in other directions. As soon as a practical technique for determining the location and size of vughs becomes available, it will be possible to adjust (ie, increase) the amount of energy liberated in blastholes surrounding vughs.

Where the mean spacing between vughs decreases, therefore, it is necessary to ensure that more time and effort are put into

(a) recording the locations of the surfaces of intersected vughs,

(b) using such (drilling) records when charging those blastholes which intersect vughs. (Ideally, these blasthole should be charged before other blastholes), and

(c) charging those blasthole which surround vughs more heavily to help counteract the loss of explosion energy in and close to each vugh.

Whilst vughs reduce the cost-effectiveness of blasting, their harmful effects can be minimised by developing and applying rapid efficient charging procedures.

4.2 Effect of Micropores

An increase in microporosity causes

(a) a decrease in ϵ_c (and, hence, an increase in the amount of energy wasted in crushing rock immediately around the charge - see Section 2.1.1),

(b) a decrease in ϵ_t, and

(c) an increase in the rate of dissipation of effective strain wave energy.

As microporosity increases, a greater proportion of the required fragmentation is achieved by the heave (ie, gas expansion) energy component, and correspondingly less is produced by the strain wave energy component of the total explosion energy. If powerful, highly coupled explosives were to be used in rocks having high microporosity, annuli of powdered rock would be produced. Where microporosity varies appreciably, therefore, blasting engineers should frequently review the suitability of

(a) the peak blasthole pressure (see Equation (1)), and

(b) the resistance to premature escape of explosion gases to atmosphere. (This depends heavily on the burden distance and both the type and length of stemming.)

5. EFFECT OF GRAIN SIZE OF ROCK

The larger-grained igneous rocks such as granite and diorite are sometimes difficult to drill, because of their silica content, but usually shatter readily when blasted. The degree of fragmentation very close to (within say four blasthole diameters of) a charge is restricted by the grain size, since fractures tend to propagate along grain boundaries rather than through the grains themselves. It follows that close-range fragmentation is usually coarser for larger-grained rocks.

In rocks with fine grains (eg, basalts, rhyolites and andesites), the degree of fragmentation produced by burn cut blastholes may be so great that the fragments re-cement and freeze in the cut. When broken, all rocks exhibit a swell or expansion factor which varies with both the rock type and the particle size of the fragmented material. The swell factor is typically 25%, but where (as is the case in burn cuts) rock fragmented by the earliest-firing charge has to be blown out through the enlarged relief holes, one may need to allow for expansion of as much as 30% if freezing of the cut is to be consistently avoided. To prevent excessive shattering and the resulting greater probability of recompaction and freezing of the cut, it is necessary to ensure that P_b is not too high for the specific conditions, and especially the grain size of the rock. The increase in swell factor with degree of fragmentation tends to explain some of the frozen burn cuts that are observed where pneumatically-charged ANFO (ammonium nitrate/fuel oil) or powerful highly coupled gelatine dynamites are used in fine-grained rocks.

6. EFFECT OF INTERNAL FRICTION OF ROCK

Rocks such as mica schist and, to a lesser degree, granite gneiss may be quite massive and yet, because of the platy nature of their constituent minerals, exhibit high values of internal friction. For this reason, these rocks cause considerable attenuation or damping of explosion-generated strain waves, and adequate fragmentation necessitates the use of

(a) high energy factors,
(b) relatively small blasthole patterns and short stemming lengths, and
(c) large numbers of blastholes (for a given tunnel cross-section or blast size).

7. EFFECT OF CONDUCTIVITY OF ROCK

Current leakage is encouraged where electric detonators are placed inside blastholes in conductive ground, especially where series blasting circuits are employed in wet and/or abrasive rocks. In highly conductive ground, great care should be taken to ensure

(a) that the insulation on detonator wires is not abraded, and
(b) that all connections in series or series-in-parallel detonator circuits are insulated.

Insufficient consideration of the conductivity of rock can cause numerous misfires and, hence, unacceptable blasting results.

Fortunately, the predicted gradual replacement of electric detonators by non-electric (shock tube-type) detonators will reduce and finally eliminate this potential problem.

8. EFFECT OF MIXED PETROLOGY

So far, this paper has considered situations in which each blast is fired in a rock having its own set of physical and mechanical properties. But there are other, more complex situations. When tunnelling in sedimentary strata, for example, there may be two or more rock types within a given blast.

In the situations shown in Fig. 9, efforts should be made to place the cut, especially if it is a burn cut, in the stronger rock. In theory, it is possible to employ a larger blasthole pattern in the weaker rock. But in practice, the blasthole pattern within a blast is usually standardised. Where the simplicity of a standard pattern is required, burden distances and blasthole spacings should be such that charges of normal length give good blasting results in the stronger rock. Shorter charges are then used in the weaker rock. If the pattern were to be larger in the weaker rock, marking and drilling the face would become too complex.

In Fig 9b, overbreak and instability potential tend to be greater along AB than along BC and, therefore, greater design effort and especially implementation care are required to control overbreak in the weaker rock. Along BC, the spacing of perimeter blastholes can be larger and the perimeter charges heavier than those along AB.

Where a blasthole lies within or passes through a thick bed of clay or similarly soft material, its charge will do little effective work and adjacent charges in stronger adjoining beds may be unable to recover the situation sufficiently. If the clay seam is thick and sufficiently weak, it could possibly be used to replace relief holes in a burn cut.

9. EFFECT OF COMPLEX GEOLOGY

Tunnel blasting is always a challenge, and is never more so than in complex rock masses. Rock masses are complex wherever their physical or petrological properties change appreciably over short distances. Rock mass complexity is greatest where both physical and petrological properties change considerably over very short distances, and especially where the effect of this high variability is exacerbated by the action of in-situ stresses or by adverse groundwater conditions.

Where petrology and physical properties vary gradually along the length of a tunnel, efforts should be made to progressively modify the blast design, so that the design is always highly compatible with the rock properties at that particular location.

Optimum changes to designs and procedures need to be based on

(a) pertinent accurate measurements/observations and prompt reporting by an experienced geologist, and

(b) the rapid yet careful application of this data, all relevant background knowledge and experience-based judgement to moulding the blast so that it maintains high compatibility with the rock mass.

Ideally, this should also be done where a tunnel is driven through a rock mass which exhibits widely varying properties over short distances. But this ideality needs to be tempered by the need for a working level of standardisation. It may well be impracticable to make frequent alterations to the blasthole pattern. In this event, it is usually preferable to select a standard blasthole pattern (to facilitate marking and drilling of the face) and then to charge blastholes most heavily in the strongest rock and most lightly in the weakest rock encountered.

10. CONCLUSIONS AND RECOMMENDATIONS

10.1 Rock properties have a considerable effect on

- (a) blast design, and especially type of blast round (full-face or otherwise), length and pattern of blastholes, explosion energy factor, and charge concentration in perimeter blastholes; and
- (b) blasting results, including the incidence of misfires, degree of fragmentation, mean advance per round, and amount of overbreak.

10.2 As the mean spacing between fissures (ie, natural cracks) decreases, the importance of rock substance strength decreases while that of rock mass strength increases.

10.3 If new effective cracks are to be produced, the dynamic tensile breaking strain of the rock needs to be exceeded.

10.4 Explosive charges should be designed so as to develop a peak radial strain which is equal to the dynamic compressive breaking strain of the rock.

10.5 Whilst rock strengths are the most important, blasting is also affected by the internal friction and grain size of the rock and by the presence of micropores and vughs (ie, macropores).

10.6 Currently, our understanding of the mechanisms of fragmentation and overbreak is inadequate. This deficiency
   (a) stems mostly from our inability to define and synthesise the numerous, complex and important effects of fissures, planes of weakness, etc on blasting; and
   (b) prevents the development of initial blast designs which are optimum.

10.7 Progress in optimising blasting has been slowed by the heterogeneous and anisotropic nature of rock. Where rock properties vary gradually along a tunnel, the blast design should be progressively modified so that it is always highly compatible with the rock properties at a particular location. Under these conditions, the very versatile perimeter charge shown in Fig. 7 is recommended. Where rock properties vary widely over short distances, it is usually more practicable to select a standard blasthole pattern and then to charge those blastholes in the strongest rock most heavily and those in the weakest rock most lightly.

10.8 Geological complexity is often greatest where both physical and petrological properties of the rock mass vary widely over short distances. Tunnel blasting is always a challenge and is never more so than in complex geology.

10.9 In the interest of maximising the overall cost efficiency of tunnelling, it is important that the effect of rock properties on blasting be investigated more intensively. There is a need for closer technical cooperation between experts in the field of blast engineering, engineering geology and rock mechanics.

10.10 In the meantime, achieving high advance rates, good overbreak control and minimum total costs requires that blasts be designed by persons who can
   (a) blend the best engineering principles with considerable experience-based judgement and then apply the resulting expertise to the development and application of initial blast designs;
   (b) examine and evaluate the results of initial blasts;
   (c) relate any deficiencies in blasting results with particular blast design parameters; and then
   (d) make appropriate and progressive changes until drilling and blasting are optimised.

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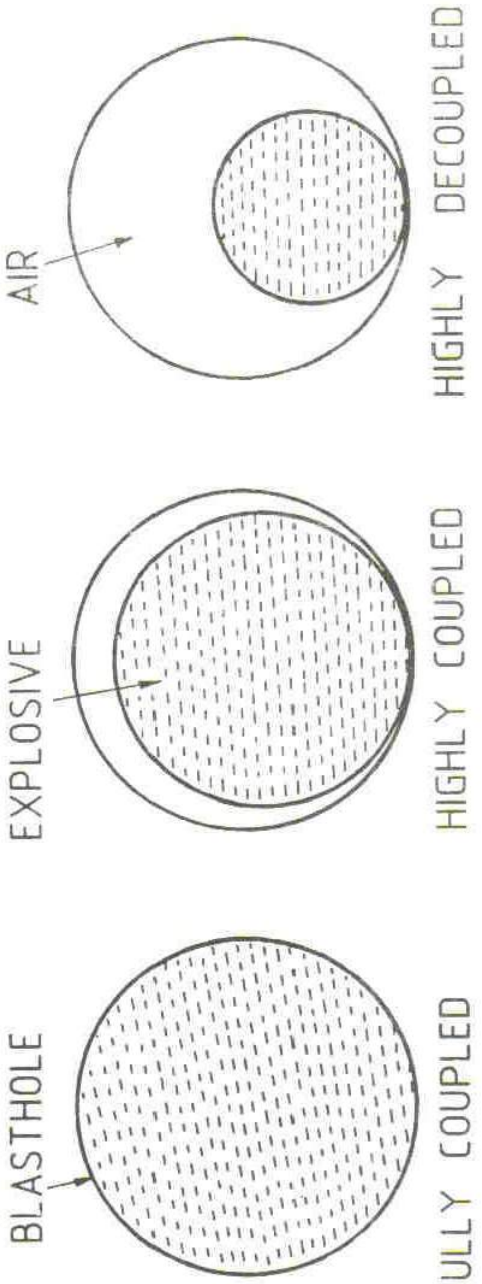

Figure 1. Degrees of coupling of explosive charges

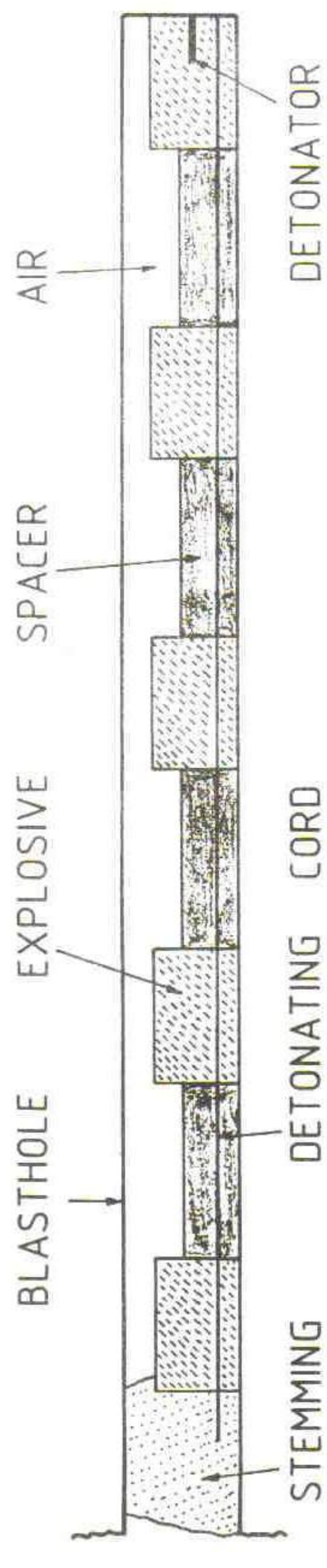

Figure 2. Use of spacers to reduce the concentration of explosion energy in blastholes.

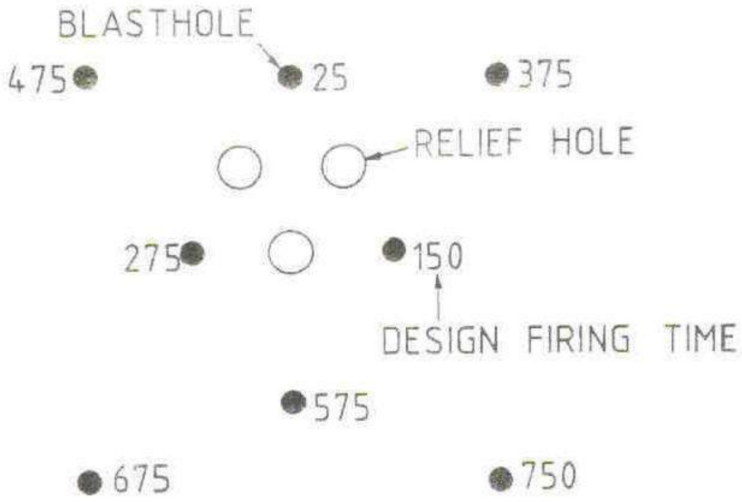

Figure 3. Highly satisfactory burn cut (design firing times expressed in milliseconds).

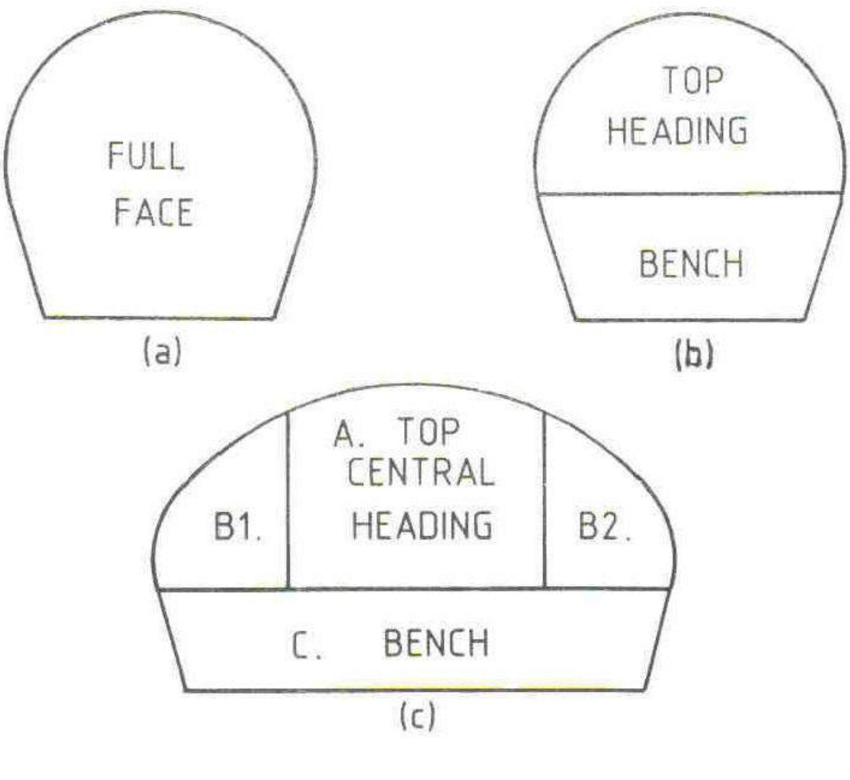

Figure 4. Single, double and triple - phase methods of blasting tunnels.

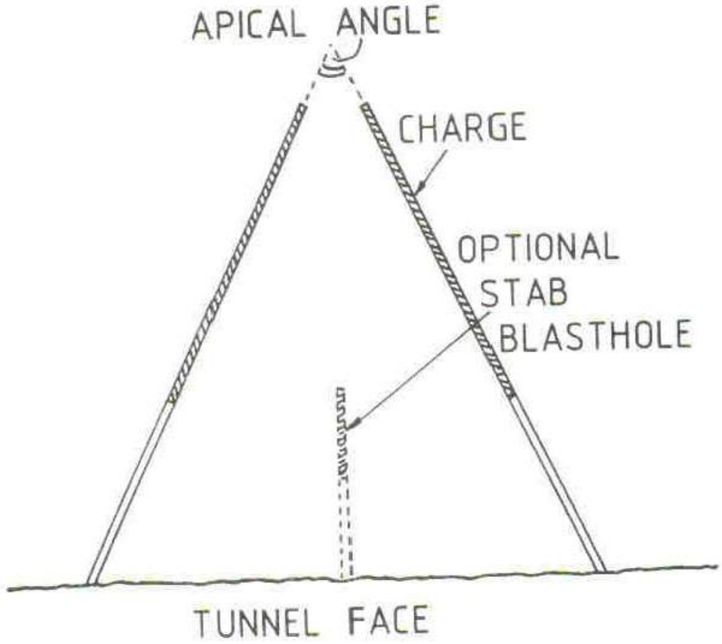

Figure 5. Apical anagle for wedge-cut blastholes.

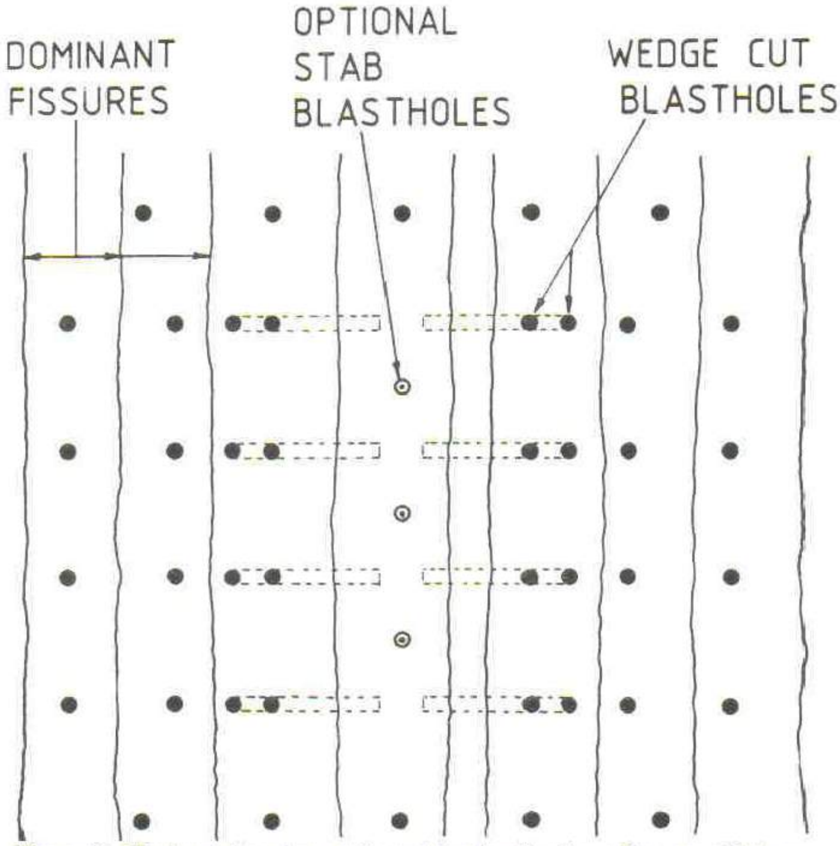

Figure 6. Horizontal wedge cut in rock having dominant fissures which are verticle and parallel to the tunnel axis.

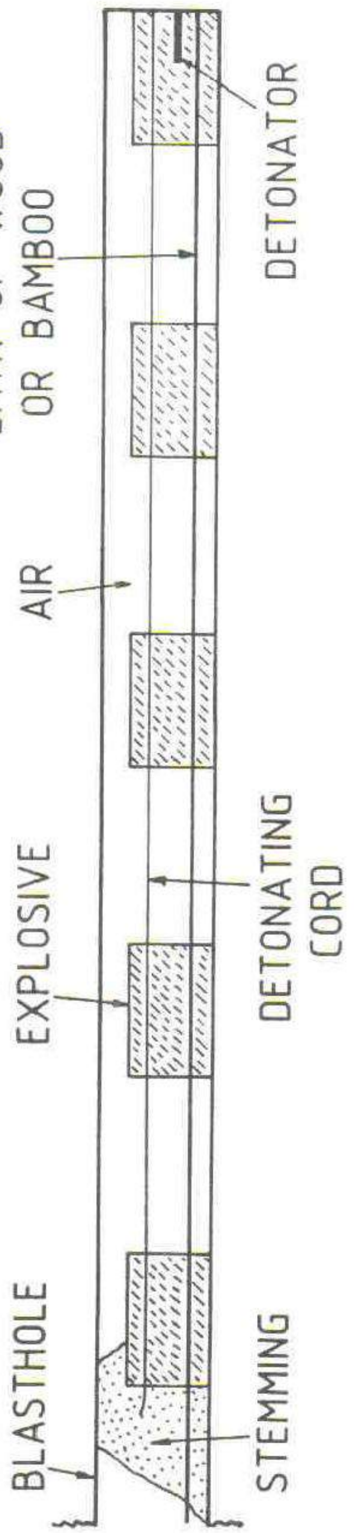

Figure 7. Controlling oveerbreak by using preassembled, air-decked charges in perimeter blastholes.

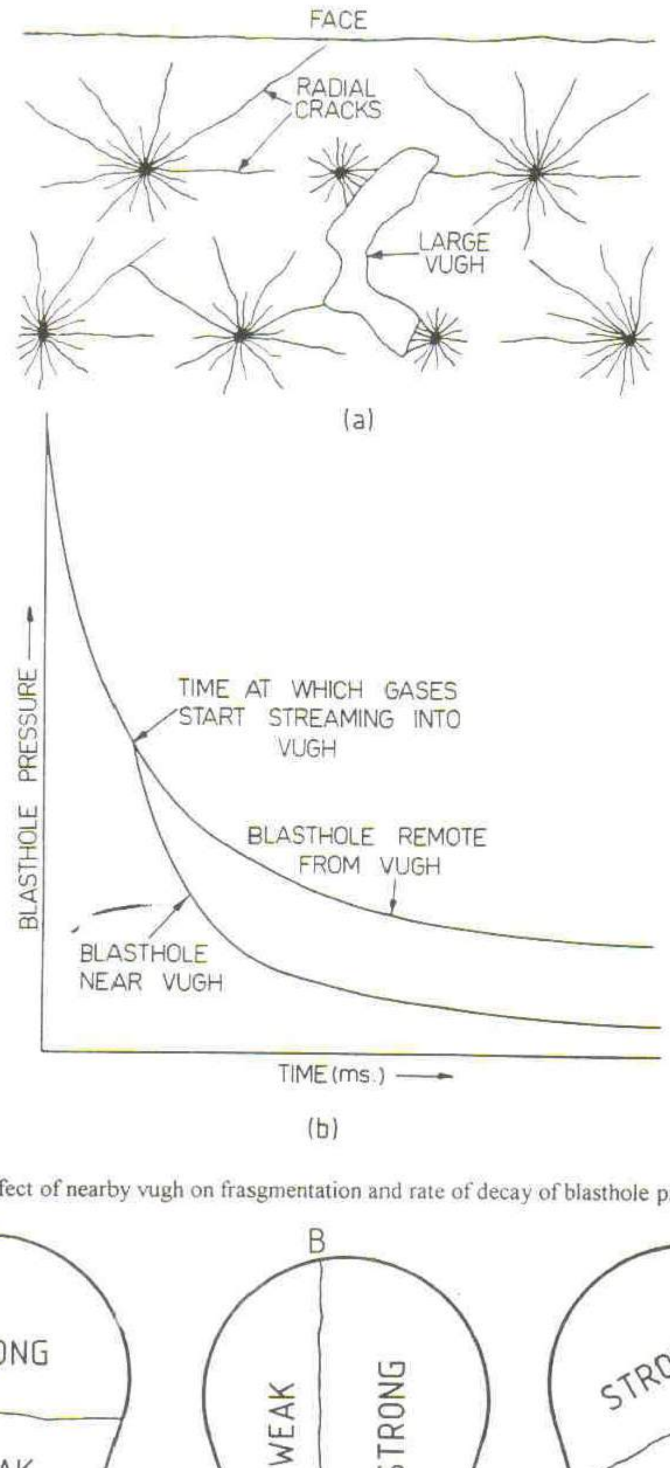

Figure 8. Effect of nearby vugh on frasgmentation and rate of decay of blasthole pressure.

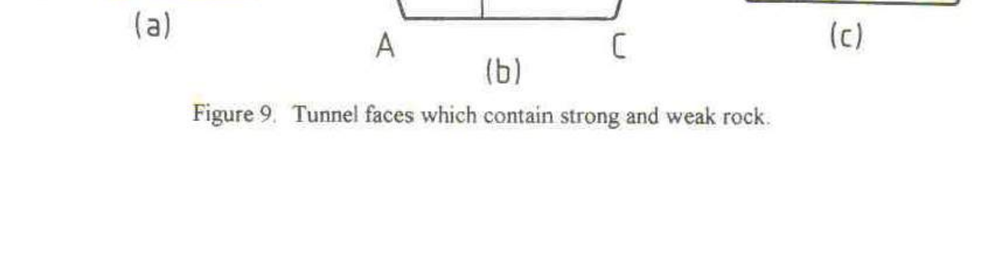

Figure 9. Tunnel faces which contain strong and weak rock.