IS 14881 (2001): Method for Blast Vibration Monitoring - Guidelines [CED 48: Rock Mechanics]

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Indian Standard

METHOD FOR BLAST VIBRATION MONITORING — GUIDELINES

ICS 17.160; 93.020

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Price Group 7

Rock Mechanics Sectional Committee, CED 48

FOREWORD

This standard was adopted by the Bureau of Indian Standards, after the draft finalized by the Rock Mechanics Sectional Committee had been approved by the Civil Engineering Division Council.

While this standard mainly pertains to the blast-induced, transient or vibratory displacement, class of blast-induced permanent displacements are introduced in Annex A for completeness as they are associated with significant transient effects at relatively small distances. Whenever vibration response is a legitimate concern, these permanent displacements can be more important than the vibrations.

Transient effects result from the vibratory nature of the ground and airborne disturbances that propagate outward from a blast. In this standard, it is assumed that no permanent displacements are produced in or on the rock or soil mass surrounding the blast. Thus the only effects are those associated with the vibratory response of facilities. Transient means that the peak displacement is only temporary (that is, lasts less than one-tenth of a second) and the structure or rock mass returns to its original position.

This standard implicitly separates measurement of vibration to control cosmetic cracking from that to reduce human response by presenting only studies of blast-induced cosmetic cracking, more than the regularly allowed 5 mm/s maximum particle velocity at high excitation frequencies.

The composition of the Committee responsible for the formulation of this standard is given in Annex B.

For the purpose of deciding whether a particular requirement of this standard is complied with, the final value, observed or calculated, expressing the result of a test, shall be rounded off in accordance with IS 2 : 1960 'Rules for rounding off numerical values (*revised*).' The number of significant places retained in the rounded off value should be the same as that of the specified value in this standard.

Indian Standard

METHOD FOR BLAST VIBRATION MONITORING — GUIDELINES

1 SCOPE

This standard covers the characters of blasting vibrations in the ground and air, instrumentation and permissible peak ground particle velocity for a dominant ground frequency.

2 RANGE OF BLAST EFFECTS

Blast effects on surrounding earth materials and structures can be divided into permanent and transient displacements. Effects of permanent displacements are presented briefly in Annex A as they are associated with significant transient effects at relatively short distances.

2.1 Structural Response to Transient Displacement

Transient effects result from the vibratory nature of the ground and air-borne disturbances that propagate outward from a blast. In this clause, it is assumed that no permanent displacements are produced. Thus the only effects are those associated with the vibratory response of facilities in or on the rock or soil mass surrounding the blast. Transient means that the peak displacement is only temporary, lasts less than one-tenth of a second, and the structure returns subsequently to its original position.

Transient structural effects can be arranged to reflect the expected distance from a blast. Beginning with the closest, transient effects are structural distortion, faulted or displaced cracks, falling objects, cosmetic cracking of wall coverings, excessive instrument and machinery response, human response and micro-disturbance. The first four effects, those that relate to structural response, are normally grouped together for experimental observation, and do not normally occur when vibration levels are regulated to prevent cosmetic cracking.

Excessive structural response has been separated into three categories arranged below in the order of declining severity and increasing distance from the occurrence. Beginning with effects that occur closest to the blast, the categories are listed here.

a) *Major (Permanent Distortion)*

   Resulting in serious weakening of the structure (for example large cracks or shifting of foundations or bearing walls, major settlement resulting in distortion or weakening of the superstructure, walls out of plumb).

b) *Minor (Displaced Cracks)*

   Surficial, not affecting the strength of the structure (for example broken windows, loosened or fallen plaster), hairline cracks in masonry.

c) *Threshold (Cosmetic Cracking)*

   Opening of old cracks and formation of new plaster cracks, dislodging of loose objects (for example loose bricks in chimneys).

These specific definitions of response shall not be described collectively as 'damage'.

2.2 Blast-Induced Air Over-Pressures

Blast-induced air over-pressures are the air pressure waves generated by explosions. The higher-frequency portion of the pressure wave is audible and is the sound that accompanies a blast; the lower-frequency portion is not audible but excites structures and in turn causes a secondary and audible rattle within a structure.

Over-pressure waves are of interest for three reasons. First, the audible portion produces direct noise. Secondly, the inaudible portion by itself, or in combination with ground motion, can produce structural motions that in turn produce noise. Thirdly, they may crack windows; however, airblast pressures alone would have to be unusually high for such cracking. The response noise within a structure (from blasting and sonic booms, respectively) is the source of many complaints. The structure and wall motions, which are vibrationally induced by air blasts and sonic booms, rattle loose objects within the structure, which then startle the occupants.

2.3 Human Response

Humans are quite sensitive to motion and noise that accompany blast-induced ground and air-borne disturbances. Therefore human response is significant in the reporting of blast-induced cracking. Motion and noise from blasting can be startling and lead to a search for some physical manifestation of the startling phenomena. Many times a previously unnoticed crack provides such confirmation of the event. Furthermore, if a person is worried and observes a crack that was not noticed before, the crack's perceived significance over one noticed in the absence of any starling activity.

In typical mining situations, significant blast-induced inaudible air over-pressure and audible noise immediately follows the ground motion and intensifies human response. Both the ground and air-borne disturbances excite walls, rattle dishes, and together tend to produce more noise inside a structure than outside. Thus both the audible noise as well as the wall rattle produced by inaudible pressures contribute to human response. Inaudible air over-pressures can vibrate walls to produce audible noise at long distances, which are inaccurately reported by occupants as ground motions.

3 CHARACTER OF BLAST EXCITATION

As shown in Fig. 1, both the ground and air-borne disturbances (upper-four time histories) produce structure response (lower-four time histories). Because of the importance of excitation frequency in determining this structural response, the full waveform of time history of the motions shall be recorded. When a critical location in a structure is known, blast response is best described by the strain at that location. Alternatively, excitation particle velocity (that shown in Fig. 1) can be measured outside the structure of concern or on the structure's foundation; however, there is correlation between visual observations of cracking with excitation particle velocity measured in the ground.

4 GROUND MOTION

Ground motion can be described by three mutually perpendicular components labelled *L* (longitudinal), *T* (transverse) and *V* (vertical) in Fig. 1. The *L* and *T* directions are oriented in the horizontal plane with *L* directed along the line between the blast and recording transducer. When a study focuses upon structural response, axes can be labelled H_1, H_2 and *V*, with H_1 and H_2 oriented parallel to the structure's principal axes.

4.1 Variation of peak motions in each component (*L*, *V* and *T* in Fig. 1) has led to difficulty in determination of the most important component. Horizontal motions seem to control the horizontal response of walls and superstructures, and vertical motions seem to control the vertical response of floors. In an absolute sense, the peak ground motion and thus ground strain is the maximum vector sum of the three components, which usually occurs at the largest peak of the three components. This true maximum vector sum is not the pseudo-maximum vector sum calculated with the maxima for each component irrespective of their time of occurrence. The pseudo-maximum vector sum may be as much as 40 percent greater than the true maximum vector sum, which is normally 5-10 percent greater than the maximum, single-component peak.

4.2 The experimental observations of threshold or cosmetic cracking, which form the basis of blasting controls, have been correlated with the maximum single component regardless of direction. Therefore, use of the pseudo-maximum vector sum for control provides a large, unaccounted for, factor of safety.

4.3 Two principal wave types are produced by blasting, body (*P/S*) surface (*R*) and are illustrated by the ground

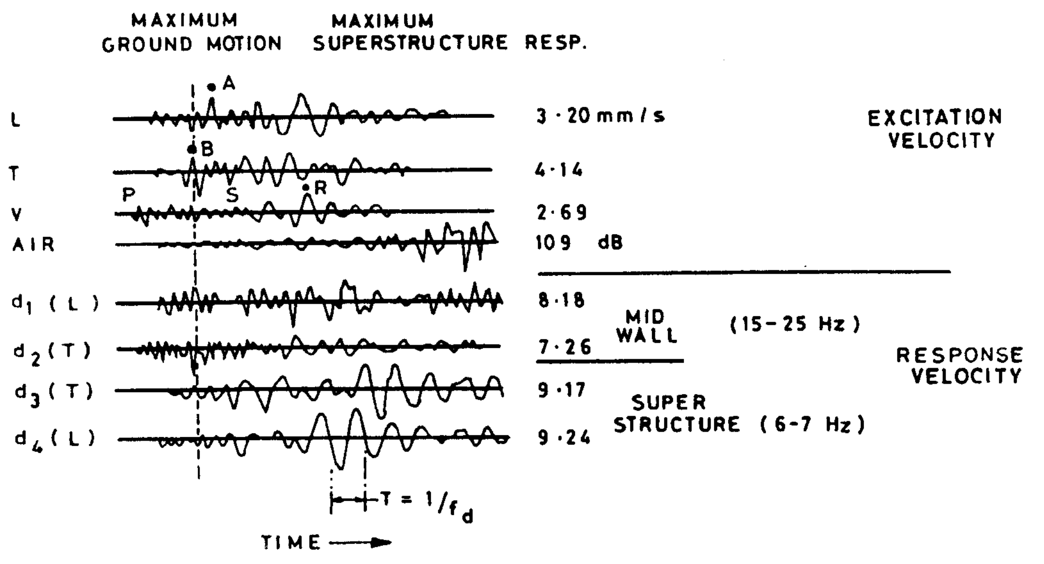


FIG. 1 COMPARISON OF (a) BLAST EXCITATION BY GROUND AND AIR-BORNE DISTURBANCES AND (b) RESIDENTIAL STRUCTURE RESPONSE OF WALLS AND SUPERSTRUCTURE

motion in Fig. 1 measured some 600 m from a typical surface coal mining blast. Body waves travel through earth materials, whereas surface waves travel close to surfaces and interfaces of earth materials. The most important surface wave is the Rayleigh wave, denoted *R* on the vertical trace in Fig. 1. Body waves can be further subdivided into compressive (compression/tension) or sound-like waves, and distortional or shear waves, denoted as *P/S* on the vertical trace in Fig. 1. Explosions produce predominantly body waves at small distances which propagate outward in a spherical manner until they intersect a boundary such as another rock layer, soil or the ground surface. At this intersection, shear and surface waves are produced. Rayleigh surface waves become important at larger transmission distances as illustrated in the vertical trace by the relatively larger "*R*" amplitude compared to the "*P/S*" amplitude.

5 ESTIMATION OF DOMINANT FREQUENCY

Dominant frequency can be estimated through: (a) visual inspection of the time history or calculated with, (b) response spectra, or (c) Fourier frequency spectra.

5.1 The accuracy or difficulty of visually estimating the dominant frequency depends upon the complexity of the time history. The type of time history record with the most easily estimated dominant frequency is one with a single dominant pulse like that shown in the inset in Fig. 2. The dominant frequency of a single pulse is the inverse of twice the time interval of the two zero crossings on either side of the peak.

5.2 The most difficult type of record to interpret is that which contains nearly equal peaks at two dominant frequencies such as that in Fig. 1. The two dominant frequencies are the initial 15-20 Hz portion (peak *A*) and the later 5-10 Hz portion (peak *B*). As can be seen in the Fig. 1, the initial portion produces the highest wall response while the second produces the greatest super-structure response. For the best frequency correlation of both types of response, both frequencies shall be calculated.

5.3 The other computational approach for determining the dominant frequency involves the response spectrum. The response spectrum is preferred over the Fourier frequency spectrum because it can be related to structural displacement and thus strains. Dominant frequency associated with each major peak is calculated by the zero crossing approach described above.

5.4 Many time histories do not contain as broad a range of dominant frequency as that in Fig.1, most approaches require only the calculation of the frequency associated with the maximum particle velocity for blasts that produce low particle velocities. The more complex frequency analyses need to be employed only when peak particle velocities approach control limits.

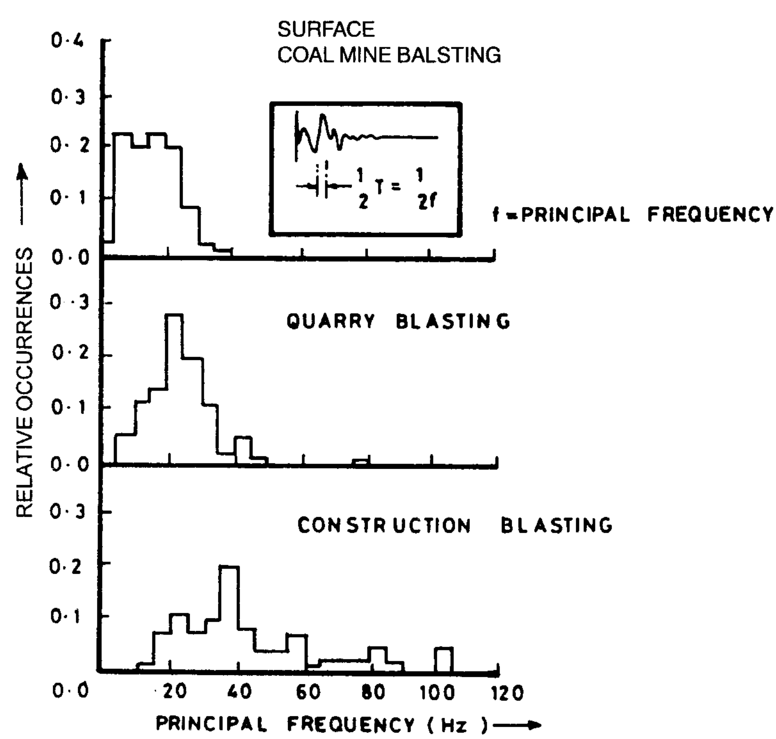


FIG. 2 DOMINANT FREQUENCY HISTOGRAMS AT NEAREST STRUCTURES

5.5 As shown in Fig. 2, the relatively large explosions produced by surface coal mining, when monitored at typically distant structures, tend to produce vibrations with lower dominant frequencies than those of construction blasts. Construction blasts involve smaller explosions, but the typically small distances between a structure and a blast as well as rock-to-rock transmission paths tend to produce the highest dominant frequencies. Such high-frequency motions associated with construction blasts have less potential for cracking adjacent structures than do lower frequency mining blasts.

6 ATTENUATION EFFECTS

Ground motions decrease in amplitude with increasing distance. Effects of constructive and destructive interference and geology are included within the scatter of data about the mean trend of the decay in amplitude with distance. While this scatter is large, the associated decay with distance is observed in all blast-vibration studies. Typical examples of this decay are shown in Fig. 3 where maximum particle velocity is plotted as a function of square-root scaled distance from the blast.

6.1 Square-root scaling, or plotting peak particle velocity as a function of the distance R, divided by the square root of the charge weight per delay $R/W^{1/2}$, is more traditional than the cube-root scaling, which incorporates energy considerations. Both square or cube-root scaling can be employed to compare field data and to predict the attenuation or decay of peak particle velocity. Site specific scaling is sometimes employed where scaled distance n takes the form of R/W^n,

where n is determined empirically by curve fitting $n = (0.4 - 0.6)$.

NOTE — Thus blasting vibrations may be reduced significantly by increasing number of delay detonators.

6.2 Several square-root attenuation relations employed are shown in Fig. 3. They are banded to reflect scatter, which is typical of blasting operations. Curve P shall be used for pre-splitting, cratering and beginning new bench levels. It is also the basis for the regulations for conservative shot design when monitoring instruments are not employed. For accurate estimation of safe change weight per delay the site specific attenuation relation shall be obtained from blast tests at major quarries.

6.3 Dominant frequencies also tend to decline with increasing distance. At larger distances, typical for mining, higher frequency body waves begin to have relatively lower peak amplitudes than the lower frequency surface waves, as shown in Fig. 1. Since lower frequencies can elicit greater structural response

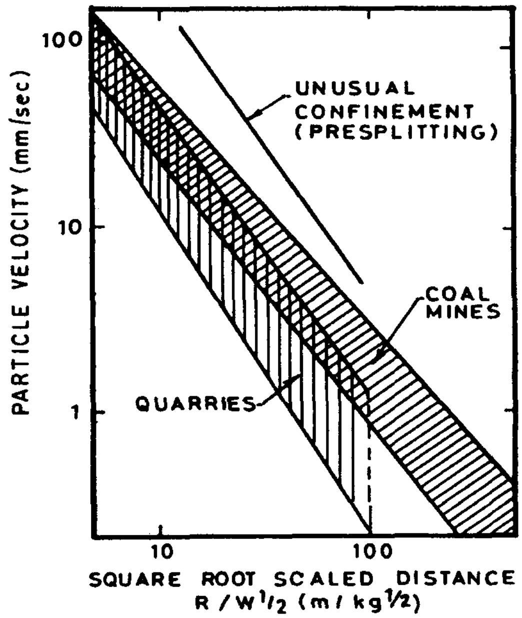


FIG. 3 ATTENUATION RELATIONSHIPS SHOWING SCATTER FROM GEOLOGICAL AND BLAST DESIGN EFFECTS AS WELL AS HIGH EXPECTED VELOCITIES FROM CONFINED SHOTS, SUCH AS PRE-SPLITTING

as shown in Fig. 1, scaled-distance limits decline with increasing absolute distance.

7 BLAST-INDUCED AIR OVER-PRESSURES

7.1 Air-borne disturbances are not directly related to ground motion, the air over-pressures generated by blasting intensify human response and thus need to be documented. The response noise in a structure (from blasting and sonic booms, respectively) is the source of many complaints. The audible portion of the over-pressure produces direct noise, while the less audible portion by itself or in combination with ground motion can produce structural motions that in turn produce noise. Over-pressure may crack windows, however, it would have to be unusually high for such cracking.

7.2 Blast-induced air over-pressure waves can be described with time histories as shown in Fig. 1. The higher frequency portion of the pressure wave is audible sound. While the lower frequency portion is less audible, it excites structures, which in turn causes a secondary and audible rattle within the structure and is the source of many complaints. The air-blast excitation of the walls can be seen by comparing air-blast excitation and wall response in the rightmost portion of the time histories in Fig. 1 where there is no ground motion. Air over-pressure can be described completely with only one transducer, since at any one point air pressure is equal in all three orthogonal directions.

7.3 Propagation of blast-induced air over-pressures is generally with cube-root rather than square-root scaled distances. Peak pressures are reported in terms of decibels(dB), which are defined as:

$$dB = 20 \log_{10}(P/P_0), \qquad (1)$$

where P is the measured peak sound pressure, and P_0 is a reference pressure of 20×10^{-6} in Pa.

7.4 The effect of two important instrumentation and shot variables is summerized in Fig. 4. First, the effect of weighting scales is evident. '*C*' weighing greatly reduces the recorded peak pressure at any scaled distance. This does not mean that the peak is reduced by changing instruments, but the '*C*' weighing system with high cut off frequency does not respond to the low-frequency pressure pulses. These low-frequency pressure peaks excite structures and occupants whether or not they are sensed by the measuring instruments. The other (5 and 0.1 Hz) labels denote the lower-frequency bounds of the recording capabilities of these linear systems.

7.5 The effect of gas venting caused by inadequate stemming in shot holes can be observed in Fig. 4 from the higher average pressures produced by the parting shots at any scaled distance. Parting shots are detonated in thin rock layers between coal strata in surface mines. Consequently, there is less hole height available for stemming, and these shots many times

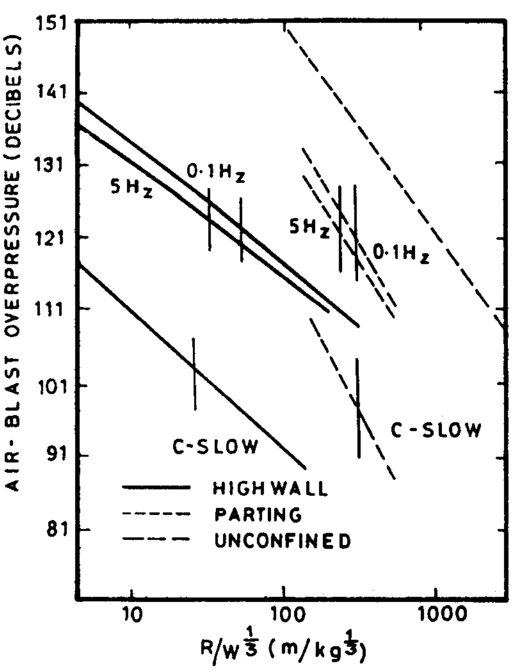


FIG. 4 ATTENUATION RELATIONSHIPS FOR AIR OVER-PRESSURES PRODUCED BY CONFINED (HIGH WALL) AND PARTIALLY CONFINED (PARTING) SURFACE COAL-MINING BLASTS AS WELL AS UNCONFINED BLASTS

eject the stemming and thereby produce abnormally high air over-pressures.

7.6 An air temperature inversion causes the sound pressure wave to be refracted back to the ground and at times to be amplified in isolated locations about 16 acres in size. Such an inversion occurs when the normal decrease in temperature with altitude is reversed because of the presence of a warmer upper layer. For propagation distances of 3-60 km, inversions produce zones of intensification of up to three times the average, attenuated or low air over-pressures at those distances, with an average increase of 1.8 times (5.1dB). At distances less than 3 km, where high air over-pressures are likely to occur, the measurements show no inversion effects.

8 MEASUREMENT TECHNIQUES AND INSTRUMENTS

8.1 A field-portable blast monitoring system operating on a 12 V battery is illustrated in Fig. 5. It consists of :

a) Transducers that converts physical motion or pressure to an electric current;
b) Cables through which current is transmitted to amplifying system;
c) Amplifying system;
d) Maganetic tap, paper or computer digital recorder, that preserves the relative time variation of the original signal for eventual permanent, hard copy reproduction by a pen recorder, light beam galvanometric recorder or dot matrix printer; and
e) Light beam oscilloscope or dot matrix printer.

There is an almost endless variety of configurations of these five basic components. However, the best involve microprocessors (computers) for data acquisition, storage and reproduction.

8.2 While particle velocity is the traditional measurement of choice, structural strains control the cracking. They shall be measured directly from, relative displacements on structures or within rock masses when critical locations are known (that is, pipelines and unusual opening geometry) and can be obtained with a variety of strain and relative displacement gauges. These critical locations may be either unknown or too many in number to economically measure. Estimation of critical locations is necessary or the past experience may be used.

8.3 Ground motion and air over-pressure time histories can be employed to calculate the relative displacement of structural components with a knowledge of the responding structure's dynamic response characteristics. These relative displacements can in

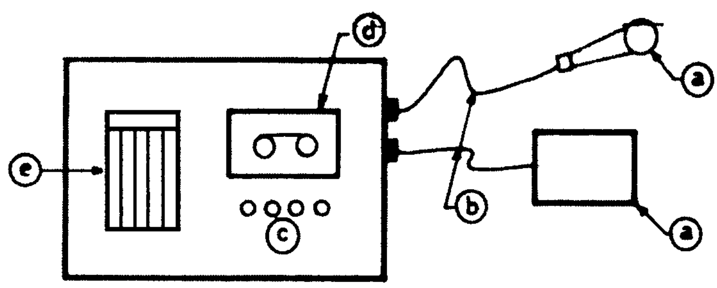


FIG. 5 IDEALIZED, FIELD-PORTABLE, BLAST-MONITORING SYSTEM THAT SHOWS THE SCHEMATIC RELATIONSHIP OF THE FIVE PRINCIPAL COMPONENTS

turn be employed to calculate strains. The accuracy of these estimates is limited by the degree to which the structure behaves as a single-degree-of-freedom system and the accuracy of the estimate of the dynamic response characteristics.

9 MEASUREMENT OF PARTICLE VELOCITY

9.1 While any of three kinematic descriptors (displacement, velocity or acceleration) could be employed to describe ground motion, particle velocity is the most preferable. It has the best correlation with scientific observation of blast-induced cracking, which forms the basis of vibration control. It can be integrated to calculate displacement. If acceleration is desired, it shall be measured directly to avoid differentiation of the particle velocity time history. Integration after vectorial addition of components shall be conducted only after possible phase shifts have been taken into account.

9.2 The location for measurement varies with structure.The excitation or ground motion is measured on the ground adjacent to the structure of interest or on the structure's foundation. Further, if it is desired to measure input excitation they shall be measured outside of and not on the structure. If it is desired to measure structural response motions, then they shall be measured on the most responsive structural members, which are not the basement or foundation walls because of the restraint provided by the ground, at top most rock surface.

9.3 Time histories of the three components of motion shall be measured because of the importance of excitation frequency. Recording only the magnitudes of peak motions will not yield information about the dominant frequency and time history details that control structural response and rock mass strains. Peak motions and dominant frequency can be employed to describe low-level, non-critical motions. Therefore machines employed to monitor critical motions (Type I , *see* **14**) shall be capable of recording time histories of selected critical motions. Machines that record only peak motions (Type II, *see* **14**) can be employed with those that record time histories to provide redundant measurement where frequency content does not vary widely and where particle velocity is low.

10 TRANSDUCER RESPONSE FREQUENCY

10.1 Frequency response is the frequency range over which the transducer's electrical output is constant with a constant mechanical motion. This constancy is normally expressed in terms of decibels (dB). For example linear within 3dB between 2 and 200 Hz means that the transducer produces a voltage output that is constant within 30 percent between 2 and 200 Hz. A transducer's response spectrum (such as those shown in Fig. 6) should be used to determine the frequencies where this difference occurs. If electronically amplifying transducers are used these shall be physically calibrated as described in **13**.

10.2 Proper frequency response for blast vibration transducers is dependent upon measurement of the 'true' phenomena, and efficient measurement of important characteristics. The entire range of frequencies necessary to describe true blast phenomena is too large for any one transducer. Blast-induced delayed gas pressure pulses occur at frequencies of less than 1 Hz, and close-in accelerations have been

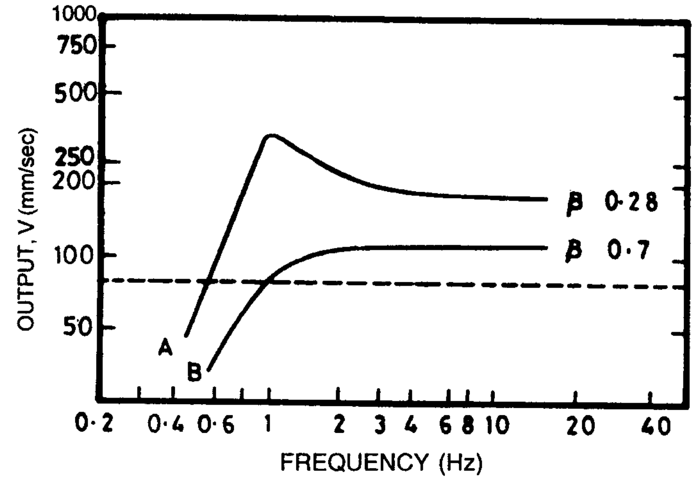


FIG. 6 TYPICAL RESPONSE SPECTRA OF A VELOCITY TRANSDUCER WITH DIFFERING PERCENTAGES OF DAMPING WITH 70 PERCENT OF CRITICAL DAMPING

measured above 100 Hz. Therefore it is necessary to reconsider the goal of defining the true phenomena when only one transducer type is employed, and the optimum choice is dependent upon the important motion characteristics.

10.3 Monitoring ground motion to control cosmetic cracking in low-rise structures is typically accomplished by measurement of ground, particle velocity over a frequency range of 2-200 Hz. This range ensures proper recording of amplitudes at excitation frequencies which; (a) encompass fundamental frequencies of structures, and (b) are associated with the peak velocity that produces the greatest response displacement (that is, are dominant). Typical structure fundamental frequencies are 5-10 Hz for two and one-storey structures and 10-30 Hz for walls and floors. Some mechanical systems may have fundamental frequencies near 100 Hz, but they are usually attached to and excited by the lower frequency walls and floors. Typical dominant excitation frequencies range from 5 to 100 Hz as shown in Fig. 2. If it becomes necessary to monitor situations with unusually low or high dominant frequencies, special transducers shall be employed that are linear in the range of interest.

11 TRANSDUCER ATTACHMENT

11.1 One of the most critical aspects of vibration monitoring is the mounting of the transducers in the field. The importance of mounting is a function of the particular acceleration of the wave train being monitored. The type of mounting on a horizontal surface is the least critical when the vertical maximum particle accelerations are less than 0.2g. In this range, the possibilities of rocking the transducer or the transducer package are small, and the transducer may be placed upon a horizontal measurement surface without a device to supply a holding force. When the maximum particle accelerations fall between 0.2 and 1.0 g, the transducer or transducer package shall be buried at least 15 cm, below ground surface when the measurement surface consists of soil. Mounting of transducers on spikes in soil is not recommended because the free response of the mounting system may affect the recorded motion. When the measurement surface consists of rock, asphalt or concrete the transducers shall be fastened to the measurement surface with either double-sided tape, epoxy or quick-setting cement (hydro-coal or other gypsum based cements set within 15-30 min). If the above methods are unsatisfactory or accelerations exceed 1.0 g, only cement or bolts are sufficient to hold the transducer to a hard surface. All transducers mounted on vertical surfaces shall be bolted in place.

11.2 Air over-pressure transducers shall be placed at least 1m above ground, pointed downward (to prevent rain damage) and covered with a wind screen to reduce wind excitation-induced false events.

12 DIGITAL TAPE AND HARD-COPY RECORDERS

12.1 Microprocessor (computer) or digital recording systems should be used as recording devices because of the ease of data acquisition and computer-linkage. The signal is sampled at a certain rate, say, 500 to 1 000 records/s, and each sample is converted to a single magnitude. Digital recording has several advantages. It is very accurate, as variation in tape speed has no effect if cassette tapes are employed as the storage medium, and records can be directly accessed by a computer.

12.2 Many of the tape systems involve separate recording and reproduction modules to reduce the complexity of recording. Care shall be exercised to determine the exact details of the system before purchasing, as tape recorder performance varies at low temperature.

12.3 A permanent record or 'hard-copy' of the vibratiosn time history is usually made on photographic film, floppy disc, battery-powered memory chips or paper. Almost all present film-based recorders employ field-developable, ultra violet high-sensitive paper in combination with light-beam galvanometers to record high-frequency motions. Those recorders which automatically print after a vibration event, may not record another event while printing. If multiple shots are likely, this reset time shall be determined. Printer behaviour in cold weather is variable and shall also be investigated.

12.4 Most recorders can be bought as either single-or-multi channel units. A four-channel unit is necessary in blast monitoring to record simultaneously the three components of the ground motion (*L*, *V* and *T*) and the air blast. Vibration equipment should include a signal-conditioning amplifier in the recorder to allow flexible amplification of the signals.

12.5 Frequency analysis of records requires a time history and thus some form of permanent record. Instruments recording only peak particle velocities will not allow a frequency analysis. Systems with light-sensitive paper or dot matrix printers allow immediate interpretation of frequency without additional costly equipment.

13 CALIBRATION

The entire vibration measurement system shall be calibrated periodically. Manufacturers supply calibration curves with their instruments that are similar to the response spectra for transducers shown in Fig. 6. Recalibration or checking requires special platforms where frequency and displacement are controlled, and in the field, a calibrating circuit to pulse the magnetic core of the geophone.

14 NUMBER OF INSTRUMENTS

14.1 While the smallest number of instruments or triaxial transducer locations for recording blast excitation motions is one, two triaxial positions would provide a more thorough documentation of the spatial distribution of effects. If only one instrument is employed, then it shall be located at the nearest or most critical receiver. This single, Type I instrument shall record time histories of the three axes of particle velocity as well as air over-pressure. Since it must monitor continuously, it must trigger (begin recording) automatically, and be capable of monitoring even while printing or communicating results. When blasting occurs at more than one general location (that is, involve different nearest structures separated by hundreds of metres), then two and four are the smallest and optimum number of instruments, respectively. A third and fifth shall be available but not deployed to insure continuous coverage in case of instrument failure.

14.2 The second and fourth instruments in the situations described above may provide a lower level of information and will be termed Type II. They must at least continuously record the peak particle velocity in one axis and may or may not measure air over-pressure. The best axis is the vertical, since no horizontal direction decision is required and surface waves usually involve a significant vertical component regardless of the direction of the maximum horizontal component. These instruments shall be located at a greater distance than the nearest structure to monitor a large area.

14.3 The third or spare instrument can be either Type I or II.Where air over-pressures will be problematic or frequencies critical, the spare shall be Type I. This spare instrument can also be employed to monitor sites where complaints develop.

14.4 The above approach describes the least number of instruments. Construction schedules may require a larger number. Measurement of structural response (in addition to excitation) may require more instruments; however, control limits are based upon excitation and not response motions.

15 EXPERIMENTAL BLAST STUDIES

15.1 When blasting projects begin, and the geological conditions change radically or new initiation systems are introduced, test blasts shall be conducted to minimize the number of instruments necessary to monitor production blasts. Instrument locations shall be chosen to produce project specific attenuation relations for both air over-pressure and ground motion. Such relations vary from project to project because of changes in geology and blasting practices. Additionally, the test blasts allow the determination of the frequency content of motions at different scaled and absolute distances.

15.2 The attenuation relation is not solely a site property. Although it is dependent upon geology, it is also heavily dependent upon the blast geometry and timing. For instance, with the same weight of explosive detonated at any instant of time, a blast with a larger burden will produce an attenuation relation parallel to that in Fig. 3 but with a larger intercept on the velocity axis. Furthermore, differing initiation timing will produce changes in the time history, both length and frequency content.

16 SAFETY CRITERIA

16.1 Data from various sets of systematic crack observations are analyzed with the assumption that every cracking observation excludes the possibility of non-cracking at a higher particle velocity. If the probability of cracking is calculated as the percentage of observations at lower levels of velocity, the result is the log-normal scaled plot of the probability of cracking particle velocity in Fig. 7.

16.1.1 There is a lower limit of particle velocity of 5 mm/s below which no cosmetic or threshold cracking (extension of hairline cracks) are observed from blasting. This observation includes data with unusually low frequencies. High frequency data (>40 Hz) show that a 5 percent probability of displaced cracking does not occur until particle velocities reach 75 mm/s. Thus at the hard rock masses at close distances (f> 40 Hz), permissible particle velocity is 75 mm/s. For ancient national monuments, the permissible particle velocity is 15 mm/s.

16.1.2 *Engineered Structures*

Engineered structures constructed of concrete can withstand maximum particle velocities of at least 75 mm/s without cracking. Furthermore, buried structures such as pipelines and tunnel linings are not free to respond as were the above ground residential structures whose response provides the data from which most limits are chosen.

16.1.3 *Restrained Structures*

Buried or restrained structures such as pipelines and rock masses cannot respond as freely as above ground structures and therefore have much larger allowable particle velocities. Whereas strains in a freely responding structure are proportional to the relative displacement between the ground and the super-structure, strains in a restrained structure such as a pipeline will usually be those of the surrounding ground, can be approximated as those produced by plane wave propagation, and are

$$\epsilon = \frac{U_c}{C_c} \quad \text{and} \quad \gamma = \frac{U_s}{C_s}$$

where ϵ and γ are axial and shear strains, C_c and C_s are compressive and shear wave propagation velocities and U_c and U_s are maximum compressive and shear wave particle velocites respectively. For cases involving one critical location along a pipelines, the pipe strains shall be measured directly on the metal.

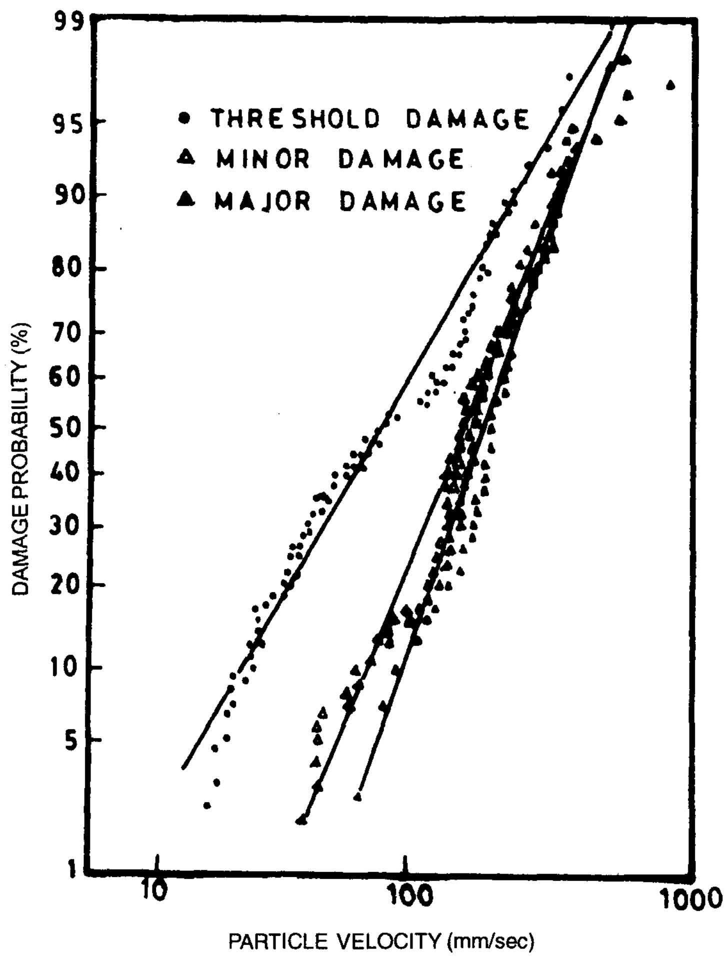


FIG. 7 PROBABILITY ANALYSIS OF BLAST CRACKING DATA

For cases involving tunnel and/or cavern liners critical strains can be estimated through calculation of the relative flexibility of the rock and liner.

16.2 Frequency Dependent Vibration Criteria

16.2.1 Structures respond most to ground motions when the excitation frequency matches the structure's fundamental frequency. As shown in Fig. 1, walls and floors respond more to the higher frequency (15-20 Hz) waves in the early portion of that time history, while the superstructure or overall skeleton of the structure responds more to the last or lower frequency (5-10 Hz) portion.

16.2.2 Differences in structural response such as that shown in Fig. 1 can be calculated from the ground motions if the natural frequency and damping of structural components are known or estimated. The measured structural response has a higher correlation coefficient with calculated single-degree-of-freedom (SDOF) response than with peak ground motion. Therefore structural motions can be estimated more accurately by assuming that they are proportional to response spectrum values at the particular structures natural frequency than by assuming that they are proportional to the peak ground motion. This improved correlation is largely a result of the consideration of excitation frequency.

16.2.3 Figure 8 compares time histories and response spectra from the longitudinal components of a small, urban construction blast and a large, surface coal mine blast. The mining blast involved detonation of 12.600 kg of ammonium nitrate fuel oil (ANFO) with a planned maximum charge per delay of 60 kg some 825 m from the recording instrument. The much smaller construction blast involved detonation of 9 kg of gelatin with a maximum charge per delay of 2.3 kg at a distance of only 15 m. Although the peak particle velocities are similar, 3.8 mm/s for the construction blast *A*, and 3.3 mm/s for the surface mining blast *B*, the response spectra differ radically. This difference is greatest in the range of natural frequencies of residential structures and their components, 5-20 Hz. In this range the surface mining motions produce response velocities that are 10 times greater than the construction blast.

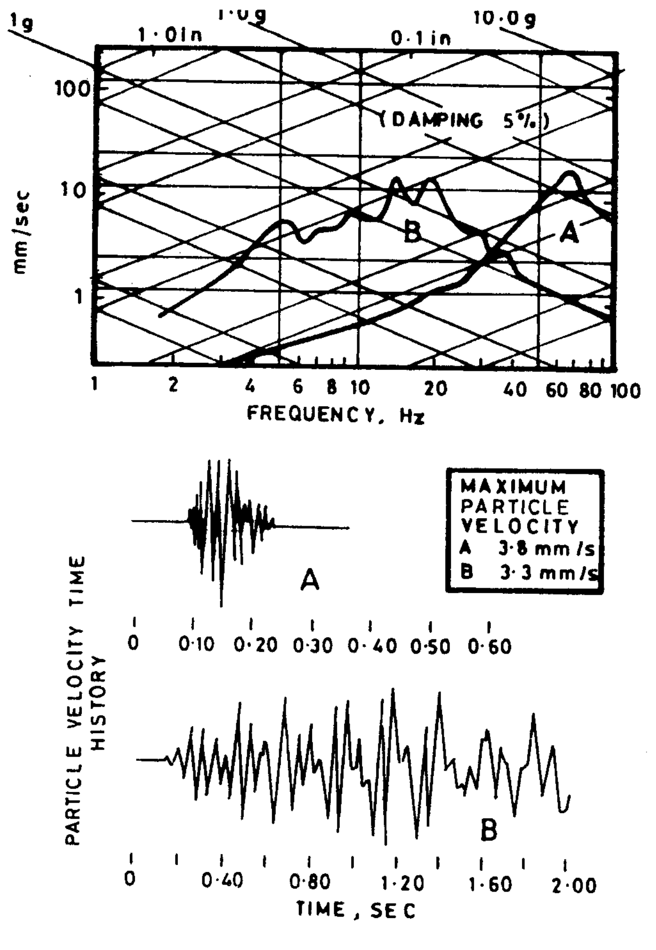


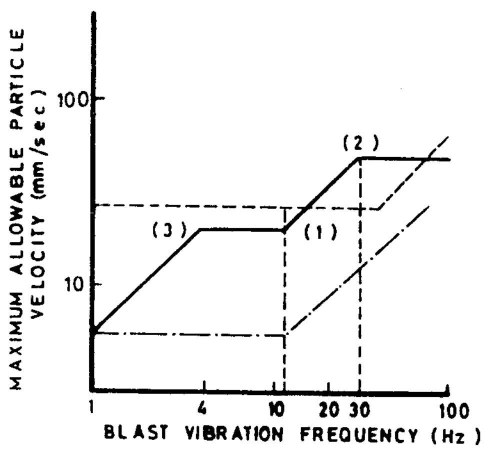
FIG. 8 COMPARISON OF TIME HISTORIES SPECTRA FROM CONSTRUCTION AND SURFACE MINING BLASTS RESPECTIVELY LASTING 0.15 AND 2.0 SECONDS

16.2.4 This lower response of structures with natural frequencies of 5-20 Hz to high-frequency excitation shown in Fig. 8 has led to the adoption of frequency-based standard. This standard allows greater particle velocities for high-frequency excitation.

16.2.5 *Frequency-Based Control with Dominant Frequency (Maximum Allowable Limit of Particle Velocity)*

Figure 9 shows the maximum allowable limit of particle velocity for the protection of residential structures as shown by firm lines. Dotted line in Fig. 9 gives safety for close construction blasting for engineered structures and dashed line is recommended for construction blasting in urban areas near older homes and historic buildings.

The dominant frequency that is consistent with Fig. 9 is that associated with the peaks in the time history with amplitudes greater than 50 percent of the peak or maximum particle velocity. The frequency of these peaks was calculated from the zero-crossing method



NOTE — Dotted line has been employed safely for close construction blasting near engineered structures. Dashed line has been employed safely for construction blasting in urban areas near older homes and historic buildings.

FIG. 9 FREQUENCY-BASED BLAST VIBRATION CONTROL LIMIT TO PROTECT RESIDENTIAL STRUCTURES

as shown in the inset for Fig. 2. Determining frequency from that associated with the peak particle velocity is a good first approximation and eliminates the need for sophisticated Fourier or, alternatively, response spectra analysis. Response spectrum analysis are the most precise approach to account for the frequency effects of structure response and shall be employed in singular cases where an exact analysis is required.

16.3 Safe Air Over-Pressure Levels

Although broken glass is normally associated with excessive air-blast over-pressures, limits are based upon wall response necessary to produce wall strains equivalent to those produced by surface coal mining-induced ground motions with peak particle velocity of 19 mm/s.

These limits are presented in Table 1. If a wall-strain level equivalent to that produced by 25 mm/s particle velocity (measured in the ground) were chosen, the allowable over-pressure would increase by 3 dB. Most cases of broken glass are reported to have been observed at air over-pressures of 136-140 dB (as measured with a linear transducer).

Table 1 Air Over-Pressure Control Limits as a Function of Instrument Frequency Weighing

(*Clause* 16.3)

Lower Frequency Limit of Measuring System (Hz - 3 dB)	Maximum Level (dB)
0.1 or lower - flat response	134 peak
2 or lower - flat response	133 peak
6 or lower - flat response	129 peak
C-weighed - slow response[1]	105 peak

[1] Almost flat response at low frequencies.

Because of the different sound-weighing scales that might be employed by monitoring instruments, the recommended levels in Table 1 differ by instrument system. Since structures are most sensitive to low-frequency motions and the greatest air pressures occur at these inaudible frequencies, A-weighed scales cannot be employed at all. Since C-weighed scales are the least sensitive at low frequencies, their use requires the most restrictive limits.

ANNEX A

(*Foreword* and *Clause* 2)

PERMANENT DEGRADATION AND DISPLACEMENT OF ADJACENT ROCK

A-1.1 Permanent effects, with the exception of fly rock, are encountered only near shot and can be divided into degradation and displacement. Degradation is normally described by cracking intensity. Such blast-induced cracking has been observed experimentally to vary with hole diameter and rock type. Small-hole-diameter construction blasting has induced cracking at distance of 1-2 m and larger-hole-diameter mining blasts are capable of producing cracks at distances of 10-15 m. Careful blast design can reduce these maximum distances.

A-1.2 Displacement can be produced by either delayed gas pressures (those that accumulate during detonation) or to a lesser extent by vibration-induced shaking. Delayed gas pressures have dislocated blocks as large as 1 000 m^3 during construction blasting. Such movement is unusual but is associated with isolated blocks, leakage of gas pressures along open joints, and poor shot design with large burdens. Vibratory or shaking-induced displacement is normally associated with unstable blocks in rock slopes and can occur wherever static factors of safety are low and ground motions produce permanent displacements that are larger than the first-order asperity wavelength on the sliding joint or plane. Gas pressure related displacement can occur up to 10 s of metres. So subsidence of ground and building motion also be monitored.

A-1.3 Fly rock is a special case of permanent displacement of rock by explosive expulsion from the top of the blast hole and has been propelled as far as 100-1 000 m. Statistical studies have shown that the probability of these extreme events are quite low under normal circumstances, 1 in 10 000 000 at 600 m. Since the probability increases with decreasing distance; blasting mats, steel plates, sand bags, wooden logs are required for any construction blasting in an urban environment to prevent all fly rock.

A-1.4 Another special case of permanent displacement is the vibratory densification of a nearby mass of loose, clean sand. The propensity for such densification is a function of density, mineralogy and grain size distribution of soils. Soils that are densifiable are loose sands, with less than 5 percent silt-size particles. These clean sands have been found to densify up to distances of 20 m after detonation of single, 5 kg charges within the loose sand mass itself. Soils that are either slightly cemented or contain more than 5 percent fines are a great deal less subject to vibratory densification from typical ground motions.

ANNEX B

(Foreword)

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(*Continued on page* 14)

(*Continued from page* 13)

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