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Vibration Control

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1. Introduction

One of the most troublesome and controversial issues facing mining and other industries related to blasting is that of ground vibration and air blast produced form blasts. It goes without saying that huge mutation in the field of industries and buildings happened in all over the world, have to be companioned with a same amount of progress in the field of rocks and minerals excavation by blasting, which is considered the backbone of this industrial prosperity. For that, accurate control must to be serious restricted to minimize blasting effect on people and environment. When a blast is detonated, some of the explosive energy not utilized in breaking rock travels through the ground and air media in all direction causing air and ground vibrations. Air and ground vibration from blasting is an undesirable side effect of the use of explosives for excavation. The effects of air and ground vibrations associated with blasting have been studied extensively. Particular attention has focused on criteria to control the vibration and prevent damage to structures and people.
There are many variables and site constants involved that collectively result in the formation of a complex vibration waveform. Many parameters controlled and uncontrolled influence the amplitude of ground vibrations such as distance away from the source; rock properties; local geology; surface topography; explosive quantity and properties; geometrical blast design; operational parameters (initiation point and sequence, delay intervals patterns, firing method). The propagation of ground vibration waves through the earth's crust is a complex phenomenon. Even over small distances, rocks and unconsolidated material are anisotropy and non-homogeneous. Close to the rock/air interface at the ground surface, complex boundary effects may occur. These difficulties restrict theoretical analysis and derivation of a propagation law, and consequently research workers have concentrated upon empirical relationships based on field measurements.
Human are quite sensitive to motion and noise that accompany blast-induced ground and air vibrations. Complaints and protest resulting from blast vibration and air overpressure, to a large extent, are mainly due to the annoyance effect, fear of damage, and the starting effect rather than damage. The human body is very sensitive to low vibration and air blast level, but unfortunately it is not reliable damage indicator. In this regard psychophysiological perception of the blast is more important than the numerical values of the ground vibration and air vibrations. Generally speaking, the key factor that controls the amount and type of blast vibration produced is energy of explosives and the distance of the structure from the blast location.

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In order to control and protect the structures from deleterious effect of ground and air vibrations, regulations have been formulated in different countries. These regulations vary from country to country depending on the type and the construction material used. Many damage criteria and propagation equations have been established and fulfilled with varying of degree of success. Its development begins from Rockwell's vibration energy prediction formula in 1934 to OSM regulations (1983) and Indian criteria (DGMS 1997). In recent years, there has been an increasing interest in the utilization of unconventional control strategies such as neural networks (NN), fuzzy logic, and genetic algorism (GA) etc. to predict and control the air and ground vibrations.

2. The nature of ground vibrations from blasting and types of elastic waves:

In blasting operations, the potential energy, contained in an explosive is suddenly released, normally with the primary intention of fragmenting rock. A secondary, and undesirable result of explosive detonation is that the surface of the ground in the vicinity of the blast undergoes displacement, the amplitude of which depends upon, distance from the blast, the energy released in the explosion and the local geological conditions.

When an explosive is detonated, rock in the immediate vicinity is crushed and shattered and an oscillatory wave is propagated through the rock mass causing particles along its path to move backwards and forwards longitudinally along the lines of advance of this primary wave, which is normally designated the P-wave. Where the P-wave strikes a free surface or change of material at any angle other than 90°, complex displacements occur which give rise to secondary or shear waves usually termed S-waves.

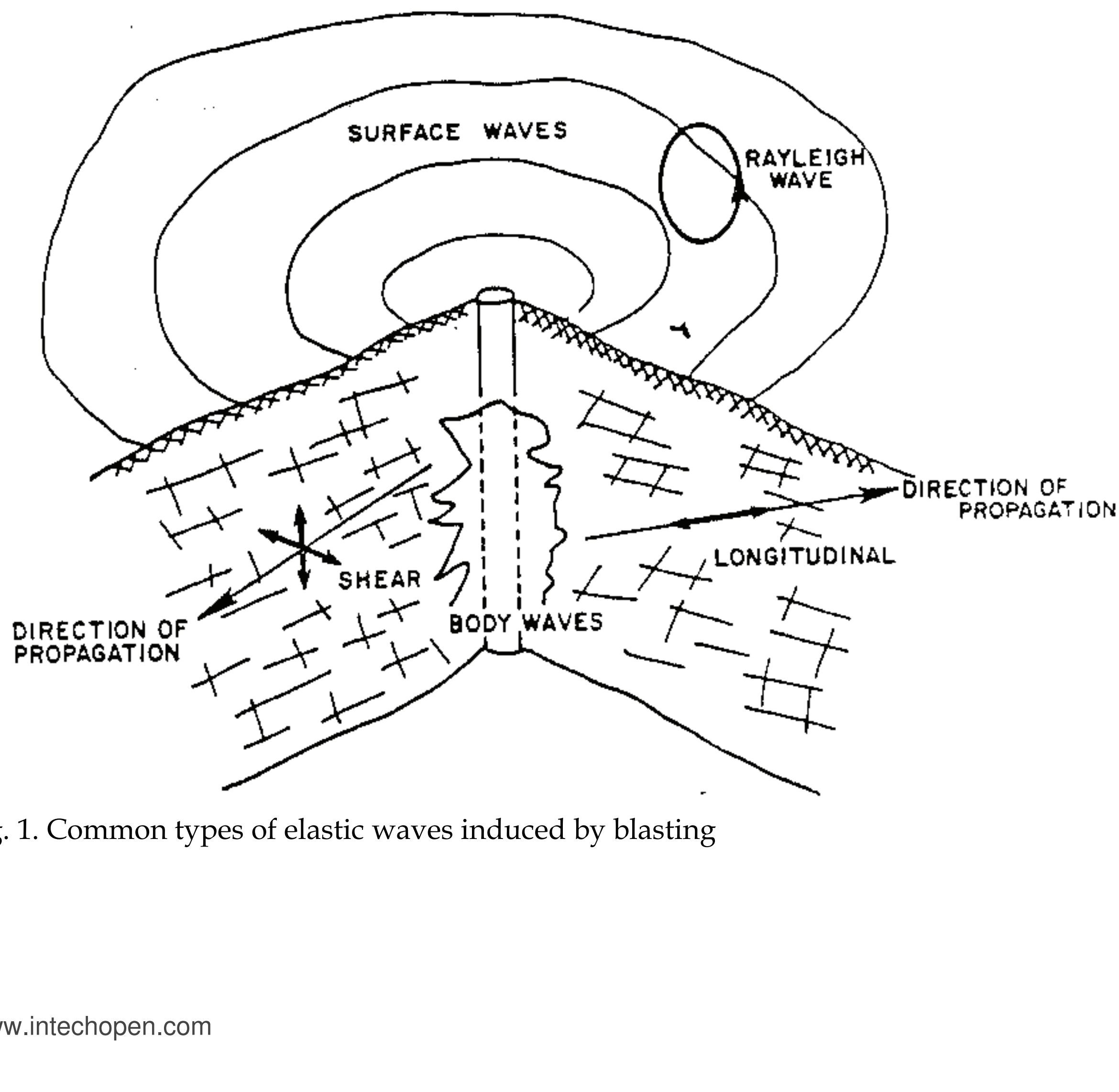
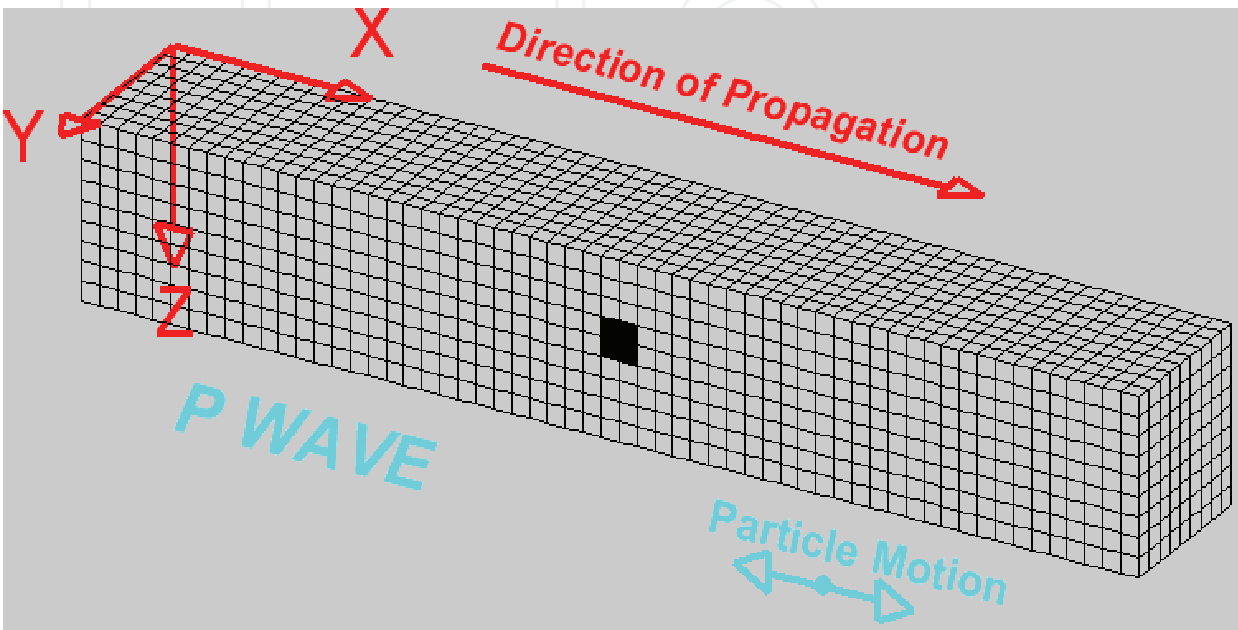
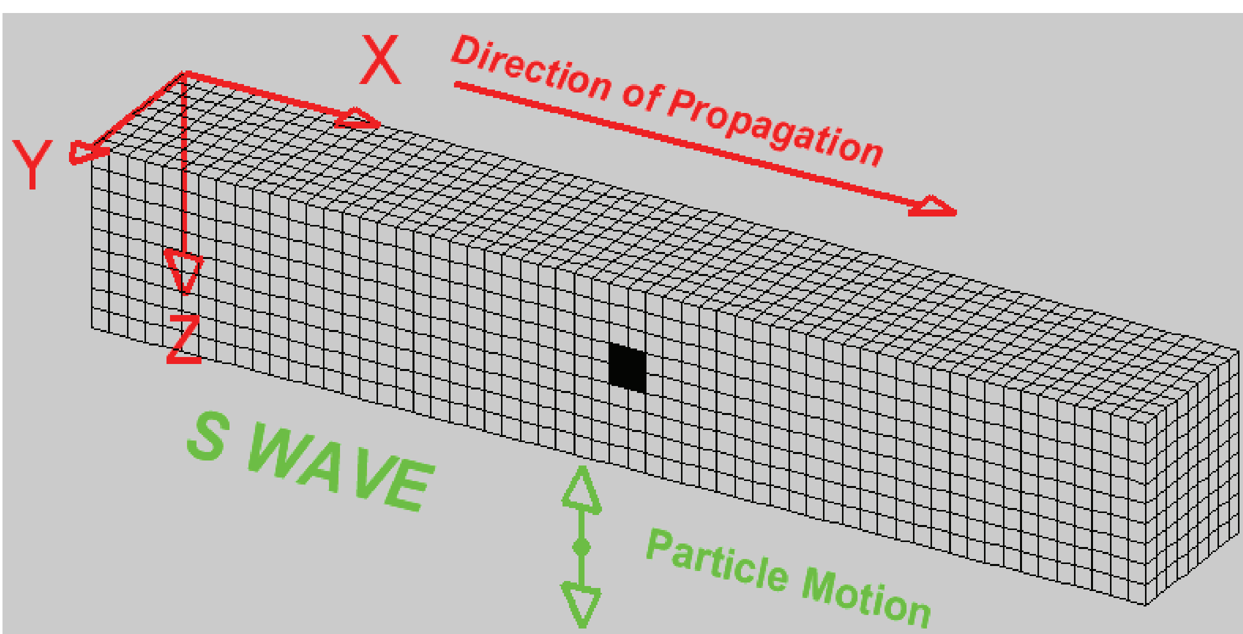


Fig. 1. Common types of elastic waves induced by blasting

The P- and S-waves are called body waves because they travel through the body of the materials, which transmit them. At the free surface between ground and air, the body waves generate a number of surface waves, each of which is characterized by the motion through which a particle in its path goes as the wave passes. Common types of elastic waves (body and surface waves) induced by blasting are illustrated in figure 1 and table [1], the direction of propagation and particle motion for body and surface waves are shown in figures (2, 3).

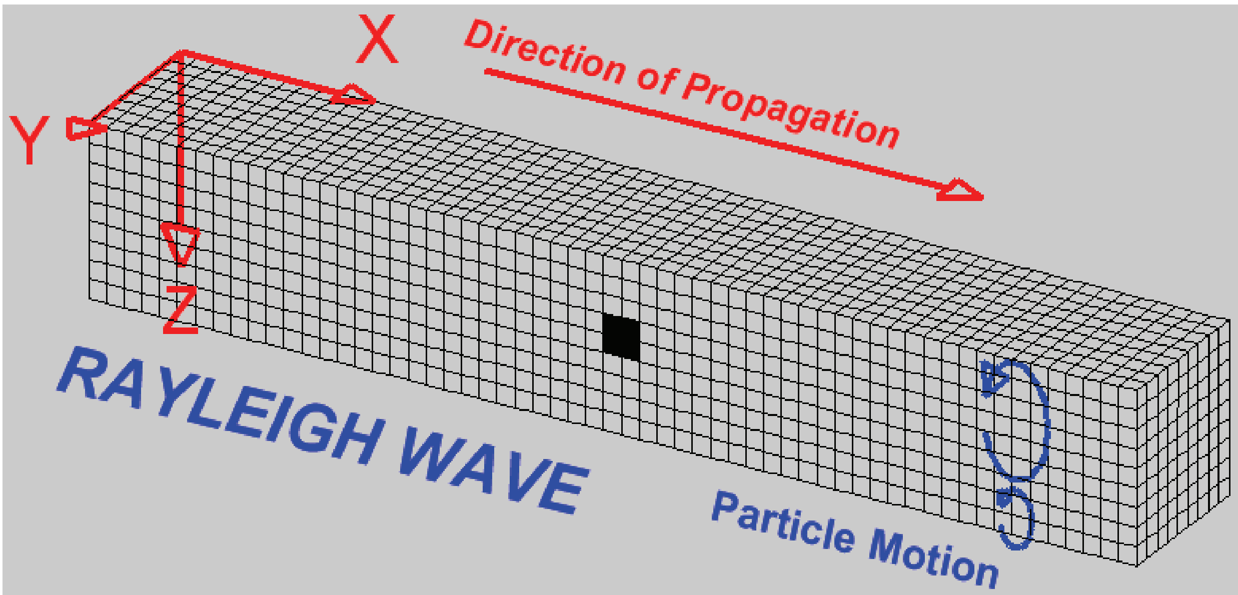


Compressional wave

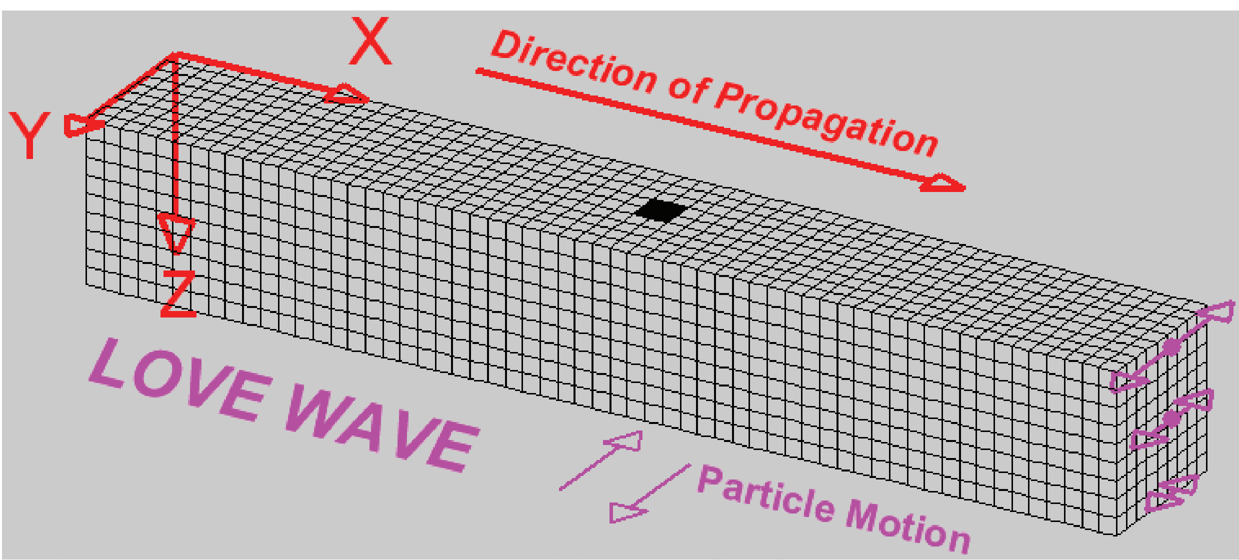


Shear wave

Fig. 2. Body waves motions (compressional and shear).



Rayleigh wave



Love wave

Fig. 3. Surface waves motion (Rayleigh and Love)

The particle motions associated with each of the major surface waves are illustrated in Figure 4. The Rayleigh or R-wave is longitudinal and causes mainly vertical retrograde motion. It is the most commonly observed surface wave, carries the major part of the surface ground energy and consequently is most likely to cause damage. The love or Q-wave (from the German querwellen) causes transverse vibration in the horizontal plane with no vertical displacement. The displacement of particles by coupled or C-waves is elliptical and inclined, having components in both vertical and horizontal directions. The use of the term coupled implies combined P-and S-type motions. The H-wave moves particles in an elliptical orbit similar to the R-wave but in the reverse direction. It has only been detected in nuclear blasting. P-waves have the highest velocity, usually in the order of 3000 - 6000 m/s (10000 – 20000 ft/s) in hard rock formations. For surface waves the following order generally obtains:

Wave Type and names	Particle Motion	Typical Velocity	Other Characteristics
P, Compress ional, Primary, Longitudinal	Alternating compressions ("pushes") and dilations ("pulls") which are directed in the same direction as the wave is propagating (along the ray path); and therefore, perpendicular to the wavefront.	VP~ 5-7km/s in typical Earth's crust >~8 km/s in Earth's mantle and core; ~1.5 km/s in water; ~0.3 km/s in air.	P motion travels fastest in materials, so the P-wave is the first-arriving energy on a seismogram. Generally smaller and higher frequency than the S and Surface-waves. P waves in a liquid or gas are pressure waves, including sound waves.
S, Shear, Secondary, Transverse	Alternating transverse motions (perpendicular to the direction of propagation, and the ray path); commonly approximately polarized such that particle motion is in vertical or horizontal planes.	VS ~3-4 km/s in typical Earth's crust; >~4.5 km/s in Earth's mantle; ~2.5-3 km/s in (solid) inner core.	S-waves do not travel through fluids, so do not exist in Earth's outer core (inferred to be primarily liquid iron) or in air or water or molten rock (magma). S waves travel slower than P waves in a solid and, therefore, arrive after the P wave.
L, Love, Surface waves, Long waves	Transverse horizontal motion, perpendicular to the direction of propagation and generally parallel to the Earth's surface.	VL ~ 2-4.4 km/s in the Earth depending on frequency of the propagating wave, and therefore the depth of penetration of the waves. In general, the Love waves travel slightly faster than the Rayleigh waves.	Love waves exist because of the Earth's surface. They are largest at the surface and decrease in amplitude with depth. Love waves are dispersive, that is, the wave velocity is dependent on frequency, generally with low frequencies propagating at higher velocity. Depth of penetration of the Love waves is also dependent on frequency, with lower frequencies penetrating to greater depth.
R Rayleigh, Surface waves, Long waves, Ground roll	Motion is both in the direction of propagation and perpendicular (in a vertical plane), and "phased" so that the motion is generally elliptical – either prograde or retrograde.	VR~ 2-4.2 km/s in the Earth depending on frequency of the propagating wave, and therefore the depth of penetration of the waves.	Rayleigh waves are also dispersive and the amplitudes generally decrease with depth in the Earth. Appearance and particle motion are similar to water waves. Depth of penetration of the Rayleigh waves is also dependent on frequency, with lower frequencies penetrating to greater depth.

Table 1. Types of seismic waves

Decreasing velocity
C ➔H➔ Q➔ R

C : coupled Raleigh wave
H: reverse Ryaleigh wave
Q: Love wave
R: Rayleigh wave

As waves travel outwards from the source of the explosion, higher frequencies are damped out and the frequency range thereafter is of the order of 3-70 Hz.

Explosions in the ground are generated under a wide variety of conditions and this may lead to the formation of one type only, all types or combinations of surface waves. In dealing with environmental problems it is the net resultant motion to which a structure or person is subjected which is of interest and hence it is usual to measure the net effect of all surface waves and not to attempt differentiation between the motion attributable to each type.

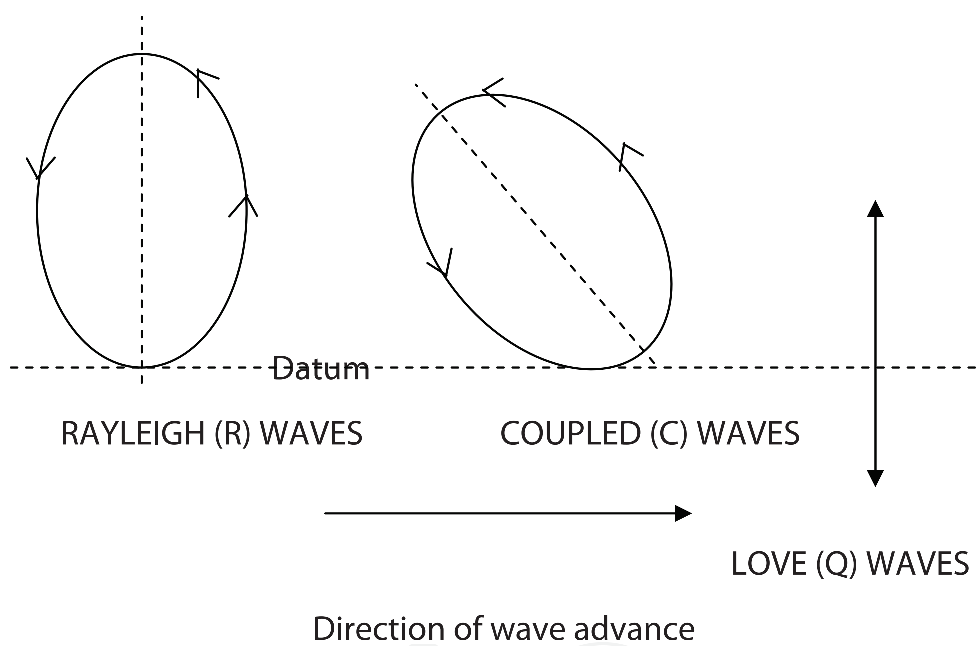


Fig. 4. Particle motions associated with R, C and Q surface waves

The material involved in the transmission of surface waves is a zone about one wave length in thickness.

All surface waves are generated at approximately the same time and, in the immediate vicinity of the blast, the total surface, displacement is controlled by the total energy contained within the waves. However, as the waves travel outwards at differing velocities, they quickly separate and maximum ground motion is then controlled by the energy contained within each individual wave. Hence maximum displacement decreases very rapidly at first but then diminishes more slowly as individual waves die out from loss of energy and dispersion. The rate at which the waves die out is dependent upon the nature of the materials through which they pass. The wave forms are elastic and are more readily transmitted through competent rock which has a relatively high elasticity, than through clays, sand and similar unconsolidated material which rapidly convert wave energy into heat by friction.

Makano in 1925 presented the point of Rayleigh wave development (E) on surface as follows, (Fig. 5).

$$E = Vr * d/(Vp^2 - Vr^2)^{1/2}$$

Where:
Vr = the Rayleigh wave velocity.
Vp = Compressional wave velocity.
d = the depth of the disturbance.

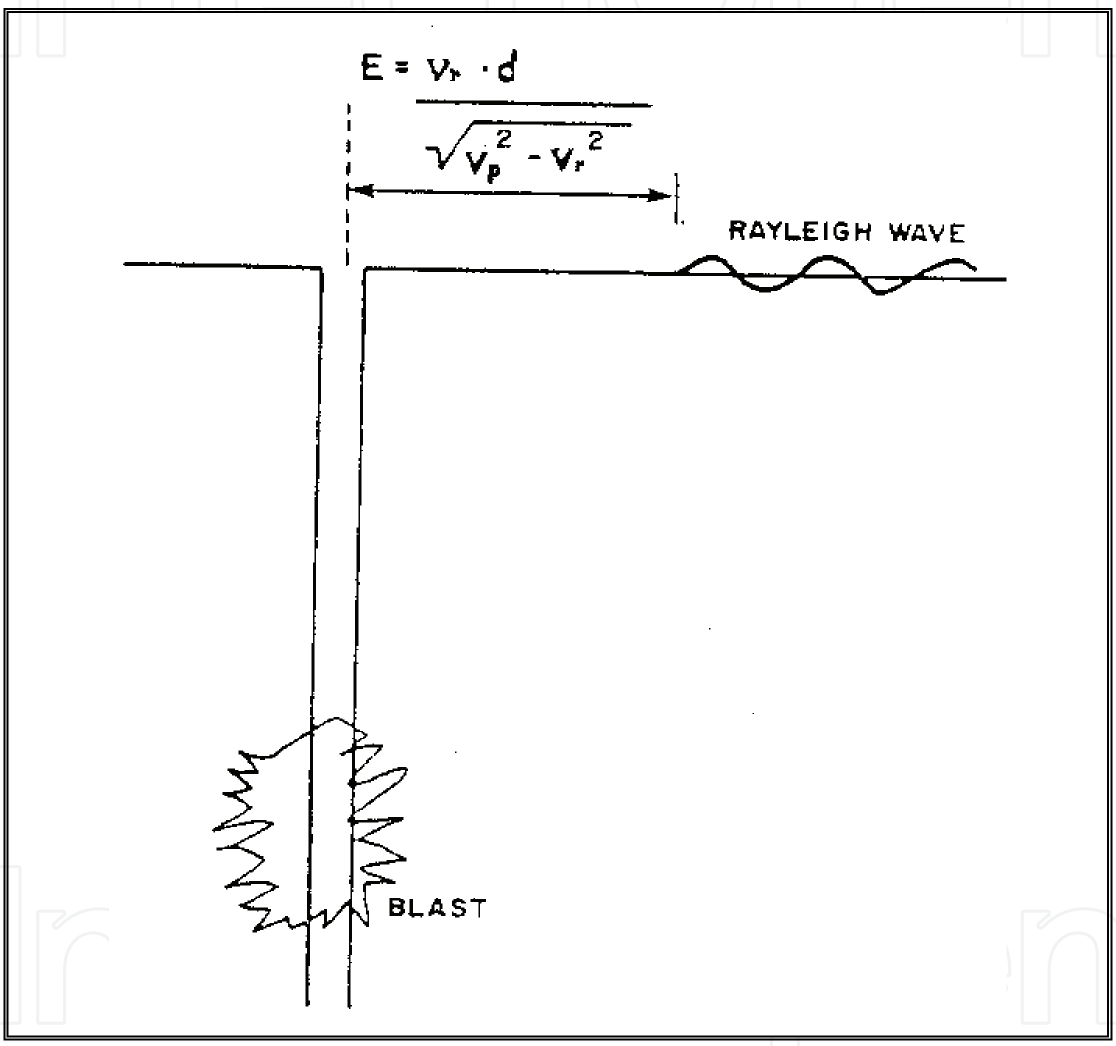


Fig. 5. Epicentral distance (E) from the charge to the point of Rayleigh wave development.

3. Effect on structures

When defining damage to residential type structures the following classifications are used:
Cosmetic or threshold damage - the formation of hairline cracks or the growth of existing cracks in plaster, drywall surfaces or mortar joints.
Minor damage - the formation of large cracks or loosening and falling of plaster on drywall surfaces, or cracks through bricks/concrete blocks.
Major or structural damage - damage to structural elements of a building.

BS 7385 1993 gives guide values with respect to all 3 of these damage classifications for residential structures in terms of peak particle velocity and frequency. These values are based on the lowest vibration levels above which damage has been credibly demonstrated.

In terms of cosmetic damage, at a frequency of 4 Hz the guide value is 15mms -1 peak particle velocity, increasing to 20mms -1 at 15 Hz and 50mms -1 at 40 Hz and above. Minor damage is possible at vibration magnitudes that are greater than twice those given for the possible onset of cosmetic damage with major damage to a building structure possible at values greater than four times the cosmetic damage values. These values apply even when a structure experiences repeated vibration events.

Although damage or the fear of damage is the major concern for neighbors of surface mineral workings the reality is that vibration levels at adjacent residential properties rarely if ever even approach the levels necessary for even the most cosmetic of plaster cracking. Engineered structures such as industrial and heavy commercial buildings and underground constructions are able to sustain higher levels of vibration than those applicable to residential type properties by virtue of their more robust design.

4. Damage criteria and regulations

Many damage criteria have been established and fulfilled with varying of degree of success. Its development stretches from Rockwell's vibration energy formula in 1934 to the present-day OSM regulations Indian criteria (DGMS 1997). A short account review of each is as follow:

- Rockwell's Energy Formula, 1934;
- USBM's Acceleration Criterion, 1935-1940;
- USBM's Formula, 1942;
- Crandell's Energy Ratio, 1949;
- Langefor's Particle Velocity Criterion, 1958;
- Edwards and Northwood's Particle Velocity, 1959;
- USBM's Particle Velocity Criterion, 1969-1971;
- Medearis's Particle Velocity and Frequency, 1976;
- Bauer's Particle Velocity Criterion, 1977;
- USBM's Variable Particle Velocity Versus Frequency, 1980;
- OSM's Current Federal Regulations, 1983;
- Indian criteria (DGMS 1997).

In 1934, Rockwell stated that vibration energy caused by blasting was proportional to frequency (f) and amplitude (A) (is proportional to f^2A^2). Field studies from 1935 to 1940 by the USBM in the frequency range 4-40 Hz and amplitude range 0.0025-12 mm related damage to acceleration have been fulfilled. These studies found that, no damage with acceleration of lower than 0.1g, minor damage (fine plaster cracks) with acceleration ranges from 0.1 to 1.0g, but major damage (fall of plaster) when acceleration is above 1.0g.

In 1942, USBM combined the effect of charge quantity, ground character and distance. This formula was found to be inadequate in view of the more complex blasting designs.

In 1949 Crandell developed the concept of energy ratio which is defined as the ratio of the square of the acceleration to the square of the frequency ($ER = a^2/f^2$). Crandell's damage criteria were based on pre- and post-blast investigations of over 1000 residential structures, He recommended that the threshold level at which minor damage occurs is about 3 while above 6 is more danger.

In 1958 A report by Langefors et al. described the relationship between ground vibrations from blasting and structural damage during a reconstruction project in Stockholm. Frequencies measured ranged from 50 t0 500 Hz and amplitudes from 0.02 to .5 mm. They concluded that particle velocity gave the best guide to damage potential and derived the results as shown in table (2).

In 1959 investigations by Edwards and Northwood for the frequency range 3-30 Hz and amplitude range 0.25-9 mm concluded that damage was more closely related to velocity than displacement or acceleration. And minor damage was likely to occur with a peak particle velocity of 100-125 mm/s, table (3) presents these damage levels.

In 1971, USBM has been set damage criteria of peak particle velocity of less than 2 in/sec would result in a low probability of structural damage to residential dwellings, see table (4).

In 1976, Medearis reported that specifying a peak ground particle velocity alone, did not take into account two very significant parameters, namely the predominant frequencies of the ground motion and the structure being existing. He concluded that Pseudo Spectral Response Velocity (PSRV) was deemed to be the best predictor of damage due to blast vibrations. For a predicted PSRV of 1.5 in/sec, the probability of damage ranged from 0 to 1 %.

In 1977, Bauer et al. has been established damage for equipment and structures depending on peak particle velocity criterion as shown in table (5). In 1980, Siskind et al. Published the results of comprehensive study of ground vibration produced by blasting on 76 homes from 219 production blasts in RI 8507. the main conclusions are peak particle velocity is still the best single ground descriptor. Also, practical safe criteria for blasts that generate low-frequency ground vibrations are 0.75 in/sec for modern gypsum board houses and 0.5 in/sec for plaster-on-lath interiors. For frequencies above 40 Hz, a safe peak particle velocity of 2 in/sec is recommended for all houses.

In 1983, the United States Office of Surface Mine (OSM) published its final regulations concerning the use of explosives for the control of ground vibrations and air blast. These regulations applied only to surface coal mining operations and designed to control blasting effects. Many non-coal surface mining operations have opted to comply with these regulations as operating guidelines. The office of OSM regulations were designed to offer more flexibility in meeting performance standards and to prevent property damage. The operator has the choice of employing any one of the the methods as in table (6) to satisfy the OSM regulations.

Particle Velocity	Damage
2.8 in/sec	No noticeable damage
4.3 in/sec	Fine cracks and fall of plaster
6.3 in/sec	Cracking of plaster and masonry walls
9.1 in/sec	Serious cracking

Table 2. Selected particle velocity damage criteria are listed as follows (Lagefors, Kihlstrom, and Westerber (1957)).

Particle Velocity	Damage
≤ 2 in/sec	Safe no damage
2.4 in/sec	Caution
> 4 in/sec	Damage

Table 3. Edwards and Northwood based their criteria in connection with the St. Lawrence project in Canada (1959).

Particle Velocity	Damage
< 2.0 in/sec	No damage
2.0-4.0 in/sec	Plaster cracking
4.0-7.0 in/sec	Minor damage
> 7.0 in/sec	Major damage to structures

Table 4. USBM (1971).

Type of structure	Type of damage	Particle velocity at which damage starts
Rigidity mounted mercury switches	Trip out	0.5 in/sec
Houses	Plaster cracking	2 in/sec
Concrete blocks in a new home	Cracks in block	8 in/sec
Cased drill holes	Horizontal offset	15 in/sec
Mechanical equipment pumps compressors	Shafts misaligned	40 in/sec
Prefabricated metal building on concrete pads	Cracked pads building twisted and distorted	60 in/sec

Table 5. Equipment and Structure Damage Criteria (Canmet, Bauer and Calder 1977).

- *Method 1*- Limiting particle velocity criterion: requires that each blast be monitored by a seismograph capable of monitoring peak particle velocity. Providing the maximum particle velocity stays below the levels specified in table (6).
- *Method 2*- Scaled distance equation criterion: requires the operator to design shots in accordance with table (6), which specifies a scaled distance design factor for use at various distances between a dwelling and blast site. No seismic recording is necessary. Providing that scaled distance in table (6) is observed.
- *Method 3*- Blast level chart criterion: This method allows an operator to use particle velocity limits that vary with frequency as illustrated in Figure 6. This method requires frequency analysis of the blast-generated ground vibration wave as well as particle velocity measurements for each blast. This method may represent the best means evaluating potential damage to residential structures as well as human annoyance from blasting. Any seismic recordings for any component (longitudinal, transverse, or vertical) for the particle velocity at a particular predominant frequency that fall below any part of the solid line graph in Figure 6 are considered safe. And any values that fall above any part of the solid line graph will increase the likelihood of residential damage and human annoyance. An investigation of the impact of surface mining blasting on a domestic building at Gilfach Lags open-cast site at U.K. was done by Rob Farufields research project. The research concluded that there is no damage below 24.1 mm/sec peak particle velocity. Djordjevic stated that a maximum ground vibration velocity of 5mm/sec has been set in

Distance from blast site (ft)	Method 1 Maximum allowed peak particle velocity (in/sec)	Method 2 Scaled distance factor to be used without seismic monitoring
0 to 300	1.25	50
301 to 5000	1.00	55
5001 and beyond	0.75	65

Table 6. Maximum permitted particle velocities (method 1 and scaled distance factors permitted to various distances from blast method 2)

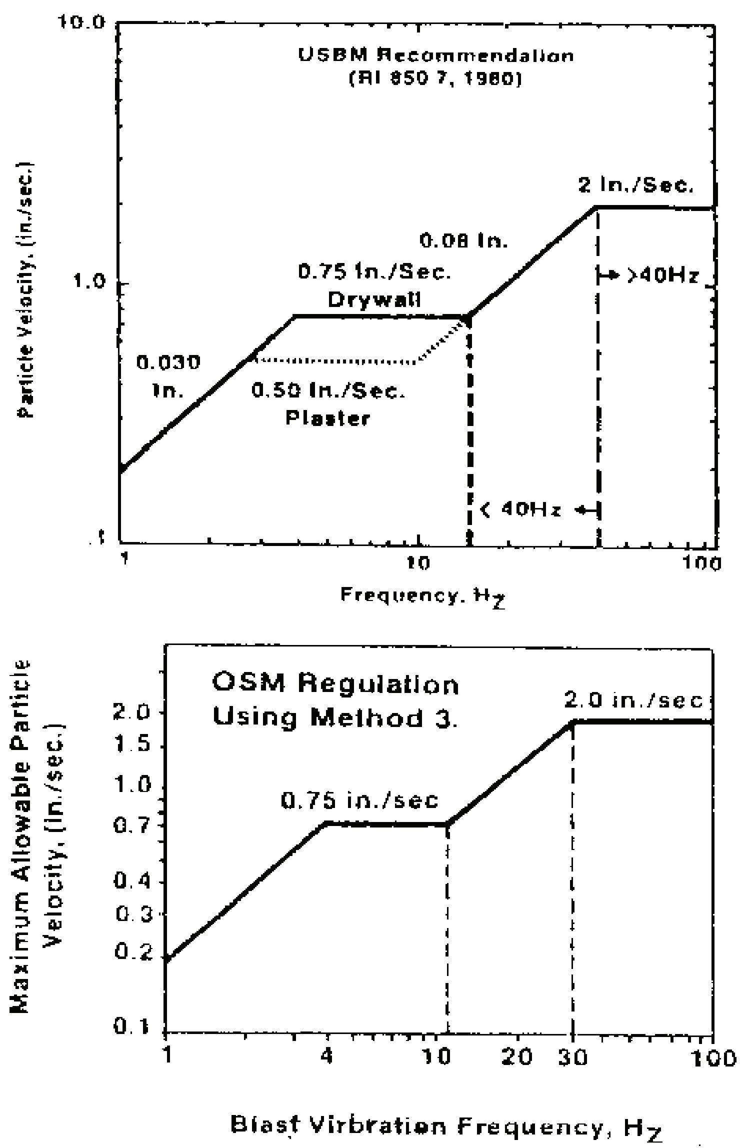


Fig. 6. Recommended safe levels of blasting vibrations by USBM and OSM

Australian Environmental Council Standard. The Australian "SSA explosive code AS 2187" has been presented as in table (7) the recommend maximum limits for the level of ground vibration in soil near the foundation buildings. Some standards of damage for some countries are shown in tables (8), (9), (10), (11), (12), and (13). The apparent discrepancies of damage standards as mentioned before result in the response of a structure to ground vibrations depends mainly upon the nature of the building, soil and rock geology, as well as the characteristics of vibration.

Peak Particle velocity (mm/sec)	**Type of building or structure**
25	Commercial and industrial building or structure of reinforces concrete or steel construction
10	Houses and low – rise residential buildings : commercial buildings not included in the third category, below.
2	Historical building or monuments and buildings of special valve or significance

Table 7. Peak Particle Velocity (PPV) criteria from AS 2187.

Buildings Class	**Maximum resultant of the particle velocities Vr (mm/s)**	**Estimated maximum vertical particle velocity Vz (mm/sec)**
I. Residential Building, offices and others similarly built in the conventional way and being in normal condition	8	4.8 – 8
II. Stall building in normal condition	30	18 – 30
III. Other building and historical monuments	4	2.4 - 44

Table 8. German Din 4150 Standard.

Structural type	**Peak particle velocity (mm/s)**		
	<10Hz	**10-50Hz**	**50-100Hz**
Commercial	20	20-40	40-50
Residential	5	5-15.0	15-20
Sensitive	3	3-8.0	8-10.0

Table 9. German Standards.

Structural type	**Peak particle velocity (mm/s)**		
	4-8Hz	**8-30Hz**	**30-100Hz**
Resistant	8	12	15
Sensitive	6	9	12
Very sensitive	4	6	9

Table 10. French Standards.

Subsoil	**Vibration (mm/s)**
Unconsolidated strata of moraine sand, gravel, clay.	18
Unconsolidated strata of moraine slate, soft limestone.	35
Granite, gneiss, hard limestone, quartizitic sandstone, diabase.	70

Table 11. Swedish Standards.

Seismic intensity categories	Effects induced on the structures	Particle velocity cm/s	
		Allowed	Limit
IV	Possible damages for village-type buildings, under pressure pipes, gas and petrol wells, mine shaft, and very fragile structures.	0.5	1.0
V	The painting is falling down, small and thin cracks appear in mortar plaster in rural and urban buildings. Possible minor damages for industrial constructions.	1.1	2.0
VI	Cracks in mortar (plaster) on the walls and pieces of mortar start to fall down in rural and urban buildings. Also minor damage for industrial constructions.	2.1	4.0
VII	Significant fractures are occurring in the basic elements of the rural buildings, great pieces of mortar are falling down in urban buildings and cracks are appearing in industrial constructions. Possible damage for pipes jointing system and fixed-mounted equipment.	4.1	8.0
VIII	Major factures occur in the resistance elements of rural and urban buildings. Cracks are produced in the resistance elements of industrial constructions.	8.1	16.0
IX	Crumbing (collapse, falling down) of some joint elements of rural and urban buildings can occur. Fractures can take place in industrial structures. Dams and underground pipes can be damaged.	16.1	32.0
X	Rural buildings are destroyed, urban constructions are seriously damaged and industrial structures are affected seriously by fracturing and dislocation of resistance elements.	32.1	64.2

Table 12. Romanian Standards.

Type of Structure	Dominant frequency, Hz		
	< 8 Hz	8-25 Hz	>25 Hz
(A) Buildings/structures not belong to the owner			
i) Domestic houses /structures (Kuchha brick and cement)	5	10	15
ii) Industrial buildings (RCC and framed structures)	10	20	25
iii) Objects of historical importance and sensitive structures	2	5	10
(B) Building belonging to owner with limited span of life			
i) Domestic houses /structures (Kuchha brick and cement)	10	15	25
ii) Industrial buildings (RCC and framed structures)	15	25	50

Table 13. Indian Standard

5. Air blast

Air vibrations are generated by the blast and propagated outward through the air under the influence of the existing topographic and atmospheric conditions. Four mechanisms are usually responsible for the generation of air blast vibrations: the venting of gases to the atmosphere from blown-out unconfined explosive charges, release of gases to the atmosphere from exposed detonating fuse (initiation system), ground motions resulting from the blast, and the movement of rock at the bench face. Audible air blast is called noise while air blasts at frequencies below 20 Hz and inaudible to the human ear are called concussions. This is measured and reported as an "overpressure" it means air pressure over and above atmospheric pressure. The noise can either be continuous (lasts more than 1 second) or be of impulsive nature such as a shock from explosions. Overpressure is usually expressed in pounds per square inch (psi), Pascal or Kilopascal (Pa, kpa), or in decibels (dB). Peak pressures are reported in terms of decibels, which are defined as:

$$dB = 20 \log_{10} (P/P_o)$$

where P is the measured peak sound pressure and P_o is a reference pressure of 2.9×10^{-9} psi (20×10^{-6} pa).

Energy transmitted in acoustic waves behaves in the same manner as seismic energy. Air blast overpressures are greatly affected by atmospheric conditions, direction and strength of wind, temperature, humidity, and cloud cover. Like ground vibrations, the peak overpressure level is controlled by the charge weight of explosive per delay and the distance from the blasthole. Unlike ground motions, air pressure can be described completely with only one transducer, since at any one point, air pressure is equal in all three orthogonal directions.

The pressure developed by noise and shock waves is the primary cause of window rattling. Nicolls et al, through the Bureau of Mines conducted extensive research in blasting and concluded that overpressure less than 0.75 psi would not result in any window damage and overpressure of 1.5 psi or more would definitely produce window damage. Maximum value recommended by Nitro Consult and generally accepted for sound pressure is equal and less than 142 dB (250 pa). Figure 7 illustrates overpressure equivalence for both types of units (dB and psi). In order to understand the overpressure levels, 0.01 psi is comparable to the maximum found in a boiler shop or to the pressure level present 4 ft from a large pneumatic riveter.

6. Human response

Human response to blast induced ground vibration is a relatively complex phenomenon and is dependent upon a range of factors of which the actual vibration magnitude is only one and not necessarily the most important. It is well recognized that the human body is very sensitive to the onset of vibration albeit very poor at distinguishing relative magnitudes. Although sensitivity to vibration varies significantly between individuals, a person will generally become aware of blast induced vibration at levels of around 1.5mms -1 peak particle velocity, and under some circumstances at levels as low as 0.5mms -1.

Once a received vibration is greater than an individual's perception threshold then it is possible for concern to be expressed about the blasting. Such concern normally relates to the vibration's potential for causing damage to the complainant's property. Concern may be

180	3.0	← Structural damage
170	0.95	← Most windows break
160	0.30	
150	0.095	← Some windows break
140	0.030	← OSHA* maximum for impulsive sound
130	0.0095	← USBM TPR 78 maximum
		← USBM TPR 78 safe level
120	0.0030	← Threshold of pain for continuous sound
110	0.00095	← Complaints likely
100	0.00030	OSHA maximum for 15 minutes
90	0.000095	
80	0.000030	← OSHA maximum for 8 hours

* Occupational Safety and Health Administration

Fig. 7. Overpressure unit conversion (dB and psi) and effects on human annoyance and structural damage.

expressed that damage has already occurred due to the recent discovery of cracking that may have been present for some time or have been caused by natural processes. More often, however, concerns are based on the fear that damage will be caused at some time in the future as a result of repeated vibration.

The degree of concern and whether or not it leads to complaints is governed by many factors. Perhaps the most obvious is the vibration itself in terms of its magnitude, duration and frequency. However, the vibration magnitude at which complaints arise varies greatly from site to site such that no common complaint threshold exists. This is considered to be in part a reflection of the fact that individuals are very poor at distinguishing between vibrations of differing magnitudes.

The susceptibility of individuals to vibration will vary from person to person depending on factors such as age, health and, to a large extent, previous exposure. It is usually the case that adverse comments are less likely once a neighbor has become accustomed to the perceived effects of blasting. An explanation of the need to blast and the significance of the vibration levels being received by a site's neighbors are paramount as is an understanding and sympathetic attitude from the operator.

Human are quite sensitive to motion and noise that accompany blast-induced ground and air born disturbances. Complaints resulting from blast vibration and air overpressure, to a large extent, are mainly due to the annoyance effect, fear of damage, and the starting effect rather than damage. The human body is very sensitive to low vibration and air blast level, but unfortunately it is not reliable damage indicator. With air overpressure blast generally levels of over 120 dB will produce some annoyance and fright throughout excite wall and rattle dishes, and together tend to produce more noise inside a structure than outside. In most cases, personal contact, assurance, and a good public relations program with the residential owners in question should alleviate the problem, assuming no structural damage. In this regard psychophysiological perception of the blast is generally more important than the numerical values of the ground vibration and air overpressure.

7. Attenuation analysis by scaled distance

The attenuation of ground vibrations in terms of the peak velocity component and airblast intensities is evaluated based on scaled distance, generally referred to as SD. The scaled distance factors for ground motions and airblast are given, respectively, by the following:

$$\text{Square-root scaled distance} \quad SRSD = R/\, W^{1/2}$$

$$\text{Cube-root scaled distance } CRSD = R/W^{1/3}$$

Where R is the shot-to-seismograph distance and W is the maximum charge weight detonated within any 8 ms time period (referred to as one delay time period). Scaled distance is a means of incorporating the two most important factors contributing to the intensity of ground motion and airblast as intensity decreases proportionally with distance and inversely with the explosive weight detonated on one time delay. In the case of ground motion, the SRSD is used (commonly referred to as simply SD) as ground motion has been shown to correlate with the square root of the charge weight. In the airblast case, air pressures correlate best with the cube-root of the charge weight (CRSD).

7.1 Vibration prediction

The prediction of ground vibration waves through the earth's crust is a complex phenomenon. Even over small distances, rocks and unconsolidated material are anisotropy and non-homogeneous. Close to the rock/air interface at the ground surface, complex boundary effects may occur. These difficulties restrict theoretical analysis and derivation of a propagation law that predict the ground vibration, and consequently research workers have concentrated upon empirical relationships based on field measurements.

Many researchers, over the world, have studied ground vibrations originating from blasting and theoretical empirical analyses have been developed to explain the experimental data. At a given location, peak particle velocity (PPV) depends mainly on the distance from the blast and the maximum charge per delay. Scaled distance The scaled-distance concept vs. particle velocity and air overpressure is generally used for blast vibration prediction. Currently the most widely accepted propagation equation for ground and air vibration considering the damage to structures is of the form.

$$V = K\left(R/W^{\beta}\right)^{-\alpha}$$

<u>Traditional empirical equations prediction:</u>

In 1949, Grandell developed the concept of energy ratio as mentioned before:

$$ER = a^2/f^2$$

Also, he suggested the following propagation equation:

$$ER. = k\, Q^2\, (50/D)^2$$

Where: ER = energy ratio;

a = acceleration, ft/sec^2 ;

f = frequency, Hz;

k = site constant;

Q = quantity of explosives, Ib;

D = distance from measuring point to blast point, ft.

In 1950, studies on wave propagation phenomena were concluded by Morris. He propounded that the amplitude (A) of particle displacement is direct proportional to the square root of the weight of the charge (Q) and inversely proportional to the distance from the blast. That is:

$$A = k\,(Q^{1/2})/D$$

Where k = the site constant and was found to vary from 0.05 for hard competent rock to 0.30 for clay up to 0.44 0r 0.5 for completely unconsolidated material.

A = maximum amplitude, in;

Q = quantity of explosives, Ib,

Habberjam and Whetton (1952) suggested a higher power for the charge weight in their formula:

$$A \;\alpha\; Q^{0.085}$$

Langefors, Kihlstrom and Westerberg (1958) suggested the following relationship:

$$V = k\,(\sqrt{Q}/D^{1/2})^{B}$$

Where k and B = site constants;

V = mm/sec or in/sec;

Q = Weight of explosives, kg or Ib;

D = distance from point of blast to measuring point, m or ft.

Assuming cylindrical explosive geometry for long cylindrical charge, Duvall and Petkof (1959); Duvall and Fogelson (1962); Duvall et al. (1963); and Daemen et al. (1983) concluded that any linear dimension should scale with the square root of the charge weight. The corresponding relationship assumes the form:

$$V = k\,(Q/D^{1/2})^{-B}$$

For spherical symmetry, the U.S. Bureau of Mines investigators suggested that any linear dimension should be scaled to the cube root of the charge size and it's supported by Ambraseys and Hendron in India. An inverse power law was suggested to relate amplitude of seismic waves and scaled distance to obtain the following relationship:

$$V = k\,(Q/D^{1/3})^{-B}$$

In 1965, Attewell et al., proposed the following shape of propagation equation:

$$V = k\,(Q/D^{2})^{n}$$

Where n = constant depending on site conditions = 0.64 to 0.96;

K = site constant, ranges from 0.013 to 0.148 (increasing constant for softer Rock)

The Romanian method, which was proposed by Enesco in 1968 to evaluate the seismic effect of blasting based on the determination of apparent magnitude "Ma" with the following empirical relationship:

$$Ma = 0.67\,(\log V^{2}max * T + \log r + 4 \log 4\, \rho\, V - 11.8)$$

Where: V_{max} = the maximum oscillation particle velocity, cm/sec;

T = oscillation period;

V = propagation velocity of elastic waves, m/sec;

ρ = the density of rock in which the seismic wave propagate, gm/cm^3;

r = distance from the shot point to measuring point, m.

This method presumes the assessment of the so-called “acceptable intensity” for construction. Through field test and using the above relationship, the safe distance corresponding to “Ma” and consequently to a certain quantity of explosive is determined.

The Russian method was suggested by Medvedev in 1968 to assess the safe distance “r” as foolows:

$$r = K_e * K_t * K_c * R_{red} * Q^{1/3}$$

Where: K_e = coefficient depending on the method of firing (instantaneous or delayed time) and the mining conditions (underground, open-pit or combined);

K_t = Coefficient depending on the characteristics of media in which the waves propagate;

K_c = coefficient depending on the type of construction (more or less damaged);

R_{red} = reduced distance depending on the function of the admissible intensity of vibration;

Q = explosive quantity (equivalent TNT).

Also, Sadovski in Russia has computed the non-dangerous explosive quantity by the following relationship:

$$V = k/D\ (Q/D)^{1/3}\ f(n)$$

Where: V = admissible particle velocity for construction, cm/sec;

k = global coefficient depending on the blasting and propagation conditions;

R = distance from the blasting point to construction, m;

Q = explosive quantity, (equivalent TNT);

F (n) = function for diminishment of seismic effect depending on firing system. It means on the number of blasting rows “n” and delay time between them.

“Δt”, the conditions are as follow:

i. For $n\ \Delta t < 0.15$ sec, $f(n) = 1\text{-}12.9\ (n\ \Delta t)^2$.

ii. For $n\ \Delta t > 0.15$ sec, $f(n) = 0.275\ /\ n\ \Delta t$.

iii. For instantaneous blasting, f(n) = 1.

The empirical relationship suggested by the Indian Standard (1973) used the concept in which blast is scaled to the equivalent distance, the relation is expressed as:

$$V = k\ (Q^{2/3}/D)^{-B}$$

Swedish Detonic Research Foundation has worked out an empirical formula to predict the vibration velocity as follows:

$$V = 700\ Q^{0.7}/D^{1.5}$$

Davis et al., (1964), Daemen et al., (1983) and others investigators considered no particular charge symmetry. They proposed the most widely general formula is of the type:

$$V = k\ Q^A\ D^{-B}$$

Ghosh and Daemen (1983) reformulated the propagation equation of U.S. Bureau of Mines and Ambraseys and Hendtron by incorporating the inelastic attenuation factor e^{-pD}, The modified equations are:

$$V = k\,(Q/D^{1/2})^{-B}\,e^{-pD}$$

and

$$V = k\,(Q/D^{1/3})^{-B}\,e^{-pD}$$

Where k, B, and p are empirical constants; p is called the inelastic attenuation factor.
In 1991, Central Mining Research Station (CMRS) in India has also established an efficient blast vibration predictor. The equation considers only geometrical spreading as the cause of the decrease in amplitude of ground vibrations:

$$V = n + k\,(Q/D^{1/2})^{-1}$$

But in practical situation, the value of "n" is always negative, then the equation will be:

$$V = -n + k\,(Q/D^{1/2})^{-1}$$

Where n is the damping factor influenced by rock properties and geometrical discontinuities.
Propagation law of blast-induced air overpressures has been studied by numerous investigators and is generally reported with cube-root rather than square-root scaled distances. Following equations are commonly used for overpressure prediction:

$$dBL = 164.4 - 241 \log (D/\,W^{1/3})$$

or alternatively:

$$P_{over} = 3300\,(D/\,W^{1/3})^{-1.2}$$

Where dBL is the overpressure decibel level, D is the distance from the blasthole (m), W is the weight of explosive detonated per delay (kg) and P_{over} is the overpressure level (pa). According to Nito-Consult AB the air overpressure propagation equation is estimated as follows:

$$P = 70 \times (0.6\,Q)^{1/3} / R \text{ kpa}$$

Where: Q is charge weight in kg and R distance in m.

Model for prediction of Threshold Value of PPV:

The model for determination of the allowed peak particle velocity has its origin in the Norwegian practice for prudent blasting in the last 30 -40 years.
The peak particle value is calculated by:

$$V = V_o * F_k * F_d * F_t$$

V_o = Uncorrected max. value of vertical particle velocity measured in mm/s.
V_o is dependent on the kind of geological material of the ground, see table [14].
F_k = construction coefficient = $F_b * F_m$
F_b = building factor, see table [15].
F_m = material factor, see table [16].

F_d = distance coefficient, which takes into consideration the distance between the blasting site and the critical object (.5 and 1 for distance 200 and 5).
F_t = time coefficient, which takes into consideration how long the construction is exposed for blast vibration, see table [17].

Ground conditions	Vertical uncorrected particle velocity mm/s			
	No cracks	Minor cracks	Major cracks	Danger cracks
Very soft soils/ soft clays	Separate valuation	-	-	-
Loose layered moraine, sand, gravel, clay (seismic velocity <2000 m/s).	18	30	40	60
Hard layered moraine, schist, soft limestone and corresponding rock (seismic velocity 2000-4000 m/s).	35	55	80	115
Granite, gneiss, hard limestone, quartzite, diabase and corresponding rock (seismic velocity >4000 m/s).	70	110	160	230

Table 14. Vertical uncorrected particle velocity V_o at different ground condition.

Class	Type of structure	Building coef. Fb
1	Heavy constructions like bridge, quays, military defense works etc.	1.70
2	Industrial- and office buildings.	1.20
3	Ordinary houses.	1.00
4	Particularly sensitive buildings, such as museums, buildings with high and arch shaped roofs or constructions with large spans.	0.65
5	Historical buildings and ruins in particular sensitive condition.	0.50

Table 15. Building coefficient for different types of constructions.

Class	Material	Material coef. F_m
1	Armored concrete, steel, wood.	1.2
2	Unarmed concrete, brick, brickwork, hollow concrete, stones, light weight concrete.	1.00
3	Porous concrete (gassed concrete).	0.75
4	Mixed bricks.	0.65

Table 16. Material coefficient for different construction material.

Duration of blasting work	Time coef. F_t
Less than 12 months.	1
More than 12 months.	0.75

Table 17. Time coefficient.

Artificial intelligence prediction:

If an unusual noise or uncertainties exists in the measured data of vibrations, statistical models have difficulty in making accurate predictions. So, the use of neural networks from a branch of artificial intelligence is very important to predict the air vibration and peak particle velocity efficiently. Artificial neural network and fuzzy logic are the two most important concepts of artificial intelligence. They are useful in modeling or prediction of one or more variables.

7.2 Artificial Neural Network (ANN)

Neural networks first became popular in the late 1980s and, more recently, in the 1990s. Compared to traditional statistical methods, neural network analysis has been found to be very useful in diverse, real-world applications. An artificial neural network can be defined as a data processing system consisting of a large number of simple, highly interconnected processing elements (artificial neurons) in an architecture inspired by the structure of the cerebral cortex of the brain (Tsoukalas & Uhrig, 1996).These processing elements are usually organized into a sequence of layers or slabs with full or random connections between the layers. The input layer is a buffer that presents data to the network. The following layer(s) is called the hidden layer(s) because it usually has no connection to the outside world. The output layer is the following layer in the network, which presents the output response to a given input. Typically the input, hidden, and output layers are designated the *i*th, *j*th, and *k*th layers, respectively. A typical neural network is “fully connected,” which means that there is a connection between each of the neurons in any given layer with each of the neurons in the next layer.

Artificial neural networks (ANNs) are a form of artificial intelligence that has proved to provide a high level of competency in solving many complex engineering problems that are beyond the computational capability of classical mathematics and traditional procedures. Back-propagation artificial neural network a Feed-forward network is considered the most popular, effective and easy-to-learn model for complex, multi-layered networks of the supervised learning techniques. The typical back-propagation network has an input layer, an output layer, and at least one hidden layer. Each layer is fully connected to the

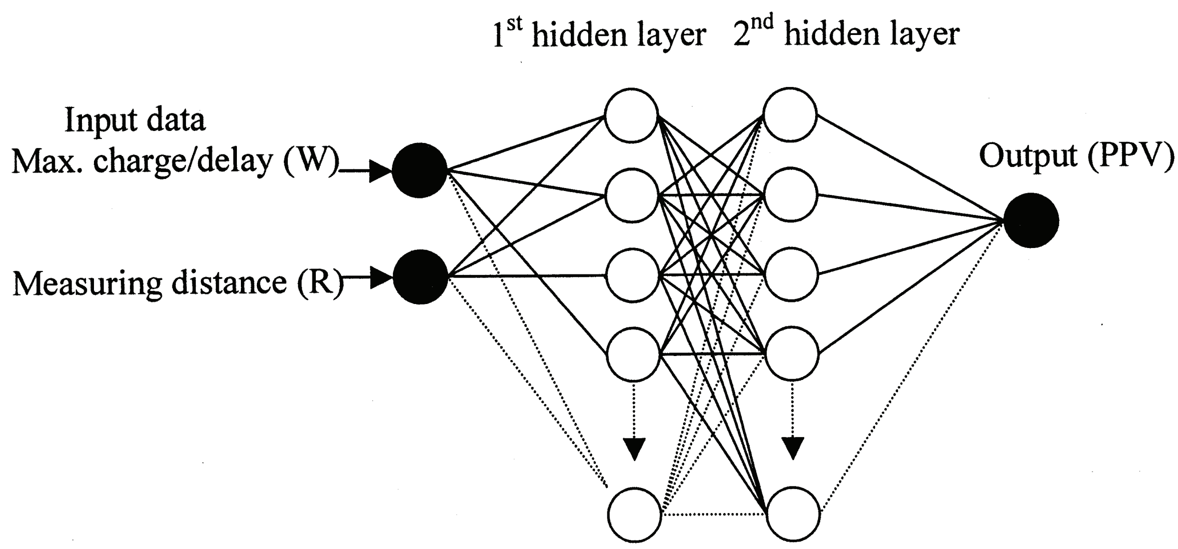


Fig. 8. Back propagation training ANN

succeeding layers, as shown in Figure 8. In the back propagation training, the connection weights are adjusted to reduce the output error. In the initial state, the network begins with a small random set of connection weights. In order for the network to learn, a set of inputs is presented to the system and a set of out puts is calculated. A difference between the actual outputs and desired outputs is calculated and the connection weights are modified to reduce this difference.

Fuzzy logic system:

Fuzzy logic is a preferable when the mathematical problem is hard to derive, and when decisions have to be made with estimated values under incomplete information. Fuzzy models can be seen as logical models which use "if–then" rules to establish qualitative relationships among the variables in the model. Fuzzy set theory enables the processing of imprecise information by means of membership functions, in contrast to the classical set theory. The classical set (called crisp set) takes only two values: one, when an element belongs to the set; and zero, when it does not. In fuzzy set theory, an element can belong to a fuzzy set with its membership degree ranging from zero to one. The basis of fuzzy logic is to consider the system states in the form of subsets or fuzzy sets, each of which is labeled with words such as "low," "medium," "big," etc. A general fuzzy inference system basically consists of; fuzzification, knowledge base, a decision-making unit, and finally a defuzzification, the fuzzy system is shown in figure 9.

8. Measurement

There are four interrelated parameters that may be used in order to define ground vibration magnitude at any location. These are:

Particle Displacement - the distance that a particle moves before returning to its original position, measured in millimeters (mm).

Particle Velocity - the rate at which particle displacement changes, measured in millimeters per second (mms -1).

Particle Acceleration - the rate at which the particle velocity changes, measured in millimeters per second squared (mms -2) or in terms of the acceleration due to the earth's gravity (g).

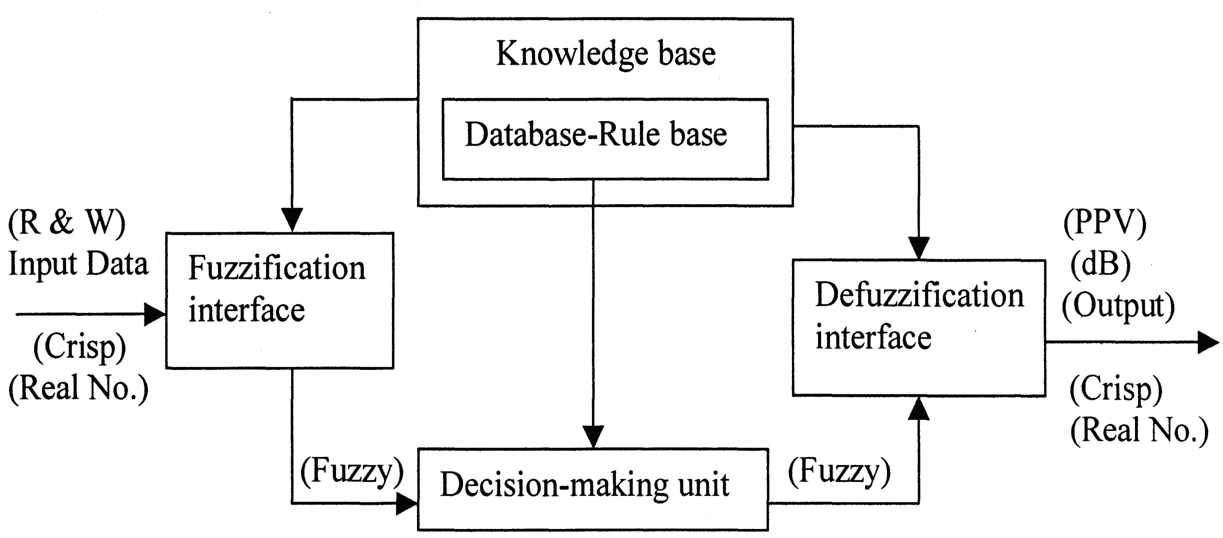


Fig. 9. A typical Fuzzy System for Fuzzy Logic Modeling Process

Frequency - the number of oscillations per second that a particle undergoes measured in Hertz (Hz).

In all standards the preferred parameter of measurement is peak particle velocity (ppv). The measurement of particles by vibration waves is usually measured in 3 mutually perpendicular directions, as particles will be oscillating in 3 dimensions, these are:

Longitudinal (sometimes termed radial) - back and forth particle movement in the same direction that the vibration wave is traveling.

Vertical - up and down movement perpendicular to the direction the vibration wave is traveling.

Transverse - left and right particle movement perpendicular to the direction the vibration wave is traveling.

9. How to control vibrations

9.1 Ground vibration

The ground vibration can be affected by certain blast design parameters:-

1. The maximum instantaneous charge or MIC is the amount of explosives fired at the same moment in time.
2. The number and frequency of delays.
   The introduction of a delay sequence can reduce the size of the maximum wave produced.
3. The height of the working bench and therefore the length of borehole.
4. The number of "decks" or layers of explosives and detonators in each hole.
5. The spacing, burden and number of holes, in the blast ratio.
6. The diameter of the shot hole, which will affect the amount of explosives used.

There are several steps an operator can take to reduce ground vibrations:

Blast design

Use a blast design that produces the maximum relief practical in the given situation. Explosions in blastholes which have good relief – i.e. those having nearby free faces – produce less ground vibration. The use of delay blasting techniques establishes internal free

faces from which compressional waves produced later in the blast can delay patterns, maximum relief can be retained.
In general, when blasting multiple row patterns, greater relief can be obtained by using a longer delay between rows than between the holes within a single row. A delay of at least 2–3 ms/m of burden between the holes within a row is recommended for the necessary relief and best fragmentation.
Use a spacing/burden ratio greater than one. The presence of weak seams or irregular back break may dictate the local use of a spacing/burden ratio close to one.

<u>Hole straightness</u>

Control drilling of blast holes as closely as possible. Establish bench marks for use in setting out the hole locations for the next blast before each blast in order to help avoid possible errors due to irregular back break.

<u>Subdrilling</u>

Restrict the amount of sub drilling to the level required to maintain good floor conditions. Typical sub drilling for holes inclined 3:1 is 30% of the burden at floor level. Tape each drill hole and match it to the face height. If hole depth is greater than intended, backfill with drill cuttings or crushed stone. Excessive sub drilling can increase vibration because of the lack of a nearby free face to create reflection waves.

<u>Charge per delay</u>

Use the following techniques to reduce charge weight per delay and, therefore, peak particle velocity.

- reduce hole depths with lower bench heights and increase specific drilling,
- use smaller diameter holes,
- subdivide explosive charges in holes by using inert decks and fire each explosive deck with initiators using different delays,
- Use electronic or mechanical timers to increase the available number of periods of delay electric blasting caps and to increase timing flexibility. Non electric delays coupled with surface delay connectors can provide similar flexibility.

<u>Explosives</u>

Eliminate or reduce hole-to-hole propagation between charges intended to detonate at different delay periods. Use explosive, such as water gels, which are much less sensitive than dynamite to hole -to-hole propagation. Hole-to-hole propagation occurs when the explosive charges or blastholes are only a few feet apart, as in trenching, decked holes, or underwater excavations, or at greater distances when blasting interbedded soft and hard layer rock, such as coral or mud-seamed rock, that is saturated with water.

<u>Using NONEL blasting system</u>

Use NONEL blasting system can reduce the wave superposition by increasing delay time among shots. In addition to reduce the air vibration by using NONEL shock tube instead of detonating cord.

9.2 Air overpressure

There are five principal sources of air overpressure from blasting at surface mineral workings:

1. The use of detonating cord which can produce high frequency and hence audible energy within the air overpressure spectrum.
2. Stemming release, seen as a spout of material from the boreholes, gives rise to high frequency air overpressure.
3. Gas venting through an excess of explosives leading to the escape of high-velocity gases, give rise to high frequency air overpressure.
4. Reflection of stress waves at a free face without breakage or movement of the rock mass. In this case the vertical component of the ground-vibration wave gives rise to a high-frequency source.
5. Physical movement of the rock mass, both around the boreholes and at any other free faces, which gives rise to both low and high-frequency air overpressure.

The steps to reduce air vibrations:

Detonating cord should be used as sparingly as possible, and any exposed lengths covered with as much material as possible. Just a few feet of exposed cord can lead to significant amounts of audible energy and, hence, high air overpressure levels. Stemming release can be controlled by detonation technique, together with an adequate amount of good stemming material. Drill fines, while readily available, do not make good stemming material. The use of angular chippings is better. It should be noted however that detonation cord and stemming release have been virtually eliminated with the use of in hole initiation techniques.

Gas venting results from overcharging with respect to burdens and spacings or, perhaps, a local weakness within the rock, and is also typified by the occurrence of fly rock. Its control is essential for economic and safe blasting, and is considerably aided by accurate drilling and placement of charges, together with regular face surveys.

The controllable parameters such as geology, Topography, and Meteorological Conditions can be controlled to some extent by adjustment of blast pattern and blaster in charge judgment for blasting operation.

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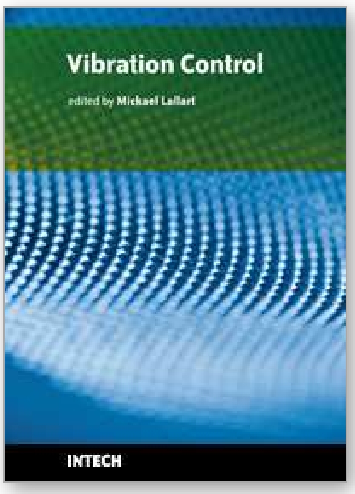

Vibration Control

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Vibrations are a part of our environment and daily life. Many of them are useful and are needed for many purposes, one of the best example being the hearing system. Nevertheless, vibrations are often undesirable and have to be suppressed or reduced, as they may be harmful to structures by generating damages or compromise the comfort of users through noise generation of mechanical wave transmission to the body. the purpose of this book is to present basic and advanced methods for efficiently controlling the vibrations and limiting their effects. Open-access publishing is an extraordinary opportunity for a wide dissemination of high quality research. This book is not an exception to this, and I am proud to introduce the works performed by experts from all over the world.

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