

Thomas K. Liu, Edward B. Kinner and Mishac K. Yegian, Haley & Aldrich, Inc., Cambridge, Mass.

A brief review of various man-made sources of ground vibration is provided. The character and effect of these vibrations on structures, humans and equipment are discussed, as appropriate, and methods by which sources of vibration can be controlled are presented.

Humans, structures, and equipment are continually being subjected to ground vibrations. These vibrations vary from the common place disturbances associated with a passing automobile or truck to less frequent shaking due to earthquakes. Other sources of ground vibration commonly include industrial activity such as that associated with the use of drop hammers and forges; construction operations using heavy equipment, blasting and pile driving; and other forms of traffic such as rail and even aircraft.

Frequently, sensitive structures or equipment must be shielded from damaging external vibrations. Conversely, vibration producing equipment is frequently isolated so that troublesome vibrations are not transmitted to adjoining facilities either through their foundations or connecting structural elements.

The transmission of vibrations through the ground will assume a role of increasing importance as metropolitan areas become more heavily developed. Likewise, the study of ground vibrations will continue to grow in importance with increasing use of settlement and vibration sensitive equipment in industry, research, medicine and other fields.

Vibration Transmission Through Earth Materials

Extensive studies have been conducted to determine the vibration transmission properties of various soils and rocks.^(9, 12, 13, 18, 21, 25, 28, 31, 37, 38, 39) It has been recognized that ground vibrations are influenced by the nature and type of soil and rock, the position of the groundwater table, the vertical sequence of subsurface soil and rock materials, the horizontal continuity of the subsurface profile, irregularities such as joints and faults, and other factors such as the presence of frozen materials.

The nature of the exciting vibration, the natural frequency and damping of the earth material involved, are important fundamental factors that influence the response of a soil or rock deposit to input vibrations. These fundamental factors will now be discussed.

In an infinite elastic medium, two kinds of waves can be generated, compressive waves (P-waves) and shear waves (S-waves).⁽²⁰⁾ These two waves represent different types of body motions and they propagate at different velocities. The motion of a compressive wave is in the direction of the wave propagation, whereas for a shear wave, the wave motion is normal to the direction of propagation. Another type of wave known as the Rayleigh wave can be encountered along the stress-free surface of an elastic half-space.⁽²⁰⁾ The motion involved in the Rayleigh wave (surface wave) has two components, one along the direction of wave propagation and another normal to the free surface. The velocity of propagation of the Rayleigh wave is approximately equal to the velocity of the shear wave.

For a proper understanding of vibration transmission through earth materials, it is essential that the engineer be familiar not only with the various types of waves that can exist, but also with the theory of wave propagation. Proper consideration should also be given to the nature of the vibration source, such as underground or surface sources, and the shape of the propagating wave front such as planar, cylindrical or spherical.⁽²⁶⁾

Excessive vibrations or dynamic settlements^(10, 12, 30) may occur due to resonance associated with a machine or other foundation resting on soil or with the soil stratum itself.⁽¹¹⁾ In order to avoid such resonance effects a proper evaluation of the natural frequency of the ground is essential. Natural or ground frequencies of earth materials are reported to vary from 5 Hz for peaty soils up to 90 Hz for hard rock. Data reported by Wiss⁽³⁵⁾ and Steffens⁽²⁸⁾ are presented in Table I. The natural frequency of the ground may vary with depth. Therefore, Steffens⁽²⁸⁾ recommended that with deep foundations, the natural frequency of the ground be determined at the bearing level of the foundation.

Another important parameter which influences the dynamic behavior of earth materials is damping. Damping is the term used to define the energy absorption potential of the rock or soil and rock system.⁽²²⁾ For example, the smaller the damping, the larger the response (vibration) especially near resonance. Whitman and Richart⁽³³⁾ described two types of damping in soils: internal damping and radiation or geometric damping. Internal damping is a measure of the energy loss due to inter-particle sliding within the soil mass. For most soils this damping ranges between 0.02 to 0.05.⁽³²⁾ Radiation damping describes the energy loss due to the propagation of waves away from the source of vibration. This damping depends primarily on the nature of the vibration source, whether it be surface or underground; the contact area between the source and the ground; and the mode of vibration such as rocking, twisting or translation. For example, Whitman and Richart⁽³³⁾ showed that for a surface footing, the radiation damping may be as low as 0.05 for the rocking mode and as high as 0.70 for the vertical translation mode.

Radiation and internal damping are also responsible for the attenuation of waves with distance away from the source.⁽⁸⁾ Richart, Hall and Woods⁽²⁶⁾ reported that in an elastic half space both body waves (compression and shear waves), and Rayleigh waves decrease in amplitude with increasing distance from a source of vibration, simply due to the geometry of the half space. For example, due to radiation (geometric) damping, the vertical component of the

Table I - Natural frequencies of earth materials as reported by Wiss⁽³⁵⁾ and Steffens.⁽²⁸⁾

Earth Material	Natural Frequency, Hz
Loose Alluvium, Peaty and Silty Soils ...	5 to 10
Clay, Soft to Stiff	15 to 25
Sand	30 to 40
Rock	40 to 90

Rayleigh wave which carries about 67 percent of the total energy from a surface source, decreases in proportion to $1/\sqrt{r}$, where r is the distance from the source. The amplitude of the body waves which carry the remaining 33 percent of the total energy, decreases in proportion to $1/\sqrt{r}$, except at the surface where this ratio becomes $1/r^2$. Therefore, Rayleigh waves, which carry the bulk of the energy emitted from such a surface source, attenuate at a much slower rate than body waves.

McNeill, Margason and Babcock⁽²¹⁾ developed attenuation curves, presented in Figure 1, from tests at a site where residual clay soils overlay steeply-dipping alternating beds of hard sandstone and soft claystone. Observations made by Wiss⁽²²⁾ from pile driving operations in different soils showed that, for a given hammer energy, vibrations in wet sand attenuated at a slower rate than in dry sand or in clay. Luna⁽¹⁹⁾ reported that under most conditions, the higher the groundwater level, the greater was the transmission of vibrations. Barkan⁽⁸⁾ conducted experimental investigations of wave propagation from foundations. He concluded that the damping constant of a frozen soil was about one half the value that existed when the soil was not frozen. Hence, with other conditions being equal, Barkan⁽⁸⁾ concluded that waves from dynamically loaded foundations propagated to larger distances in winter than in summer. This observation contradicts those of Ferahan and Hurst⁽¹⁵⁾ and Sutherland⁽²⁰⁾ who measured smaller amplitudes of traffic induced vibration through frozen than unfrozen soils. Sutherland⁽²⁰⁾ also reported that the Road Research Laboratory of Great Britain observed that the damping capacity of frozen silty clay specimens was higher than unfrozen specimens.

Permissible Levels of Vibrations

A number of criteria have been suggested to define permissible levels of vibration with regard to nuisance to humans and damage to buildings.^(7, 9, 14, 15, 16, 17, 19, 23, 27, 28, 29, 34) Criteria that have been suggested include the maximum values of displacement, velocity, acceleration, rate of change of acceleration or the square of acceleration divided by frequency (*Energy Ratio*).

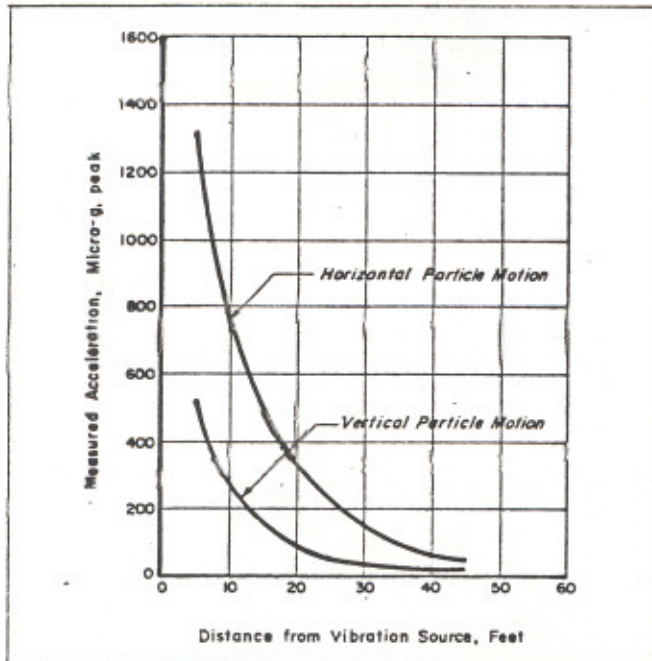


Figure 1 - Attenuation curves for Rayleigh Waves (after McNeill, Margason, and Babcock⁽²¹⁾).

If vibration is assumed to be harmonic, then the above quantities can be related to each other as follows:⁽²⁷⁾

Max. displacement = X_0

Max. velocity = WX_0

Max. acceleration = W^2X_0

Max. rate of change of acceleration = W^3X_0

Max. energy ratio = $A^2/f^2 = 4\pi^2V^2$

where W is the circular frequency in rad./sec., V is the velocity in ft./sec., f is the frequency in Hz, and A is the acceleration in ft./sec.².

A criterion which has gained wide acceptance is expressed in terms of a limiting particle velocity, V .^(17, 17, 27, 28) The effects of different levels of vibration on humans are illustrated in Figure 2. It is seen that vibrations inducing a particle velocity greater than 0.5 in./sec. are considered to be very annoying to people. Safe limits of vibrations, from steady-state motion or blasting, for structures, building components and sensitive equipment are presented in Figure 3.

Luna,⁽¹⁹⁾ Crandell⁽⁹⁾ and others preferred to employ the Energy Ratio to express permissible levels of ground vibration. For example, Crandell⁽⁹⁾ reported that an E. R. greater than 6 will cause damage to residential buildings and values greater than 9 will cause major damage to most types of buildings.

Hendron and Dowding⁽¹⁶⁾ suggested the use of response spectra of blast-induced ground vibration to determine the damage potential of blasting vibrations. This procedure, as compared to the peak velocity criterion, is more broadly applicable since the response spectra describes the response of the structure, taking into account structural damping, over the whole range of frequencies, rather than the limiting frequency range defined by the peak ground velocity.⁽²²⁾

Vibrations from Traffic

It has been recognized that ground vibrations may be due to passage of motor vehicles^(15, 29, 30) railway^(20, 23, 26, 30) and airborne vibrations including that from aircraft.⁽¹⁰⁾ Vibrations from traffic may cause damage to buildings and sensitive equipment and be a nuisance to people. Northwood,⁽²³⁾ reported levels of traffic induced vibrations ranging from about 0.001 in./sec., which may be damaging to sensitive laboratory instruments (Figure 3), to about 0.01 in./sec. which is just perceptible to humans, (Figure 2).

Traffic vibrations may cause densification of cohesionless soils resulting in total and differential settlements which can be detrimental to structures. Terzaghi and Peck,⁽³⁰⁾ presented a case study where the influence of traffic vibrations on a sand deposit resulted in excessive settlements of new structures. In Holland it was found that newly constructed buildings experienced uneven settlements such that the structures tended to rotate away from the roadway. This behavior was attributed to greater densification of the sands prior to the construction of the buildings by traffic related ground vibrations close to the roads than on the far sides of the structures.

Crockett⁽¹⁰⁾ investigated damage from traffic vibration in medieval cathedrals of England and Wales. Over 40 ancient structures were examined with inspections being made for settlement of foundations and cracking of vaulted roofs and other elements. A number of cathedrals were chosen as controls which had no roads around them. Crockett reported that no unexplained preferential settlement or cracking was disclosed within the "control" cathedrals. However, pre-

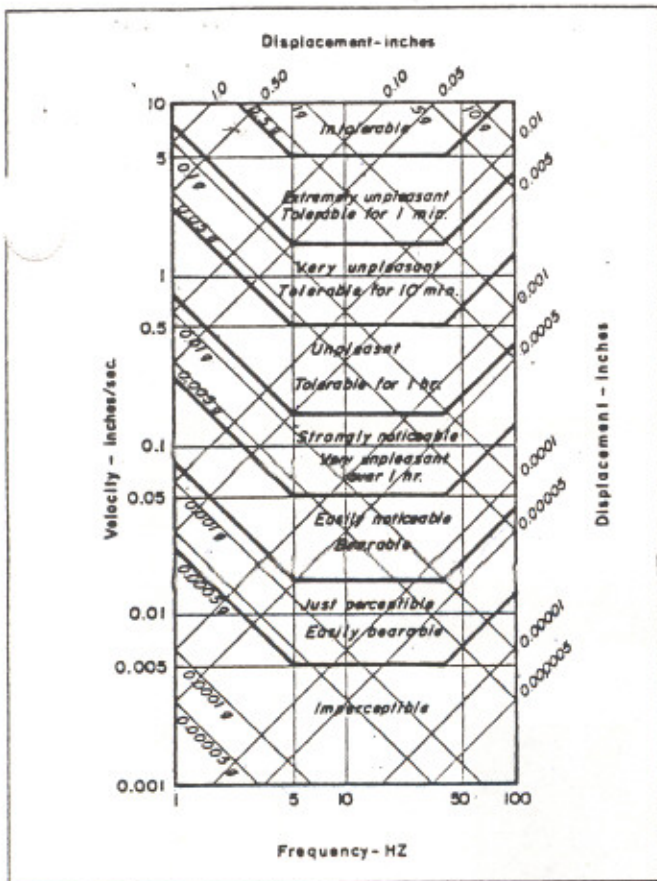


Figure 2 - Effect of vibration upon humans (after Whitman²⁴).

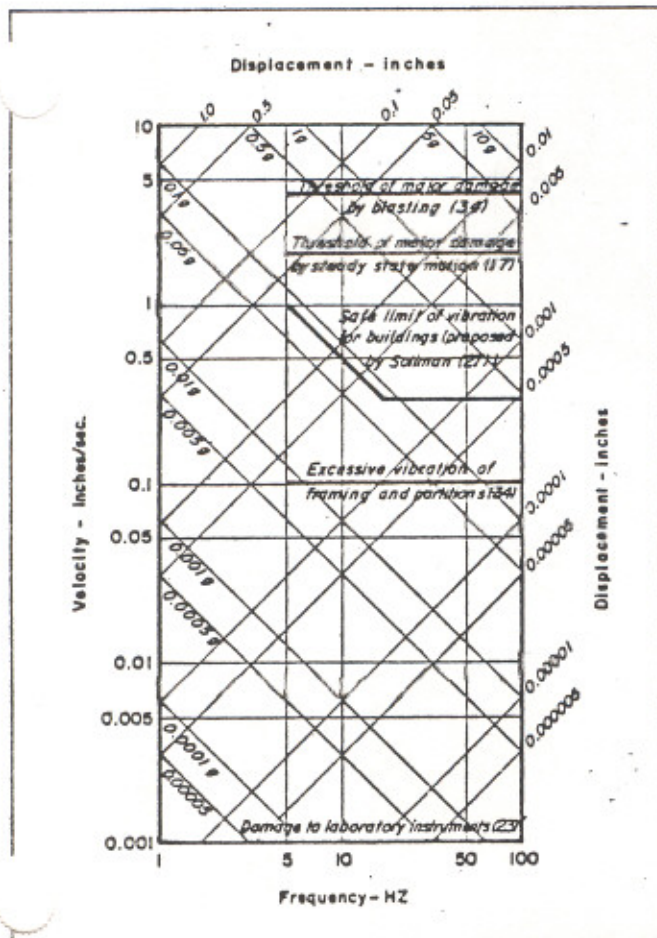


Figure 3 - Effect of vibration upon structures (after Whitman²⁴).

dominant cracking and settlement was reported within the structures located adjacent to the roads. In all cases, the predominant cracking was reported on the roadway sides of the structures. In a later paper, Crockett,⁽¹¹⁾ presented estimates which indicate that some of the cathedrals studied may be settling as much as 0.5 in. per century due to traffic induced vibrations.

In order to determine the various factors influencing the level of vibration caused by traffic, an extensive field investigation was conducted by Sutherland.⁽²⁹⁾ The City of Winnipeg, Canada, in which the tests were performed, is principally underlain by clay soils deposited in glacial Lake Agassiz. Tests were made using a trolley bus weighing 25,000 lbs. and a gasoline bus weighing 15,000 lbs. The vehicles were tested on a city street adjacent to a timber frame house that had been instrumented with seismographs. Distances from the house to the paths of vehicle movement were varied from about 30 to 65 ft. In some of the tests, ramps of up to 3-1/16 in. in height were placed on the roadway to simulate irregularities on the street surface due to ice formation in the winter. Tests were also conducted in the winter to assess the effect of frozen ground on transmission of vibrations. The following observations were made:

1. For a smooth roadway surface, vibrations monitored from the two vehicles were approximately the same. When ramps were introduced, greater vibrations were monitored for the heavier vehicle.
2. Running the two vehicles at different speed indicated that increasing the speed of the vehicles slightly increased the measured amplitude of vibration.
3. Compared with the vibrations resulting from the trolley bus running freely over a 3-1/16 in. high ramp, the vibrations from severe braking tests were much less, and the vibrations from acceleration tests were about the same for the same initial vehicle speed.
4. For the same vehicle speed and weight, vibrations increased when the roadway surface irregularity was increased by using higher ramps (See Figure 4).
5. The two center lanes of the roadway had a total asphalt and concrete thickness of 24 in. while the other lanes had a combined thickness of asphalt and concrete of 10 in. The author concluded that slightly less vibration was observed from vehicle passage on the thicker roadway.
6. Vibrations decreased in intensity as the distance of the vibration source from the observation point increased. For example, with the trolley bus passing at 34 mph over a 2-1/16 in. ramp, peak vertical vibrations at 10 ft. were about 0.0016 in. and at 60 ft. about 0.0005 in.
7. Duplicate tests were run on both frozen and unfrozen ground. The tests disclosed that the amplitudes of vibration in winter, with the soil frozen, were much less than those obtained from tests in the summer. The decrease was attributed to greater damping characteristics of the frozen soil.

For all the test conditions in his study, Sutherland concluded that the level of vibrations induced on clay soils was not strong enough to cause structural damage to buildings constructed on adequate foundations. It was stated, however, that the vibrations might cause further damage where damage already existed.

Vibrations induced by rail transportation have been considered.^(20, 22, 28) Northwood⁽²³⁾ concluded that a system with welded rails in good condition and employing vehicles with the minimum of unsprung weight in the wheel structure would be expected to produce much less vibration than a system with open rail joints and heavy unsprung wheel

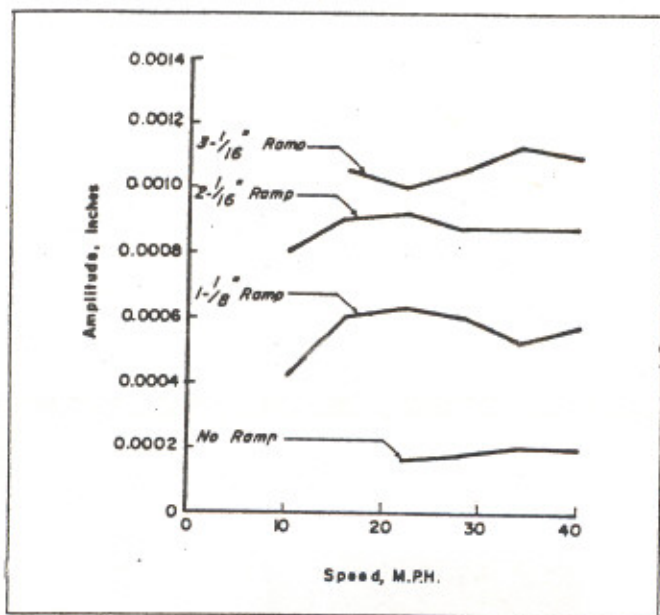


Figure 4 - Effect of ramp size upon amplitude of traffic vibration caused by 25,000 lb. trolley bus (after Sutherland²⁴).

structures. Major⁽²⁰⁾ has recommended that vibration sensitive structures be set back from rail lines and that foundation isolation schemes be employed where necessary. Richart, Hall and Woods⁽²⁶⁾ reported that ground motion velocities as high as 0.08 in./sec. were caused by rail traffic. From Figure 2 it is seen that velocities of this magnitude are considered to be unpleasant if of extensive duration.

Vibrations from Construction Operations

Construction operations are frequently alleged to have caused damage to buildings. A number of studies have been conducted to investigate the levels of vibration associated with the movement and operation of construction machinery — the driving of sheet piling and load bearing piles and blasting operations. A summary of some of the principal studies relevant to these topics follows.

Ferahian and Hurst⁽²⁵⁾ studied the ground vibrations that were caused by the movement and operation of construction equipment. They instrumented three buildings in Winnipeg, Canada and monitored vibrations caused by a pavement breaker, crawler loader, backhoe, vibratory roller, vibratory plate compactor, jack hammers, and a concrete mixer truck. Building No. 1 was a timber residential duplex, whereas buildings No. 2 and No. 3 had timber frames and brick wall and were founded on piles driven to "refusal." The subsurface profile typical of the test site consisted of a 60 ft. layer of highly plastic clay overlying limestone bedrock. Data from the study are presented in Figure 5. It is seen from the figure that the maximum measured particle velocity never exceeded 1.0 in./sec. By comparison with Figure 3, it is seen that the maximum measured velocities are lower than what is generally considered to be structurally damaging to buildings. Values of the particle velocities monitored in building No. 1 that were caused by a 28 ton concrete mixer truck and a Chevrolet automobile running at various speeds are presented in Figure 6. In all cases, the vibrational velocities never exceeded 0.2 in./sec. Ferahian and Hurst,⁽²⁵⁾ concluded that vibrations caused by the movement and judicious operation of construction machinery are not of such intensity as to cause building damage.

The driving of sheet piling and bearing piles is often alleged to cause damage to nearby structures due to exces-

sive vibrations and total or differential settlements of foundations. Vibrations from pile driving may be transient if an impact hammer is used or steady-state if a sonic hammer is used.⁽²³⁾ Dalmatov, Ershov and Kovalevsky,⁽²²⁾ Wiss⁽²⁶⁾ and Luna⁽¹⁹⁾ described some of the factors which influence ground vibrations caused by pile driving. Some of the principal findings from these investigations follow:

1. Studies of field tests have shown that the disturbing effect of pile driving diminishes with penetration of the pile into the ground.^(17, 12, 19, 26)
2. The influence of the soil type and the energy delivered by a pile driving hammer upon the resulting vibrations are illustrated in Figure 7. The abscissa represents a

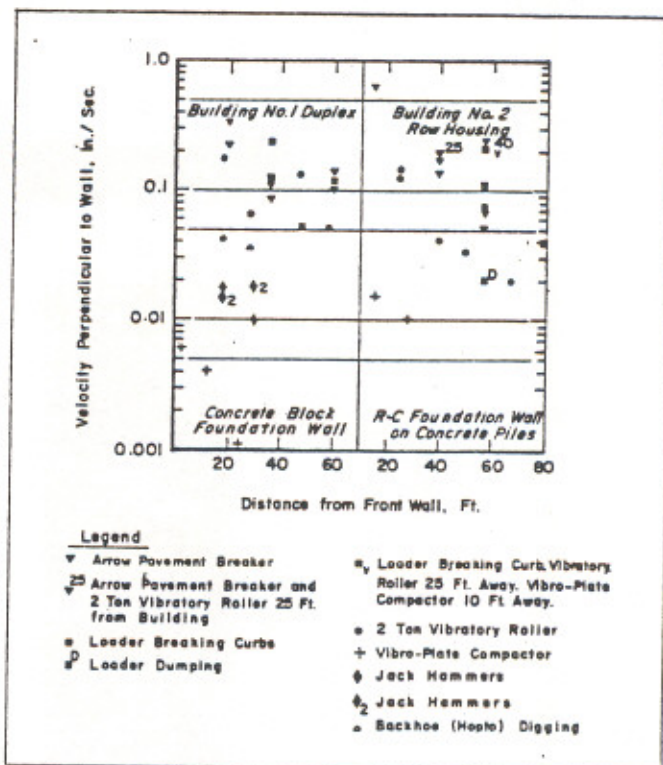


Figure 5 - Vibrational velocities caused by the operation of construction machinery (from Ferahian and Hurst⁽²⁵⁾).

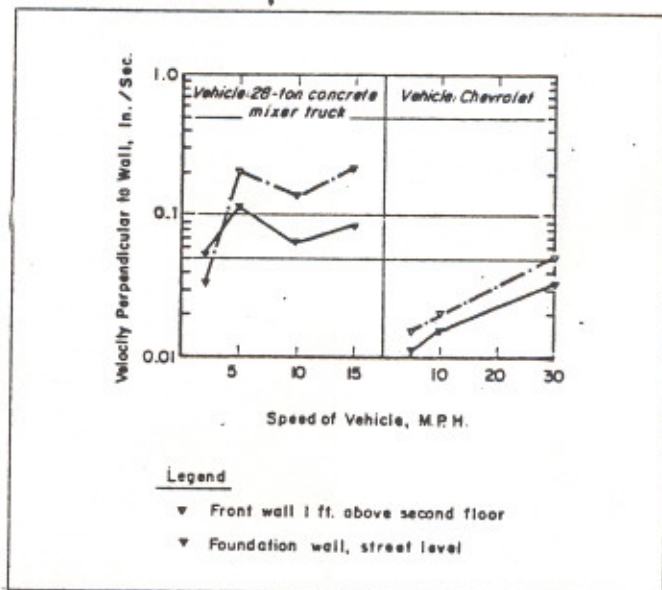
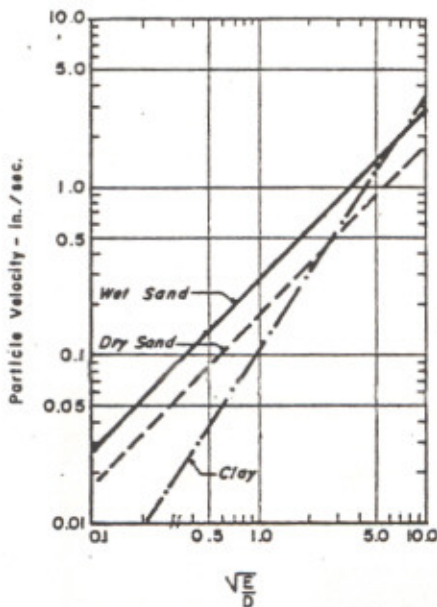


Figure 6 - Vibrational velocities in building No. 1 caused by vehicles, 48 ft. away, driven over a 3-inch-high ramp (after Ferahian and Hurst⁽²⁵⁾).



Note: E is the rated energy of the pile hammer in ft.-lb., D is the distance of the pile tip from point of reference in ft.

Figure 7 - Maximum vibration intensities expected from pile driving in wet sand, dry sand, and clay (after Wiss²⁶).

scaled energy factor which is the ratio of the square root of the energy delivered by the hammer, in ft.-lb. to the distance of the pile tip from the point of reference. From this figure it is observed that for scaled energy factors less than about 5, the particle velocity in wet sand is higher than in dry sand or clay.

Matov, Ershov and Kovalevsky⁽¹²⁾ have shown that accelerations caused by pile driving decrease exponentially with distance away from the pile. Wiss⁽²⁵⁾ confirmed this observation (See Figure 7).

4. The normal vibration levels from a sonic hammer may be one order of magnitude lower than those of an impact hammer. However, because vibrations from a sonic hammer are of steady-state character, effects on humans should be considered.
5. Wiss⁽²⁵⁾ observed that for practical purposes, there were no differences, in terms of the scaled energy factor, in the vibrations produced by driving different types of piles including sheet piles, wood piles and H-piles.

In many engineering projects, the use of explosives may be required. Blasting operations, if not conducted properly, may produce vibrations and noise which may cause damage to buildings and disturb people.

Crandell,⁽⁹⁾ recommended the use of the following equation which relates Energy Ratio to the amount of explosive, in pounds, used per delay, C; the distance, in feet, from the center of explosion, D; and the type and condition of the soil expressed in terms of the parameter, K:

$$E.R. = (50/D)^2 C^2 K = A^2/f^2$$

in which, A and f are ground acceleration and frequency, respectively.

The parameter K depends upon the density and consistency of the earth material. As discussed earlier, earth materials transmit vibrations at different frequencies. Therefore, for the same input motion, the degree of damage is dependent on the earth material present. For example, Crandell⁽⁹⁾ reported measured frequencies of vibrations in

rock ranging from 40 to 90 Hz. Therefore, the E.R. imposed upon structures through rock may be small even though accelerations may be very large. On the other hand, Energy Ratios measured through saturated sedimentary soils, with frequencies as low as 5 to 7 Hz, may be of sufficient magnitude to cause damage. The value of K for different soils encountered by Crandell in his investigations ranged between 0.001 to 0.004.

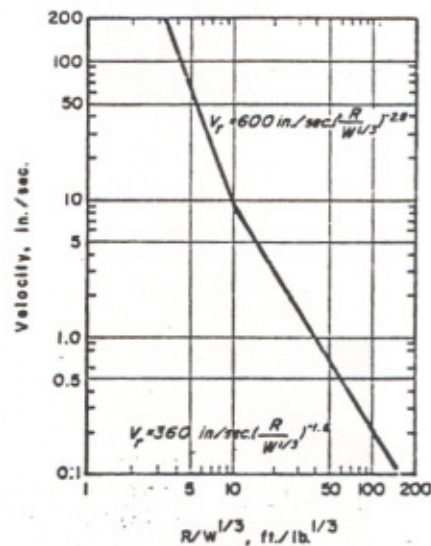
The principal recommendations suggested by Crandell relative to the use of E.R. as a damage evaluation criterion are as follows:

1. Use charge delays to limit the amount of energy released at any instant. This limits the magnitude of maximum induced acceleration.
2. If the E.R. in the ground is 3 or more, old pre-stressed structures are likely to be damaged. Energy ratios close to 6 will cause damage to residential buildings and structures with brick load bearing walls. Energy ratios greater than 9 can be expected to cause major damage to buildings.

Hendron and Oriard⁽¹⁷⁾ preferred to express the damage evaluation criterion in terms of the particle velocity. Figure 8 presents their recommended curve for preliminary estimates of maximum radial particle velocity. It is important to note that in this figure the scaled range is expressed in terms of the cube of the root of the maximum weight of charge per delay. Other investigators, such as Oriard, Devine and Duval,⁽¹⁷⁾ preferred to use square root scaling rather than the cube root scaling.

Vibration Control

Different sources of vibrations emit waves of different characteristics. For example, wind-induced vibrations in structures may have predominant frequencies in the range of 0.01-0.1 Hz. Vibrations due to earthquakes and rail traffic may have predominant frequencies in the range of 1-10 Hz and 10-100 Hz respectively.⁽²³⁾ Therefore, tall buildings which commonly have fundamental frequencies between 0.5-1.0 Hz are more susceptible to vibration damage from



Note: R is the slant range in ft.
W is the weight of charge per delay in lb.

Figure 8 - Maximum particle velocity versus scaled range according to cube root scaling (after Hendron and Oriard¹⁷).

earthquakes than from wind or railway vibrations. On the other hand, most floors of residential buildings have natural frequencies between 10-30 Hz and therefore resonance due to traffic vibrations may result in sufficiently high particle velocities (on the order of 0.1-0.3 in./sec.) so as to be a nuisance to people.⁽²⁸⁾

Methods of vibration control are employed to reduce or eliminate vibrations that would otherwise be damaging to structures and equipment or troublesome to humans. Frequently, not only a "source" of vibration is required to be prevented from emitting troublesome vibrations but some structures and machines must also be protected from excessive incoming vibrations. Isolation schemes employed for these two purposes are known as "active" and "passive" respectively.⁽³⁾

Trenches and sheet piling have been used with varying degrees of success in both active and passive isolation. (6, 8, 12, 21, 23, 26, 28, 36, 37) Barkan,⁽⁸⁾ presented a number of case studies where open trenches were not effective in screening vibrations. He concluded that the depth of the open trench must be greater than 0.3 times the wave length of the propagating wave in order for isolation to be effective. Woods⁽³⁶⁾ conducted field model tests in silty sands to determine the effectiveness of open trenches and sheet piling in controlling vibrations. For active isolation, he found that fully enclosing circular trenches, having depths equal to at least 0.6 times the generated Rayleigh wave length, were effective in reducing the vibrations outside the trenches to about 25 percent of the original value. The circular trenches in these tests were located at radial distances from the vibration source equal to 0.3 to 0.9 times the generated Rayleigh wave length. Similarly located partial trench circles, having central angles less than 90 degrees, were found not effective in reducing vibrations. In passive tests, Woods^(36, 37) found that longer and deeper trenches were necessary, to accomplish a given amplitude reduction, as the distance for the vibration source to the trench increased. The width of open trench was found to have little effect in the passive tests. Woods⁽³⁶⁾ conducted tests to simulate effect of using sheet piling for vibration control. The tests disclosed that open trenches were much more effective in controlling vibrations than the sheeting.

In cases of low frequency vibrations involving long wave length, Dolling⁽¹³⁾ proposed that the use of thixotropic fluids in deep trenches will be more economical than the use of sheet piling. Trenches backfilled with gravel, expanded aggregate, and plastic foam have been reported successful.⁽²¹⁾ McNeill, Margason and Babcock⁽²¹⁾ reported the successful application of passive isolation involving the use of a combination of deep driven steel sheet piling and a near surface trench void (see Figure 9).

Absorbers have been used extensively in control of vibration.^(1, 2, 3, 4, 5, 8, 20, 23, 25, 32) Northwood⁽²³⁾ described absorbers that were employed to eliminate vibrations caused to buildings by railways. Machines producing vibrations are frequently separated from the sub-structure or foundation by vibration-damping layers which also provide static support.⁽²⁰⁾ Some of the commonly used isolation pads include cork, rubber, felt, PVC, and timber. An example of one such system is illustrated in Figure 10. For efficient isolation, it is essential that the natural frequency of the isolation pad be much smaller than the forcing frequency causing the vibration.⁽²⁸⁾ Steel-springs and dampers have been successfully used to reduce not only vertical vibrations but also horizontal motions that are caused by earthquakes or machines.^(3, 4)

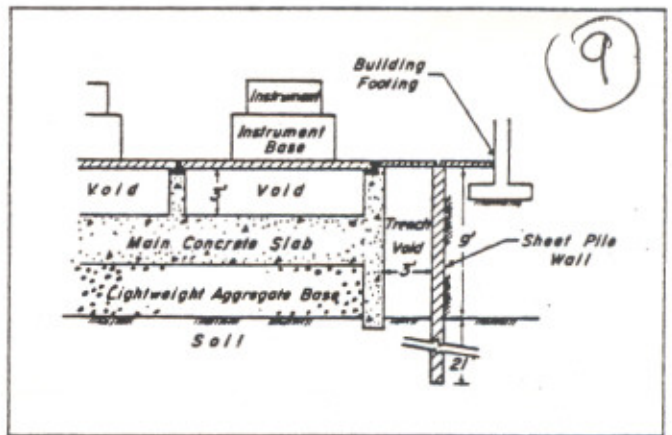


Figure 9 - Example of passive isolation (after McNeill, Margason, and Babcock⁽²¹⁾).

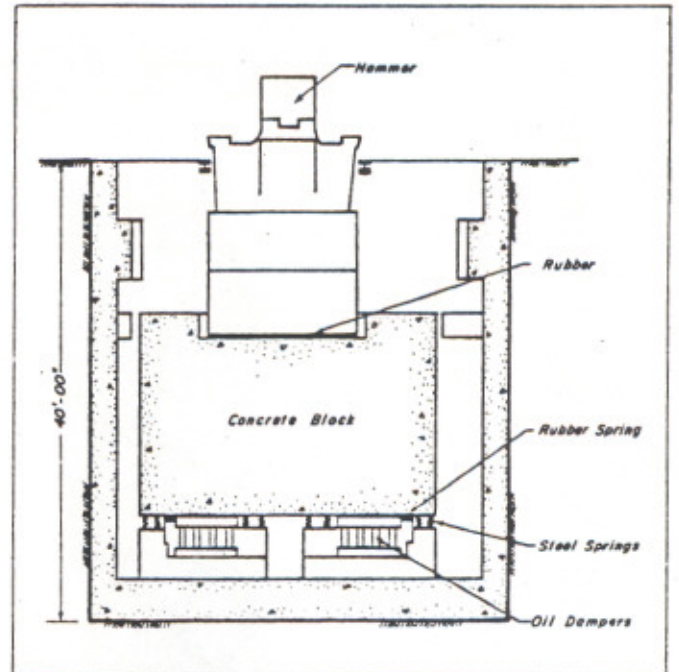


Figure 10 - A very large forging hammer foundation with absorbers (after Crockett⁽¹¹⁾).

If the foundation soil is granular, chemical solidification of the soil may be an efficient and economical method of reducing vibrations. Tschebotarioff,⁽²²⁾ reported a case study in which the use of chemical grouting reduced the amplitude of vibration to about one-seventh of the original movement of the foundation block.

Sand and gravel beds have been placed under buildings in attempts to reduce vibrations and noise transmission. However, it is now recognized^(24, 28) that such practices do little in reducing vibrations transmitted to a building. In fact placement of loose sands under structures may be detrimental to building or equipment function due to differential settlement and tilting.

Summary

A review of the nature and sources of ground vibration has been presented. The sources of vibrations that have been discussed include: road and rail traffic, construction machinery, and pile driving and blasting operations. Vibrations from these sources may be steady-state such as vibrations emitted from a machine foundation or a sonic pile driver or transient such as those caused by blasting or traffic.

Ground vibration from the above sources may range in

intensity from damaging to structures to barely perceptible to humans. Published information indicates that levels of traffic induced vibrations are rarely high enough to cause damage to structures unless densification of cohesionless soils occurs or vibration sensitive equipment is present. Vibrations from construction machinery, pile driving, and blasting are of temporary nature and can frequently be adequately controlled by proper planning of the construction operations and judicious use of the vibration causing equipment.

Where ground vibration causes some concern, vibration control schemes can be employed. Such methods were briefly discussed in this article and case studies where some of these techniques have been successfully implemented were presented. For a successful vibration control, it is imperative for the engineer to have a good knowledge of the theory of wave propagation, the wave transmission properties of earth materials involved, and the nature and type of ground vibration which is to be controlled.

References

1. Anonymous, (1963), "Floating Foundations Isolate Vibrations," *Engineering*, London, 22 February.
2. Anonymous, (1965), "Anti-Vibration Pads in Building Structures," *Engineering*, London, 29 January.
3. Anonymous, (1965), "Absorbent Anti-Vibration Mountings," *Engineering*, London, 29 January.
4. Anonymous, (1957), "Vibration Isolators Steady Plant Walls," *Engineering News-Record*, Vol. 159, No. 9, August.
5. Anonymous, (1963), "Anti-Vibration Pads for Railway Buildings," *Engineering*, London, 14 June.
6. Alpan, I., (1966), "The Passive Isolation of a Precision Autograph," Symposium, Vibration in Civil Engineering, London.
7. Alpan, I. and Meidav, Ts., (1963), "The Effect of Pile Driving on Adjacent Buildings, A Case History," Proceedings, RILEM, Budapest, Vol. II.
8. Barkan, (1962), *Dynamics of Bases and Foundations*, McGraw-Hill.
9. Brandell, F. J. (1949), "Ground Vibration Due to Blasting and its Effect Upon Structures," *Boston Society of Civil Engineers*, Vol. 36, No. 2.
10. Crockett, J. H. A., (1963), "Traffic Vibration Damage in Medieval Cathedrals," Proceedings, RILEM, Budapest, Vol. I.
11. Crockett, J. H. A., (1966), "Some Practical Aspects of Vibration in Civil Engineering," Symposium, Vibration in Civil Engineering, London.
12. Dalmatov, B. L., Ershov, V. A. and Kovalevsky, E. D., (1967), "Some Cases of Foundation Settlement in Driving Sheet-piling and Piles," Proceedings International Symposium on Wave Propagation and Dynamic Properties of Earth Materials, August, Albuquerque, New Mexico.

13. Dolling, J. J., (1966), "Efficiency of Trenches in Isolating Structures Against Vibrations," Symposium, Vibration in Civil Engineering, London.
14. Dowance, G. and Seguin, M., (1966), "Effects of Vibrations on Buildings," Symposium, Vibrations in Civil Engineering, London.
15. Ferahian, R. H. and Hurst, W. D. (1968), "Vibration and Possible Building Damage Due to Operation of Construction Machinery," American Public Works Assoc. 1968 Yearbook.
16. Hendron, A. J. and Dowling, C. H. (1974), "Ground and Structural Response Due to Blasting," 3rd International Congress, International Society for Rock Mechanics, September, Denver, Colorado.
17. Hendron, A. J. and Oriard, L. L., (1972), "Specifications for Controlled Blasting in Civil Engineering Projects," Proceedings of the 1st North American Rapid Excavation and Tunneling Conference, Chicago, Illinois, June.
18. Korenev, B. G., Pikulev, N. A. and Sheinin, J. S., (1963), "Transient Resonance During Starting and Stop of Equipment and Some Methods of Reducing Vibrations," Proceedings, RILEM, Budapest, Vol. II.
19. Luna, W. A., (1967), "Ground Vibrations Due to Pile Driving," Raymond Foundation Facts, Vol. III, No. 2.
20. Major, A., (1962), "Vibration Analysis and Design of Foundations for Machines and Turbines," Collet's Holding Limited, London.
21. McNeill, R. L., Margason, B. E. and Babcock, F. M., (1965), "The Role of Soil Dynamics in The Design of Stable Test Pads," AIAA, Guidance and Control Conference, Minneapolis, Minnesota.
22. Newmark, N. M., (1965), "Notes on Shock Isolation Concepts," Symposium, Vibration in Civil Engineering, London.
23. Northwood, T. D., (1973), "Isolation of Building Structures from Ground Vibration," ASME, Design Engineering Conference, Isolation of Mechanical Vibration Impact and Noise, September.
24. Northwood, T. D., Crawford, R. and Edwards, A. T., (1963), "Blasting Vibrations and Building Damage," *The Engineer*, London, May.
25. Racicots, R. L. and Scanlan, R. H., (1967), "Studies on Foundation Design for Isolation from Ground Vibration," Proceedings International Symposium on Wave Propagation and Dynamic Properties of Earth Materials, ASCE Conference, Albuquerque, New Mexico.
26. Richart, R. E., Hall, J. R., and Woods, R. D., (1970), *Vibrations of Soils and Foundations*, Prentice-Hall, Inc.
27. Soliman, J. I., (1963), "Criteria for Permissible Levels of Industrial Vibrations with Regard to Their Effect on Human Beings and Buildings," Proceedings, RILEM, Budapest, Vol. I.
28. Steffens, R. J. (1966), "Some Aspects of Structural Vibration," Symposium, Vibration in Civil Engineering, London.
29. Sutherland, H. B., (1950), "A Study of the Vibrations Produced in Structures by Heavy Vehicles," Proceedings, 30th Annual Meeting, Highway Research Board.
30. Terzaghi, K. and Peck, R. B., (1957), *Soil Mechanics in Engineering Practice*, John Wiley and Sons, Second Edition.
31. Tschebotarioff, G. P., (1964), "Vibration Controlled by Chemical Grouting," *Civil Engineering*, May.
32. Waller, R. A., (1966), "Some Economic Aspects of Anti-Vibration Devices," Symposium, Vibrations in Civil Engineering, London.
33. Whitman, R. V. and Richart, F. E., (1967), "Design Procedure for Dynamically Loaded Foundations," ASCE, Soil Mechanics and Foundation Division, November SM6.
34. Whitman, R. V., (1974), Personal Communications with Professor R. V. Whitman, Massachusetts Institute of Technology, Cambridge, Mass.
35. Wiss, J. F., (1967), "Damage Effects of Pile Driving Vibration," Highway Research Report No. 155.
36. Woods, R. D., (1968), "Screening of Surface Waves in Soils," *Journal of Soil Mechanics and Foundation Division*, ASCE, July SM4.
37. Woods, R. D. and Richart, F. E., (1967), "Screening of Elastic Surface Waves by Trenches," Proceedings, International Symposium on Wave Propagation and Dynamic Properties of Earth Materials, August, ASCE Conference, Albuquerque, New Mexico.

