CHAPTER 7. DAMAGE PREDICTION AND CONTROL(1)

7-1. Introduction.

a. A necessary part of all blasting operations is the estimation of potential damage to nearby surface and underground structures and to local rock surfaces that are to remain in place. Damage to nearby surface structures, such as buildings, bridges, concrete foundations, etc., can result from airblasts, ground vibrations, and flyrock. Damage to underground structures such as tunnels and tunnel linings can result from ground shock and subsequent vibrations. Damage to rock surfaces results from crack propagation into the solid rock immediately behind the blasthole.

b. Equations for predicting the amount of airblast, ground motion, flyrock, and cracking require so-called site constants obtained by performing simple controlled tests with instrumentation and careful observation. From only a few such tests, it is possible to determine the necessary constants so that reasonably accurate predictions can be made.

c. Methods and techniques for preventing damage by controlling the amount of airblast, ground vibration, flyrock, and cracking are generally known and should be made a part of all blasting operations. Damage criteria have been developed for various types of structures and ground vibrations. These criteria can be used with propagation laws for air and ground vibrations to estimate safe charge sizes for various distances to structures.

7-2. Airblast. Airborne vibrations and airblast are generated when explosives are detonated in stemmed drill holes in rock by the following processes:

Conversion of ground vibration to air vibrations at free rock surfaces.

Release of high pressure gases to the atmosphere through the broken rock.

Release of high pressure gases to the atmosphere through the drill hole after the stemming has been pushed out.

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(1) This chapter, except paragraph 7-4, was prepared by Wilbur I. Duvall, U. S. Bureau of Mines. Also see EM 385-1-1, General Safety Requirements.

Release of high pressure gases to the atmosphere by exposed detonating fuse lying on the surface of the rock.

Of these four processes the last three contribute the most energy to the airblast waves.

a. Damage from Airblast. For residential structures, cracked plaster is the most common type of failure in airblast complaints. However, research has shown that windowpanes fail before any structural damage to the building occurs.[30] Airblast pressures of only 0.03 psi can vibrate loose window sashes, which may be a source of annoyance complaints but do not represent damage. Windowpanes that have been stressed by poor mounting or house settlement may fail when subjected to pressures as low as 0.1 psi. Airblast pressures of 1.0 psi will break windowpanes and as pressures exceed 1.0 psi, plaster cracking, which depends on wall flexibility, will start to develop. Thus, it is recommended that air pressures exerted on structures resulting from blasting be kept below 0.1 psi.

b. Propagation of Airblasts.

(1) Extensive research has been conducted on the determination of the airblast pressure generated by the detonation of explosives on the surface of the ground.[31-34] From the data given by Perkins,[33,34] the airblast pressure as a function of distance D and charge size W for the explosion of spherical charges at the ground surface under normal atmospheric conditions is given by

$$P = 175\left(D/W^{1/3}\right)^{-1.4}$$

where

P = airblast pressure, psi

D = distance, ft

W = charge size, lb

For surface excavation, the explosives are placed in drill holes and confined by stemming, which reduces the amount of airblast considerably.

(2) Fig. 7-1 shows the airblast to be expected for different depths of burial DOB for buried spherical charges. In this figure both depth of burial, in feet, and distance from charge, in feet, are scaled by the cube root of the charge weight, in pounds. The plotted points in Fig. 7-1

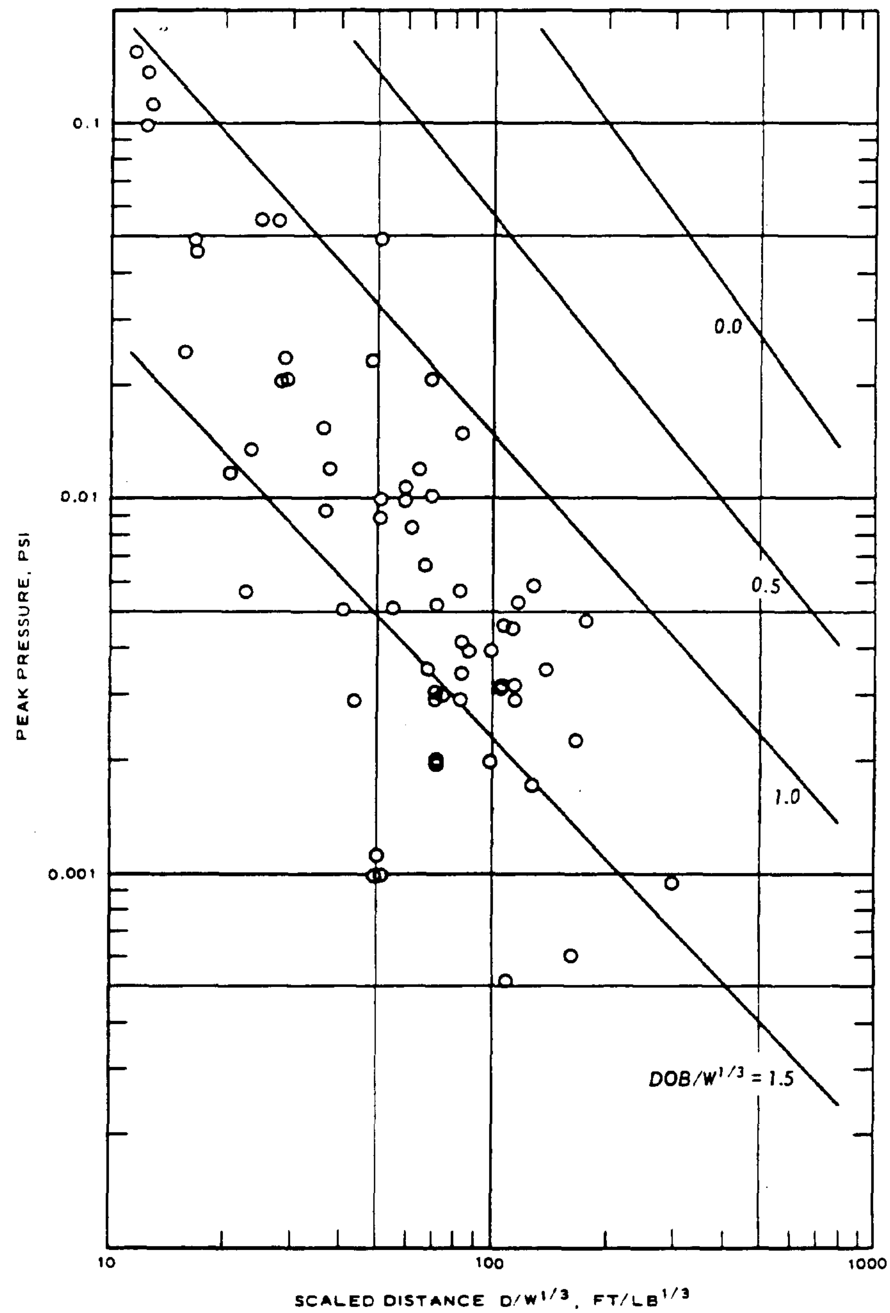

Fig. 7-1. Propagation laws for airblast pressure from spherical charges for various scaled depths of burial and from quarry blasting rounds

are Bureau of Mines observed airblast pressures for multiple-hole quarry blasts. For the quarry blast data, the charge weight is the maximum charge detonated per delay interval. The charge per delay interval is the sum of the charges in the holes that are detonated simultaneously. From the location of the data points, the scaled depth of burial for the quarry blast is usually less than 1.0. This scaled depth of burial corresponds roughly to the scaled burden for each shot hole. From Fig. 7-1, a scaled distance of 20 $ft/lb^{1/3}$ should be sufficient to assure airblast pressures of less than 0.1 psi for multiple-hole quarry blasts that are well stemmed and cap initiated.

c. Excessive Airblast Pressure.

(1) The primary causes of excessive airblast pressures are insufficient burden, insufficient stemming in each blasthole, exposed detonating fuse, and adverse weather conditions. A well-designed blasting round that breaks and moves rock efficiently seldom produces excessive airblast pressures. If detonating fuse is used, it should be covered with sand to minimize airblasts. Exposed detonating fuse and lack of stemming in blastholes can increase airblast pressures by a factor of 10 or more.

(2) Under certain adverse weather conditions, such as temperature inversions, cloud cover, and high wind velocity, local high airblast-pressure regions can develop at large distances from the shot point.[33, 34]

(3) These local high-pressure regions are a result of focusing of sound waves. As temperature inversions exist most frequently during the period from 1 hr before sunset to 2 hr after sunrise, blasting operations should be confined to the intervening daytime period if airblast is to be avoided. Postponement of blasting operations should be considered during daytime hours when a heavy low-level cloud cover exists. Also blasting operations should not be conducted when wind velocities in excess of 15 mph are in the direction of nearby residential structures.

d. Recording Equipment.

(1) Airblast pressures are recorded generally by two types of equipment--microphones and piezoelectric pressure gages. The microphone has proven satisfactory for pressure measurements from 0.1 to 1 psi. Overpressures greater than 1 psi are usually recorded by the piezoelectric type of gage.

(2) Air waves from multiple-hole delayed blasting produce recording problems not encountered with instantaneous surface blasts. A

record of the air wave from millisecond delayed blasting does not appear as a typical single pulse, but instead, has an oscillatory character that can have rarefaction phases comparable to the compressional phases. Therefore, sound recorders with slow response may not give true peak overpressure values because of addition of peaks that are only a few milliseconds apart.

7-3. Ground Vibrations. The detonation of an explosive confined in a drill hole generates a large volume of gas at high temperatures (2,000-5,000° C) and high pressures (0.2×10^6 to 2.0×10^6 psi). The sudden application of a high pressure to the cylindrical surface of the drill hole generates a compressive stress pulse in the rock, which travels outward in all directions (para 2-2). This compressive pulse constitutes the source of the ground vibrations that result when explosives are detonated in holes in rock. These vibrations are extremely intense near the source but decay in amplitude as they travel away from the source. Therefore, it is important to know the general relationship between the intensity of these vibrations as a function of the size of charge detonated and the distance from the source.

a. Damage from Ground Vibration.

(1) The level of ground vibration necessary to cause various types of damage to various types of structures can best be established by case-history studies where the ground vibrations are measured near a structure and the resulting damage correlated with the level and frequency of ground vibration. An inspection of building and structures in the area of potential damage including photographs and measurements before and after blasting would be useful in handling damage claims.

(2) For residential structures the initial indication of damage from ground vibrations produced by blasting is extension of old plaster cracks or dust falling from old plaster cracks. An increase in severity of ground vibration can cause intensified cracking of plaster, falling of plaster, cracking of masonry walls, and separation of partitions from exterior walls and chimneys.

(3) Damage to structures is most closely associated with the peak particle velocity of the ground vibration in the vicinity of the structure. Fig. 7-2 summarizes the damage data from the literature. Major damage may be defined as serious cracking and fall of plaster, and minor damage as opening of old plaster cracks. There is a large spread in the data because the amount of vibration that a given structure can withstand varies considerably from structure to structure depending upon its method of construction, past stress history, and conditions

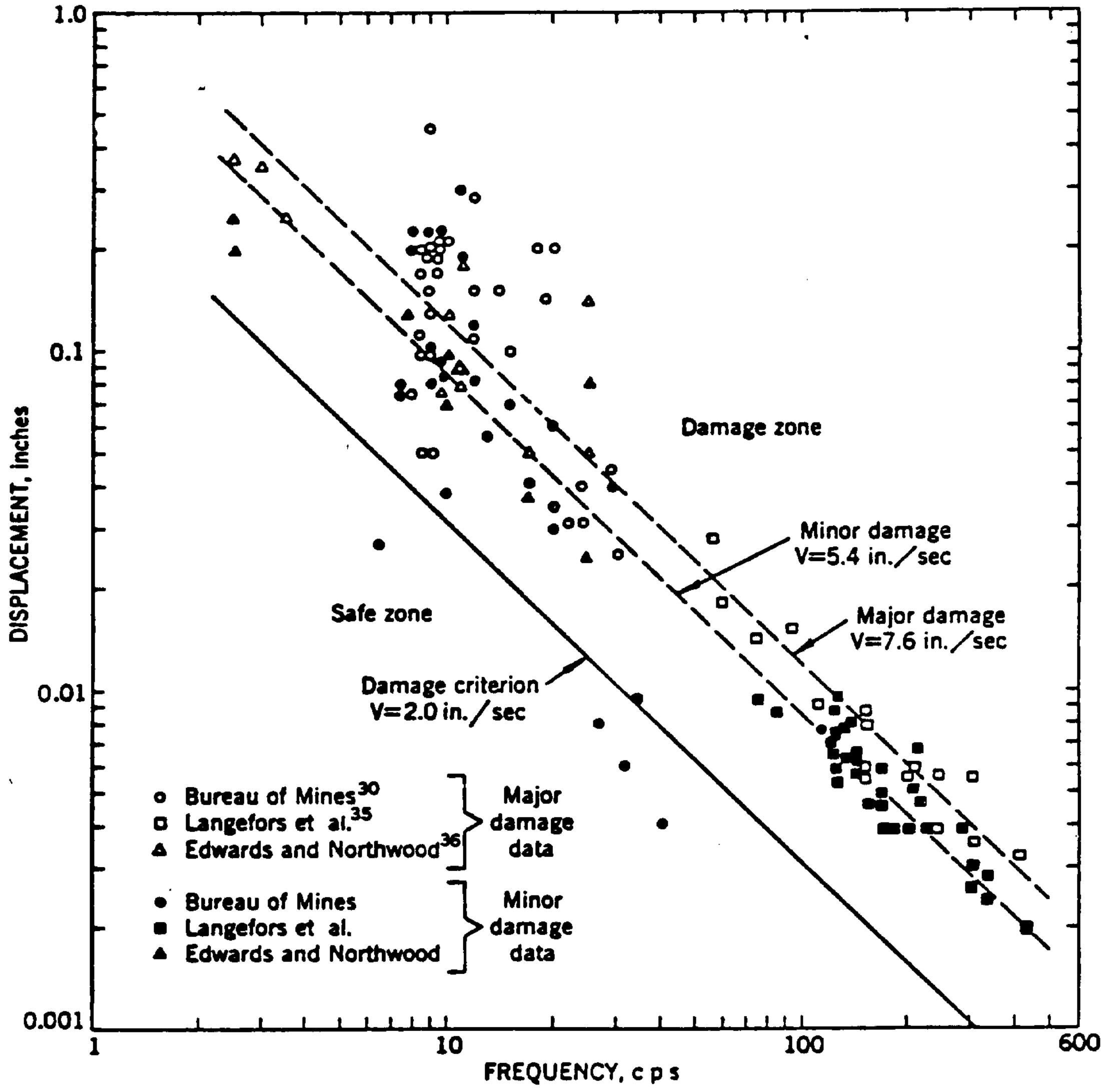

Fig. 7-2. Summary of damage criterion data for frame structure (modified from ref 37)

of the ground upon which it rests. On the average, major damage begins to occur at a peak particle velocity of 7.6 inches per second (ips) and minor damage at 5.4 ips. On the basis of the data in Fig. 7-2 a particle velocity of 2 ips appears reasonable as a separation between a relatively safe zone and a probable damage zone. Just because a vibration level of 2 ips is exceeded, damage will not necessarily occur. For example, Fig. 7-3 summarizes all the published data where the

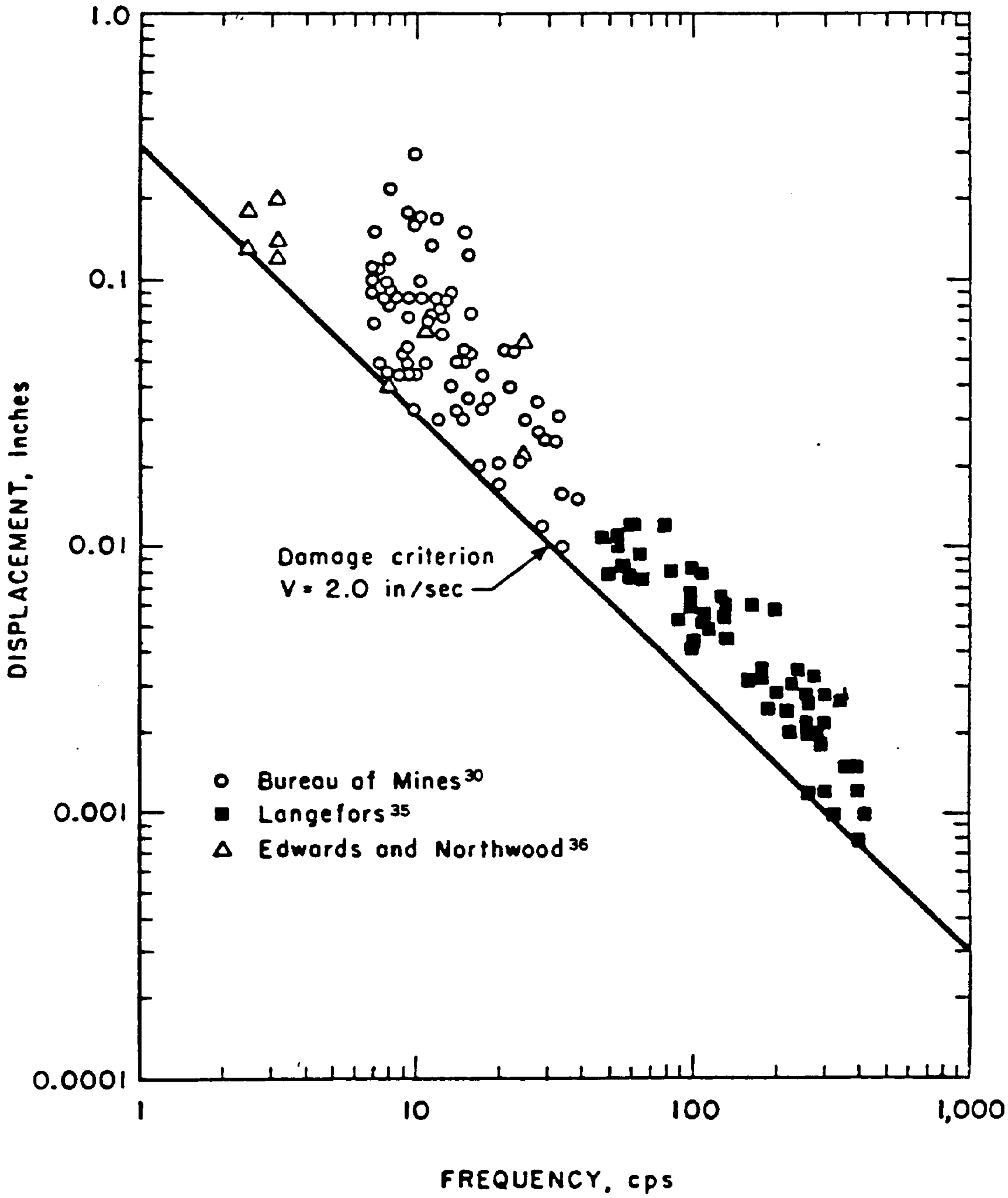

Fig. 7-3. Summary of nondamaging data above recommended safe vibration level for frame structures (modified from ref 37)

vibration level was above 2 ips and no damage was detected. Also, just because the vibration level is below 2 ips, does not mean that damage will not occur in some structures. Very low vibration levels can be associated with damage in poorly constructed structures as in a structure previously stressed by settlement or unstable soil conditions.

(4) From the data given in Figs. 7-2 and 7-3, and taking into consideration the spread of the data, it may be concluded that if one or more of the three mutually perpendicular components (radial, vertical, and transverse) of vibration in the ground near a residential structure has a peak particle velocity in excess of 2 ips, there is a fair probability that damage to the structure will occur.

(5) For many years the criterion for damage to residential structures was based upon energy ratio.[38] As defined, energy ratio was equal to the acceleration squared divided by the frequency in cycles per second (cps); an energy ratio of 3 was considered safe and an energy ratio of 6 was considered damaging to structures. It should be noted that for sinusoidal vibrations, an energy ratio of 3 corresponds to a peak particle velocity of about 3.3 ips. Thus, the newer recommended safe vibration level for residential structures is about the same as that recommended by Crandell[38] when one takes into account that energy ratio is based on resultant acceleration. If all three components of particle velocity had a maximum value of 2 ips at the same time, the resultant velocity would be 3.5 ips.

(6) It should be emphasized that the discussion above applies to residential structures where the vibrations were the result of detonating normal explosives buried in holes in rock or soil. Figs. 7-2 and 7-3 show that the frequencies of the vibrations were generally above 8 cps. Most residential types of structures have resonant frequencies below 8 cps, thus the phenomenon of resonance is not too important in the above-mentioned data. However, for very large blasts, such as underground nuclear blasts, the predominant frequencies in the vibrations would be lower than 8 cps. Thus, the phenomenon of resonance for residential structures would be important. As a result the criterion for safe vibration levels for no damage to residential structures could be much lower than 2 ips for underground nuclear blasts. The large number of claims of damage resulting from the Salmon nuclear event, a deep underground explosion where the vibration levels were less than 2 ips, seem to substantiate this conclusion.[39]

(7) Vibration levels that are safe for residential structures are annoying and often uncomfortable when experienced by people. Complaints from the public are as troublesome as legitimate damage claims. Fig. 7-4 shows the subjective response of the human body to sinusoidal

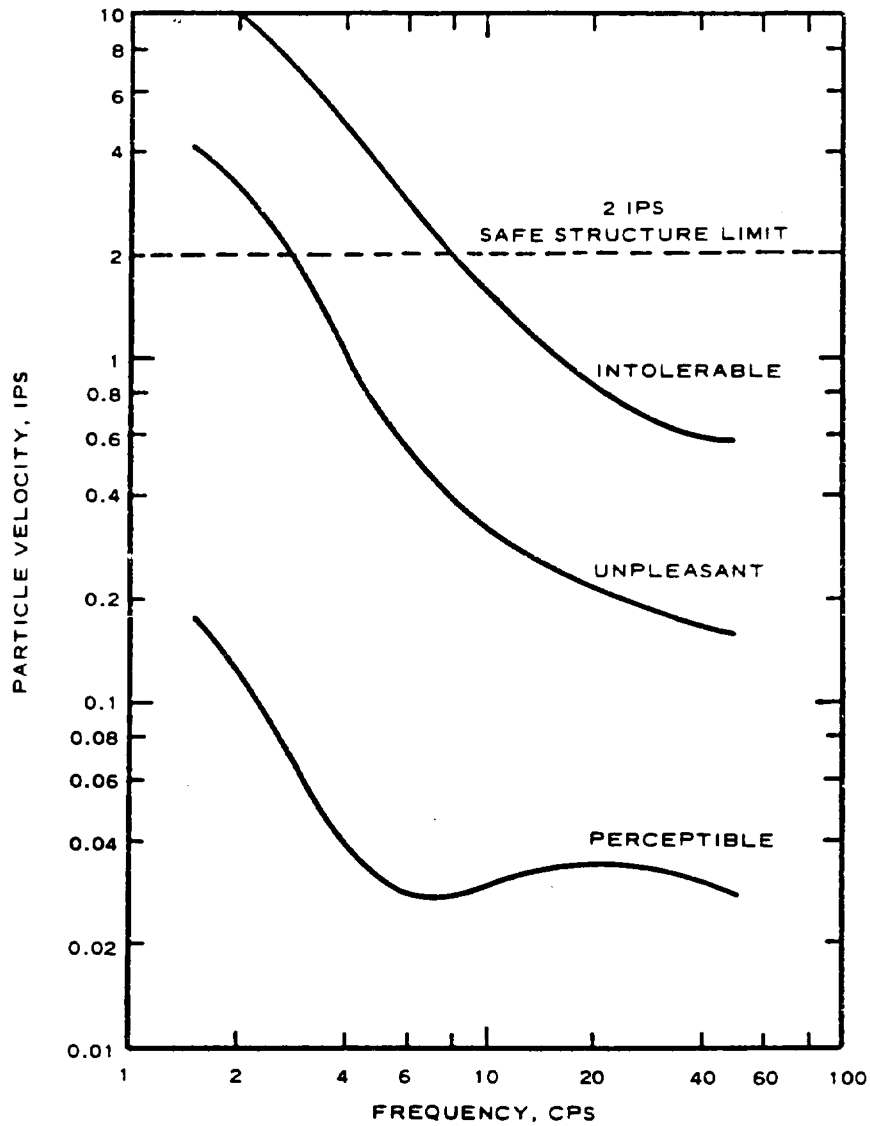

Fig. 7-4. Subjective response of the human body to vibratory motion

vibratory motion.[40] This figure shows that in the range of 10 to 100 cps, vibration levels between 0.1 and 0.3 ips are considered unpleasant by most people. As the major frequency components of vibrations from quarry blasts usually lie in the range of 10 to 100 cps, it is recommended that where possible, vibration levels be kept below 0.2 ips to minimize the number of nuisance complaints from owners of residential structures.

(8) In rural areas the most common complaint from the public may be of damage to water wells. The trouble may be only temporary agitation and cloudiness of the water or the well may be damaged and require repairs. A program of observation of several wells, if possible during a period of testing, should help in reducing the problem and complaints.

(9) Particle velocity damage criteria for unlined tunnels can be inferred from data obtained during the Underground Explosion Test Program.[41,42] The outer limit for irregular spalling and falling of loose rock from the tunnels when subjected to ground vibrations from blasts on the surface were at average scaled distances of 4.4 $ft/lb^{1/3}$ for tunnels in granite and 5.1 $ft/lb^{1/3}$ for tunnels in sandstone. The average measured strain ε in granite at a scale distance of 4.4 $ft/lb^{1/3}$ was 200 microinches/inch (μin./in.), and the average observed strain in sandstone at a scale distance of 5.1 $ft/lb^{1/3}$ was 250 μin./in. The average propagation velocity c in granite was 14,500 fps and in sandstone was 7,400 fps. Using the relation

$$v = \varepsilon c$$

the particle velocity v for damage to occur in unlined tunnels in granite is computed as 35 ips and in sandstone as 22 ips.

(10) Dynamic breaking strains for five rock types were obtained by instrumented crater tests.[43, 44] Table 7-1 summarizes the breaking strains, propagation velocities, and calculated particle velocities for failure. Based on these data, a damage criterion for unlined tunnels subjected to ground vibration from explosion is about 20 ips for the

Table 7-1. Strain and Particle Velocity at Failure for Five Rocks

Rock Type	Dynamic Breaking Strain μin. in.	Propagation Velocity fps	Particle Velocity at Failure ips
Granite	360	18,500	80
Sandstone	550	5,000	33
Marlstone	310	13,000	48
Chalk	300	7,500	27
Salt	310	14,500	54

weaker rocks with somewhat larger values for the stronger rocks. If controlled tests at a given site are not possible, it is recommended that ground vibrations be kept below 20 ips to prevent damage to rock walls of underground openings near blasting operations.

(11) A particle-velocity damage criterion for massive monolithic concrete structures, such as bridge piers, concrete foundations, concrete dams, and concrete tunnel linings, can be estimated from average physical properties of concrete and the relation

$$v = \frac{\sigma}{\rho c}$$

where

v = particle velocity for failure, fps

σ = failure tensile strength, psi

ρ = mass density, $\frac{\text{lb sec}^2}{\text{ft}^4}$

c = propagation velocity, fps

For example, if $\sigma = 600$ psi, $\rho = \frac{140 \text{ lb/ft}^3}{32.2 \text{ ft/sec}^2}$ or 4.3, and $c = 15{,}000$ fps, then $v = 16$ ips. Thus, an estimated safe vibration level for concrete structures would be about 10 ips.

(12) As the safe vibration levels for underground rock structures and massive concrete structures have been inferred from physical property data, it is recommended that these values be used with caution by approaching these safe levels gradually. Thus, instrumentation should be used to determine the vibration levels at the structures as the scaled distance from the blast is reduced.

b. Recording Equipment.

(1) Ground vibrations resulting from blasting are usually measured by means of either a displacement or velocity seismograph. These instruments are usually self-recording and can be purchased as a complete unit. However, it is also possible to use displacement gages, velocity gages, or accelerometers with appropriate amplifiers and recorders.

(2) Displacement seismographs consist of three mutually perpendicular pendulums. Magnification of the displacement, by means of

optical lever arms, is usually fixed at some value between 25 and 75. The displacement seismograph is generally mounted on three leveling screws that rest on the ground or floor of a structure, and the center of gravity of the instrument is above the level of the surface on which the instrument rests. A permanent trace of the ground displacement as a function of time is made on 2- to 3-in.-wide photographic paper traveling at a speed of 4 to 5 ips. The useful frequency range is from about 5 to 50 cps; the dynamic recording range, which is the ratio of maximum signal deflection to minimum readable deflection, is about 20, and the maximum acceleration allowable is approximately 0.2 g.[45,46] For a sinusoidal vibration of frequency f, the relation between peak acceleration a and peak displacement u is

$$a = 4\pi^2 f^2 u$$

Thus, the allowable range of displacement that can be recorded depends upon the frequency of the vibration. Displacement seismographs can be used to measure the peak particle velocity v of the ground motion. The maximum slope of the displacement-time record is the peak particle velocity. If sinusoidal vibrations are assumed, the particle velocity can be calculated from

$$v = 2\pi f u$$

(3) As damage criteria are usually based on particle velocity, it is recommended that particle velocity be measured directly rather than be inferred from displacement or acceleration. Velocity seismographs for recording vibration from blasting consist of three mutually perpendicular coils free to move in a magnetic field. These are mounted in a box, which may be buried in the ground or placed on the surface of the ground or floor of a structure. Associated with the seismometer box is another box containing amplifiers, galvanometers, a multiple-channel paper recorder, and a d-c power supply. The sensitivity of these seismographs is adjustable in the range from 20 to 0.2 in. of record motion per 1 ips ground motion, and their useful frequency range is from 2 to 300 cps. The recording paper speed is about 4 ips. Velocity seismographs also have a greater dynamic range and a better frequency range than the displacement type seismographs. Because the seismometer box can be buried in the ground, the limitation of the 0.2-g level inherent in displacement seismographs is not applicable.

c. Propagation of Ground Vibrations.

(1) Charge size per delay interval and distance from the blast are

the two most important parameters that determine the vibration levels produced in the ground by multiple-hole quarry blasting. Other variables such as burden, spacing, hole depth, hole size, stemming height, and type of explosive have only a minor effect upon the vibration level and in quarry blasting can be neglected.

(2) Controlled tests to study the vibration levels from instantaneous and millisecond-delayed blasts demonstrated that the vibration level in the ground was dependent on the charge weight per delay interval and not on the total charge weight for millisecond-delay blasts.[47] An increase in the number of delay intervals does not affect the vibration level provided that the delay interval is greater than 8 msec and the charge weight per delay remains constant.

(3) Normally, for spherical or concentrated charges, seismic effects in the ground would be expected to scale in proportion to the cube root of the charge weight. However, for quarry blasts variations in the charge size per delay interval are obtained by changing hole size and the number of holes per delay interval, with the charge length remaining practically constant. This method of changing charge size per delay interval is more nearly represented by square root scaling. A general propagation relation for peak particle velocity as a function of distance and charge size per delay interval has been established[48] as

$$v = H\left(D/W^{1/2}\right)^{-\beta}$$

where

v = peak particle velocity of any one component of vibration (radial, transverse, or vertical), ips

D = distance from blast area to point of measurement, ft

W = charge weight per delay interval, lb

H, β = constants (e below).

The quantity $(D/W^{1/2})$ is the scaled distance.

(4) A typical example of data for peak particle velocity versus scaled distance for one particular site is shown in Fig. 7-5. Note that the data for each component of peak particle velocity tend to group about straight lines on log-log coordinates and that the standard deviations of the data about these straight lines are less than ±50 percent of the mean values. If one assumes that the data given in Fig. 7-5 are representative of all future blasts at this particular site, the probability of having a blast that produces a vibration level greater than 2 ips at a

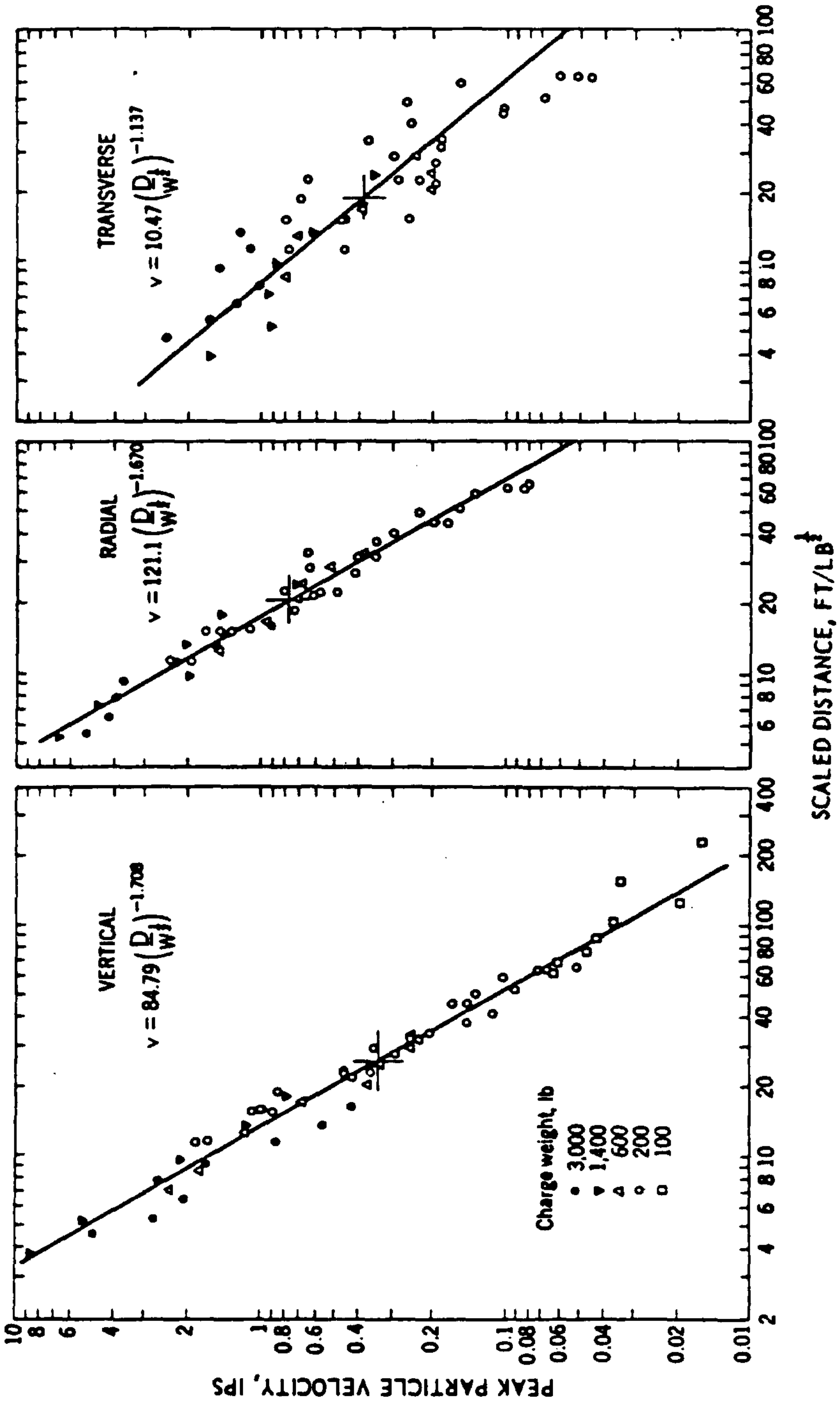

Fig. 7-5. Particle-velocity data versus distance for one site

scaled distance of 20 $ft/lb^{1/2}$ is relatively small. Thus, for this particular site a safe scaled distance for prevention of damage to residential structures by blasting vibrations is 20 $ft/lb^{1/2}$. This scaled distance can serve as a guide at this particular site for determining the weight of explosive per delay interval that can be used at a given distance from a residential structure without exceeding the safe vibration level. All that is necessary is to make the charge weight per delay interval sufficiently small or the distance sufficiently large so that the quantity $D/W^{1/2}$ is greater than 20 $ft/lb^{1/2}$.

(5) The above-described procedure for obtaining a safe scaled distance for prevention of damage to structures by means of ground vibrations from blasting implies that at a particular site, a series of blasting tests must be conducted to determine the particle-velocity propagation relation for that site. Such a procedure may not be necessary if one is willing to accept rather large scaled distances and if one has available particle-velocity propagation data from a large number of sites.

(6) A scaled distance of 50 $ft/lb^{1/2}$ can be considered a minimum safe scaled distance for any blasting site without prior knowledge concerning its vibration characteristics. If at any site a scaled distance of 50 $ft/lb^{1/2}$ limits the charge weight per delay interval unreasonably because of the close proximity of residential structures, it may be possible to use a smaller scaled distance by performing tests at the site to determine the constants in the propagation equation.

d. Reducing Vibrations.

(1) As explained above, the general propagation relation for ground vibrations from blasting is of the form

$$v = H(D/W^{1/2})^{-\beta}$$

The quantity $(D/W^{1/2})$ is the scaled distance. The particle velocity varies inversely with scaled distance, and ground vibration levels can be reduced by increasing the scaled distance. To increase the scaled distance requires increasing the distance or decreasing the charge size per delay interval.

(2) For instantaneous blasting, the charge size can be reduced by using standard or millisecond-delay detonators. For delayed detonations the effective charge size that controls the level of vibration is the maximum amount of charge detonated per delay interval. The total number of delays used does not affect the vibration level. Delay intervals

as short as 8 msec are as effective in reducing the vibration levels as are the longer delay intervals. There may be occasions when 5-msec delay intervals are too short for effectively reducing vibration levels.

(3) For delayed blasting the maximum charge per delay interval can be reduced by reducing the number of holes that detonate per delay interval. For delayed blasting where the number of holes per delay interval is one, the maximum charge size per delay interval can be reduced by decreasing the charge per hole. To reduce the charge per hole requires changing the hole depth, hole size, burden, spacing, and stemming.

(4) In some special cases it may be necessary to reduce the charge size per delay interval by using decked charges in a single hole separated by sufficient stemming to prevent sympathetic detonation. Each deck charge is then detonated at a different delay interval.

(5) A presplit failure plane between the blast area and a structure may or may not be effective in reducing vibration levels at the structure. This method of reducing vibration levels at a given location is not recommended without controlled tests with instrumentation. For a presplit fracture plane to effectively reduce vibration levels, it must intercept the travel path for the ground vibration and be a good reflector. To be a good reflector the presplit fracture plane must form a complete crack which is air filled. If the crack becomes filled with water or sand or if numerous contacts exist across the fracture plane, effective vibration reduction will not result.

e. Calibration of Site Vibration Levels. For effective ground vibration control, the propagation law constants H and β should be determined for each blasting site. These constants can be determined by measuring the three components of particle velocity at two or three distances for several blasts of different charge sizes. The charge size should be varied by changing the number of holes per delay interval. From these data, log-log plots of peak particle velocity for each component as a function of scaled distance are made as shown in Fig. 7-5. The data should group about a straight line. The slope of the line is β and the value of v at $D/W^{1/2} = 1$ is H. The values of H and β will, in general, be different for each component of peak particle velocity (radial, vertical, and transverse). After determining the values of H and β for one specific direction, additional data in other directions should be obtained to determine if the propagation law is the same for all directions from the blasting area.

7-4. Flyrock.

a. The high velocities and, consequently, great range of flyrock may be caused by particle acceleration resulting from escape of explosion gases and from spalling. Gas acceleration is considered to be dominant. If the rock mass contains weak zones, the explosion gases will tend to escape along these paths of least resistance, and thus may be concentrated in particular directions. Massive rock will tend to remain in large blocks that are merely loosened, while highly fractured rock is blown out at high velocities by the escaping gases.

b. Excessive flyrock from spalling is usually the result of an excessive charge for a hole or row of holes near the face. Flyrock can also be caused by loading individual holes too near the top. The velocity of spall-accelerated flyrock may be greater than that of gas-accelerated flyrock. This may account for anomalous rocks ejected to very great range.

c. Cratering experiments from high-explosive charges have provided some data on ranges of flyrock. Charges are usually completely contained (i.e. create no visible crater) at a depth (in feet) corresponding to about 3.5 $W^{1/3}$, where W is charge weight (lb) of TNT or its equivalent.[49] From the standpoint of crater volume, the optimum charge depth is approximately 1.5 $W^{1/3}$. Presumably, most quarry blasting will be accomplished at depths between these two extremes. Both spall and gas acceleration of ejecta have been observed for a limited number of cratering experiments in the near-optimum range, with the latter mechanism generally predominating. Fig. 7-6 illustrates the ranges of flyrock that have been observed from such experiments. Note that sixth-root scaling has been applied to these ranges; this scaling exponent is considered to be correct from both theoretical and practical aspects,[50,51] and may be applied to the scaling of flyrock data obtained during site testing.

d. Ejection of flyrock is not necessarily reduced by decreasing the total weight of explosive, either for a conventional blast or a concentrated (point) charge detonation. The most effective method of controlling flyrock in conventional rock blasting operations is by good blasting design as discussed in Chapter 5. A thorough investigation of the rock structure to locate weaker rock, careful design of the pattern, and proper loading of the holes should result in an efficient blast with little or no flyrock. Heavy wire mesh mats spread on the bench and face to be blasted are commonly used as a means of control.[52] In some cases, low-numbered, delayed holes are believed to have more tendency to fly than following delays. For this reason the instantaneous and lower number holes have sometimes been covered by blasting mats while succeeding holes were not.

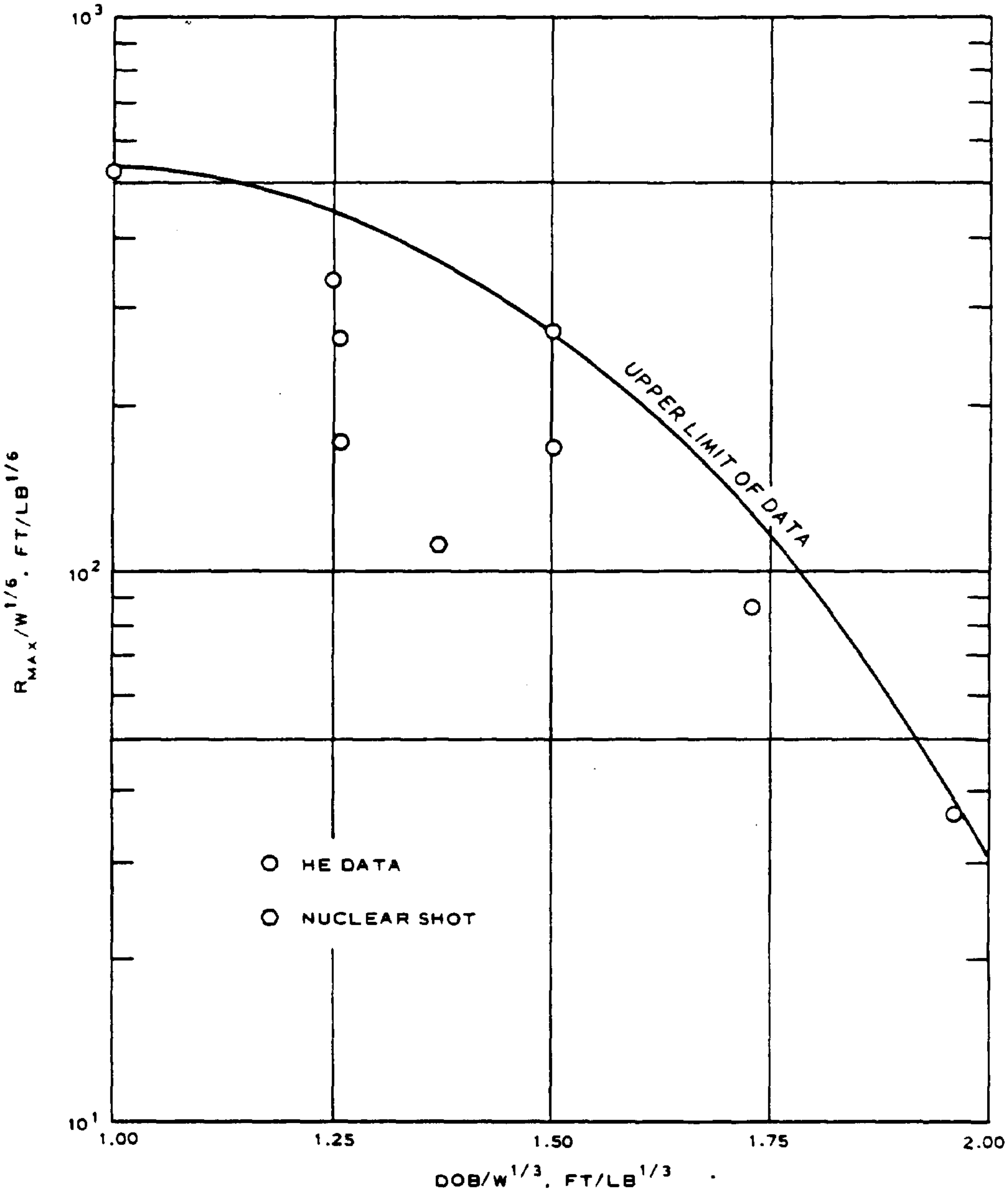

Fig. 7-6. Maximum observed ranges of natural missiles for buried explosions in basalt. Data are from a tabulation in ref 52