DRAWBACKS OF BLAST VIBRATION REGULATIONS

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ABSTRACT

The purpose of this paper is to present an overview of the existing criteria of ground vibrations generated by blasting. It is shown that these criteria have limited liability because they were found for specific categories of structures. A new approach is suggested for assessment of the damage in structures on the basis of measurement of structure vibrations that provides the flexibility of implicitly considering a variety of soil-structure interaction and structure conditions. It is explained the new frequency-independent safe-level criterion that has to be chosen as 51 mm/s (2 in/s) for the PPV of structural vibrations. Attention is brought to seismographs with properly obtained calibration curves that have to be used for vibration measurements. Positive flexibility is demonstrated in assessment of structure and component of concern vibrations from blasting.

INTRODUCTION

Blasting is used during rock excavation for foundations, highway construction, quarry operations and mining. Explosions fracture the rock in the immediate area of the blast and generate elastic waves in soils. These waves may detrimentally affect surrounding structures and their contents. The vibration effects vary from annoying people and disruption of some businesses to possible structural damage. The level of ground and structure vibrations caused by blasting depends on explosive type and weight, delay-timing variations, blasting technology, site geology, scaled distance, parameters of waves propagating at a site, susceptibility ratings of adjacent and remote structures, and other factors.

It is necessary to separate the vibration effects of blasting from damaging influence of environmental forces on structures. The major deterioration of structures in time is observed from environmental forces such as precipitations, daily and seasonable changes in temperature, changes of building material properties under influence of moisture and drying, wind speed and direction, soil conditions and soil behavior under structure loading, and human activities. Unlike of vibration effects of blasting, environmental forces decrease gradually strength of materials. Structures with existing damage may be affected by blast in a greater degree than sound structures. To reveal the blast effect, it is necessary to inspect structures before and after the blast.

Not all vibrations are adverse. Some of them are benign. It is the task for vibration analysis to determine benign from adverse vibrations. There is a number of federal, state and local regulations of blasting that provide guidelines for assessment of measured vibrations but with limited liability. At the present, there is no universally accepted standard for safe ground vibrations. Nevertheless, International Standard ISO 4866 refers some major regulations of ground vibrations for different types of buildings.

VIBRATION DAMAGE CRITERIA

A number of attempts have been made to connect vibration parameters (displacement, velocity, acceleration, and frequency) with observed human annoying, disturbances of sensitive devices, and structural damage, *e.g*. Crandell (1949), Medearis (1977), Siskind et al. (1980), Dowding (1996) and others. Duvall and Fogelson (1962), Wiss (1968), and Nichols et al. (1971) found that structural damage could be well correlated with the peak particle velocity (PPV) of ground vibrations. The PPV is a measure of vibration intensity. The criterion for structural damage of residential buildings was set at 51 mm/s (2 in/s) peak particle velocity in the frequency range of 3-100 Hz. The most extensive study of ground vibrations from blasting was made during the 10-year research program by the U.S. Bureau of Mines (USBM), Nichols et al. (1971). Vibrations were measured and evaluated, damage criteria for residential structures and empirical safe blasting limits were established.

The USBM's 51 mm/s (2 in/s) vibration criterion for ground vibrations with no regard to frequency was used to regulate blasting but could not properly reflect the effect of a variety of dynamic soil-structure interaction. Therefore this criterion was not able to prevent numerous complaints from habitants. It became necessary to take into account the dominant vibration frequency to assess the vibration effect on structures. Intensive studies of residential structural damage in connection with measured displacement and velocity at the frequency range of 1-100 Hz was made by the USBM. As a result, the frequency-based safe limits for cosmetic cracking threshold shown in Figure 1 were developed, RI 8507 (Siskind et al. 1980). As safe-level guidelines, these limits reduced the existing 51 mm/s (2 in/s) safe-level criterion by a factor of 3 to 4 in the frequency range of 4-12 Hz. It is necessary to point out that the RI 8507 has been recognized as the great achievement that provided the safety of low-rise residential structures from vibrations generated by mining blasting.

Then the USBM's criteria were modified for regulation of blasting by U.S. Office of Surface Mining (OSM). These criteria are presented in Figures 1 and 2. The OSM criteria have the following displacement and velocity values for the four ranges of the dominant frequency: 0.76 mm (0.03 in) for 1-3.5 Hz, 19 mm/s (0.75 in/s) for 3.5-12 Hz, 0.25 mm (0.01 in) for 12-30 Hz, and 51 mm/s (2.0 in/s) for 30-100 Hz. Dowding (1996) displays the OSM criteria together with his own approach to control vibrations and the German DIN 4150 Standard (Figure 2). The Dowding's special control lines employ several less restrictive bounds for close-in urban blasting. The DIN 4150 criteria for residences are very conservative. However, according to Siskind (2000), the specified limit levels in the DIN 4150 are not damage-based. This standard intends to minimize perceptions and complains. Therefore the German Standard and the OSM criteria have the different applications.

Siskind (2000) mentioned also a simple distance-dependent set of the PPV criteria used by OSM and other regulatory bodies: 32 mm/s (1.25 in/s) for 0 to 91 m (0-300 ft), 25 mm/s (1.0 in/s) for 91 to 1,524 m (300-5,000 ft), and 19 mm/s (0.75 in/s) for distances greater than 1,524 m (5,000 in/s).

The British Standard BS 7385 and the USBM's (OSM's) criteria are depicted in Figure 3. It can be seen that the BS 7385 considers two lines of the safe limits depending on a type of buildings. Line 1 with the frequency-independent criterion of 51 mm/s (2 in/s) attributes to industrial and heavy commercial buildings. Line 2 with the frequency-based safe limits similar to the OSM criteria attributes to residential or light commercial type buildings.

Other vibration safe limits presented in Wiss (1968) and Siskind (2000) are of interest. All PPV criteria of ground vibrations are in mm/s (in/s): 102 (4) = commercial and engineered structures; 127 (5) = vibration tolerance for buried utilities including wells and pipelines; 127 (5) = lowest vibration for masonry foundation cracking from blasting; 254 (10) = threshold for cracking of mass concrete; 305 (12) = damage threshold for underground works.

LIMITATIONS OF EXISTING CRITERIA

Dowding (1996) noted that the RI 8507 involved no direct measurement of blasts with dominant frequencies below 5 Hz and also very few construction blasts with dominant frequencies above 40 Hz. Therefore the frequency zones below 4 Hz and above 30 Hz are not well defined regarding the relationship between PPV and frequency and are a subject of further research.

The RI 8507 study focused on low-rise residential structures like one-two story houses adjacent to mining facilities and resulted the guidelines for prevention of cosmetic cracking and other structure damage. However, the application of such safe limits to other superstructures and different underground structures is incorrect. It is necessary to point out that the RI 8507 provides no distinction of type, age or stress history of structures that may considerably affect the safe limits. To overcome a gap between practical goals and the existing vibration criteria, some Department of Transportation (DOT) prepared vibration specifications with reasonable precautions to prevent damage of existing structures. These specifications required different levels of vibration monitoring and control depending on structure susceptibility rating, proximity to construction sources of vibrations, sensitivity of the local population to nuisance and city or state policy.

Different opinions are available regarding the application of existing regulations. On the one hand Oriard (1999) made summary comment on vibration: "Routine blasting operations which conform to standard regulations and standard criteria would not be expected to have any adverse effect on soils on a properly prepared building site". This statement overestimates the role of the exiting safe limits and could mislead interpretation of the vibration effects for some cases. For example, Quesne (2001) reported a case of ground and house exterior walls vibrations measured at distances approximately 1.6 to 6.4 km (1 to 4 miles) from a blast site. Velocities of ground vibrations were below the 0.5 ips value and in accordance with USBM RI 8507 and OSM regulations such ground vibrations indicate no possible structural damage. However, the amplification factors of wall vibrations were found from 4x to 9x as high as vibration measured at the ground and resulted in numerous cracks in the different house structures. On the other hand Siskind (2000) wrote that most regulatory bodies, including OSM, recognize "that a more rigorous treatment may be needed in special cases, such as that outlined in RI 8507".

NEW APPROACH

Intensity of structural vibrations depends on soil-structure interaction that determines structure responses to the ground excitation. If the dominant frequency of ground vibrations is lower or higher than the natural frequency of building horizontal vibrations, the PPV of building vibrations will be similar or less than the PPV of ground vibrations. The proximity of the frequency of ground vibrations to the building's natural frequencies may generate the condition of resonance in the building and PPV values of building vibrations may increase in several times.

The existing damage criteria were obtained on the basis of correlation of the damage in structures with the intensity of ground vibrations. This approach indirectly takes into account soil-structure interaction to prevent structural damage of low-rise houses with possible amplification of resonance structural vibrations from 2x to 4.5x in the frequency range of 4-12 Hz. However, there are a considerable diversity of buildings and underground facilities. These structures and their parts, for instance, floors, internal walls etc., have different responses to the same ground vibrations. Besides, subjects of concerns are structure contents like fine china in residential houses, computerized systems, instrument cabinets, medical apparatuses and other sensitive devices in offices that also have their own responses to ground excitation. For example, spectra of wall, equipment and ground vibrations from an impact made by a falling weight of 1 tonne dropping from a height of 1 m on the ground nearby the structure are depicted in Figure 4. It can be seen different responses to the same impact. The amplitude of the instrument cabinet response was three times larger than the amplitude of the ground response, but the dominant frequency of cabinet vibrations was six times smaller. These values changed to +(-) 4 in comparison of cabinet and wall vibrations. It is impossible to correlate responses of various receivers of vibrations with the same ground PPV.

To receive the proper vibration responses, it is necessary to measure vibrations immediately on the receivers of vibrations. Assessment of the damage in structures should be made on the basis of measurement of structure vibrations, not ground vibrations. Such an approach is more accurate and has the substantial advantage in comparison with ground vibration measurement because structure responses provide the flexibility of implicitly considering the variety of soil-structure interaction and structure conditions. Also, it can eliminate misrepresentation of the exiting vibration criteria.

The frequency-independent safe-level criterion of 51 mm/s (2 in/s) has to be chosen for the PPV of structural vibrations. It should not be a surprise because this criterion was implied in the application of the existing vibration criteria. Let analyze how the USBM (OSM) safe limits are put into practice. The criterion of ground vibrations is 51 mm/s (2.0 in/s) for the frequency range of 30-100 Hz. It means that PPV values of structural vibrations at the same frequencies are equal or less than 51 mm/s (2.0 in/s). Other criterion of ground vibrations equals 19 mm/s (0.75 in/s) for the possible condition of resonance of low-rise houses at frequencies from 3.5 to 12 Hz. With expected amplification from 2x to 4.5x of structural vibrations, PPV values of structural vibrations can reach values of 38-86 mm/s (1.5-3.38 in/s) and it is anticipated that structures exposed to such vibrations should not have cosmetic cracks. Obviously, the criterion of 51 mm/s (2.0 in/s) can be accepted for structures with potential resonant vibrations and will provide the safety of structures independently of values of the amplification factor.

Siskind (2000) presented USBM accumulated results of the damage in structures produced by ground vibrations from surface mine blasting (Figure 5). These results were obtained from 718 blasts and 233 documented observations of cracks. Non-damaging blasts are not shown in Figure 5 although some of them produced relatively high level, even exceeding 51 mm/s (2.0 in/s), of ground vibrations. It can be seen that for the general frequency range of 1-400 Hz, the minor and major damage in structures mostly occurred at the PPV of ground vibrations greater than 51 mm/s (2 in/s). At frequencies between 30 and 400 Hz, the PPV of structural vibrations are rather close to PPV values of 102-254 mm/s (4-10 in/s) of ground vibrations because of substantial structural damage revealed. At frequencies between 2 and 30 Hz the minor and major damage in structures mainly happened at the PPV of ground vibration higher than 51 mm/s (2 in/s) and could be as a result of resonant horizontal vibrations of buildings (2-12 Hz) and walls (12-20 Hz) and also resonant vertical floor vibrations (8-30 Hz). At the same time data presented in Figure 5 manifested the threshold damage in structures in the wide range of ground vibrations from 13 mm/s (0.5 in/s) to 279 mm/s (11 in/s) that can be explained by the effect of structure type, age and stress level, and also substantial amplification of structure resonant vibrations at low ground vibrations.

One more argument can be added to support the suggested approach. In the middle of 1940s, the Moscow Institute of Physics of the Earth suggested the safe criteria of 30-50 mm/s (1.18-1.97 in/s) for structural vibrations generated by blasting. These criteria are successfully used in Russia for years.

Measurement of ground vibrations is necessary for assessment of densification and liquefaction of soils. At short distances from the blast, densification is expected, but surface settlements extend beyond the zone of densification. At long distances from the source, sometimes a few miles from blasting, surface waves with low frequencies and long durations produce considerable structure vibrations that may provoke surface settlements.

Damage in structure contents may occur as a result of influence of vibration displacement, velocity, acceleration and frequency. Displacement of 0.1 mm and acceleration of 0.25 g are employed as the vibration limits in Sweden for computer systems subjected to short duration construction blasting. Boyle (1990) collected data regarding tolerable vibrations of mainframe disk drives provided by computer manufactures such as IBM, ICL, Hewlett Packard and NCR and received the following results. Constant amplitude vibration limits over the frequency range of 5-500 Hz: functional limits are between 0.2 g and 0.25 g and survival limit is 0.5 g. Random vibration limits over the frequency range of 5-500 Hz: functional limit is about 0.3 g and survival limit is about 2.7 g. Impact vibration limits: functional limit for impact with maximum 11 ms duration is about 3 g. This value is commented as a slightly conservative estimate because disk drives have still functioned at vibration level up to 4 g at ground level under earthquake simulation tests.

MEASUREMENT OF VIBRATIONS

It is obvious that ground and structure vibrations should be measured properly. Three issues are important to receive correct records.

First, a contemporary transducer for velocity measurement is the portable assembly of a triaxial pack of geophones with the frequency response from 2 Hz to 300 Hz. These transducers are convenient tools with many options for measurement of vertical, radial and transverse vibration components. It is necessary to point out that a geophone's sensor has the natural frequency between 6.5 Hz and 9.5 Hz and therefore a flat velocity-frequency response starts at the frequency about 15 Hz. Manufacturers use software to compensate a resonance amplification of the sensor and receive a flat frequency response between 2 Hz and 15 Hz. Therefore the set of measured calibration curves of the whole transducer has to be submitted by manufacturers because results obtained without calibration curves could be misleading. Dowding (1996) demonstrated examples of the measured velocity-frequency responses. Also, it is important to verify linearity of the flat velocity-frequency response in the seismic range of transducers. The transducer should have a calibrated linear response in the region of the measured frequency, Skipp (1978).

Second, ground motion may excite natural vibrations of the seismograph-ground system and distort records of ground vibrations. Natural vibrations of the seismograph-ground system can be excited at a field test by slight impacts on the seismograph and the natural frequencies can be determined from the records. It is important to find the frequency zones where records can be changed, Svinkin (1973).

Third, there are simple mathematical relationships between peaks of displacement, velocity and acceleration. Displacement calculations from velocity records are correct, but analogous acceleration calculations do not always yield proper results because velocity measurement cannot detect high frequency components of ground vibrations. Accelerometers and geophones have the opposite principles for vibration measurements. If acceleration limits are available for sensitive devices or foundation settlements, acceleration must be measured in parallel to velocity measurements.

FLEXIBLE USE OF SAFE VIBRATION LIMITS

A number of factors affect vibration environment during construction, Svinkin et al. (2000). The first assessment of vibration effects should be made before the beginning of construction activities. As a part of pre-construction survey, measurement of existing vibration background should be made to obtain information regarding effects of exiting vibration sources. Besides, the presence of sensitive devices and/or operations, such as electronics, optical and computerized systems, medical facilities, etc. placed usually on the floors, requires measurement of floor vibrations. For some locations, for example, with equipment sensitive to vibration, a new Impulse Response Function Prediction (IRFP) method can be adapted to predict vibrations from blasting. This method has been developed to determine complete time domain records on the ground, structures and equipment prior to installation of impact machines, Svinkin (2002). The PPV of vibration records obtained prior to the beginning of construction activities should be compared with the safe limits.

During blast operations, certain flexibility should be used in a choice of safe vibration levels from the existing criteria. For example, a historic brick building is located in close proximity to a construction site. On the one hand there are the strict PPV criteria for historic and some old structures. On the other hand at the time of blasting at the neighboring site, this building being not residential is under remodeling construction and the vibration criteria for such a building can be substantially increased depending of structure conditions. Cosmetic and architectural cracks are not important for such a building. Major attention has to be brought to finding and assessment of structural cracks and analysis of crack's behavior during blasting because structural damage cracks (such as of several mm in beams, columns or foundations, settlement cracks in masonry, structural weakening) may affect the integrity of building support.

The existing criteria should be used as guidelines, and structure conditions must be taken into account in a choice of the safe vibration limits. It is necessary to make direct measurement of structural vibrations accompanied by observation of the results of dynamic effects. Different vibrations and crack development can be expected in various parts of multi-story buildings. Ground and structure vibrations may exceed the safe criteria, but if inspection after blasts reveals no increase in crack length and width, blasting should be continued under previous conditions.

Vibrations generated by blasting can disturb people at much lower values of velocity and displacement than vibration levels considered as the safe limits for structures at frequencies higher than 4.5 Hz as illustrated in Figure 7. If few blasts are produced per day, it is reasonable to use these criteria for general description of events but not as the vibration limits because the ANSI limit for human task performance under steady-state vibrations is 51 mm/s (2 in/s). Moreover the ANSI limit for human health under steady state vibrations equals 102 mm/s (4 in/s). Such limits for transient vibrations should be higher.

CONCLUSIONS

Excavation blasts are used in construction and quarry/mining for natural resources. Vibrations caused by blasts during rock excavation are subject for concerns about their harmful effects on structures and humans. This problem is important for surface blasting operations at adjacent and sometimes remote residential areas.

Threshold cracking limits have been developed for low-rise houses adjacent to mining facilities. The application of such criteria to other superstructures and different underground structures is erroneous. Structure conditions should be taken into account in determination of the tolerable limits.

Assessment of the damage in structures should be made on the basis of measurement of structure vibrations, not ground vibrations. Such an approach is more accurate and has the substantial advantage in comparison with ground vibration measurement because structure responses provide the flexibility of implicitly considering the variety of soil-structure interaction and structure conditions. The frequency-independent safe-level criterion of 51 mm/s (2 in/s) has to be chosen for the PPV of structural vibrations.

Users are cautioned to check the manufacturer's specifications, including calibration curves, regarding the applicable range of the transducers used.

During blasting, certain flexibility should be used in a choice of the safe vibration levels from the existing safe criteria for structures and their contents.

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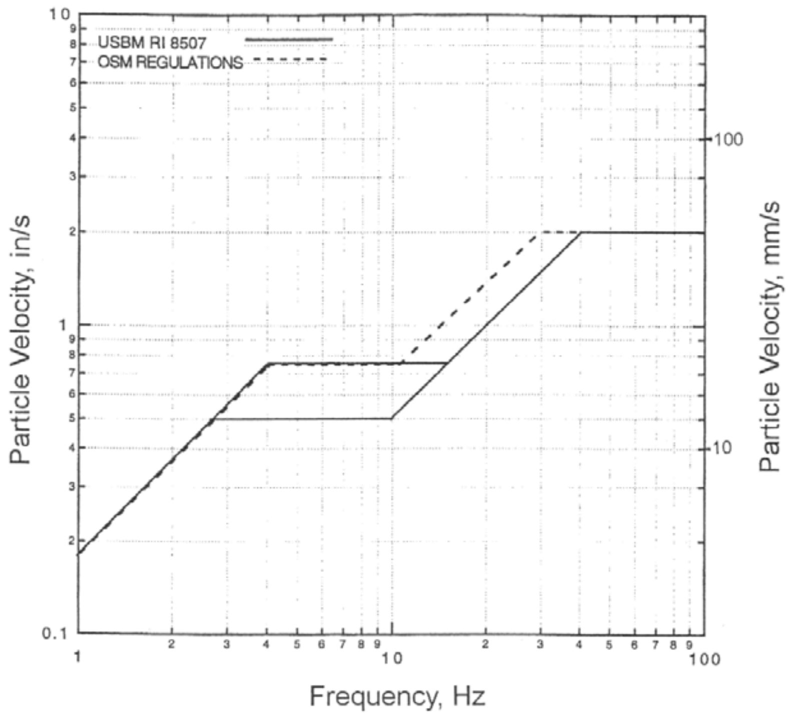

Figure 1. Safe level blasting criteria from USBM RI 8507 and OSM derivative version. (After Siskind, 2000.)

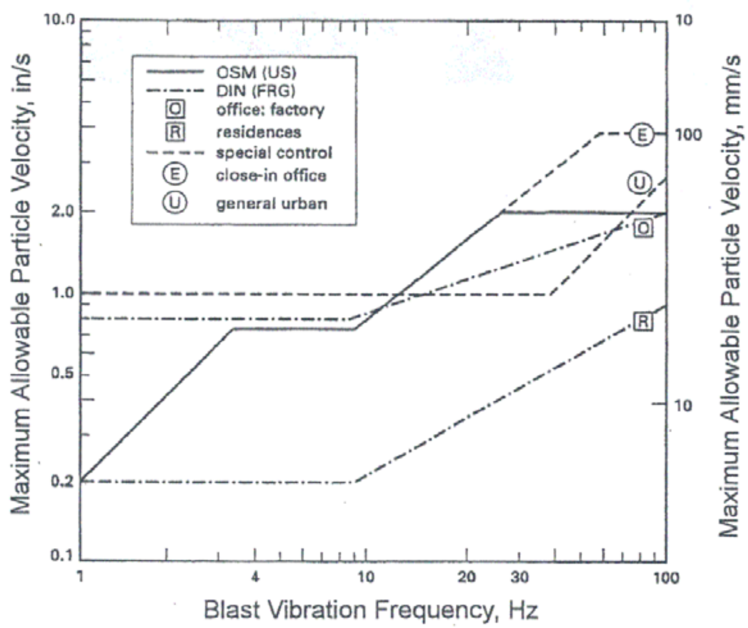

Figure 2. Comparison of different frequency-based velocity-displacement control limits. (From Dowding, 1996.)

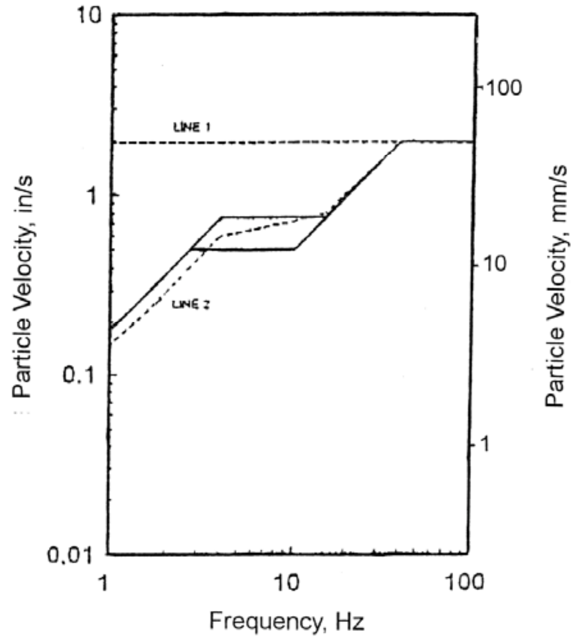

Figure 3. Vibration guidelines - USBM RI 8507 (solid line) compared to BS 7385 (dashed line). Line 1: reinforced or framed structures, industrial and heavy commercial buildings; line 2: unreinforced or light framed structures, residential or light commercial type

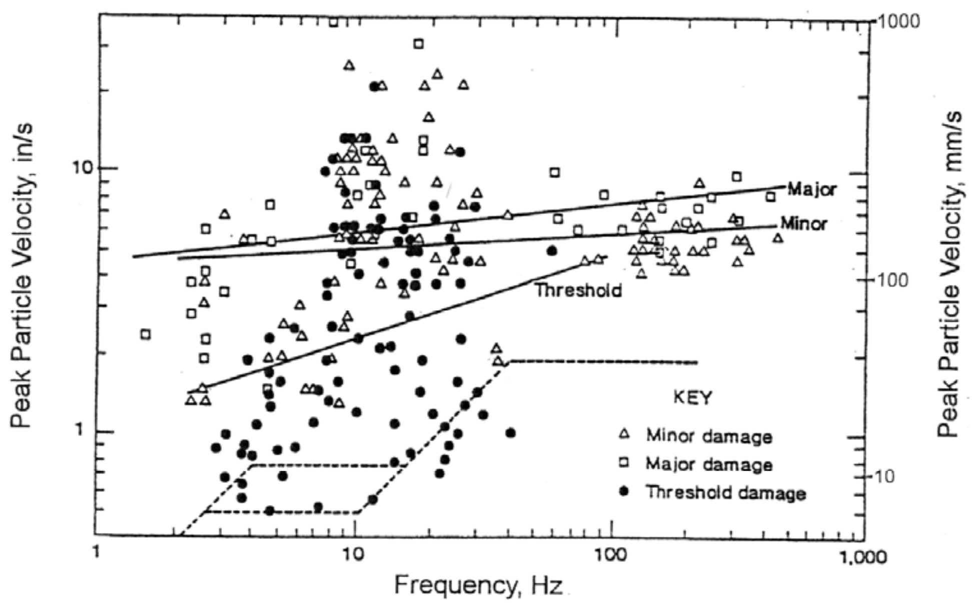

Figure 5. Ground vibration damage summary adapted from RI 8507. Dashed lines define USBM recommended safe limits. Solid lines are regressions representing data means, and symbols shown are positive damage observations. (After Siskind, 2000.)

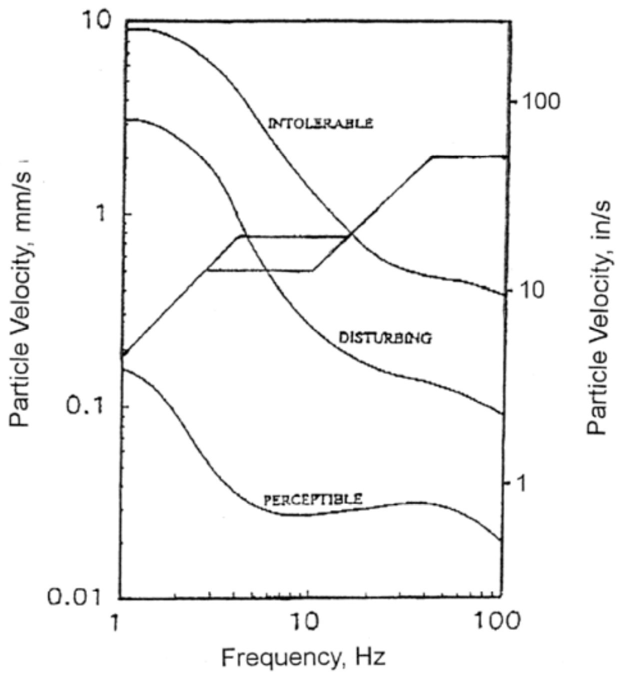

Figure 6. Safe vibration limits (USBM RI 8507) and human perception (Rathbone, 1963). (From AASHTO Designation: R 8-96.)