CHAPTER 33

Land vibrations, air blast and their control

33.1 INTRODUCTION

The principal disturbances created by blasting are: vibrations, air blast and fly rock, Fig. 33.1. All of them can, under some circumstances, cause damage to structures nearby and, apart from this, be the source of permanent conflict with the inhabitants who live close to the operation. Dust formation is also quite frequent and difficult to control.

In order to solve these problems, it is necessary to have more highly qualified blast superintendents so that they can reduce the level of disturbances at a reasonable cost. Another issue to take into account is the job of information and public relations, which is becomming a necessity, undertaken by the directors of the operation. This can be even more effective than an exhaustive study by specialists in the matter.

This chapter analyzes the theory of vibration and air blast produced by blasting, the methodology of study, the applicable damage criteria and the design parameters which must be taken into consideration by the technician to be able to control these environmental alterations.

33.2 PARAMETERS WHICH AFFECT VIBRATION CHARACTERISTICS

The parameters which affect the characteristics of vibrations are, practically, the same ones which influence the results of the blasts. They can be classified in two groups: controllable and uncontrollable by the users of explosives.

The local surrounding geology and rock geomechanics have great influence on vibrations.

In homogeneous and massive rock masses the vibrations are propagated in all directions; but in complex geological structures, the wave propagation can vary with the direction and, consequently, give different attenuation indexes or laws of propagation.

When the rocky substratum is covered by soil overburden this usually affects the intensity and frequency of vibrations. Soil usually has less elasticity modulus than the rocks and, for this reason, the wave propogation velocity diminishes in this type of material. The vibration frequency *f* also dimishes, but displacement *A* increases significantly as the overburden thickens.

The magnitude of the vibrations decreases rapidly with distance increase if soil overburden is present because a large part of the energy is used up in overcoming friction between particles and in displacing them.

At points close to the blasts, the characteristics of the vibrations are affected by the factors of blast design and their geometry. At large distances from the blast, the design factors are less critical and the transmitting medium of rock and soil overburden dominates the wave characteristics.

The surface materials modify the wave trains making these last longer and have lower frequencies, therefore increasing the response and potential damage to nearby structures.

From a study carried out by Stagg and Dowding (1980), it can be deduced that the vibration frequencies in coal mines are lower than those generated in quarries and construction jobs, Fig. 33.2, which is justified by the long length of the explosive columns, the complexity of the geological structures and by the presence of soil overburden.

An appreciable amount of the energy transported by vibrations in coal mines has a frequency that is lower than 10 Hz. This induces important ground displacement and high stress levels, which provoke damages in structures with resonance frequency between 4 and 12 Hz.

In another statistical study on more than 2700 registers carried out by Nobel's Explosive Company Limited, it can also be observed that 90% of the blasts in coal mines produces vibration frequencies under 20 Hz. The number of blasts in quarries that give frequencies between 4 and 21 Hz is approximately 80%, Fig. 33.3.

The phenomenon of low frequencies is most clearly seen in underwater blasts or in rock masses that are saturated with water.

33.2.2 *Charge weight per delay*

The magnitude of ground and air vibrations at a determined point varies with the explosive charge that is detonated and the distance of that point from the blast area. In blasts where more than one period number of detonator is used, the largest charge per delay has the most direct influence on vibration intensity and not the total charge used for the blast, as long as the delay interval is sufficient to avoid constructive interferences between the waves generated by the different groups of blastholes.

When there are various blastholes in a blast with detonators which have the same nominal delay time, the

Photo 33.1. Alterations produced by blasts: vibrations, air blast, fly rock and dust.

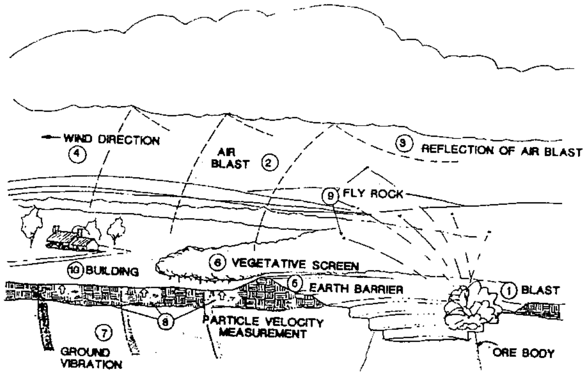


Fig. 33.1. Disturbances originated by rock blastings.

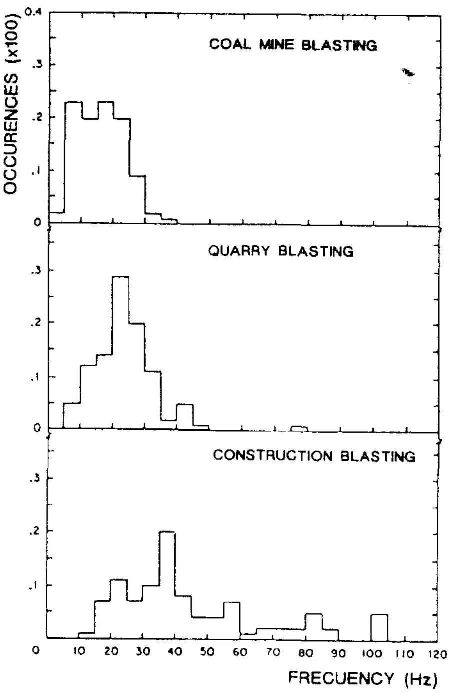


Fig. 33.2. Predominating frequencies of vibrations from coal mine, quarry, and construction blasting (Dowding et al. 1980).

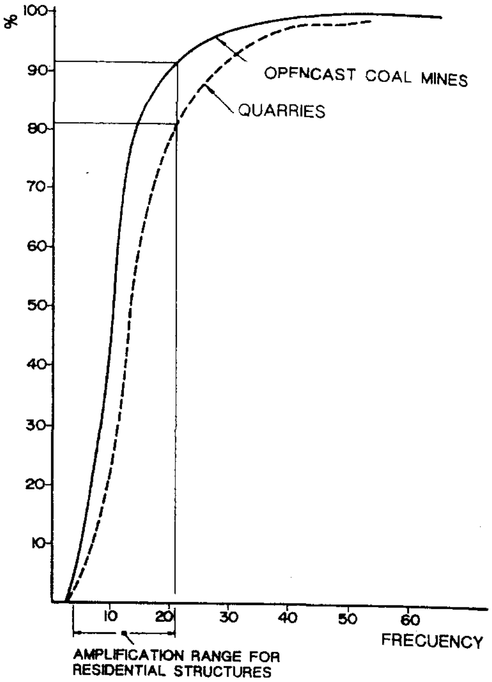


Fig. 33.3. Predominant vibration frequencies in surface coal mines and quarries.

Table 33.1. Cooperation fractions for different types of detonators.

Detonator	Period number	Period (ms)	Scatter (ms)	Cooperation within period (Reduction factor)
VA-MS/Nonel	1-10	25	5-10	½
VA-MS/Nonel	11-20			⅓
VA-MS/Nonel	24-80	100	20- 50	¼
VA/MS	1-12	500	100-200	⅙

Note: These values are only for frequencies over 20 Hz.

maximum charge weight per delay is usually less than the total, owing to cap scatter in the break times of each detonator system. For this reason, in order to determine said charge weight per delay, a fraction of the total number of charges initiated by detonators of the same nominal delay is estimated. Thus, for example, for the detonators manufactured by Nitro Nobel AB the following cooperation fractions can be estimated (Persson, 1980) Table 33.1.

The charge weight per delay is the most important individual factor that affects the generating of vibrations. The relationship that exists between vibration intensity and the charge is of potential type, therefore, for particle velocity the following exists:

$$v \propto Q^{a}$$

The investigations carried out by the US Bureau of Mines show that the value of a is around 0.8.

33.2.3 *Distance from point of blast*

The distance from the blasts has, as happens with the charge, great influence on the magnitude of vibrations.

As the distance increases, vibrations diminish according to a law of the following type:

$$v \propto \frac{1}{D^b}$$

where the value of b, according to the US Bureau of Mines, is around 1.6.

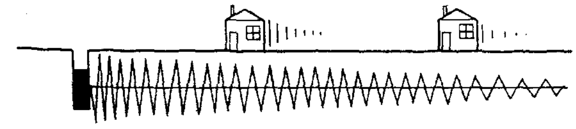
Another effect of distance is due to attenuation of the high frequency wave components, as the earth acts a filter through which the lower frequencies pass. Thus, at long distances the ground vibrations will have more energy in the low frequency range, Fig. 33.4.

33.2.4 *Powder factor*

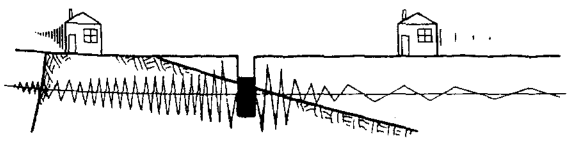
Another interesting and sometimes confusing aspect is the powder factor.

When confronted with vibration problems, some engineers propose to reduce the powder factor of the blast, but nothing is farther from the minimum level situation. Blasts have been recorded in which the powder factor was reduced 20% from the optimum and the vibration levels measured were two or three times higher as a consequence of the confinement and poor spatial distribution of the explosive, causing lack of displacement and swelling energy.

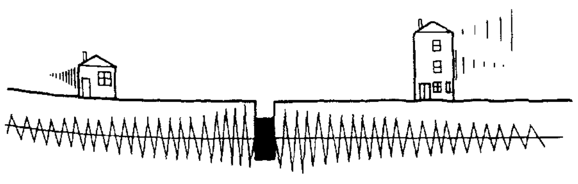
In Fig. 33.5, the powder factor influence can be observed in extreme situations and close to the optimum level in bench blasting.



a. EFFECT OF DISTANCE



b. EFFECT OF GEOLOGY



c. EFFECT OF RECEIVING STRUCTURES

Fig. 33.4. Effects of site conditions on blast vibrations.

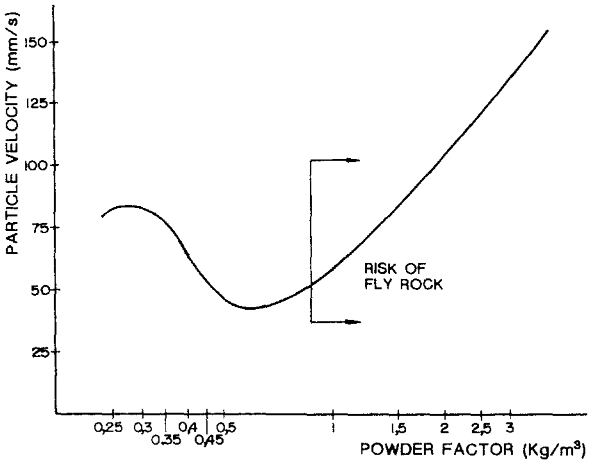


Fig. 33.5. Powder factor influence on vibration intensity.

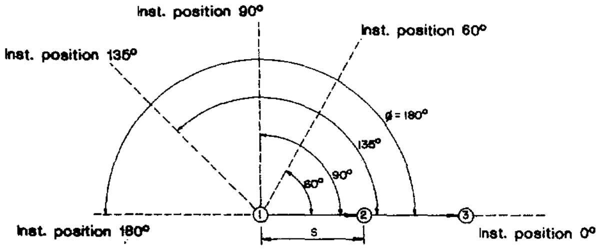


Fig. 33.6. Typical recording instrument positions and firing angles for a 3 hole blast, with a firing sequence of 1-2-3 from left to right (Wiss and Linehan).

33.2.5 *Types of explosives*

There is a correspondence between the particle velocities and the strains induced in the rocks, and this constant of proportionality is the impedance of the rock medium.

Therefore, the first practical consequence is that those explosives which generate lower blasthole pressures will also produce lower vibration levels. These explosives are those of low density and detonation velocity such as ANFO. If the same amount of ANFO is compared with a common slurry, or with an aluminized watergel, the intensity of vibrations generated by the first is 2 and 2.4 times lower respectively. This finding has been supported by various engineers such as Hagan and Kennedy (1981), Matheu (1984), etc.

In vibrographic studies, if explosives of very different strengths are used, the charges should be normalized to a standard explosive of known strength. Usually ANFO is chosen as the reference explosive, as it is the most widely used.

33.2.6 *Delay Period*

The delay intervals between blasthole detonations can be referred to as the nominal delay or effective delay time.

The first is the difference between the nominal initiation times, while the effective delay time is the difference of the arrival times of the pulses generated by blasthole

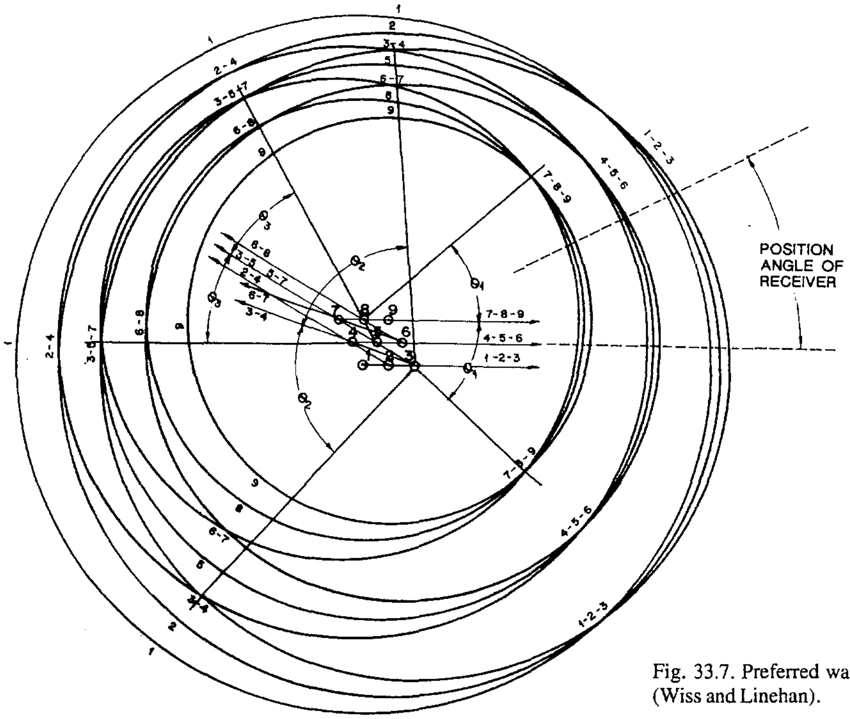


Fig. 33.7. Preferred wave collaboration directions in a multiple blast (Wiss and Linehan).

detonation fired with consecutive periods. In the simple case of a single row of holes, these parameters are interrelated by the following equation:

$$t_e = t_n - \frac{S \times \cos \phi}{VC}$$

where: t_e = Effective delay time, t_n = Nominal delay time, S = Spacing between holes, VC = Propagation velocity of the seismic waves, ϕ = Angle between successively detonated holes and the position of the sensor or recording instrument.

In Fig. 33.6, the case of a single row of blastholes with different relative positions of the recording instruments.

The critical angle of the relative position where the seismic waves arrive at the same time and, therefore, a collaboration can occur between them, will be that where $t_e = 0$, and can be determined from:

$$\phi_c = \arccos \frac{VC \times t_n}{S}$$

In Fig. 33.7, a multiple blast is represented and the directions where there is a more probable interaction of the waves according to the theoretical break direction of the holes.

When referring to the minimum delay time that eliminates constructive interferences or has summing or interacting effects, in the first studies carried out by Duvall et al. (1963), intervals of 8 and 9 ms were suggested, calculated from the testing done in limestone quarries. Langefors (1963) points out that with intervals of more than 3 times the vibration period it can be assumed that there is no interaction between adjacent blastholes that are detonated in sequence, as the signals are absorbed. Wiss and Linehan (1978) suggest a nominal delay time between successive delay intervals of 17 ms, to eliminate the summing effect of the vibrations. In another study done by Nobel's Explosives Co. of Great Britain, on secuenced blasts with delay times between charge weights per hole of under 25 ms, the existance of constructive interferences in the maximum vibration level is confirmed, Fig. 33.8.

33.2.7 *Geometric parameters of the blasts*

The majority of the geometric design parameters have a considerable influence on vibrations generated by blasting. Some comments on the subject are:

– *Drilling diameter.* The increase in drilling diameter is negative as the amount of explosive per hole is proportional to the square of the diameter, which would give very high charge weights per hole on occasions.

– *Bench height.* The relationship $H/B > 2$ should be maintained, whenever possible, in order to obtain good fragmentation and eliminate toe problems, as well as reducing vibration levels because the charges are less confined.

– *Burden and spacing.* If the burden is excessive, the explosion gases find resistance to fragmentation and rock displacement, and part of the explosive energy is transformed into seismic energy which increases vibration intensity, Fig. 33.9. This phenomenon is most noticeable in presplitting blasts, where total confinement exists and vibrations of around five times those of a conventional bench blast can be registered.

If burden size is small, the gases escape and expand towards the free face at a very high speed, giving impulse

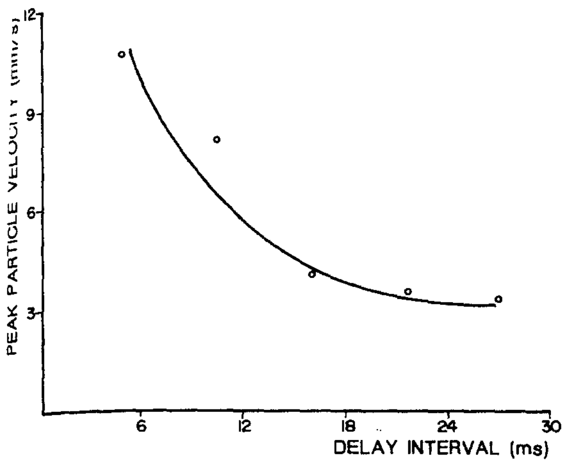


Fig. 33.8. Influence of the delay period upon the maximum vibration level.

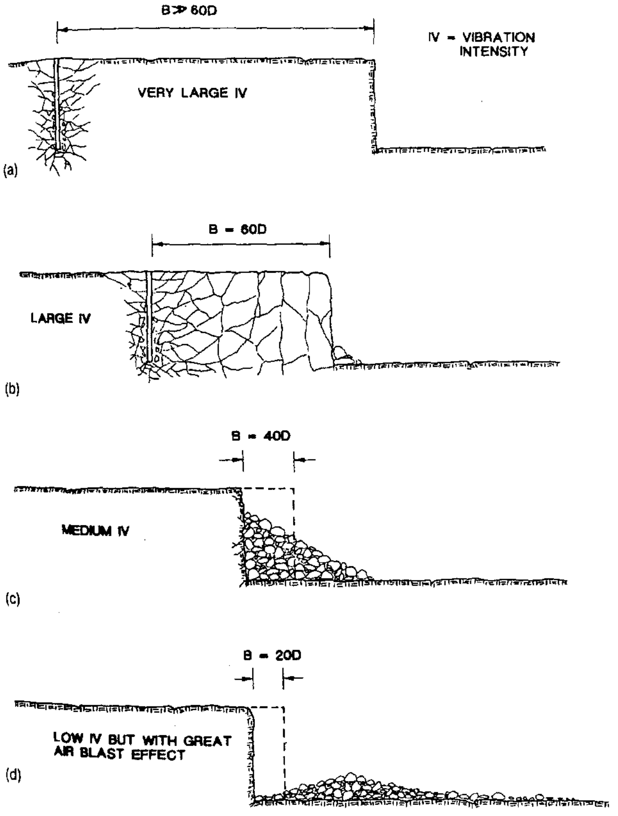


Fig. 33.9. Effects of the explosion according to the distance of the charged shothole from the free face (Berta, 1985).

to the rock fragments and projecting them uncontrollably, apart from provoking an increase in air blast and noise.

Spacing has a similar influence and its dimension actually depends on the burden value.

– *Subdrilling.* When longer than necessary lengths are used, each additional section collaborates each time with a lesser amount of energy for shearing and rock movement at the base, which means that a higher percentage of the explosive energy is converted into ground vibrations. This also makes for superfluous expense in drilling and explosives, and the floor is left irregular.

– *Stemming.* If stemming is too high, apart from fragmentation problems, confinement is increased and vibration levels are possibly higher.

– *Blasthole inclination.* Inclined blastholes allow better use of energy at floor level, and even reduce vibrations.

– *Decked charges (decoupling).* Tests carried out by Melnikov, using decked charges of 65 to 75%, show that fragmentation is improved and the size distribution is more uniform.

The percentage of secondary blasting is reduced from 2 to 10 times as well as the powder factor and the intensity of ground vibrations, Fig. 33.10.

– *Size of the blasts.* The dimensions of the blasts are limited, on one hand, by the maximum charge weights per hole that have been determined in the vibrographic studies based on the laws of propagation, types of structures to be protected and characteristic parameters of the disturbance phenomena.

33.3 CHARACTERISTICS OF GROUND VIBRATIONS

In the following paragraphs some theoretical aspects of the generation and propagation of vibrations produced in rock blasting are analyzed; although it must be indicated that this is just a mere approximation to the problem, as the actual phenomena are much more complex owing to the interaction of different types of waves and their modifying mechanisms.

33.3.1 *Types of generated seismic waves*

The vibrations generated in blasting are transmitted through the ground as seismic waves. The wave front is displaced radially from the point of detonation. The different seismic waves are classified in two groups: *body waves* and *surface waves.*

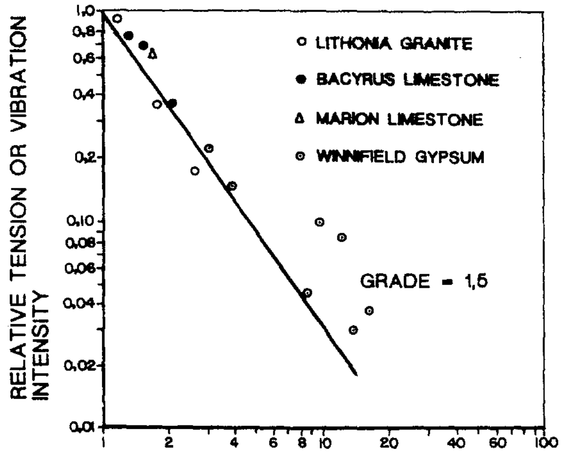


Fig. 33.10. Decked charge influence in vibration intensity.

The first type of body waves are called *Primary or Compressional.* These wave propagate through the ground materials alternatingly producing compressions and dialations, with particle movement in the direction of wave propagation. These are the fastest waves and they change the volume but not the shape of the materials through which they propagate.

The second type are made up of *Transverse or Shear – S waves* which move the particles in a direction that is perpendicular to that of wave propagation, Fig. 33.11.

The velocity of the transverse waves is somewhere between that of the longitudinal waves and the surface waves. The materials through which they propagate change in shape but not in volume.

The surface waves that are usually generated in rock blasts are: Rayleigh-R waves and Love-Q waves. Other types of surface waves are the Channel waves and the Stonelly waves which are not important as they supply very little information.

The Rayleigh waves are characterized by eliptical particle orbit, usually a motion that is contrary to the propagation direction of the wave. The Love waves are faster than the Rayleigh and give particle motion that is transverse to that of propagation.

The propagation velocity of the *P* and *S* waves depends on the elastic constants of ground materials and can be estimated from the following equations:

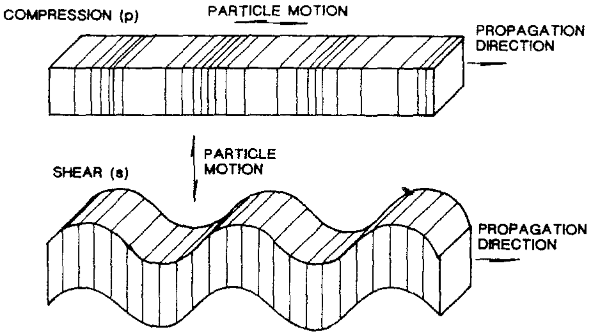


Fig. 33.11. Compressive-P and Shear-S waves.

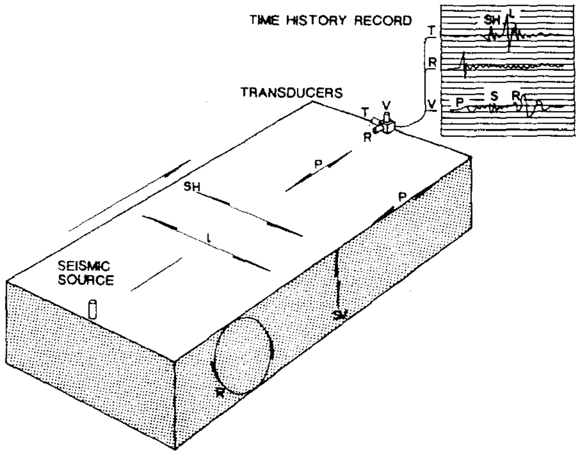


Fig. 33.12. Different wave types.

$$VC_p = \sqrt{\frac{E \times (1 - \nu)}{\rho_r \times (1 - 2\nu) \times (1 + \nu)}}$$

$$VC_S = \sqrt{\frac{E}{2 \times \rho_r \times (1 + \nu)}}$$

where: ρ_r = Rock density, ν = Poisson's ratio, E = Young's modulus, VC_p and VC_s = Propagation velocities of the longitudinal and transverse waves, respectively.

For a material with a Poisson coefficient of 0.25, it can be stated that VC_p is 1.73 times VC_s, and that the velocity of the Rayleigh waves is 0.9 VC_s.

As the waves travel with different velocities and the the number of delays in the blasts can be large, the generated waves interact with one another in time and space, producing for complex movements which require that the instruments be placed in three directions: radial, vertical and transversal, Fig. 33.12.

The distribution of the energy transported by the different types of waves has been studied by several investigators such as Miller and Pursey (1955), Vorob'ev (1973), etc. who have come to the conclusion that the Rayleigh waves carry between 70 and 80% of the total energy.

In the blasting manual by Du Pont, it is stated that this type of wave dominate the surface ground movement at several hundred meters from the blast and, as many structures and buildings around the operations are farther than 500 m away, the Rayleigh waves constitute the highest potential damage risk.

33.3.2 *Wave parameters*

The passing of a seismic wave through a rock medium puts all of its particles in motion, which is called vibration.

A simplification for the study of blast generated vibra-

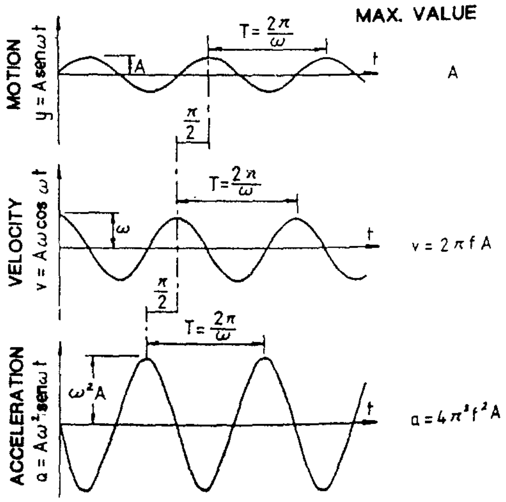


Fig. 33.13. Harmonic wave motion.

tions consists of considering these as harmonic motion type waves, Fig. 33.13.

The basic parameters for analysis are:

- *Amplitude (A)*. Maximum displacement of a particle from its rest position.
- *Particle velocity (v)*. Velocity at which a particle moves.
- *Acceleration (a)*. Velocity per unit time, i.e., $a = v/t$.
- *Frequency (f)*. Complete number of oscillations or cycles per second. The frequency is the inverse of the period T_s.

The displacement y at any instant is worth:

$$y = A \times \text{sen}\,(\omega t)$$

where:

$$\omega = 2 \times \pi \times f = 2 \times \pi \times \left(\frac{1}{T_s}\right)$$

The length of the wave λ for a propagation velocity of VC is:

$$\lambda = VC \times T_s = VC \times \left(\frac{1}{f}\right)$$

The relationships between displacement, velocity and acceleration of the particle are:

$$y = A \times \text{sen}\,(\omega t)$$

$$v = \frac{dy}{dt} = A \times \omega \times \cos(\omega t)$$

$$a = \frac{dv}{dt} = -A \times \omega^2 \times \text{sen}\,(\omega t)$$

When only the maximum absolute values of these parameters are taken into account, the previous relationships are converted into:

$$v_{\max} = A \times \omega = A \times 2 \times \pi \times f$$

$$a_{\max} = A \times \omega^2 = A \times 4 \times \pi^2 \times f^2 = v_{\max} \times 2 \times \pi \times f$$

33.3.3 *Geometric attenuation*

The density of the energy of propagating waves generated by the detonation of an explosive charge diminishes as the waves reach larger volumes of rock. Given that the ground vibrations induced by the blasts comprehend a complex combination of waves, it would seen logical to take into consideration certain geometric attenuation factors for each type. In a homogeneous, elastic and isotropic medium, the amplitude drops due to geometric absorption, and its drop, for different types of dominating waves, is proportional to:

- $1/DS$ for body waves in an (semi)infinite medium.
- $1/DS^{0.5}$ for Rayleigh waves.
- $1/DS^2$ for body waves that travel along a free surface.

Where DS is the distance from the seismic source (Richart et al. 1970).

33.3.4 *Non-elastic absorption*

In nature, the rock masses do not constitute an elastic, isotropic and homogeneous medium for vibration propagation. To the contrary, numerous non-elastic or non-dispersive effects appear which provoke a loss of energy during wave propagation, which is added to that caused by geometric attenuation. There are numerous reasons for the non-elastic attenuations, and each has different degrees of influence:

- Dissipation in a nonelastic matrix owing to the relative movement in the intercrystaline surfaces and planes of discontinuity.
- Attenuation in saturated rocks owing to fluid movement with respect to the matrix.
- Flow inside the cracks.
- Dispersion of stresses induced by absorbed volatiles.
- Reflection in porous rock or with large cavities.
- Energy absorption in systems that have phase changes, etc.

33.3.5 *Interaction of elastic waves*

The interaction of seismic waves in time and space can bring about a concentratin or focusing which gives attenuation coefficient values that are higher or lower than predicted or theoretically calculated.

The topography and geometry of the geological formations can produce the reflection and concentration of wave fronts in certain points.

33.4 AIR BLAST CHARACTERISTICS

Air blast is the pressure wave that is associated with the detonation of an explosive charge, whereas noise is the audible and infrasonic part of the spectrum: from 20 Hz to 20 kHz. Air blasts are the low frequency air vibrations with values that are usually under 20 Hz.

According to Wiss and Linehan (1978), the causes of these disturbances are the following:

1. Ground vibration brought on by an explosion (Rock pressure pulse).
2. Escape of gases from the blasthole when the stemming is ejected (Stemming release pulse).
3. Escape of gases through the fractures created in the rock mass face (Gas release pulse).
4. Detonation of the initiating cord in the open air.
5. Displacement of the rock at bench face as the blast progresses (Air pressure pulse).
6. Collision between the projected fragments, Fig. 33.14.

The combination of vibrations associated with these sources give a mobile front of air overpressure that travels from the blast point. As air is compressible, it absorbs part of the pressure wave energy to later set it free

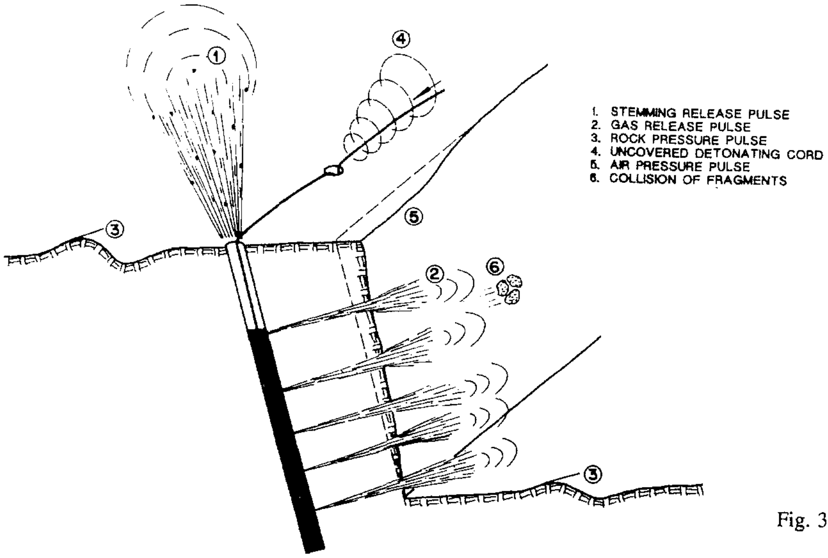


Fig. 33.14. Air blast fronts in blasting.

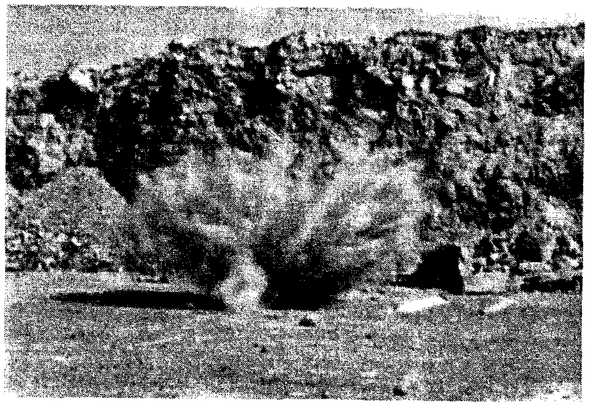


Photo 33.2. Effect of a detonating cord covered with sand.

through expansion of the hot gases, causing depression in those points.

Air blast characteristics are not easy to predict. Factors such as climate, topography, etc. intervene which, along with the actual blast design, can give different results in each case.

As mentioned before, air blast contains a considerable amount of low frequency energy which can eventually produce direct damage on structures; however, high frequency vibrations are more common and are felt in windows, dishes, doors, etc.

33.5 INSTRUMENTATION FOR RECORDING AND ANALYZING VIBRATIONS AND AIR BLAST

In order to carry out a study of vibrations and air blast, special instrumentation is required, as follows:

– A seismograph system which detects and records ground movement.

– A computer system which analyzes the recorded signals.

The most frequent ranges of the different characteristic parameters of blast induced vibrations are shown in Table 33.2.

33.5.1 *Recording and analyzing equipment*

The recording system consists of several components which carry out the following functions:

– Detection by sensors.

Table 33.2.

Parameter	Range
Displacement	10^{-4} to 10 mm
Particle velocity	10^{-4} to 10^3 mm/s
Particle acceleration	10 to 10^5 mm/s
Length of pulse	0.5 to 2 s
Wave length	30 to 1500 m
Frequency	0.5 to 100 Hz

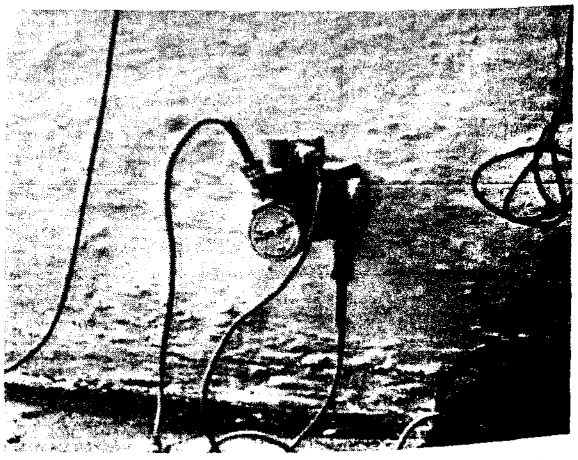


Photo 33.3. Triaxial recording station consisting of three accelerometers.

- The transmission of the electric signals emitted by the sensors through the conductor wires, and
- Recording of the signals with a seismograph for its posterior study and analysis.

In Fig. 33.15, a schematic diagram of the operations and instrumentation used in the study of vibrations is represented.

The sensors make up the first element of the measuring system and should be planted well in contact with the ground so that they vibrate as part of the earth, emmiting the signal which represents the true ground motion. This contact can be achieved by simply placing the sensors on the ground, by screwing them to blocks of aluminum or other nonferric material, which is the least recommendable if the sensors are electrodynamic; anchoring them next to a metal block by means of an expansion plug introduced into a hole made in the rock, which is the most common system used in firm ground; setting the sensors inside a box and burying it in the earth, used when the ground is not consolidated; and other less frequent alternatives such as drilling blastholes and cementing them to create a firm base, using synthetic resins, etc.

There are two tendencies as to where the sensors should be placed: one, on the ground near the structures to be protected; and another, on the structures themselves, bearing in mind that the latter will reflect the response of the construction and not record the ground movement.

As to the vibration sensors, the most widely used are the vibration seismographs and the acceleration seismographs. The first are the most popular, as particle velocity has become the parameter used to correlate the vibrations with the damage produced by the blasts.

They are electromagnetic type transducers which emit an electric tension that is proportional to the velocity of the vibration particle. The electric signal is generated by a mobile coil within the field of a stationary magnet, Fig. 33.16. The range of application is limited by the actual resonance frequency of the vibration seismograph, which is usually between 5 and 15 Hz and up to a maximum of 200 to 300 Hz. As can be seen, they are not recommendable when low frequencies exist.

The acceleration seismographs are based on the difference of potential generated by a piezoelectric crystal under force. This force is proportional to the mass of the cristal by the acceleration of vibratory movement, Fig. 33.17.

The recorders are instruments that allow visualization and amplification of the signals coming from the sensors. They can be of various types: those which only record peak values on paper, those which are continuous on photographic paper, printed by ultraviolet light galvanometers, those of needle and thermic paper, those which use magnetic tape cassette or record, recording analogic signals registered by the sensors.

These have the advantage of allowing the signal to be reproduced whenever necessary, introducing filters, integrators, etc. between said signal and the recorder.

The analogic recording on magnetic tape is carried out with different techniques which are adapted to the pertinent conditions: modulated frequency recording – inter-

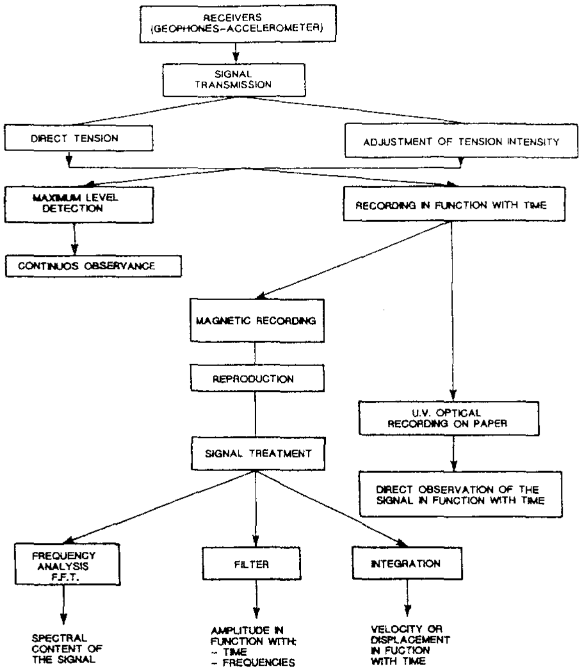


Fig. 33.15. Schematic diagram of the recording and analysis of vibrations.

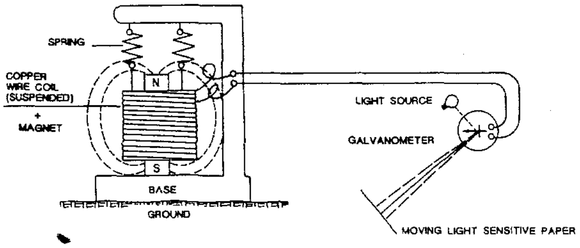


Fig. 33.16. Velocity gauge.

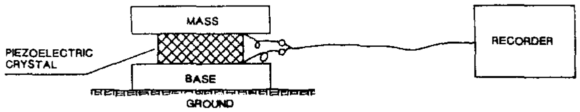


Fig. 33.17. Acceleration seismograph (accelerometer).

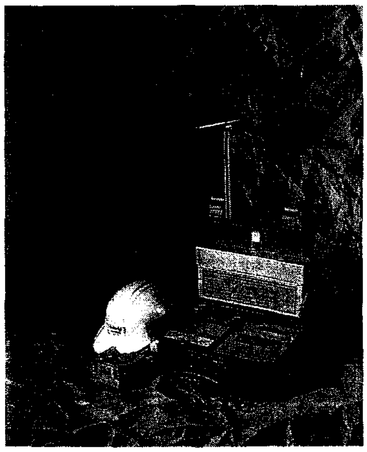


Photo 33.4. Seismograph for blast monitoring.

esting for low frequencies, direct recording for high frequencies, and multiplexed recording when a large number of signals come in.

The seismograph system is usually composed of analog or digital instruments to reproduce and visualize the signals.

When the signals are recorded on magnetic tape, these can be reproduced for a complete analysis, including the calculation of the Rapid Transform of Fourier in order to obtain the density of impulse frequency received or the energy destribution of seismic movement as function of the frequency. Apart from this, with the graphics obtained as function of the time, the maximum vibration level and its corresponding period can be predicted, as well as the length of the disturbance, etc.

When necessary, the signals can be filtered, integrated or derived, in order to eliminate certain components or calculate other parameters from the primitive recording; for example if acceleration has been measured, integrate one or two times to obtain particle velocity or displacement, respectively.

Lastly, it should be indicated that the sensors, although treated with care, should be checked periodically for sensitivity, and possible variation with use.

Air blast is usually measured with a sonometer, which is easy to transport and install. It should be placed away from reflecting surfaces, in front of shielding objects and making certain that there is no background noise or wind to modify the recording.

Special attention should be paid in selecting the scale of consideration, according to the measurements required.

33.6 CALCULATORS OF PROPOGATION LAWS FOR LAND AND AIR VIBRATIONS

One of the fundamental stages in the study and control of vibrations generated by blasting is the determination of the laws that govern their propagation in different mediums of land or air.

There are several methods used to estimate the ground movements produced by blasting. These methods are relatively simple as, if not, they would not have been readily accepted in the practical field of mining and civil engineering.

33.6.1 *Calculators for ground vibrations*

One of the first propagation equations was suggested by Morris (1950) and is as follows:

$$A = K \times \frac{\sqrt{Q}}{DS}$$

where: A = Maximum particle amplitude (mm), Q = Explosive charge weight (kg), DS = Distance from blast to recording point (m), K = Characteristic constant of the site which varies from 0.57, for competent hard rocks, up to 3.40 for unconsolidated ground.

Leconte (1967), when revising the vibration control techniques suggested substituting the maximum particle amplitude of the Morris equation for the vector sum of the particle velocity, as follows:

$$v = K_{vr} \times \frac{\sqrt{Q}}{DS}$$

Amongst the most rigorous posterior investigations, those of Blair and Duvall (1954) and Duvall and Petkof (1959) are worthy of mention as they also try to correlate the intensity of generated seismic movement with the explosive charge weight and the distance to the source. In the supposition that the explosive column is a symmetrical sphere, the conclusion was that any lineal dimension should be corrected by the cubic root of the explosive charge. Similar results were obtained by Ambraseys and Hendron (1968) and Dowding (1971).

In a general sense and taking particle velocity as the most characteristic vibration parameter, it was found that the intensity of the seismic waves and the scaled distance (cocient between the distance and the charge elevated to an exponent) followed the law below:

$$v = K \times \left[\frac{DS}{Q^{1/3}}\right]^{-n}$$

where: v = Particle velocity, DS = Distance, Q = Maximum charge per delay, K, n = Empirical constant.

If cylindrical charges are used, it has been observed by dimensional analysis that the distances should be corrected by dividing them by the square root of the charge, Devine (1962), Devine and Duvall (1963), then being able to define the following laws of propagation, Fig. 33.19:

$$v = K \times \left[\frac{DS}{Q^{1/2}}\right]^{-n}$$

This formula has been one of the most widely used up to present by numerous investigators, official organisms, users and manufacturers of explosives.

Other authors such as Atewel et al. (1965), Holmberg and Persson (1978), and Shoop and Daemen (1963) do not take into consideration a particular charge symmetry and use the following general equation:

$$v = K \times Q^{a} \times DS^{b}$$

where K, a and b are empirical constants estimated for a determined site by means of a multiple regression analysis.

At relatively small distances, in comparison with the charge length, the propagation law $v = K \times Q^{a} \times DS^{b}$ can be modified by taking into account the following geometric model, Fig. 33.20.

If one takes as basis a lineal charge concentration q_l (kg/m), the particle velocity v can be obtained by integrating the previous equation with respect to the relative position along the length of the charge.

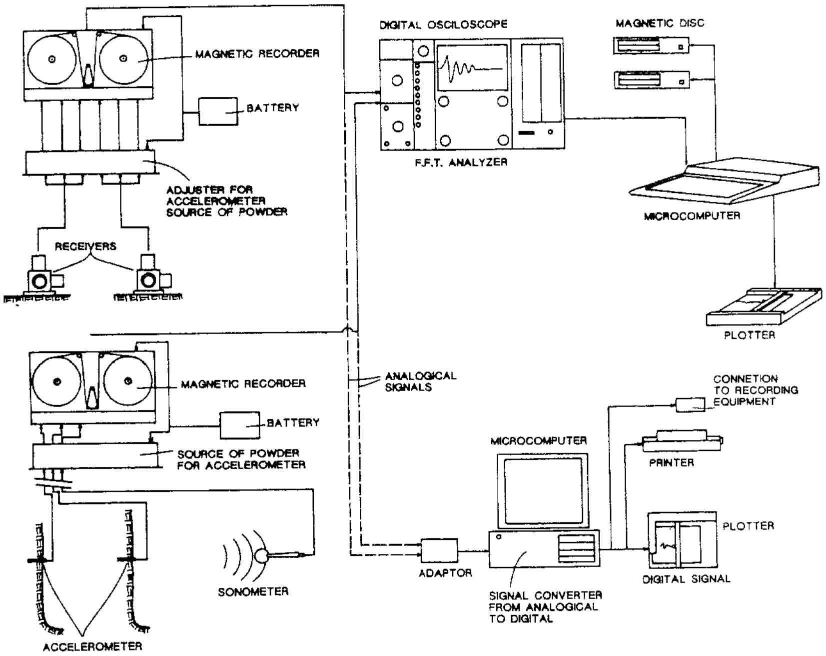


Fig. 33.18. Seismograph systems for recording and analyzing vibrations and air blast.

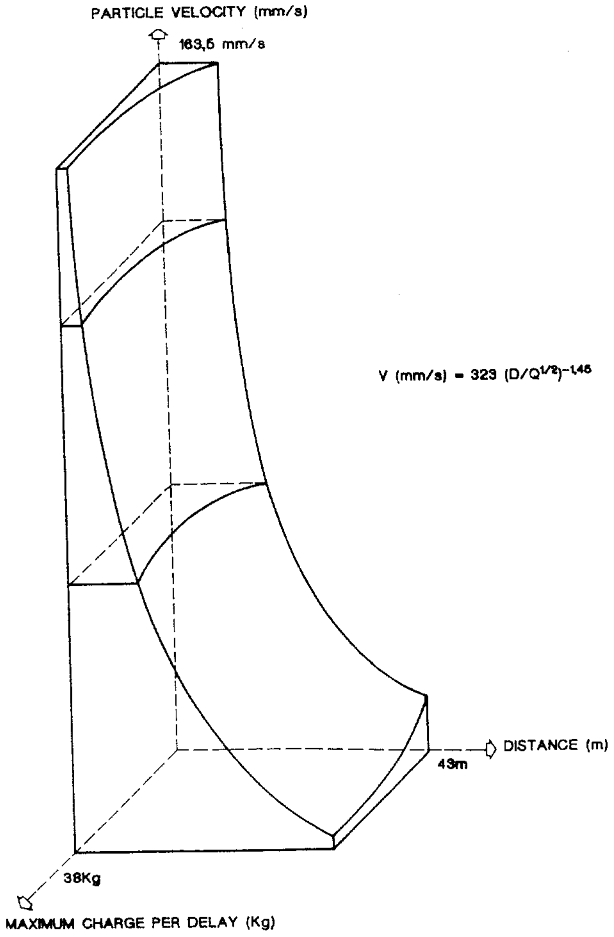


Fig. 33.19. Tridimensional representation of a vibration propagation law.

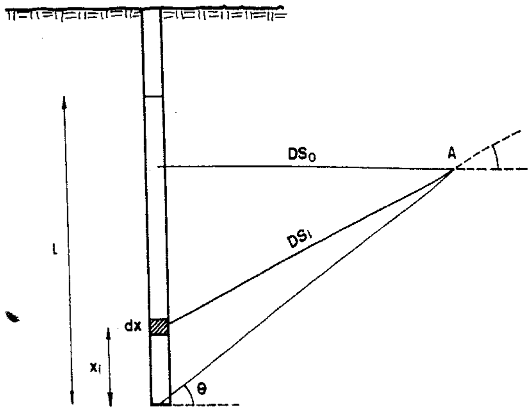


Fig. 33.20. Integration over charge length to calculate particle velocity at an arbitrary observation point (Holmsberg and Persson).

The distance from any part of the charge to point A is given by:

$$DS_i^2 = DS_o^2 \times (DS_o \times \text{tag}\,\theta - x_i)^2$$

where: DS_o = Minimum distance from charge to point A, θ = Angle of inclination, x_i = Distance from lower end of the elemental charge q_i.

$$q_i = q_l \times \mathrm{d}x$$

Integrating l along the total length of the charge, the maximum particle velocity is given by:

$$v = k \times q_l^{\,a} \times \left[\int_o^l \frac{\mathrm{d}x}{DS_o^1 + (DS_o \times \text{tag}\,\theta - x)^{2b/2a}}\right]^a$$

For competent rocks, such as Swedish granites, there are some constants with values $k = 700$, $a = 0.7$ and $b = -1.5$, with v expressed in mm/s.

In the Figs 33.21 and 33.22, the value of v is shown as function of DS, minimum distance from the point of interest to the elongated charge, and the lineal charge concentration for an explosive such as ANFO.

This method of calculation is very interesting when wishing to preserve the resistance characteristics of the remaining masses, in surface mining slopes as well as underground walls, as it enables the estimation of maximum charges for blastholes near the surface of the cut.

The Swedish school, headed amongst others by Langefors, Kilhström and Gustafsson, relates the charge levels $Q/DS^{3/2}$ with particle velocity by using the equation:

$$v = K \times \left[\frac{Q}{DS^{3/2}}\right]^{1/2}$$

Lundborg (1977), basing his observations on data of the US Bureau of Mining (Nicholls et al, 1971) found a law $v = f(DS, Q)$, and proposed the following equation:

$$\log v = 4.08 + 0.14 \log Q - 2.06 \log DS + 0.22 \log Q \times \log DS$$

which is represented as a tridimensional surface. A simplification consists in adapting a plane to said surface, obtaining the following equation:

$$\log v = 2.86 + 0.66 \log Q - 1.54 \log DS$$

The investigations carried out in the last few years have permitted a better prediction than with the typical lines represented on bilogarithmic paper, using the curved lines in correlations following the tendencies of the pairs of data Just and Free (1980), and López Jimeno et al. (1985). Although the exponential fall has been acknowledged for some time, e.g. Duvall and Petkoj (1959), it has not been taken into account in the predictor equations until recently.

Just and Free (1980), propose the following propagation law, based on observations in controlled blasts:

$$v = K \times (DS/Q^{1/3})^{-1} \times e^{-\alpha(DS/Q^{1/3})}$$

assuming that the body waves are predominant and that spherical divergency exists.

Ghosh and Daemen (1983) take into consideration the nonelastic absorption to take into account the exponential fall of v, making it proportional to $e^{-\alpha DS}$, Fig. 33.23.

They suggest, depending upon the types of waves, the following propagation laws:

1. *Body waves* that are predominant (e.g. close to the blast) and measured on the surface:

$$v \, \alpha \, \frac{1}{(DR)^2} = \left[\frac{DS}{Q^{1/2}}\right]^{-2} \quad \text{and} \quad v \, \alpha \, e^{-\alpha DS}$$

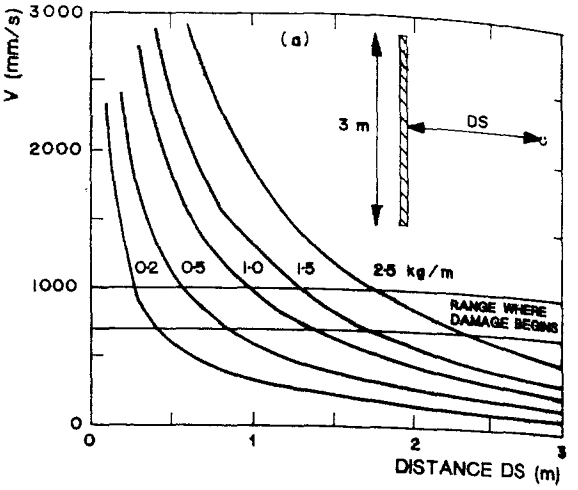


Fig. 33.21. Blastholes of small diameter and length charged with ANFO (Holmberg and Persson).

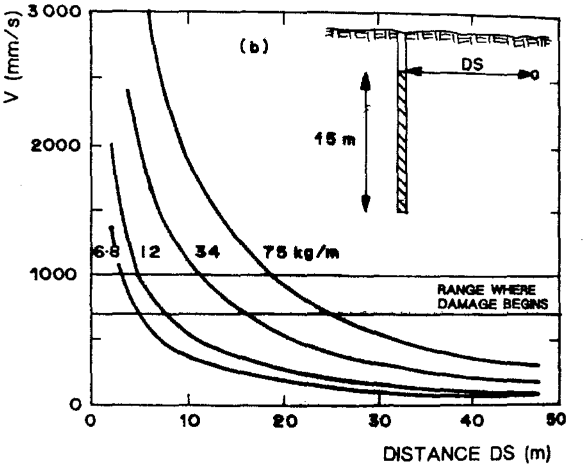


Fig. 33.22. Blastholes of large diameter and length charged with ANFO (Holmberg and Persson).

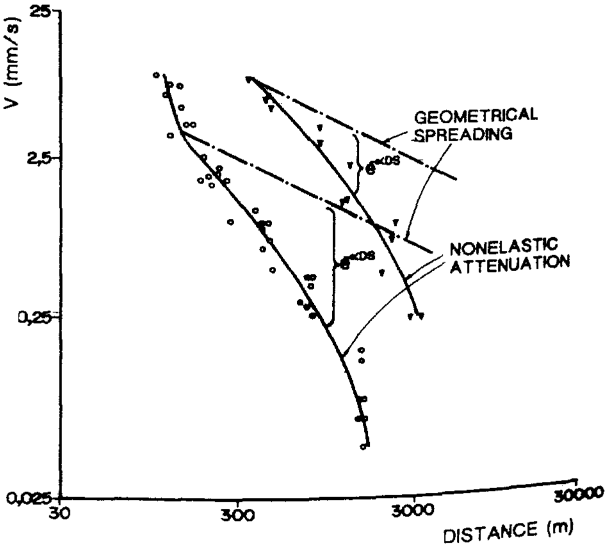


Fig. 33.23. Vibration propagation laws with geometric absorptions and nonelastic exponential attenuations (Ghosh and Daemen, 1983).

where DR = Scaled distance.

Therefore, the following exists:

$$v = K_1 \times \left[\frac{DS}{Q^{1/2}}\right]^{-2} \times e^{-\alpha DS}$$

2. *Body waves* that are predominant (e.g. close to blast) and measured under the ground surface.

$$v \,\alpha \frac{1}{(DR)} = \left[\frac{DS}{Q^{1/2}}\right]^{-1}, \text{ therefore}$$

$$v = K_2 \times \left[\frac{DS}{Q^{1/2}}\right]^{-1} \times e^{-\alpha DS}$$

3. *Rayleigh waves* that are predominant (e.g. at large distances from the blast).

$$v \,\alpha \frac{DS}{(DR)^{0.5}} = \left[\frac{DS}{Q^{1/2}}\right]^{1/2}, \text{ therefore}$$

$$v = K_3 \times \left[\frac{DS}{Q^{1/2}}\right]^{-1/2} \times e^{-\alpha DS}$$

The exponent of Q will depend upon the geometry of the explosive charge, as indicated previously, ⅓ for spherical charges and ½ for cylindrical. The general equations which enclose the former ones are, therefore:

$$v = K \times \left[\frac{DS}{Q^{1/2}}\right]^{-n} \times e^{-\alpha DS}$$

$$v = K \times \left[\frac{DS}{Q^{1/3}}\right]^{-n} \times e^{-\alpha DS}$$

33.6.2 *Theoretical prediction of ground vibrations*

When instrumentation and equipment to carry out a study of vibrations are available, the intensity of the disturbances originated by blasting can be predicted with a theoretical model, G. Berta (1985), taking into account that the seismic energy transmitted to the rock by the explosive can be evaluated with the two following equations:

$$E_s = 2\pi^2 A^2 f^2 \times 2\pi DS^2 \times \rho_r \times VC \times T_v \times 10^{-6}\,(MJ)$$

$$E_s = n_t \times n_1 \times n_2 \times E_T \times Q$$

where: A = Displacement (m), f = Frequency (Hz), DS = Distance from the explosion point (m), ρ_r = Density of the rock (kg/m^3), VC = Seismic velocity (m/s), T_v = Duration of the vibration (s), n_t = Breaking factor (Charges laid on the ground $n_t < 0.4$; Charges without a free face $n_t > 0.4$), n_1 = Impedance factor =

$$1 - \frac{(Z_e - Z_r)^2}{(Z_e + Z_r)^2}$$

n_2 = Coupling factor =

$$\frac{1}{e^{D/d} - 1{,}72}$$

E_T = Energy per unit of mass (MJ/kg), Q = Amount of explosive (kg), Z_e = Impedance of explosive (kg · m^{-2} · s^{-1}), Z_r = Impedance of rock (kg · m^{-2} · s^{-1}), D = Blasthole diameter (mm), d = Charge diameter (mm).

From the previous equations the following is obtained:

$$A(\mathrm{m}) = \sqrt{\frac{n_t \times n_1 \times n_2 \times E_T \times Q \times 10^6}{4 \times \pi^3 \times f^2 \times \rho_r \times VC \times DS^2 \times T_v}}$$

As the significative duration of vibration is considered to be five times the period:

$$T_v = 5\,T_s = \frac{5}{f}$$

and, as the ground frequency is calculated with:

$$f = (kf \times \log DS)^{-1}$$

where kf is a characteristic ground constant which influences the reduction of frequency with distance, Table 33.3. The amplitude and acceleration values can be calculated from:

$$A(\mathrm{m}) = \sqrt{\frac{n_t \times n_1 \times n_2 \times E_T \times Q \times kf \times \log DS \times 10^6}{20 \times \pi^3 \times \rho_r \times VC \times DS^2}}$$

$$v(\mathrm{m/s}) = \frac{\sqrt{Q}}{DS} \times \sqrt{\frac{n_t \times n_1 \times n_2 \times E_T \times 10^6}{5 \times kf \times \log DS \times \pi \times \rho_r \times VC}}$$

The previous formula is only valid when DS is over 1 meter.

Example

Consider a cylindrical charge of 10 kg in a granite bench with one free face.

The data of the explosive is:

$E_T = 4.52$ MJ/kg

$Z_e = 9.5 \times 10^6$ kg · m^{-2} · s^{-1}.

Table 33.3.

Type of ground	kf value
Water logged sands and gravel	0.11-0.13
Compact alluviums	0.06-0.09
Hard and compact rock	0.01-0.03

The characteristic rock parameters are:

$$\rho_r = 2700\ \text{kg/m}^3$$
$$VC = 5000\ \text{m/s}$$
$$kf = 0.01$$
$$Z_r = 13.50 \times 10^6\text{kg} \cdot \text{m}^{-2} \cdot \text{s}^{-1}.$$

and the relationship blasthole diameter/charge diameter is $D/d = 1.06$.

What is the probable vibration intensity at a distance of 150 m?

$$v = \frac{\sqrt{10}}{150} \times \sqrt{\frac{0.4 \times 0.98 \times 0.85 \times 4.52 \times 10^6}{5 \times 0.01 \times \log 150 \times \pi \times 2700 \times 5000}} =$$

$$0.012\ \text{m/s} = 12\ \text{mm/s}$$

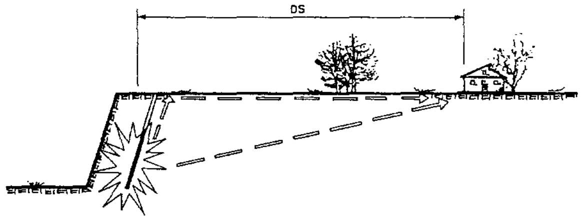


Fig. 33.24. Building situated at a distance *DS* from a position where blasting occurs.

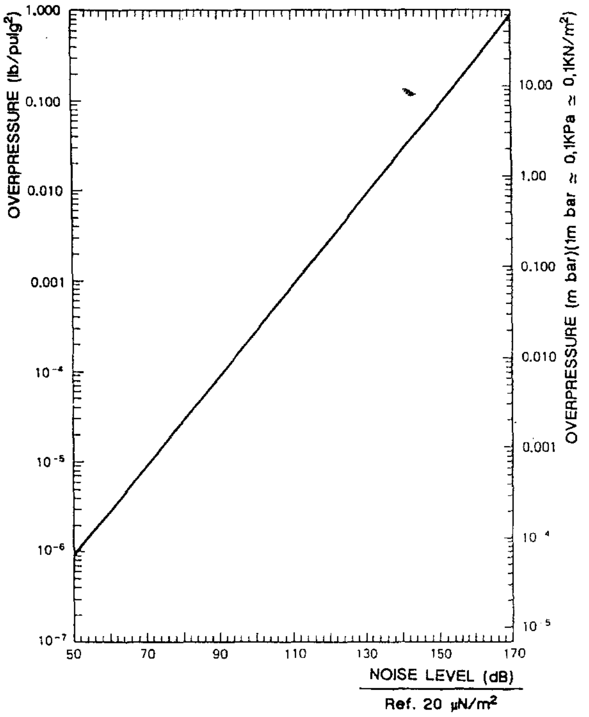


Fig. 33.25. Nomograph for overpressure conversion at noise level (Sisking et al. 1980).

33.6.3 *Air blast estimators*

The law of air blast propagation is accepted to be of the following type:

$$SP = K_1 \times \left[\frac{DS}{Q^{1/3}}\right]^{-K_2}$$

The audible component, which is the part of the spectrum comprehended be 20 Hz and 20 kHz, also called *noise*, is commonly measured in dB. The decibel is defined in terms of overpressure with the equation:

$$NR = 20 \log \frac{SP}{SP_o}$$

where: NR = Noise level, SP = Overpressure (N/m²), SP_o = Pressure of the lowest audible sound ($20 \cdot 10^{-6}$ N/m²), Figs 33.25 and 33.26.

If experimental data for air blast is not available, a first estimation can be found from the nomograph given by Ladegaard-Pedersen and Daily (1975), Fig. 33.27, obtained for bench blasting with a stemming height of 30*D*. Knowing the scaled distance and burden, the most probable air blast level can be determined.

33.7 STUDIES OF VIBRATION AND AIR BLAST

33.7.1 *Planning for study of vibrations*

The two basic objectives for a study of vibrations are:

- Finding the law of propagation of the vibrations to later determine the maximum charge weight per hole for a given distance and a previously adopted prevention criteria.
- Finding the predominating vibration frequencies for

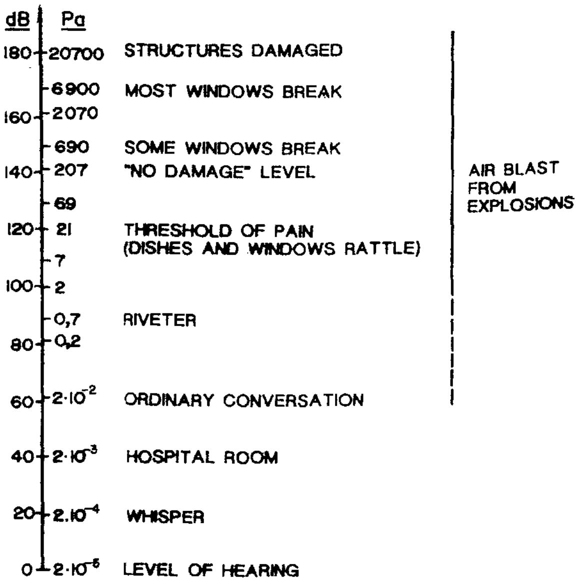


Fig. 33.26. Human and structural response to sound pressure level.

the rock mass to be excavated, thus permitting the most effective initiation sequence to be established.

To carry this out requires a previous geological analysis of the area between the blasts and the structures to be protected. In function with the findings, a scaled down blast can be designed, either individual or multiple, in which the charge weight per hole or distances can be varied, in order to cover a wide range of scaled distances.

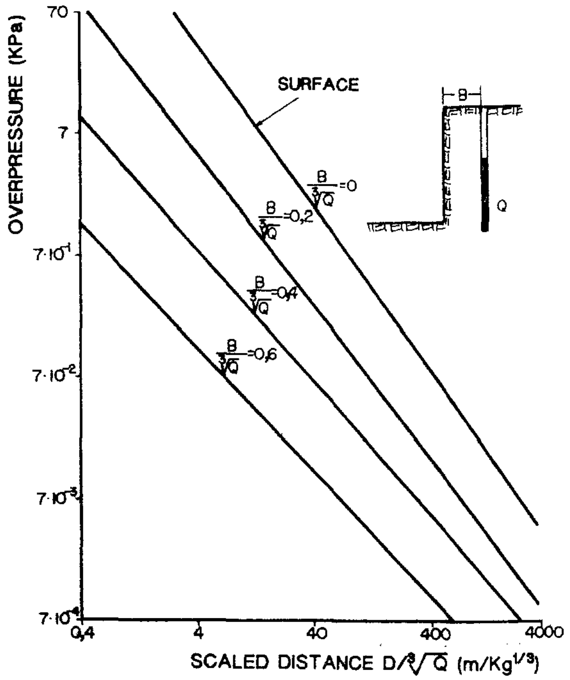


Fig. 33.27. Prediction of air overpressure from the geometry and charge of the blasts.

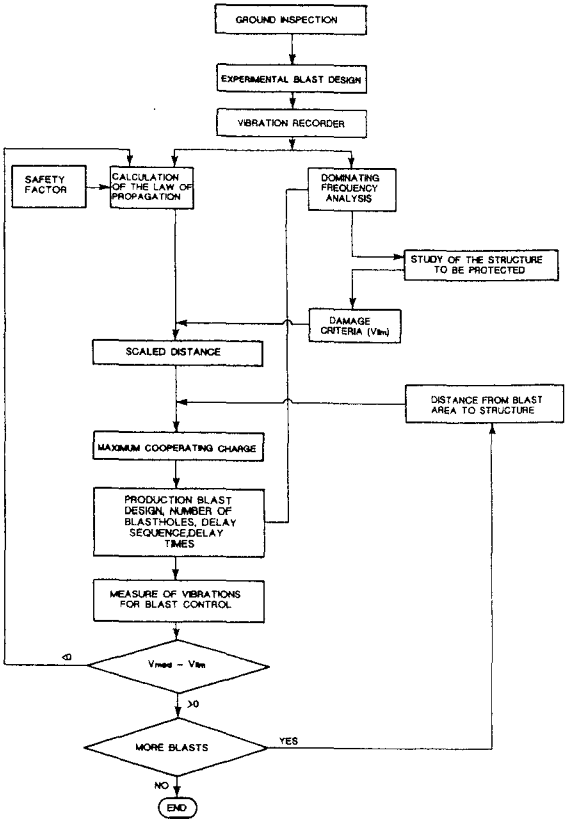


Fig. 33.28. Planning for a study of vibrations.

Once the results of the first blasts have been given, it can be decided which of the components is the most interesting to measure if the recording stations are not triaxial and, above all, when a large number of sensors are not available.

The minimum number of blasts recommended is between 8 and 10, and the execution conditions as to confinement, priming, etc. should be similar to those used in production blasting because frequently conservative postures are adopted, firing practically without a free face.

The spatial situation is also important, because a study carried out at a determined level and within a geological-structural context may not be, on occasions, extrapolated to other areas. All vibration studies have a limited value where space and time are concerned.

Once the records have been reproduced and analyzed in the laboratory, Fig. 33.29, they can be compared stadistically to ascertain the law of propagation.

Previously, all data will have been summed up in a Table, giving, for example, the maximum vibration levels, v if it is particle velocity, and the Scaled Distances DR, if the law to be obtained is of the following type:

$$y = a \times x^b$$

where: y = Particle velocity v, x = Scaled distance DR.

Logarithms can be taken and a straight line can be adjusted by squared minimums, Fig. 33.30.

$$\log y = \log a + b \times \log x$$

where:

$$b = \frac{\Sigma (\log x) \times (\log y) - \dfrac{(\Sigma \log x) \times (\Sigma \log y)}{n}}{\Sigma (\log x)^2 - \dfrac{(\Sigma \log x)^2}{n}}$$

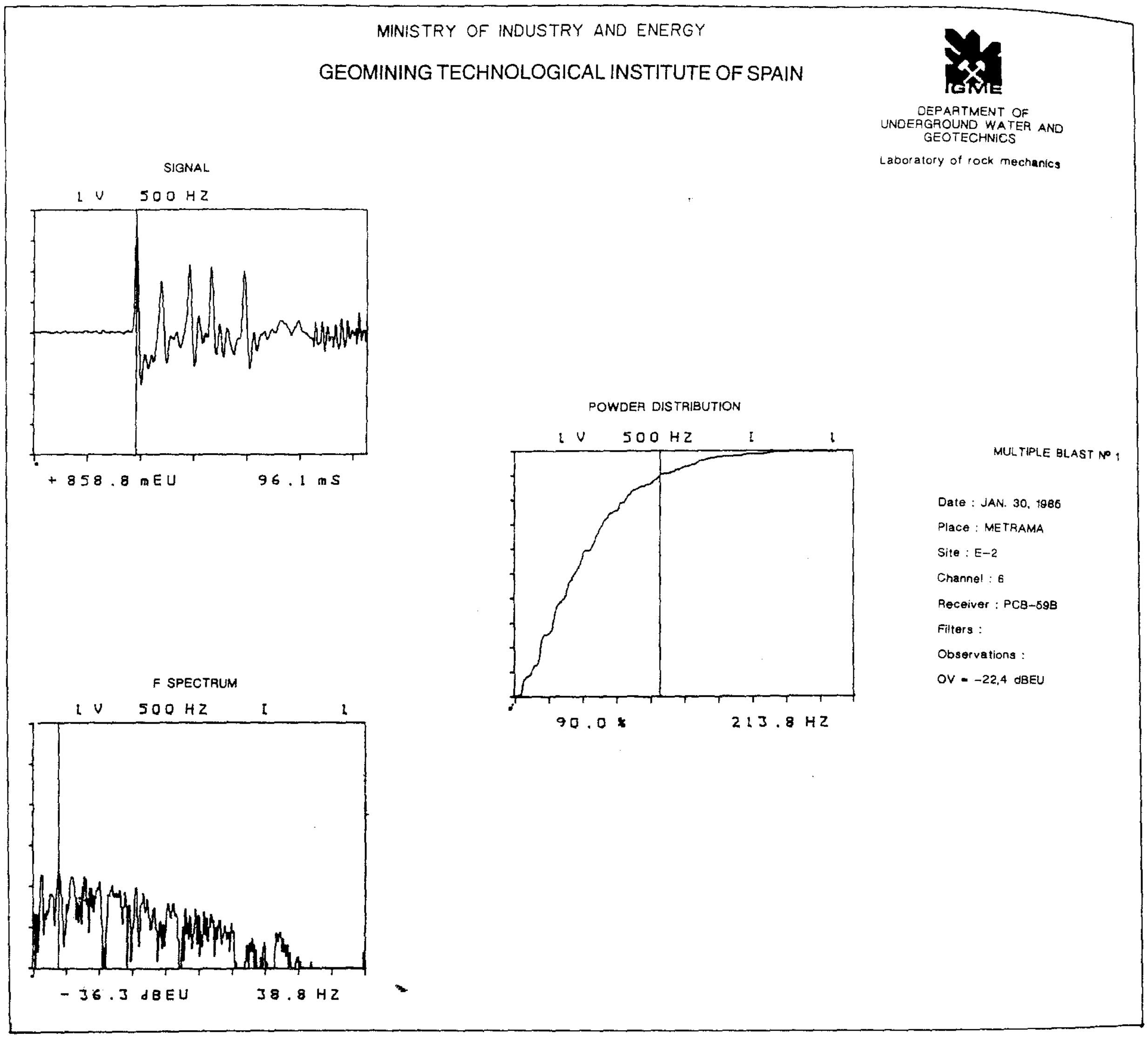
and

$$a = \text{Exponential} \left[\frac{\Sigma \log y}{n} - b \frac{\Sigma \log x}{n} \right]$$

and the lineal coefficient r from:

$$r^2 = \frac{\left[\Sigma (\log x) \times (\log y) - \dfrac{(\Sigma \log x) \times (\Sigma \log y)}{n} \right]^2}{\left[\Sigma (\log x)^2 - \dfrac{(\Sigma \log x)^2}{n} \right] \times \left[\Sigma (\log y)^2 - \dfrac{(\Sigma \log y)^2}{n} \right]}$$

If the Standard Deviation is also calculated, it would be possible to draw the parallel lines between which a determined number of values can be found (e.g. 95%), thus adopting a Safety Factor for the law of propagation.



Date : JAN. 30, 1986
Place : METRAMA
Site : E-2
Channel : 6
Receiver : PCB-59B
Filters :
Observations :
OV = -22,4 dBEU

Fig. 33.29. Example of a vibration recording obtained in a blasting for one component.

There are numerous equations (laws) that can be adjusted and, amongst all of them, the one which best suits the occasion should be chosen. This is now carried out with small computer programs which have been specially prepared.

Once the law has been estimated and the threshold of damages decided, the value of the scaled distance can be ascertained from the equation, enabling the preparation of the table of maximum co-operating charges for different distances.

For example, if the law obtained for a determined percentage of probability or safety level is:

$$v = 1400 \times DR^{-1.6}$$

where

$$DR = \frac{DS}{\sqrt{Q}}$$

and v is not to be over 30 mm/s, Fig. 33.30. The Table of Charges-Distances will correspond to $DR = 11.04$ m/kg$^{1/2}$ and therefore, the following values will exist, Table 33.4.

The method to be applied for air blast is very similar.

On the other hand, it is interesting to study how the duration of seismic excitement increases and frequency diminishes in relationship with distance to the point of blast, adjusting laws of the following type:

$$f(\text{Hz}) = K_1 \times DS^{-K_2}, \text{ and}$$

$$T_v\,(\text{s}) = K_1' \times DS^{+K_2}$$

Table 33.4.

Distance to the blast (m)	Max. co-operating charge (kg)
100	82
300	738
500	2050
700	4017

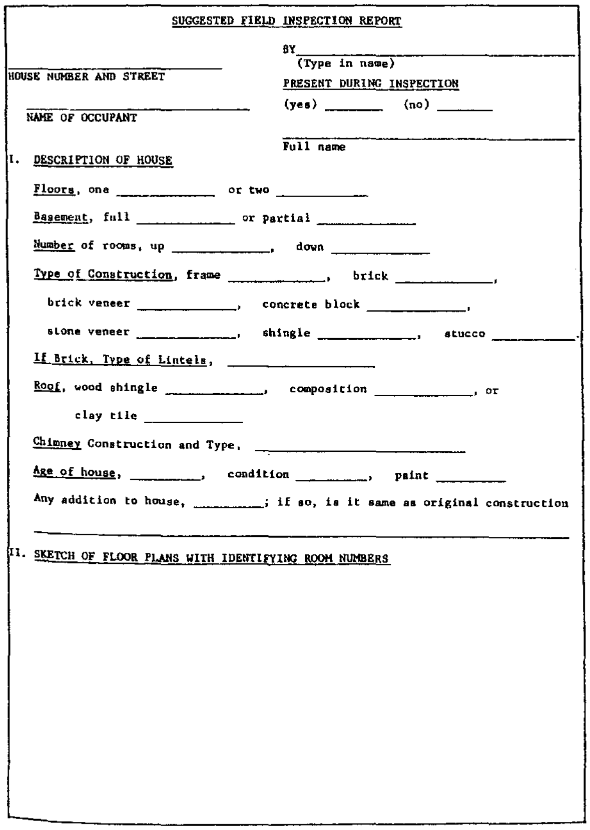
The value of T_v should refer to a same type of blast, as in multiple rounds with a total time t_v, $T_v = k \times t_v$ is fulfilled, with K taking on values of 3, 4 or even more at several hundred meters.

33.7.2 *Inspections previous to blasting*

The objective of these inspections is to compile data in a written document which gives the condition of a structure before commencing excavation work with explosives. Many buildings have cracks in unknown places and their occupants accuse the vibrations and air blast generated by blasting as the cause.

In some countries, these inspections are normal practice and, in the US, the Office of Surface Mining contemplates that any inhabitant having property at less than 800 meters from a blasting area can ask the Administration for a previous study.

The first advantage of this documentation is that it makes the residents of areas close to the blast aware of the fact that many cracks and imperfections in their buildings are originated by other than seismic causes, such as changes in weather, humidity, wind, ground conditions and the constructive quality itself. The second advantage



SUGGESTED FIELD INSPECTION REPORT

BY ____
(Type in name)

____
HOUSE NUMBER AND STREET

PRESENT DURING INSPECTION
(yes) ____ (no) ____

____
NAME OF OCCUPANT

____
Full name

I. DESCRIPTION OF HOUSE

Floors, one ____ or two ____

Basement, full ____ or partial ____

Number of rooms, up ____, down ____

Type of Construction, frame ____, brick ____,

brick veneer ____, concrete block ____,

stone veneer ____, shingle ____, stucco ____.

If Brick, Type of Lintels, ____

Roof, wood shingle ____, composition ____, or

clay tile ____

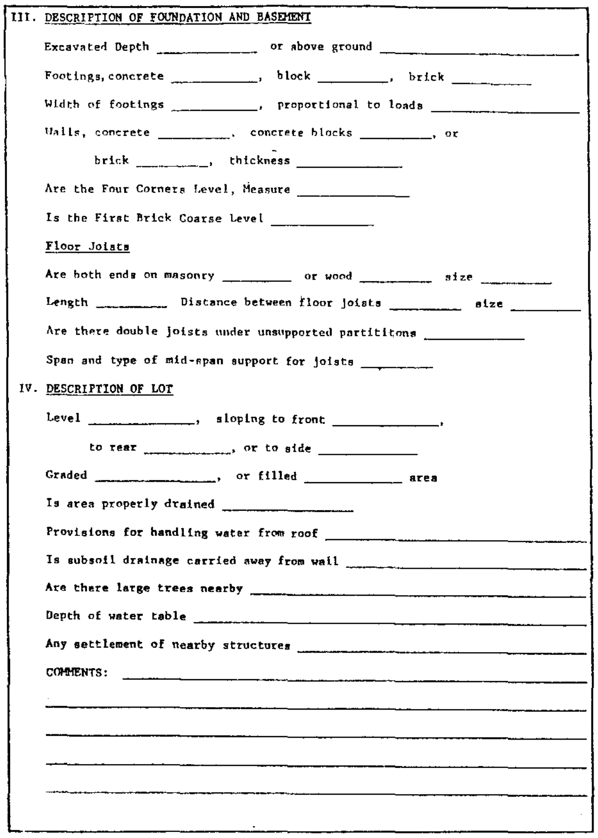
Chimney Construction and Type, ____

Age of house, ____, condition ____, paint ____

Any addition to house, ____; if so, is it same as original construction

____

II. SKETCH OF FLOOR PLANS WITH IDENTIFYING ROOM NUMBERS



III. DESCRIPTION OF FOUNDATION AND BASEMENT

Excavated Depth ____ or above ground ____

Footings, concrete ____, block ____, brick ____

Width of footings ____, proportional to loads ____

Walls, concrete ____, concrete blocks ____, or

brick ____, thickness ____

Are the Four Corners Level, Measure ____

Is the First Brick Coarse Level ____

Floor Joists

Are both ends on masonry ____ or wood ____ size ____

Length ____ Distance between floor joists ____ size ____

Are there double joists under unsupported partititons ____

Span and type of mid-span support for joists ____

IV. DESCRIPTION OF LOT

Level ____, sloping to front ____,

to rear ____, or to side ____

Graded ____, or filled ____ area

Is area properly drained ____

Provisions for handling water from roof ____

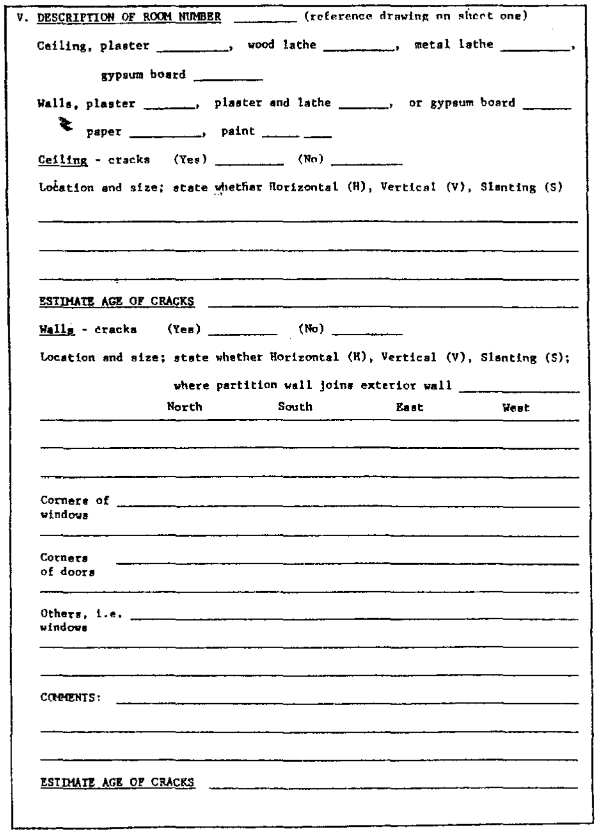
Is subsoil drainage carried away from wall ____

Are there large trees nearby ____

Depth of water table ____

Any settlement of nearby structures ____

COMMENTS: ____



V. DESCRIPTION OF ROOM NUMBER ____ (reference drawing on sheet one)

Ceiling, plaster ____, wood lathe ____, metal lathe ____,

gypsum board ____

Walls, plaster ____, plaster and lathe ____, or gypsum board ____

paper ____, paint ____

Ceiling - cracks (Yes) ____ (No) ____

Location and size; state whether Horizontal (H), Vertical (V), Slanting (S)

____

ESTIMATE AGE OF CRACKS ____

Walls - cracks (Yes) ____ (No) ____

Location and size; state whether Horizontal (H), Vertical (V), Slanting (S);

where partition wall joins exterior wall ____

North South East West

____

Corners of windows ____

Corners of doors ____

Others, i.e. windows ____

COMMENTS: ____

ESTIMATE AGE OF CRACKS ____

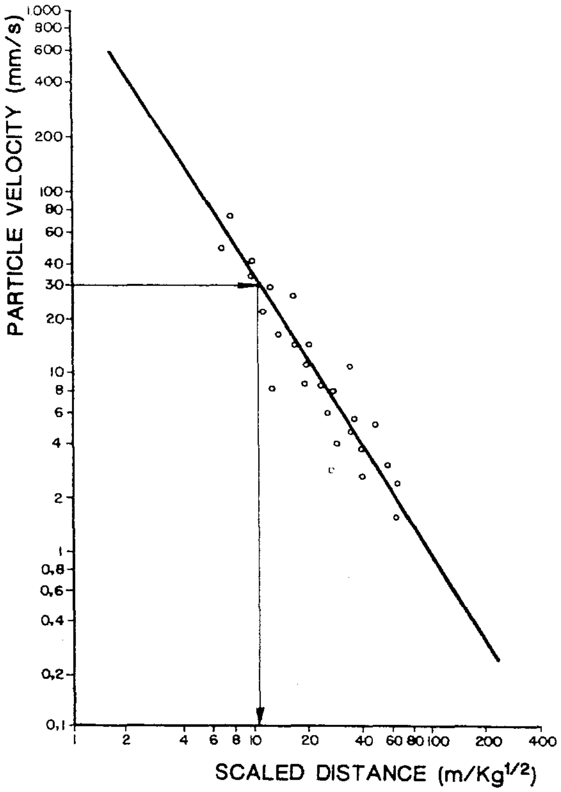


Fig. 33.30. Adjusted law of propagation.

is that the documentation can be used, if the occasion arises, to verify or contest the damage claims attributed to vibrations.

On many occasions, the initial cost of drawing up these documents is greatly compensated by the lower number of claims and conflictive situations with lawsuits between the companies and residents who are closeby. A trained person can inspect 7 or 8 homes in one day.

The procedure used for describing the condition of a structure should be as systematic and detailed as possible, writing down all visible defects and even taking photographs, if necessary. Each document should contemplate, first of all, the identity of the owners, address and situation of the residence, and the date of inspection, Fig. 33.31 shows the system used by Vibra-Tech for a study of the inside of a home. Other aspects to take into account are those which refer to the outside of the structure, garages, foundations, etc.

33.8 DAMAGE PREVENTION CRITERIA FOR BUILDINGS

33.8.1 *Building response*

Damages that appear in structures from vibration type effects depend upon the dynamic response of the building which itself, at the same time, is conditioned by various factors such as:

– Type and characteristics of the vibrations, duration, frequency, transmitted energy, etc.

– Type of ground on which the structure sits.

– Vibratory characteristics of the structural and non-structural entity of the building and modifying factors.

A parameter which is important in controlling potential damage by blast induced vibrations is their dominating frequency. In the cases where the natural frequency of the buildings is very close or equal to the dominating frequencies, a resonance phenomenon is produced with magnifying effects, Fig. 33.32.

The natural frequencies of the buildings or structures can generally be calculated analytically with simple equations, widely used in seismic engineering, such as the following:

– Buildings with prefabricated or reinforced concrete walls:

$$T_s = 0.06 \times \frac{h_v}{L_p} \times \frac{H_v}{2L_p + H_v}$$

– Buildings with framework structure of reinforced concrete:

$$T_s = 0.09 \times \frac{H_v}{L_p}$$

– Buildings with metal structure:

$$T_s = 0.10 \times \frac{H_v}{L_p}$$

In all the previous equations: t_S = Period (s), H_v = Height of building (m), L_p = Floor dimension, taken in the direction of the vibration whose effect is desired to be indicated (m), h_v = Height of each floor (m).

The typical frequency values are found between 5 and 15 Hz, being lower as the number of floors increase.

The ceilings and walls vibrate independently from the superstructure and usually have natural frequencies between 12 and 20 Hz.

Another parameter that is as important as the natural frequency is absorption. The common values of these coefficients in residential type structures (Dowding et al. 1980) vary around 5%.

The vibrations in buildings can be magnified due to the response of the structural elements of which they are composed, Fig. 33.33. Therefore, more attention should be paid to the times of the milisecond delay detonators. When lowering charge weights per hole and increasing blasting times, dangerous vibration frequencies may be generated if they are close to those of resonance. For example, using milisecond delay detonators of 30 ms, and leaving a number unused, a vibration of 1000/60 = 16.7 Hz is being caused, which is within the range of potential damages. This phenomenon has been proved by the authors in recorders near the blast areas. (López Jimeno and Abad, 1986).

A simple method to predict the structural response of a building to vibrations is the Fast Fourier Transform (FFT) application. FFT informs in practice about what frequency band, and responsible wave length is needed to be omitted for avoiding damage and disturbances. FFT

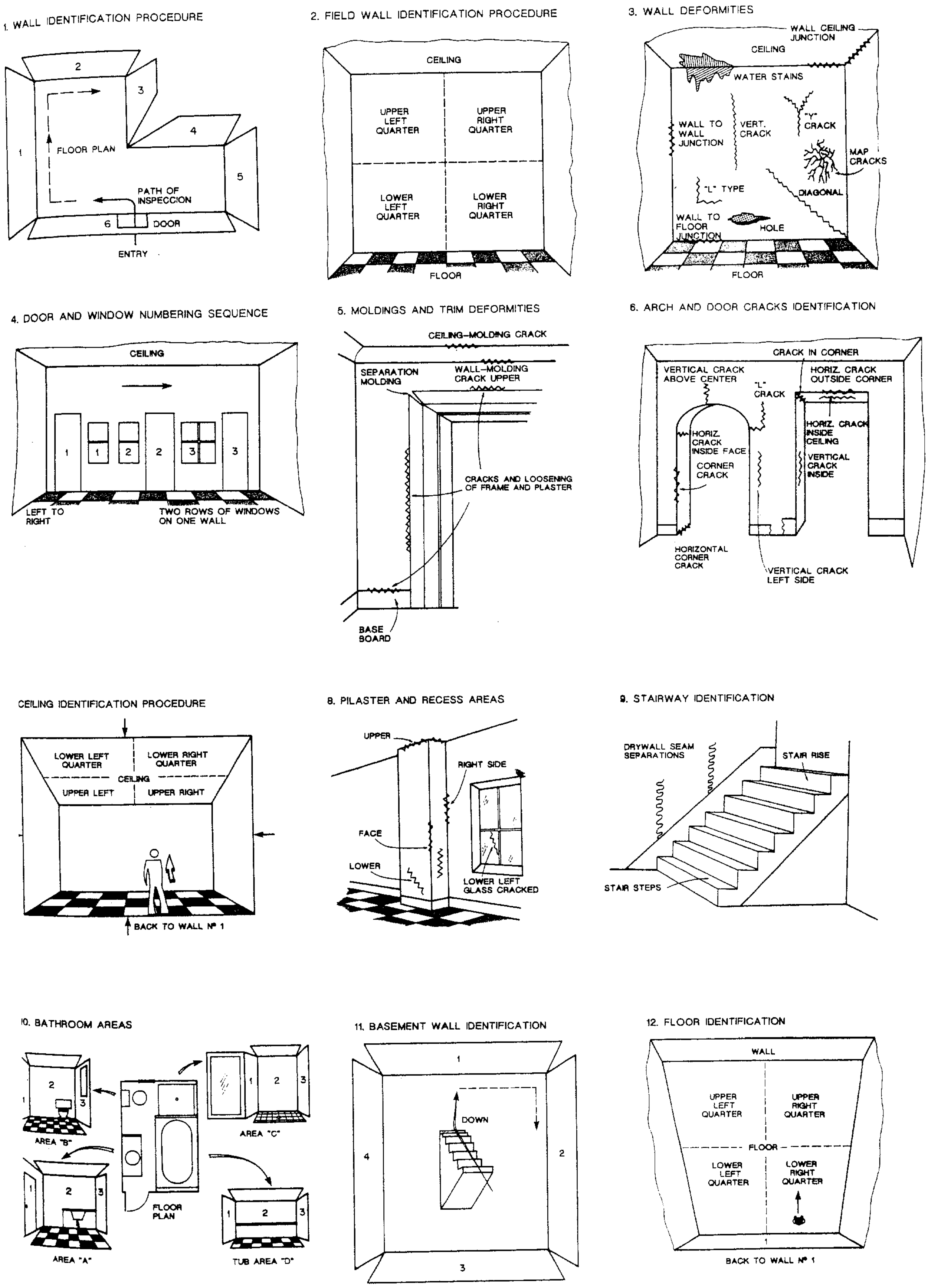


Fig. 33.31. Home inspection system.

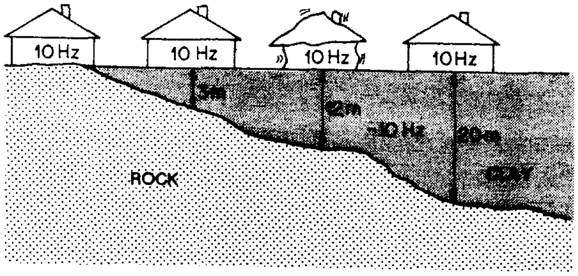


Fig. 33.32. Magnification effects when the building's natural frequency is close to the dominating frequency in the earth (Clark et al.).

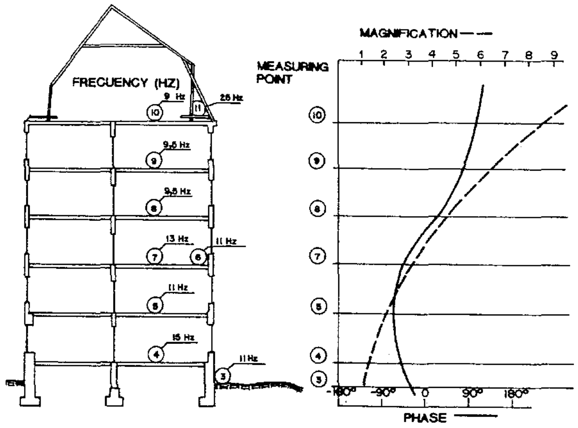


Fig. 33.33. Magnification within a building (Clark et al.).

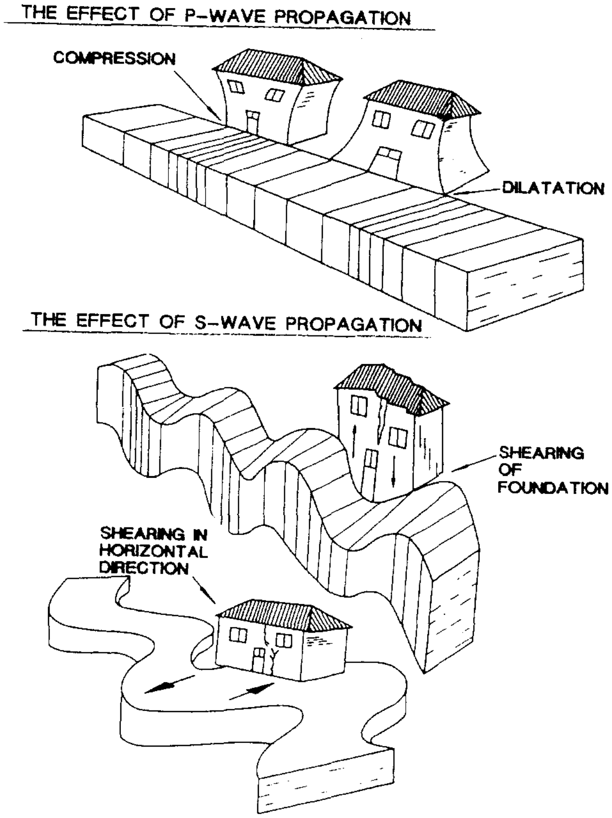


Fig. 33.34. Effects of the *P* and *S* waves on structures.

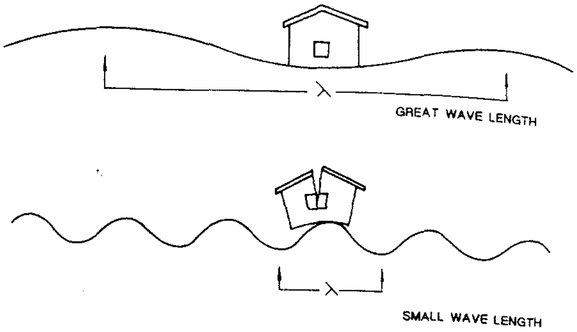


Fig. 33.35. Interaction between the building foundations and vibrating ground.

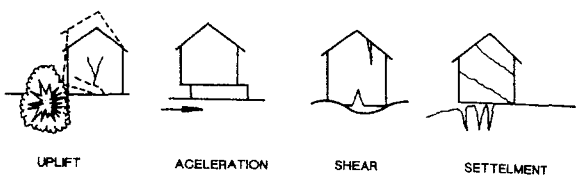


Fig. 33.36. Types of damage.

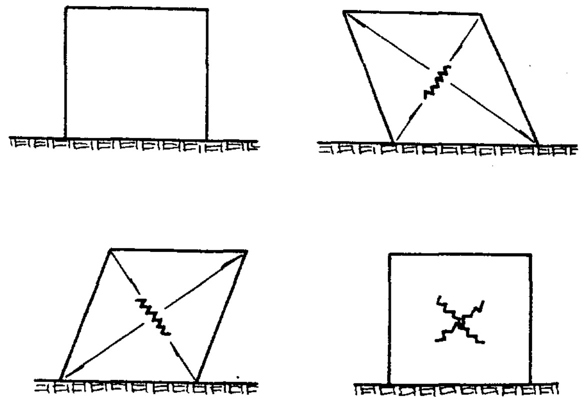


Fig. 33.37. Vibration X-crack pattern.

analysis is the less costly and simplest way today and can be utilized for practically every blast design, solving successfully resonance and magnification problems.

The types of damage are diverse, Fig. 33.36: uplifts due to gas intrusion when the constructions are very close to the blast area, relative acceleration of the ground, shearings and settlements of the foundations.

When refering to the characteristic type of cracks produced by seismic motion, the most representative are those called X-cracks, because when the structures are deformed by relative movement of the bases, tensile stresses are created on the diagonals of the parallelograms which cause damage by compression, overcoming the strength of the materials, Fig. 33.37.

33.8.2 *Damage prevention criteria*

After finding the law which governs the propagation of the seismic waves in a rocky medium, the degree of maximum vibration tolerated by different types of structures near the excavation must be estimated in order to prevent damage.

The decision of which criteria or levels of vibration prevention should be adopted is usually a delicate issue. This requires expert knowledge of the mechanisms which intervene in the phenomena of blasting and the responses of structures. A risky criterium can cause damages and imperfections, whereas a conservative posture could upset or even paralize the development of mining or civil engineering activity with explosives.

The prevention criteria for vibrations produced by blasting has been subjected to study since the beginning of the century. Worthy of mention are: the investigations of Rockwell in 1927, Thoenen and Windes in 1942, who used particle acceleration as the most characteristic parameter; Crandell in 1949, who used the energy ratio, Morris in 1950, who established a new damage criterium based on the amplitude of vibration, and Langefors and Kihlström in 1958, who adopted particle velocity as the most important parameter, proposing different levels, depending upon the intensity of potential damages. Afterwards, in 1963, these authors took into consideration the type of ground upon which the structures had their foundations, proposing criteria with wider outlooks. During the decade of the sixties and seventies, numerous investigators such as Northwood, Crawford, Edwards, Duvall, Fogelson, Nicholls, etc., exposed different safety limits, all based on particle velocity, already forseeing the necessity of adjusting those prevention levels to the different types of constructions, as done by Ashley in 1976, Chae in 1978, Wiss in 1981, etc.

In another step towards developing and perfecting the criteria, apart from the type of rock under the foundations, the type of structure to be protected was introduced as another variable as important as vibration frequency, publishing the French Regulation AFTES (1976), the Standars Association of Australia Regulation, the DIN, (1983), etc. All mentioned criteria is summed up graphically in Fig. 33.38.

Afterwards, several investigators such as Dowding (1977), Medearis (1977), Maik (1979), Walker, Young and Davey (1981), Sisking, Stagg, Kopp and Dowding (1981), etc. directed their efforts towards the correlation of structure response with damages produced by different vibration intensities, through analysis of the seismic spectrums. One fact that has become more noticeable day by day in these investigations is the increasing importance of the low frequencies.

However, even though the criteria and application of techniques known in seismic engineering have evolved, the discrepancies between engineers and organisms are still quite noticeable, especially when the studies are of a local nature. It must also be noted that rarely are clear and concise recommendations or calculations given by operators who do not have a profound knowledge of the phenomenology of vibrations.

Another aspect worthy of mention is that in the majority of cases, the damage threshold is adopted for structures and buildings, without taking into account their contents. Sometimes there might be computers, electric relays or other sensitive equipment which must be protected from even lower vibration levels than those for the building itself.

Lastly, the O.S.M. (Office of Surface Mining) in the United States, in 1983, acknowledging the dependence that exists between the dominating vibration frequency and the distances to the blast area, published the following recommendations for protecting buildings near the mines, Table 33.5.

The criteria shown are not only useful as damage thresholds, but also as a starting point when recording equipment is not available. Thus, for example, when there is a house at 1000 m distance from the blast, the maximum co-operating charge recommended is:

$$DR = \frac{DS}{\sqrt{Q}} = 24.5 \text{ m/kg}^{1/2};$$

$$Q = \left[\frac{DS}{DR}\right]^2 = \left[\frac{1000}{24.6}\right]^2 = 1666 \text{ kg}$$

33.8.3 *Damage prevention criteria for air blast*

Air blast usually produces fewer problems than ground vibrations. Window panes usually break before structural damage occurs; cracks in the plaster, for example.

The criteria proposed by Siskind and Summers (1974), to avoid window pane breakage are shown in Table 33.6.

The probability of window pane breakage for a determined overpressure can be estimated with the equation proposed by Redpath:

$$PR_c\,(\%) = 2.043 \times 10^{-7} \times A_v^{1.22} \times \Delta P^{2.78}$$

where: A_v = Area of the window pane (m^2), ΔP = Overpressure (mbar).

Special attention should be paid when comparing noise levels, as the dB(L) refer to a logarithmic scale. An overpressure of 120 dB(L) is 78.6% more than one of 115 dB(L). See Table 33.7, with the values in kPa.

Table 33.5.

Distance to blast area	Max. particle velocity (mm/s)	Recommended scaled distance when instrumentation is not available (m/kg$^{1/2}$)
0 to 90 m	32	22.30
90 to 1500 m	25	24.50
> 1500 m	19	29.00

Table 33.6.

	Limit noise level		
	Lineal peak* dB(L)	C-peak dB(C)	A-peak dB(A)
Safety level	128	120	95
Precaution level	128-136	120-130	95-115
Limit level	1336	130	115

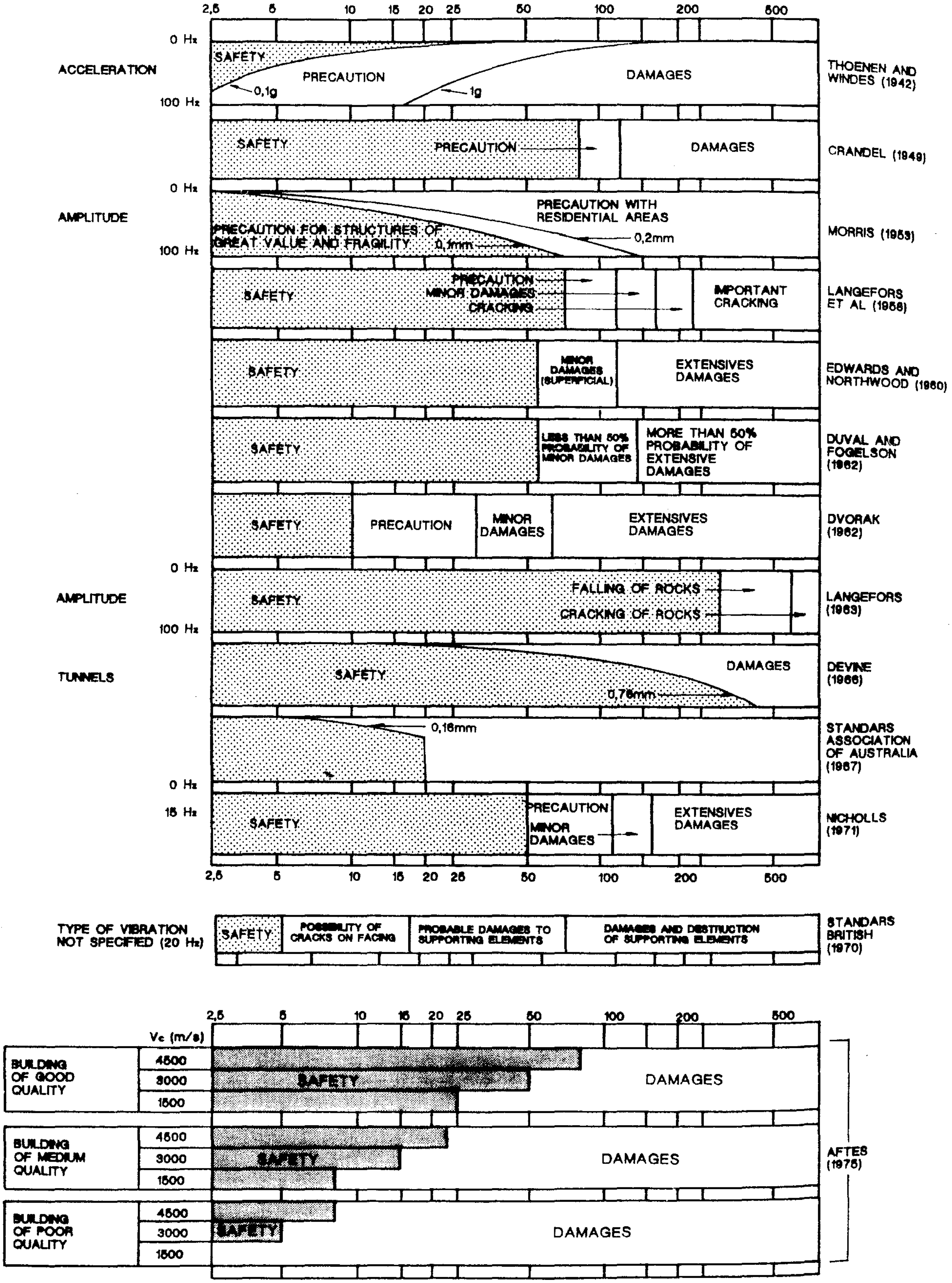
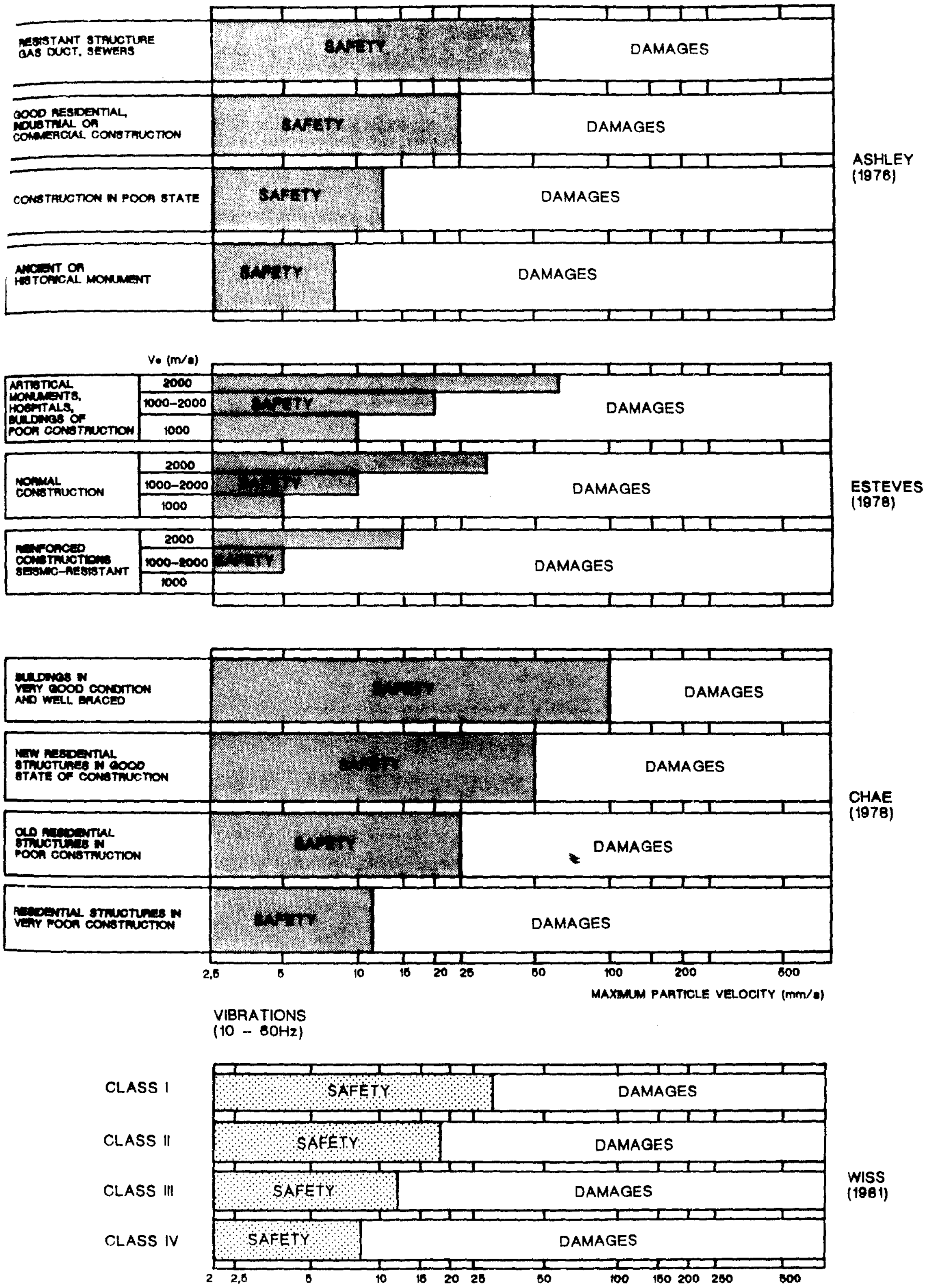


Fig. 33.38. Damage criteria.



LEGEND

CLASS I : METALLIC BUILDING OR OF REINFORCED CONCRETE
CLASS II : BUILDINGS WITH OUTSIDE WALLS AND PILLARS OF CONCRETE, INSIDE WALLS OF CONCRETE OR MASONRY
CLASS III : BUILDINGS AS BEFORE BUT OF WOODEN STRUCTURE AND WALLS OF MASONRY
CLASS IV : CONSTRUCTION VERY SENSITIVE TO VIBRATIONS; OBJECTS OF HISTORICAL INTEREST

Fig. 33.38. Damage criteria (cont.).

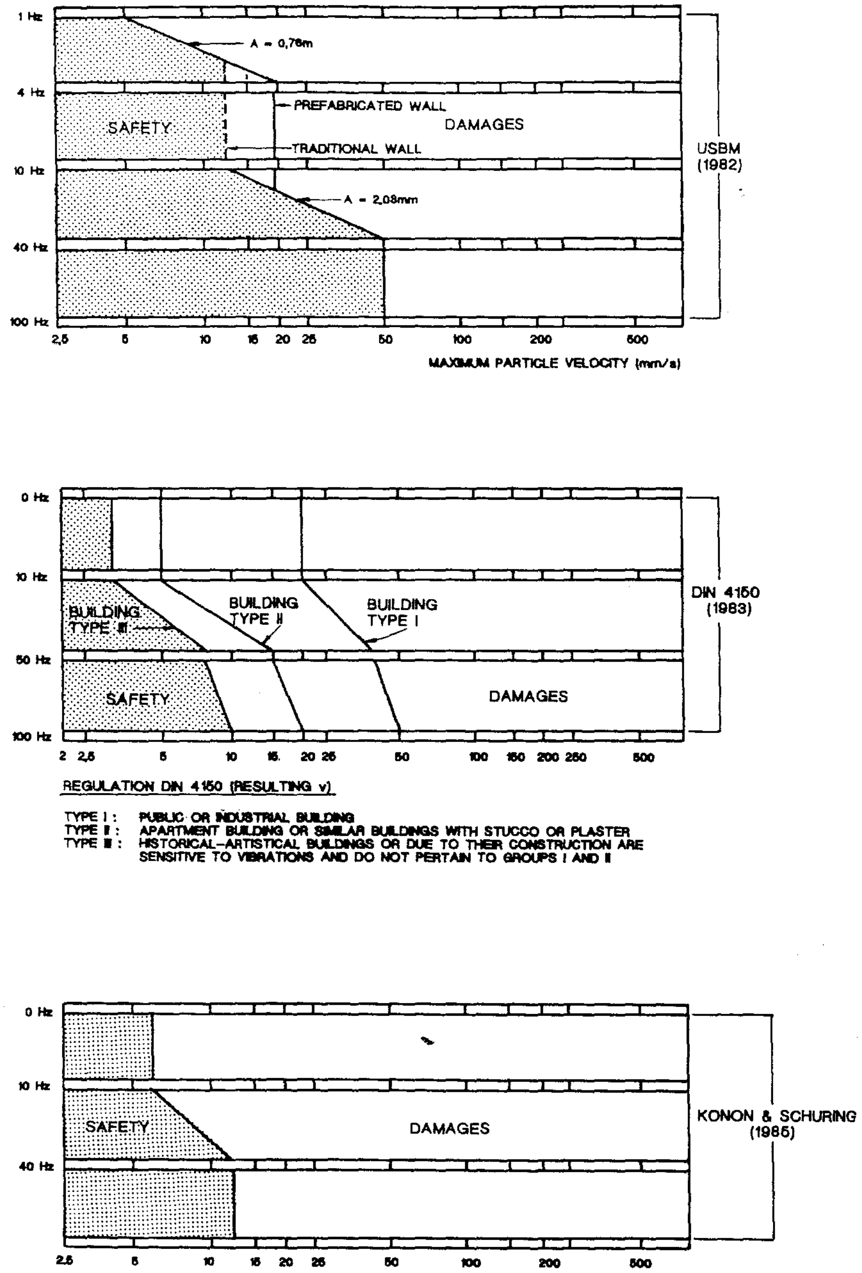


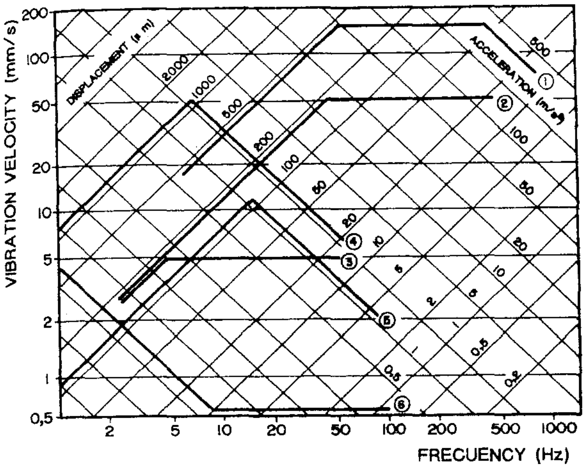
Fig. 33.38. Damage criteria (cont.)

Table 33.7.

Overpressure	Probable effect	
180 dB(L)	20.0 kPa	Important damage to conventional structures
> 170	> 6.3	Cracks will appear in plaster
170	6.3	Many window panes will break
150	0.63	Some window panes will break
140	0.2	Probable breakage of large window panes
136	0.13	Limit of air blast proposed by U.S.B.M.
120	0.02	Complaints
115	0.0112	< 6% of overpressure which can cause breakage of large window panes

Table 33.8 (Baker, 1973).

Description	Intensification factor
Simple negative gradient	0
Simple positive gradient	5
Zero gradient near the surface and with positive gradient above	10
Negative gradient near surface with strong positive gradient above	100



1. DIRECT DAMAGE ON BUILDINGS FROM BLAST GENERATED VIBRATIONS
2. UPPER LIMIT RECOMMENDED FOR BLAST
3. UPPER LIMIT RECOMMENDED FOR SINKING PILES VIBRATORY COMPACTORS, DEEP DYNAMIC COMPACTORS AND TRAFFIC ON WHEELS
4. MAXIMUM VALUE FOR IBM COMPUTERS IF THE DURACTION OF THE VIBRATION IS UNDER 5s
5. MAXIMUM VALUE FOR IBM COMPUTERS IF THE DURACTION OF THE VIBRATION IS OVER 5s
6. LIMIT OF HUMAN PERCEPTION

Fig. 33.39. Damage criteria.

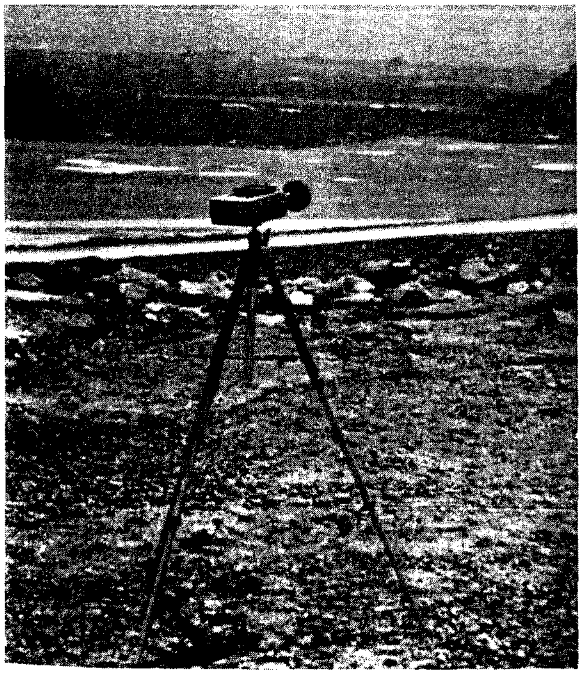


Photo 33.5. Sonometer installed to measure air blast.

Other important aspects to take into account are the atmospheric conditions at the moment of the blast. In Table 33.8, five different situations are shown and the intensification factors of air blast that can be expected.

33.9 EFFECTS OF VIBRATIONS AND AIR BLAST ON PEOPLE

One of the factors to be considered when blasting is the physiological response of human beings, as with levels under the maximum admissible for prevention of damage to structures, there can be an index of perception which could make people think of probable damage, Fig. 33.40.

Therefore, it is frequent that in many projects the vibration thresholds are based more on human response than on the probability of damages.

There are numerous regulations on human response to vibrations, the two most important being ISO-2631 and DIN-4150. Other investigations such as those of Reiher-Meister, Crandell, Goldman, Rathbone, etc., who represent graphically where different levels of perception are established in function with vibration intensity and frequency, Fig. 33.41.

An analytical procedure of estimation is proposed by Steffens (1974), based on the calculation of a parameter *K*.

$$K = \frac{0.005\,A \times f^2}{(100 + f^2)^{1/2}} = \frac{0.8\,v \times f}{(100 + f^2)^{1/2}} = \frac{0.125 \times a}{(100 + f^2)^{1/2}}$$

where: f = Frequency (Hz), A = Amplitude (μm), v = Particle velocity (mm/s), a = Acceleration (mm/s^2).

According to this value of *K*, the levels of perception of Table 33.9, are distinguished

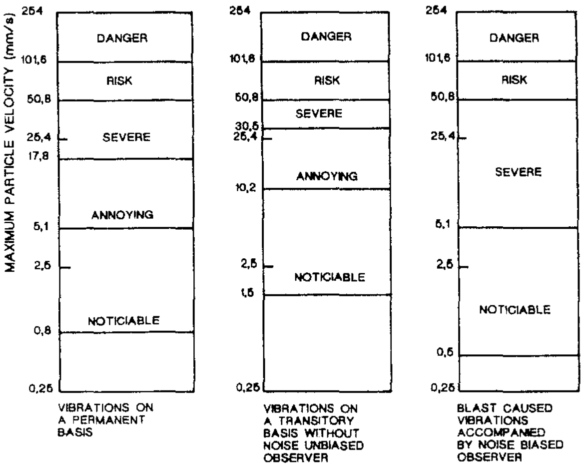


Fig. 33.40. Human response to vibrations, according to whether they are accompanied by noise or not (Oriard).

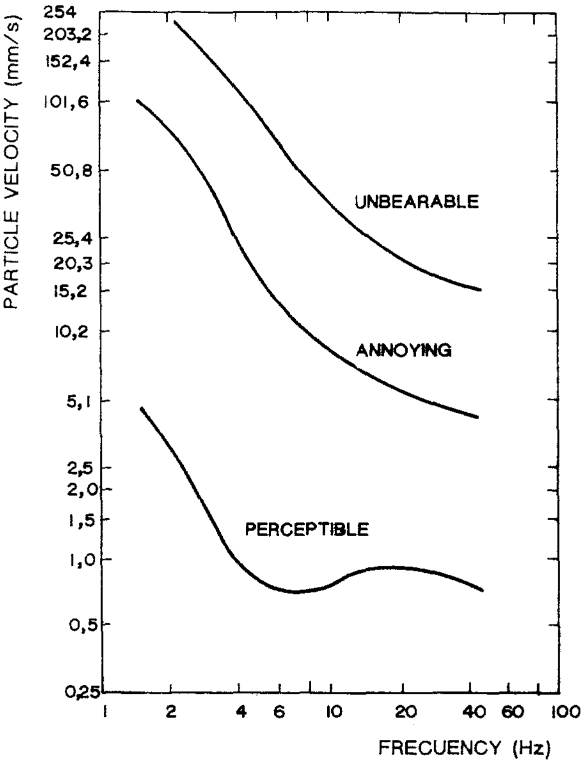


Fig. 33.41. Human response to vibration according to Goldman (1948).

Table 33.9.

Value of K	Level of perception
< 0.1	Not perceptible
0.1	Almost perceptible
0.25	Barely perceptible
0.63	Perceptible
1.6	Easily perceptible
4.0	Highly detectable
10.0	Severely detectable

33.10 EFFECTS OF VIBRATIONS ON ROCKMASSES

Vibrations have two fields of action on rock masses. On one hand they affect the integrity of the rocks or their compressive strength parameters and, on the other, can provoke wall or slope collapse when unstabilizing actions are introduced.

In the first instance, the critical vibration velocity can be determined after finding the longitudinal wave propagation velocity in the rock mass, the density and the tensile strength of the rock.

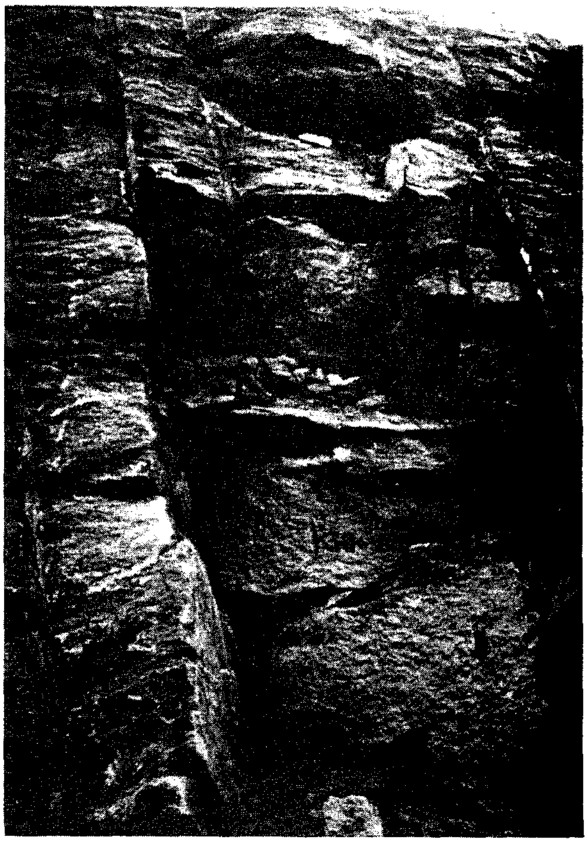


Photo 33.6. Damage produced in a presplit blast caused by overcharging.

$$RT = \rho_r \times v_{\text{crit}} \times VC$$

$$v_{\text{crit}} = \frac{RT}{\rho_r \times VC}$$

where: RT = Tensile strength, ρ_r = Density of the medium, VC = Propagation velocity of longitudinal waves.

Thus, for a rock with $\rho_r = 2.6$ t/m^3 and $VC = 4500$ m/s, the following exists:

$$v_{\text{crit}}\,(\text{mm/s}) = \frac{RT\,(\text{MPa})}{0.117}$$

According to Oriard (1970), the damage threshold in rock slopes is around 60 cm/s of particle velocity.

Afterwards, Bauer and Calder (1971), give the criteria shown in Table 33.10.

Fig. 33.42, gives, in a general sense, the predictable damages due to effect of vibrations in function with the maximum charge weight per unit of delay and the distance from the center of gravity of the blast to the recording point.

Fig. 33.43, shows a procedure to estimate the damages to rock masses from blast vibrations.

When referring to wall stability, this can be determined by the relationship between the active forces, which tend to produce sliding or failure, and the resisting forces, which oppose the movilization of the masses implicated. Although the behavior of a wall when confronted with dynamic effects is complex, owing to the numerous factors that concur, one of the simplified methods to calculate the safety coefficient consists in supposing that the acceleration or velocity due to the seism of the blast is changed into a static force in a determined direction and is proportional to the weight of the sliding mass.

In the case of a block resting on an inclined plane, Fig. 33.44, the equation that gives the Safety Factor, *SF* depreciating the effect of the vertical component of vibratory movement, is:

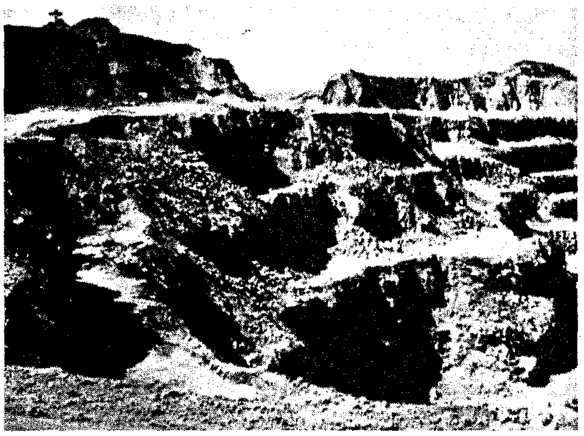


Photo 33.7. Backbreak and face loose rock on final pit slope.

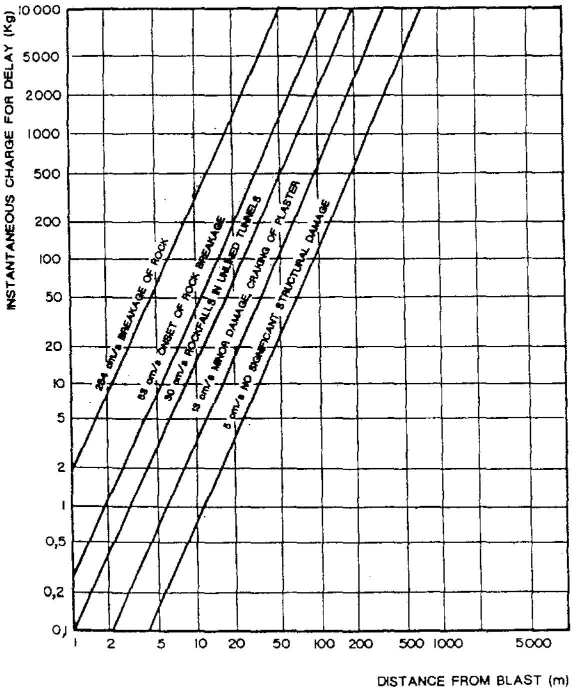


Fig. 33.42. Relationship between maximum charge weight per delay, distance and peak particle velocity.

Table 33.10.

Particle velocity (cm/s)	Predictable damages
< 25	No danger in sound rock
25-60	Possible sliding due to tensile breakage
60-250	Strong tensile and some radial cracking
> 250	Complete breakup of rock masses

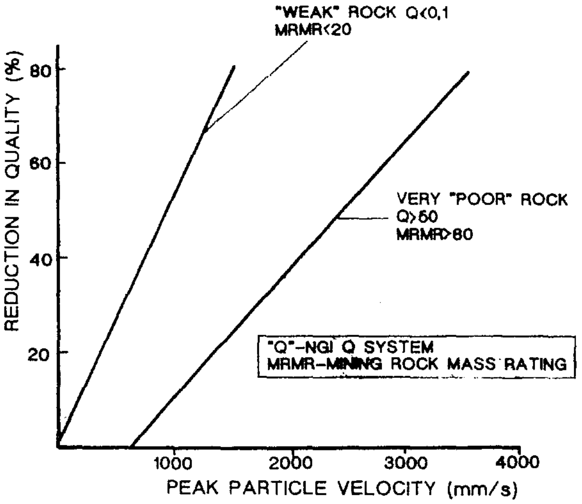


Fig. 33.43. Loss of rock mass quality according to vibration level.

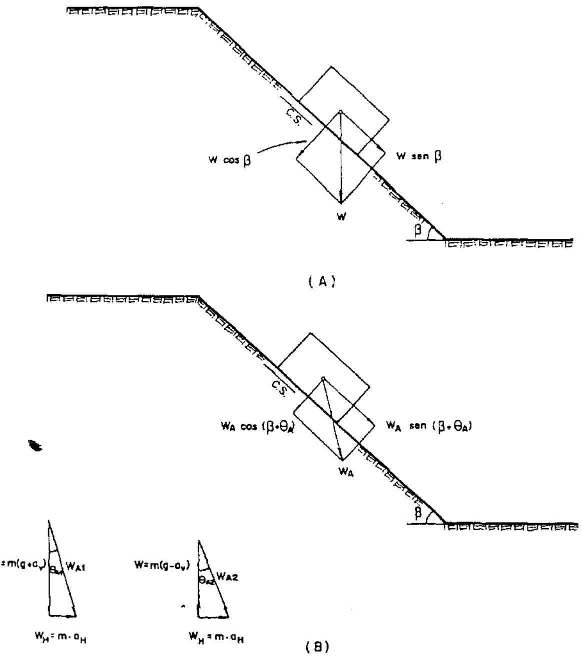


Fig. 33.44. Unstabilizing effect of vibrations in a block resting on a slope.

$$FS = \frac{C_h \times S_p + W_A \times \cos(\beta + \theta_A) \times \mathrm{tg}\,\phi}{W_A \times \mathrm{sen}\,(\beta + \theta_A)}$$

where: C_h = Cohesion, S_p = Contact area of the block, W_A = Weight of the block, β = Slope angle, ϕ = Friction angle, θ_A = Angle caused by longitudinal component of vibrations.

In the particular case of zero cohesion and with the following values: $\beta = 32°$ and $\phi = 37°$, the Safety Factor is 1.2, but if the vibrations act with a longitudinal component v_H = 6 mm/s, with a frequency of 25 Hz, *SF* changes to be 0.98 and block sliding is produced.

Depending upon the type of failure, calculation models can be developed to determine Safety Factors for different levels of vibrations or viceversa, Fig. 33.45.

33.11 EFFECT OF VIBRATIONS ON FRESHLY POURED CONCRETE

In actual practice, numerous occasions arise when it is necessary to build concrete structures at the same time when excavations by blasting are being carried out. For example, linings during tunnel driving, foundations for the primary crushing buildings near open pits, etc.

Fig. 33.46, shows prevention criteria given by Oriard depending upon curing or hardening time of the concretes, although such recommendations cannot be made extensive to all types of concrete.

As can be observed, during the hardening period of 0 to 4 hours, the concrete is still not hard and the admissible levels are relatively high. From 4 to 24 hours, it begins to harden slowly, and after 7 days it reaches a strength that is approximately ⅔ of the final product (28 days), allowing a progressive intensification of the vibrations.

The empirical equations which can be used for an orientative calculation of the maximum co-operative charges, according to age of concrete and distances to blast are:

Fill and mass concrete

$$Q = 38.20 \times 10^{-3} \times DS^{1.86} \times K$$
$$(DS \text{ in m and } Q \text{ in kg})$$

where: $K = 1.0$ for t = 0-4 hours, $K = 0.16$ for t = 4-24 hours, $K = 0.3$ for t = 1-3 days, $K = 0.7$ for t = 3-7 days, $K = 2.3$ for t = 7-10 days, $K = 5.5$ for t = + 10 days.

Reinforced or structural concrete

$$Q = 14.55 \times 10^{-3} \times DS^{1.86} \times K$$
$$(DS \text{ in m and } Q \text{ in kg})$$

where: $K = 1.0$ for t = 0-4 hours, $K = 0.08$ for t = 4-24 hours, $K = 0.37$ for t = 1-3 days, $K = 1.0$ for t = 3-7 days, $K = 3.0$ for t = 7-10 days, $K = 7.58$ for t = + 10 days.

Other factors to take into account are the characteristic frequencies of the vibrations, external hardening conditions, areas of rock-concrete contact, etc.

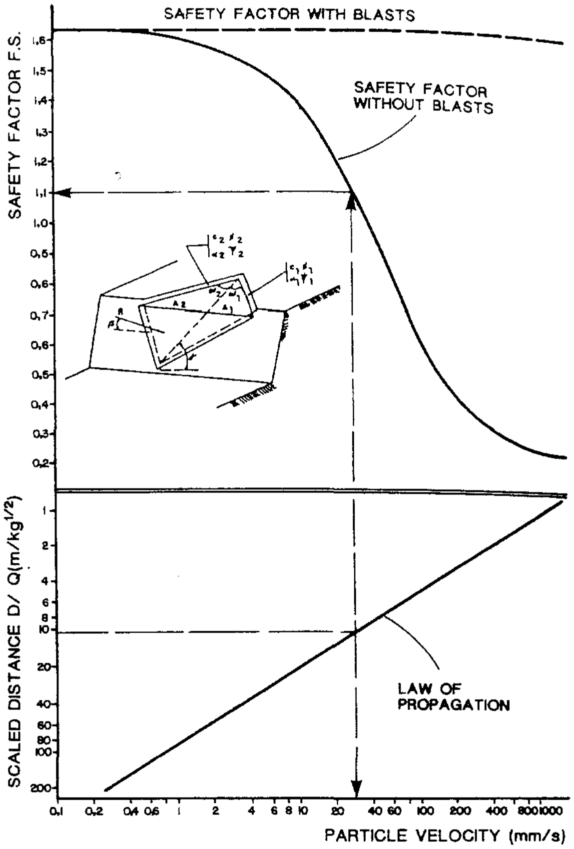


Fig. 33.45. Variation of the Safety Factor for a block with a wedge cut in function with scaled distance.

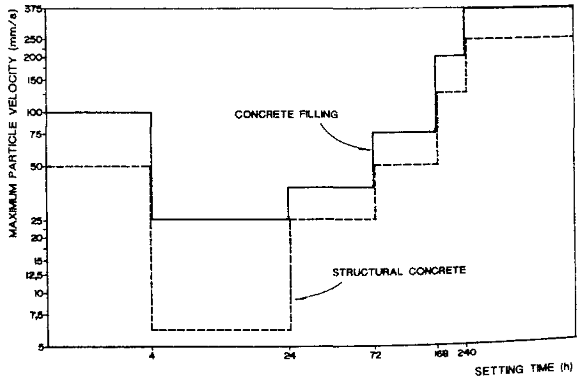


Fig. 33.46. Maximum particle velocity in function with hardening time.

On the other hand, Isaac and Bubb (1981), summed up all their experiences and those of Scandinavian investigators in a graph where, according to the strength acquired by the concrete, the maximum vibration level is determined.

In the construction of some nuclear plants in Spain the following criteria have been used:

Fill concrete

$$v_{adm}\,(\text{mm/s}) = 100 \times \frac{RC\,(t)}{15} \leq 100$$

where: $RC(t)$ = Strength acquired by the concrete after a time t (MPa).

With the limitations:

- Time passed after pouring the concrete ≥ 8 h.
- Maximum particle velocity ≤ 100 mm/s.

Structural concrete

$$v_{adm}\,(\text{mm/s}) = 60 \times \frac{RC(t)}{25} \leq 100$$

With the same limitations as before.

33.12 RECOMMENDATIONS FOR REDUCING GROUND VIBRATION AND AIR BLAST LEVELS

Although each case should be carefully analyzed, the principal measures that can be taken for reducing blast generated vibrations are:

- Minimizing the explosive charge per milisecond delay: Reducing the drilling diameter; Shortening the length of the holes; Decking the charges in the holes and initiating them at different times; Utilizing the maximum number of detonators or delay times possible, with sequenced explosives or milisecond delays if the commercial series of electric blasting caps is surpassed, Figs 33.48 and 33.49.
- Reduce the number of blastholes having instantaneous detonators, as these give higher dispersion that the highest numbers of the series.
- Choose an effective delay time between holes and rows which avoid wave interaction and give good rock displacement.
- Set the initiation sequence in a way that it progresses away from the structure to be protected, Fig. 33.50.

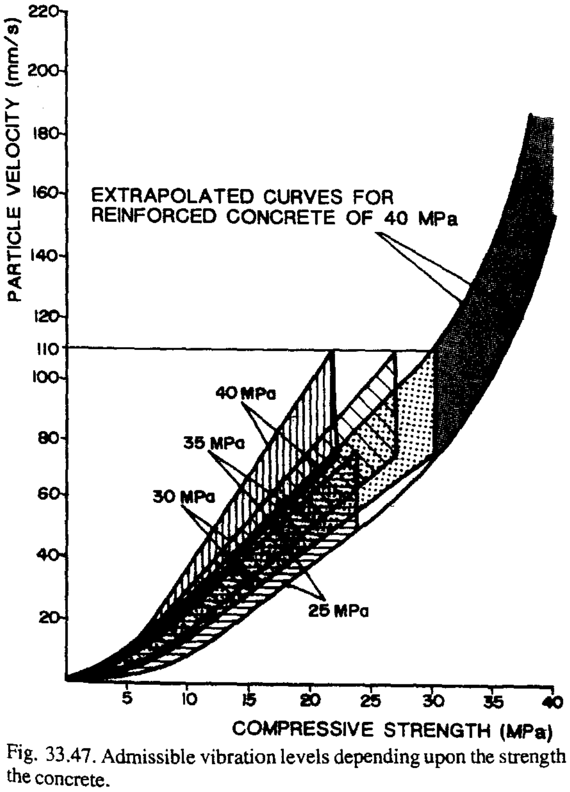


Fig. 33.47. Admissible vibration levels depending upon the strength of the concrete.

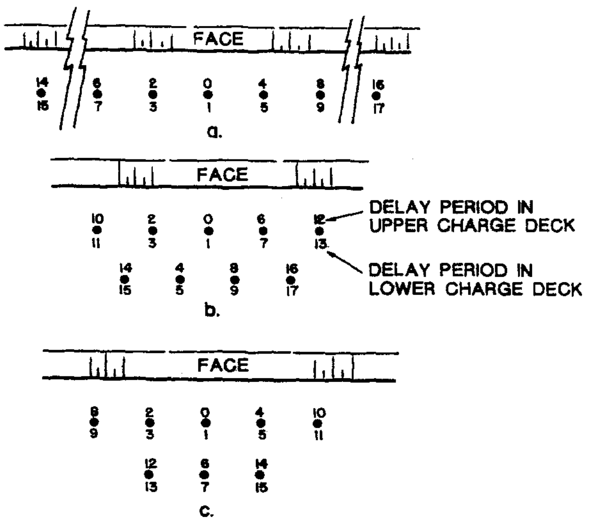
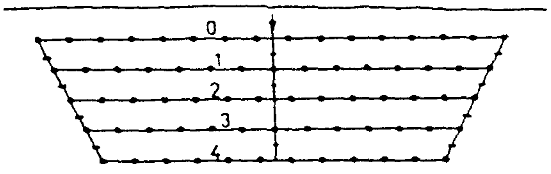
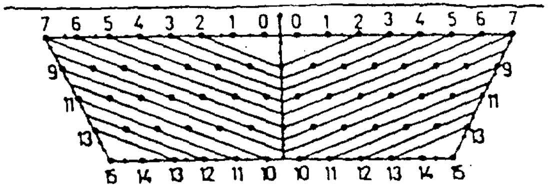


Fig. 33.48. Blasts with decked charges in the holes.



a. STAGGERED IN LINE



b. STAGGERED "V2"

Fig. 33.49. Multiple blasts with the same number of holes and different durations.

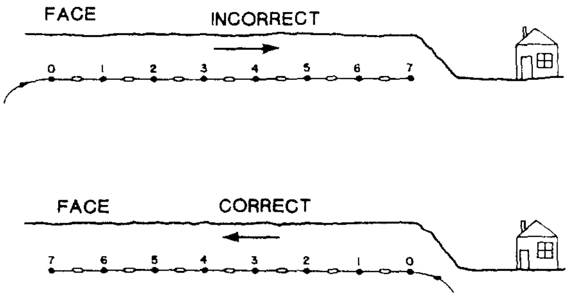


Fig. 33.50. Initiation sequence in relation to the structure to be protected.

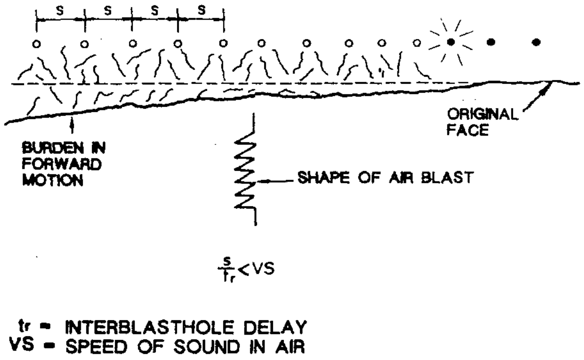


Fig. 33.51. Blast progression along a face and simulation of air blast.

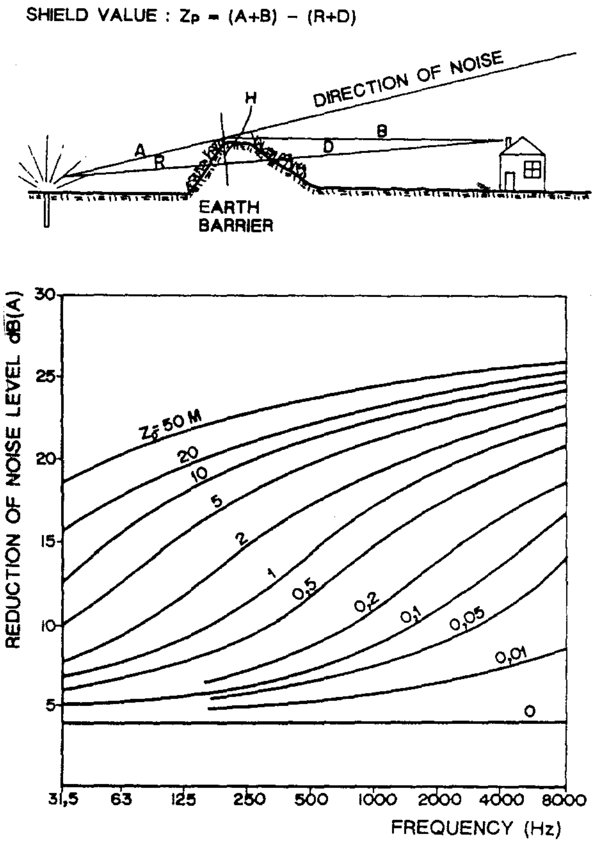


Fig. 33.52. Interposing shields between the blasts and receiving points.

– Use the adequate powder factor, as when it is lowered the charge confinement can increase and, consequently, so will the intensity of vibrations. Obviously, an excessive consumption will create an unnecessary overload, accompanied by great disturbing effects.

– Place the pattern with a relationship $H/B > 2$.

– Control drilling so that the patterns coincide with the nominal ones.

– Use only the subdrilling necessary to acheive good breakage.

– Use the largest possible face blast area.

– Create shields or discontinuities between the structures to be protected and the masses to be blasted.

As with ground vibrations, the recommendations for air blast reduction are:

– Minimize charge weight per milisecond delay. (See the corresponding part about ground vibrations).

– Choose delay times so that the blast progresses along the face at a velocity lower than that of sound in the air (< 340 m/s), Fig. 33.51.

– Increase confinement of the explosive charges with long stemming heights > 25*D*, but not excessive, and use adequate inert material.

– Avoid using detonating cord, and when it is necessary, cover it with fine sand of a minimum thickness of 7 to 10 cm.

– Never fire blasts when the direction of the wind is critical.

– Select patterns and sequences that avoid cooperative wave interaction.

– Inspect the state of the faces before blasting in order to correct the charges with in the blastholes with burdens that are under the nominal.

– Control the explosive charge in ground with solution cavities to eliminate pocket concentrations.

– Place earth or other types of shields between blast and receiving point, Fig. 33.52.

33.12.1 *Reducing vibrations with precision detonators*

The effect of lineal interference or superposition of the wave trains generated by different sequenced explosive

Photo 33.8. Face displacement in a one-hole blast for a vibration study.

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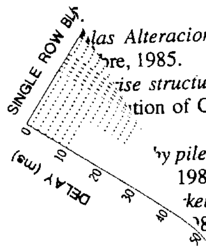


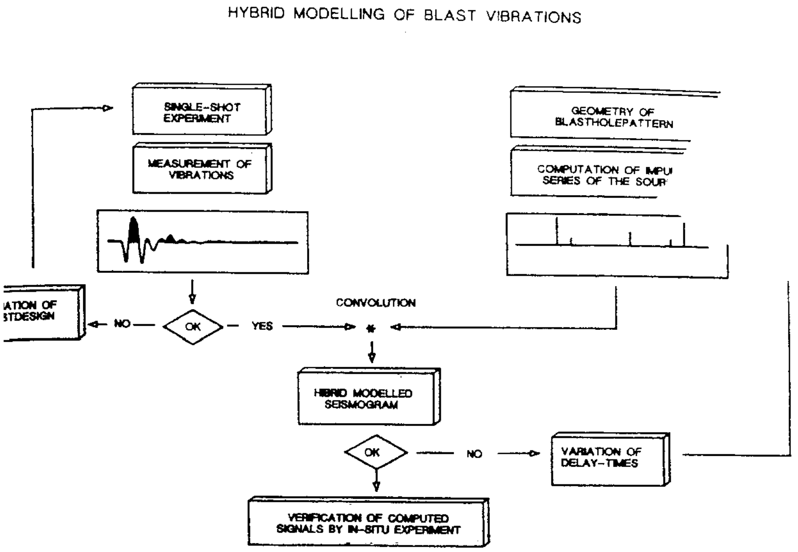
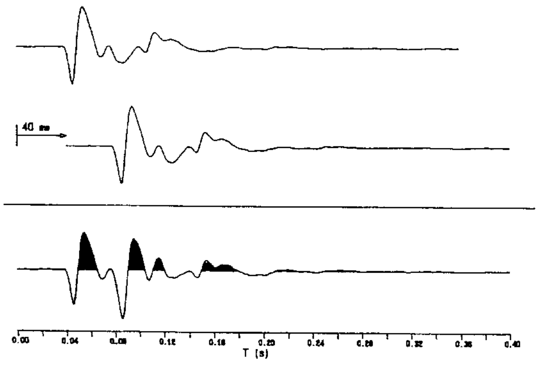


Fig. 33.53. Phases of vibration simulation in multiple blastings.



33.54. Seismograph resulting from the superposition of two wave ıs that are 40 ms apart.

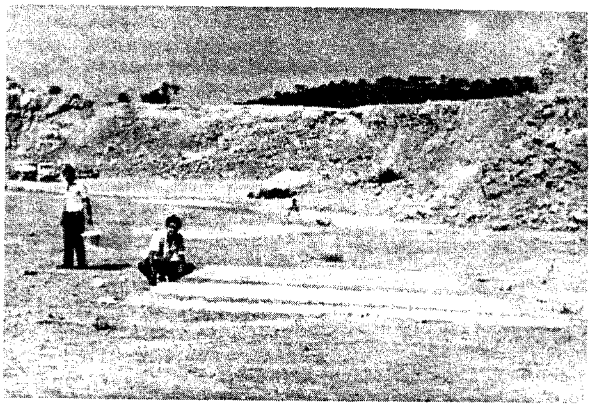
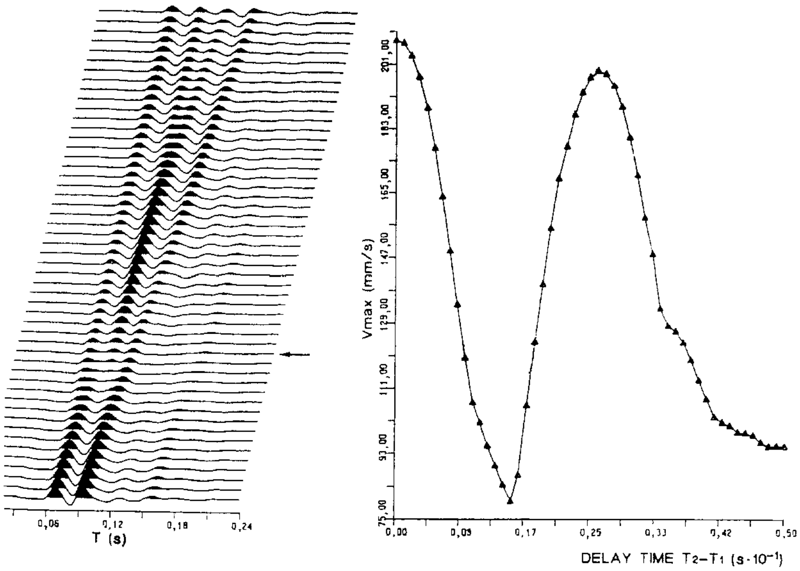


Photo 33.9. Field tests to measure the effectiveness of noise and air blast reduction in a detonating cord covered with sand.



33.55. Results of the superposition of two signals on the peak vibration value when varying delay times.

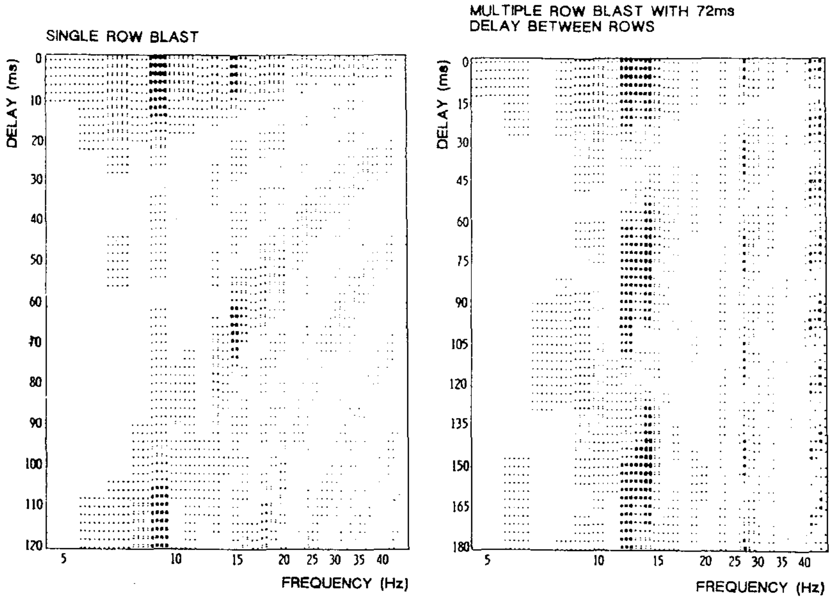


Fig. 33.56. Frequency patterns vs delay time. (a) Row with 4 blastholes with 2 ms increases between charges, (b) Two rows of 4 blastholes, with 72 ms delay between holes in row, and 3 ms increase between rows.

charges is a phenomenon which has drawn much attention lately. Supposing that each hole of a blast produces the same vibration, but delayed in time by sequenced initiation, it is possible to simulate the recording that would be obtained – with its maximum particle velocity and dominating frequencies – by combining the vibrations of a group of blastholes with a given geometry and initiation sequence.

In Fig. 33.53, a simulation procedure is given for the vibrations of a blast, having on hand the actual recording of the signal produced by only one hole.

As an example of these simulations, Fig. 33.55 shows the result of the superposition of two equal wave trains between which exists a time difference of 40 ms.

In practice, the milisecond detonators give a dispersion (cap scatter) in initiation times, increasing with the higher series numbers. For this reason, the computer simulators should be more probabilistic than deterministic, and the Monte Carlo method can be applied to establish the initiation times of each charge by creating aleatory numbers and by using the functions of density of the nominal milisecond delay times.

Recently, with the development of high precision detonators, the old idea of achieving the superposition or destructive interferences of vibrations so that that the peaks and valleys of two waves would be nullified, thus reducing vibrations, has taken on importance and constitutes a field of investigation that is reaping benefits.

The use of these electronic accessories, along with sequential blasting machines, gives an infinite number of combinations. The simulation of the results obtained simplifies making the most appropiate choice to reduce vibration levels and control frequency.

Fig. 33.55 gives the results of variation in delay timing, with increases of 1 ms, in the superposition of two signals. As can be observed, the delay of 15 ms gives the lowest maximum vibration velocity.

In the same manner, the spectral analysis of Fourier can be carried out in order to determine the dominating frequencies that would be generated. Fig. 33.56 shows two simulations that correspond to a single row blast and to another multiple blast where two different delay intervals, multiples of 2 and 3 ms respectively, are studied. Each row of the graph represents the spectra of frequencies with which the theoretical optimum sequence can be determined to avoid low frequencies, proven to be the most dangerous, in a blast of prefixed geometry.

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CHAPTER 34

Flyrocks and their control

34.1 INTRODUCTION

Flyrock, also called rock throw, is the uncontrolled propelling of rock fragments produced in blastings and constitutes one of the main sources of material damage and harm to people.

The conditions which favor flyrock are as follows:

Geology
Intensely fissured and jointed rocks facilitate the appearance of flyrocks more than massive and homogeneous rocks. However, as the latter require large quantities of energy to obtain a good fragmentation, this type of rock usually causes more problems.

Very careful control should be be observed when blasting in karstied ground with a large number of voids and vugs.

Explosives and their distribution
The explosives which have a high Bubble Energy (ANFO, for ex.) produce more rock throw than others which have a more elevated Strain Energy, such as gelatin explosives.

As to distribution, it has to be made certain that the geometric variables of the blast coincide with those of the design, especially in the following cases:

– When the top part of the bench is broken due to excessive subdrilling from the benches above or unsufficient stemming to avoid the risk of crater effect, Fig. 34.21.

– When the face is very irregular, with areas along the length of the explosive column which have very little burden.

The blast design
As indicated in other chapters, flyrock control starts with a correct blast design.

In multiple blastings, apart from inspecting the state of the face of the round and correctly size the stemming, it is fundamental to choose the timing of the stemming between rows, so as not to have too much confinement in the last blastholes which can produce flyrock.

34.2 MODELS TO CALCULATE THE THROW OF FLYROCK

The empirical models proposed by the Swedish Lunsborg and Persson and the American Roth are tools that predict the maximum throw of flyrock.

Below, the most important points of these models are cited.

34.2.1 *Swedish model*

The Swedish Detonic Research Foundation (1975) developed a theoretic model that permits the estimation of the maximum distance reached by a fragment under optimum conditions.

From scaled tests, with high speed photography and theoretical calculations, the following equations are proposed to determine the initial velocity of throw in the blastings where crater effect was produced:

$$v_o = \frac{10\,D \times 2600}{T_b \times \rho_r}$$

where: v_o = Initial velocity (m/s), D = Diameter of the blasthole (Inches), T_b = Size of the rock fragments (m), ρ_r = Rock density (kg/m^3).

By using the standard equations of ballistic trajectory and taking into account that the product $v_o \times T_b \times \rho_r$ depends upon the diameter of the blasthole, the maximum throw length was calculated.

The results obtained are shown in Fig. 34.2, or they can be found analytically from:

$$L_{\max} = 260 \times D^{2/3}$$

$$T_b = 0.1 \times D^{2/3}$$

In practice of bench blastings, it has been proven that the throw lengths are much smaller than when crater effects are produced. Therefore, in well designed blasts, the throw lengths can be calculated from Fig. 34.3. For example, for a specific charge of 0.5 kg/m^3, the maximum throw range would be given by:

$$L_{\max} = 40 \times D$$

and if the blastholes were drilled to 102 mm (4″), it would be:

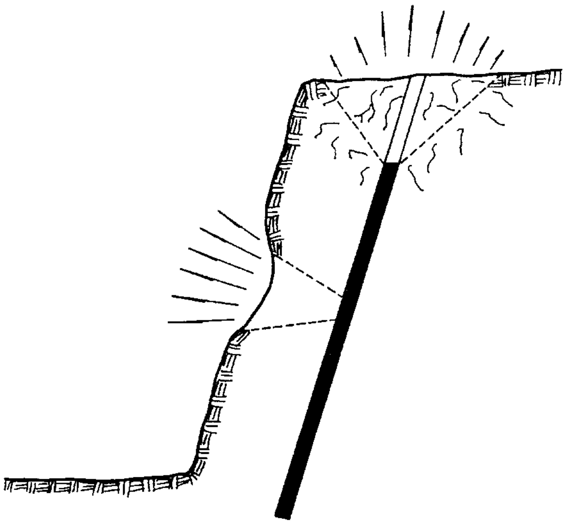
$$L_{\max} = 160\ \text{m}$$

$$T_b = 0.25\ \text{m}$$

34.2.2 *American model*

This model, owed to Roth (1979), is based upon the

oto 34.1. Flyrock during the blasting.



ig. 34.1. Crater effects that could cause flyrock in bench blasting.

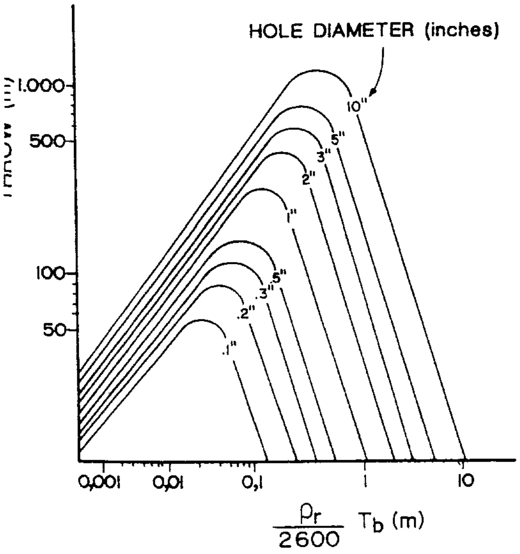


Fig. 34.2. Calculated maximum throw versus boulder size with blast-hole diameter as a parameter (Lundborg et al.).

equation proposed by Gurney to calculate the initial velocity of the fragments propelled by an explosive:

$$v_o = \sqrt{2E} \times f(q_l/m_l)$$

where: v_o = Initial velocity, $\sqrt{2E}$ = Gurney's constant, function of the explosive, q_l = Concentration of explosive per unit of length, m_l = Total mass of material per unit of length.

For the flyrock coming from vertical faces the equation has been modified to:

$$v_o = \sqrt{2E'} \times q_l/m_l$$

where $\sqrt{2E'}$ is smaller than $\sqrt{2E}$ as the direction of detonation is tangent to the rock. The author suggests taking $\sqrt{2E'} = VD/3$ *for many explosives, where VD* is the detonation velocity. For ANFO, the value of the radical is 0.44 *D*.

If the energy losses are taken into account, the previous equation is transformed into:

$$v_o^2 = 2 \times E' \times \left(\frac{q_l}{m_l}\right) \times$$

$$\left[1 - \frac{k_1 \times E_s + K_2 \times E_j}{E'}\right] - 2\,K_3 \times E_r$$

where: E_s = Seismic energy generated per unit weight of explosive, E_j = Energy to crush a unit weight of rock, E_r = Energy absorbed to fragment a unit weight of rock, K_1, K_2, K_3 = Proportionality constants.

The equations of v_o^2 expressed in (m/s) for different types of rocks are transformed into:

Granite

$$v_o^2 = 3{,}487 \times 10^6\,(q_l/m_l) - 584$$

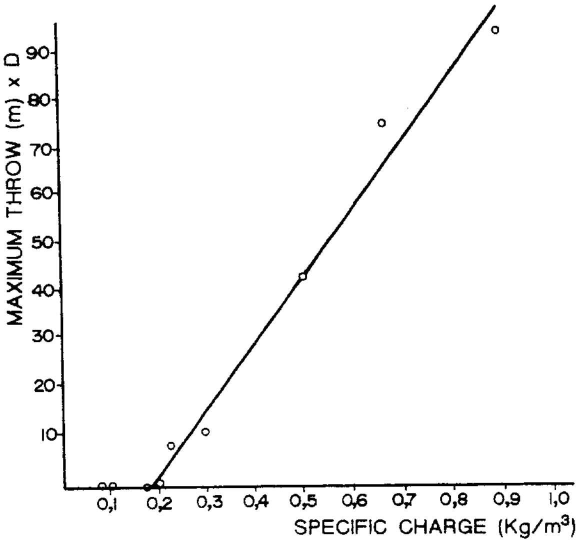


Fig. 34.3. Maximum throw length as a function of specific charge.

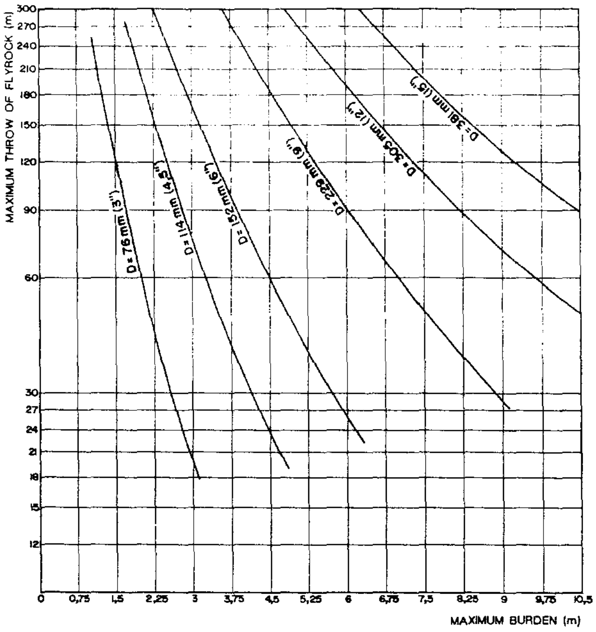


Fig. 34.4. Maximum range of vertical face flyrock from ANFO loaded shots in limestone.

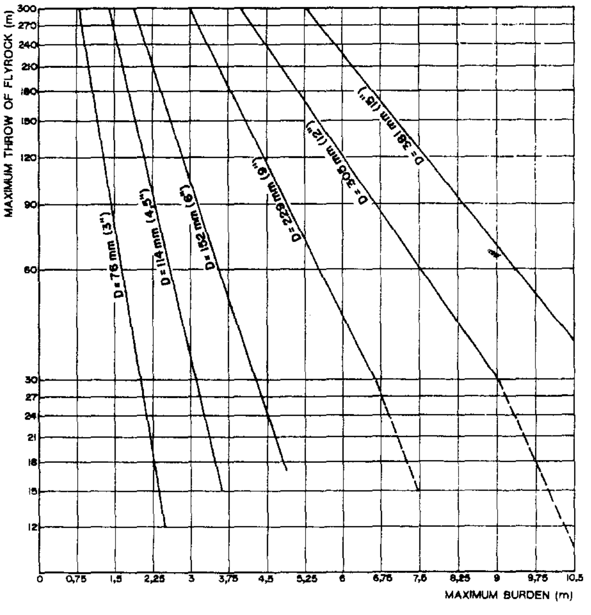


Fig. 34.5. Maximum range of vertical face flyrock from ANFO loaded shots in granite.

Limestones and dolomites

$$v_o = 3 \times 10^6 (q_l/m_l) - 200$$

Going back to the ballistic trajectory formulas, the theoretical maximum ranges for a single blasthole can be estimated.

For flyrock coming from a free face, the estimations can be based upon the nomographs of the Figs 34.4 and 34.5. Knowledge of the type of rock, the diameter of the blasthole and the type of explosive are a requirement. As these nomographs were determined for ANFO, if watergels are used the distances should be increased by 50 %. The burden value should also be corrected if cavities or rock loss exist on the free face from previous blastings.

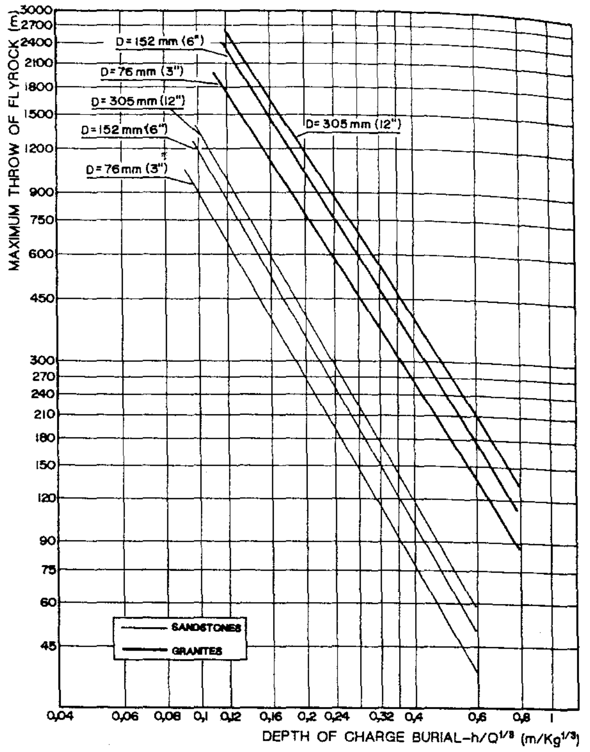


Fig. 34.6. Maximum range for bench top flyrock for ANFO loaded shots in granite and sandstone.

For flyrock from the bench tops, an empirical approximation is proposed, based upon the reduced depth $h/Q^{1/3}$, where h is the depth of the end of the charge and Q is the total quantity of explosive, Fig. 34.6.

34.3 COVERINGS

Coverings are all the elements used to cover the blastings in order to avoid rock throw or any other material that could harm people, buildings etc.

Generally speaking, any protection system should comply to the following characteristics:

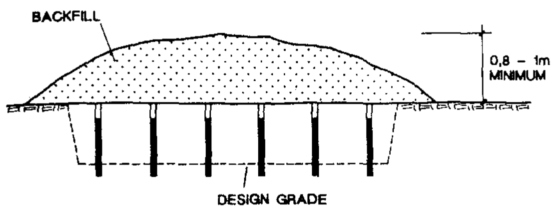
- Reduced weight and high resistance.
- Ease of union or overlaping of the elements
- Permeability to gases.
- Ease in placing and removing.
- Economical and reusable.
- Good size to cover large areas, etc.

According to the type of blast, different coverings will be used.

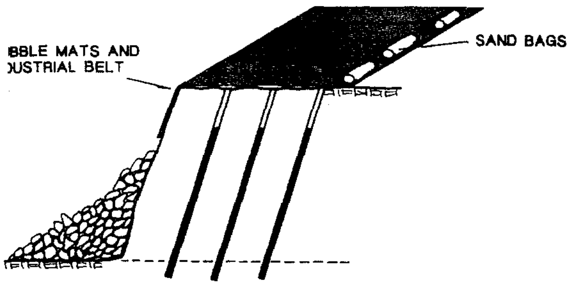
34.3.1 *Ditch blasting and excavation of lots*

When blastings are carried out in small ditches and inhabited areas are nearby, a covering of loose sand can used with thicknesses equal to the stemming height, intaining a minimum of 0.8 to 1 m, Fig. 34.7.

Owing to the weight of the sand, the explosive charges ould be slightly larger than in unprotected blastings.



. 34.7. Protection of a ditch blast by means of a sand covering.



g. 34.8. Protection of a bench blast.

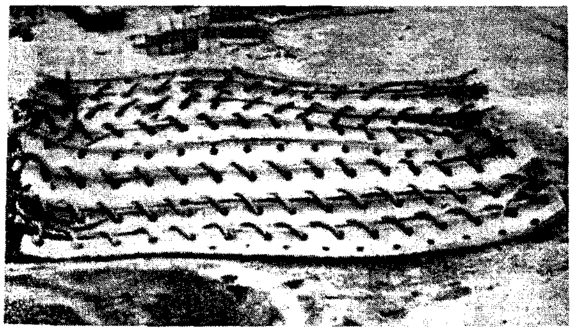


Photo 34.2. Blasting mat.

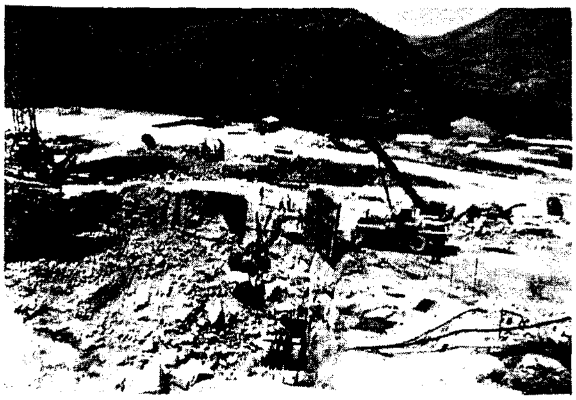


Photo 34.3. Placing of a heavy covering upon a small blast.

Another system consists in overlaping conveyer belts and pinning them down to the ground with sandbags, for example. At the same time metal screening or mesh, nylon nets, or rubber tires that overlap, etc., can be used.

In lot excavations with explosives, the most common system is that of the conveyor belts. These should cover the horizontal surface of the round as well as the free bench face, Fig. 34.8.

In all instances it is necessary to make certain that the connection circuits are all right before and after the coverings have been placed.

34.3.2 *Secondary blastings*

Secondary blastings are a common source of flyrock. In order to control these, besides using the protection systems mentioned, it is recommended that the boulders be removed to areas where they do not disturb the operation, and that the blasts be sufficiently closed in by the slopes of the exploitation to eliminate part of the noise produced by the secondary blast and, at the same time, take advantage of the shielding effect of the faces with respect to the fragments of flying rock.

34.3.3 *Demolitions*

In demolition work, the blastholes drilled in the exterior structural elements should be protected by heavy screens made up of hanging conveyor belts. Special pistols are used to nail them in place, and underneath the holding points there should be sufficient space to allow the gases to escape because, if this is not done, the protections would be torn down in the first blasting.

Other types of complementary protections are metallic screens and bales of straw.

On the other hand, as the lower parts of the structures are usually not protected, it is necessary to close all the door and window openings to avoid rock throw from the interior. In these operations, heavier materials are used such as wooden boards, metal plates, sandbags, etc., which should be installed before charging the blastholes to eliminate possible damage to the circuit lines of the blast. Occasionally, the whole perimeter of the structure to be demolished is covered with geotextile sheets which act as complementary protection.

34.3.4 *Safety area from which the round is fired*

In any surface operation, during the blasts there is always a desired displacement of the muckpile, a normal rock throw distance, and a safety area around the blast. The size of these zones depends upon the characteristics of the blasting, making them vary from blast to blast. However, the prediction models can serve as a tool to define these three areas, Fig. 34.9.

The rock throw that falls in the safety area, farther away than normal, as well as that that surpasses it should be studied in order to establish their origin and the corrective measures to be taken.

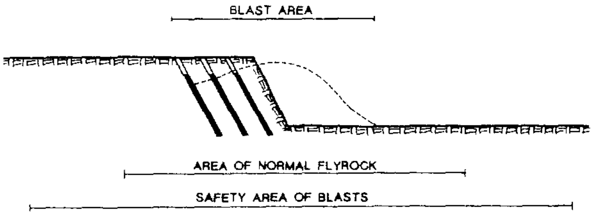


Fig. 34.9. Areas around the blasts in function with rock throw.

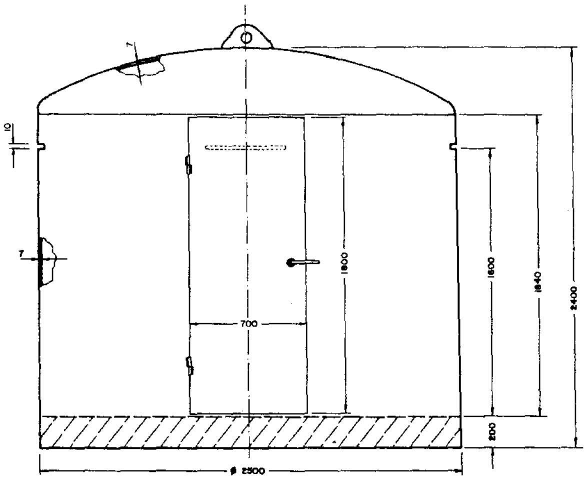


Fig. 34.10. Blasting shelter to protect the shot firer.

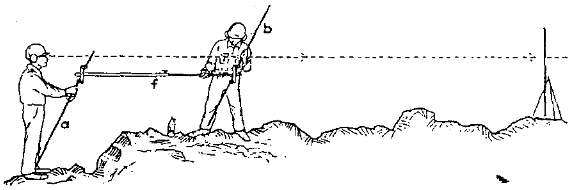


Fig. 34.11. Marking out of a blast in irregular ground.

As to where the shot firer should be placed to fire the rounds, he should be outside the safety areas and use some system of protection such as a metallic blasting shelter, Fig. 34.10, nearby underground operations, front end loader shovels, etc.

34.4 RECOMMENDATIONS FOR CARRYING OUT BENCH BLASTINGS

In order to control rock throw in bench blasts, apart from the adequate protection measures, the following recommendations should be followed:

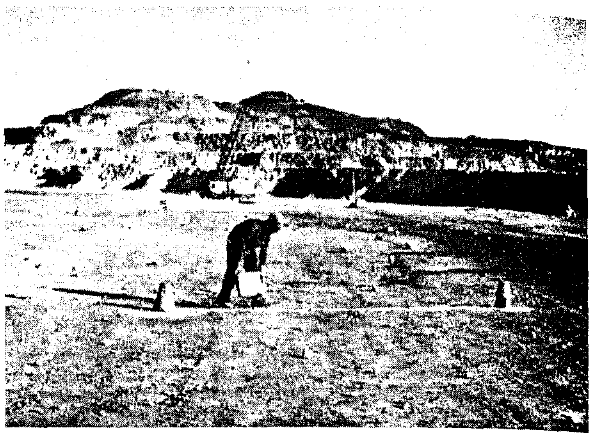


Photo 34.4. Marking out the collaring points in a large diameter blast.

- Perfect marking out of the drilling patterns, especially in ground with an irregular profile, Fig. 34.11.
- Control of the deviations and depths of the blastholes.
- Burden size for the blastholes of the first rows.
- Check for vugs in the rock mass.
- Control of the charging of the explosive and its distribution along the length of the blasthole.
- Careful stemming, measuring its height and using the proper material.
- Selection of an initiation sequence that gives good break direction to the blast.
- Initiation in the bottoms of the holes.

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CHAPTER 35

Safety measures for drilling and blasting operations

.1 INTRODUCTION

order to carry out drilling and blasting under safe nditions, the following aspects must be observed:

1. Comply with the Rules and Regulations that are in ect.
2. Proper technical instruction for the operators, asters and personnel who handle explosives.
3. Machinery, explosives, accessories and initiation stems must be used under safety conditions.

The drilling superintendent should supervise these ree conditions as, if not, the risk of accident will crease owing to over confidence, distractions, lack of owledge and non-compliance with the safety rules, c.

In this chapter, a general guide of basic recommenda- ons is given which obviously should be complemented ith the existing legislation.

5.2 BLASTHOLE DRILLING

5.2.1 *General safety measures for blasthole drilling*

he operation of drilling implies following a series of afety measures in order to minimize potential hazards to eople as well as to material objects.

Drilling will be carried out according to the existing ules or policies, either official or those set by the compa- y.

The operators should have received proper training nd have studied the instruction book for the machine or nachines which they are to handle, Fig. 35.1.

The members of the drill crew should be given gar- nents which provide adequate protection (helmets, oots, gloves, glasses, masks, etc.), and use clothing and ccessories that are not loose so as to avoid their catching n the moving parts of the machine.

The personal protection objects and those for the nachine should be in good condition; if not, do not ommence drilling.

The protection systems for the machine should not be disconnected, in order to avoid damage to itself or to people.

The starting and manuevering controls should be protected so as to avoid manipulation by other people, which could constitute a risk.

The compressor on the rig should be equipped with a fire extinguisher and a first aid kit, which the operators must know how to use.

If the work conditions are poor or dangerous, the equipment should not be used.

Place warnings on the control pannel to advise of these conditions.

There should be signs that are well visible advocating the necessity of personal protection, Fig. 35.2.

35.2.2 *Safety precautions before starting equipment*

The crew members should be prepared to assume possible risks and have the means to confront them, as well as knowing where to look for help.

The driller should check the whole rig, even if everything was working correctly in the previous shift.

The drill crew should inspect the premises where they are going to work, its potential limitations, as well as the accesses to the area.

The pressurized hoses will be securely anchored, especially the main hose, which should have an additional safety cable at the connection point.

The threads and connection elements must be correctly tightened.

Check all fluid levels, oiling points and cleanliness of the machine according to the manufacturer's instructions, and make certain that all tools and equipment are in proper places and in good condition.

Possible fuel and other fluid losses must be watched, and the deposits will be purged according to the service instructions.

35.2.3 *Safety measures during starting*

When starting the machine, the following precautions should be observed:

- Make certain that unnecessary personnel are not on the rig or in the surroundings.
- Check to see that all controls are in the correct position.
- Inspect any possible warning signs or instructions on the rig.
- Start the drill by authorized operator, from the proper position and in the open air or with good ventilation.
- Never leave the rig when it is running.