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Transportation and Construction Vibration Guidance Manual

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California Department of Transportation
Division of Environmental Analysis
Environmental Engineering
Hazardous Waste, Air, Noise, Paleontology Office

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15. Abstract This manual provides practical guidance to Caltrans engineers, planners, and consultants who must address vibration issues associated with the construction, operation, and maintenance of California Department of Transportation (Caltrans) projects. The guidance and procedures provided in this manual should be treated as screening tools for assessing the potential for adverse effects related to human perception and structural damage. General information on the potential effects of vibration on vibration-sensitive research and advanced technology facilities is also provided, but a discussion of detailed assessment methods in this area is beyond the scope of this manual. Chapters 9 and 10 are a primary reference for developing a vibration monitoring plan for construction activities.		
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Acronyms and Abbreviations

A	acceleration
AASHTO	American Association of State Highway and Transportation Officials
Caltrans	California Department of Transportation
dB	Decibels
D_s	Square-Root Scaled Distances
FFT	fast fourier transform
FTA	Federal Transit Administration
ft-lbs.	foot-pounds
g	acceleration of gravity
Hz	Hertz
ICE	International Construction Equipment
in.	inches
in/sec	inches per second
in/sec^2	inches per second per second
ISO	International Standards Organization
kg	kilograms
kHz	kilo-Hertz
lbs	pounds
L_v	Vibration velocity level
mm	millimeters
mm/sec	mm/sec
mm/sec^2	mm/sec per second
MRI	magnetic resonance imaging
ms	millisecond
NCHRP	National Cooperative Highway Research Program
NIST	National Institute of Standards and Technology
OSMRE	Office of Surface Mining and Reclamation Enforcement

PETN	pentaerythritol tetranitrate
PPA	peak particle acceleration
PPV	peak particle velocity
psi	pounds per square inch
P-wave	primary waves
RI	Report of Investigations
rms	root-mean-square
R-wave	Rayleigh wave
sec.	seconds
S-wave	shear waves
USBM	U.S. Bureau of Mines
V	velocity
VdB	velocity level in decibels

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Chapter 1
Introduction and Background

This manual provides practical guidance to Caltrans engineers, planners, and consultants who must address vibration issues associated with the construction, operation, and maintenance of California Department of Transportation (Caltrans) projects.

Operation of construction equipment and construction techniques such as blasting generate ground vibration. Maintenance operations and traffic traveling on roadways can also be a source of such vibration. If its amplitudes are high enough, ground vibration has the potential to damage structures, cause cosmetic damage (e.g., crack plaster), or disrupt the operation of vibration-sensitive equipment such as electron microscopes and advanced technology production and research equipment. Ground vibration and groundborne noise can also be a source of annoyance to individuals who live or work close to vibration-generating activities. Pile driving, demolition activity, blasting, and crack-and-seat operations are the primary sources of vibration addressed by Caltrans. Traffic, including heavy trucks traveling on a highway, rarely generates vibration amplitudes high enough to cause structural or cosmetic damage. However, there have been cases in which heavy trucks traveling over potholes or other discontinuities in the pavement have caused vibration high enough to result in complaints from nearby residents. These types of issues typically can be resolved by smoothing the roadway surface.

Freight trains, mass-transit trains, and light-rail trains can also be significant sources of ground vibration and groundborne noise in the environment. Caltrans is usually not involved in the construction of rail projects. There are, however, instances in which construction or modification of a roadway requires the relocation of existing rail lines. In these cases, Caltrans must consider the effects on ground vibration associated with relocated existing tracks.

The guidance and procedures provided in this manual should be treated as screening tools for assessing the potential for adverse effects related to human perception and structural damage. General information on the potential effects of vibration on vibration-sensitive research and advanced technology facilities is also provided, but a discussion of detailed assessment methods in this area is beyond the scope of this manual. Most situations involving research and advanced technology facilities will require consultation with experts with specialized expertise in this area.

The information in this manual is meant to be informative and educational to those individuals who must address vibration from construction equipment, explosives, and facility operations. As such, the information presented herein is considered both reliable and accurate. However, because the authors have no control over the conditions under which the information might be used, any and all risk associated with the use of the information contained herein lies with the user of this manual. This document is not an official policy, standard, specification, or regulation and should not be used as such. Its content is for informational purposes only.

This manual does not supersede previous Caltrans publications on earthborne vibration. Rather, it is intended to supplement previous publications and to improve knowledge and information related to this issue. Caltrans has been involved in the evaluation of earthborne vibration since 1958 and has conducted numerous studies since that time. A Caltrans report titled *Survey of Earth-borne Vibrations due to Highway Construction and Highway Traffic* (Report CA-DOT-TL-6391-1-76-20) compiled a summary of results, findings, and conclusions of 23 studies completed in the 17-year period between 1958 and 1975. A Caltrans technical advisory titled *Transportation Related Earthborne Vibrations (Caltrans Experiences)* (Technical Advisory TAV-02-01-R9601) that was prepared in 1996 and updated in 2002 provides information from these 23 studies and other Caltrans vibration studies. This technical advisory is provided in Appendix A.

The following is an overview of the information presented in this manual. Because of the unique nature and effects of blasting, a separate chapter on that topic is presented.

- **Chapter 1, "Introduction and Background,"** summarizes the layout of this manual and provides background information on groundborne vibration.

- **Chapter 2, "Basic Physics of Ground Vibration,"** discusses the basic physics of groundborne vibration.

- **Chapter 3, "Vibration Sources,"** discusses the various sources of groundborne vibration that are of concern to Caltrans.

- **Chapter 4, "Vibration Propagation,"** discusses groundborne vibration wave types and vibration propagation models.

- **Chapter 5, "Vibration Receivers,"** discusses vibration receivers that are of concern to Caltrans: people, structures, and equipment.

- **Chapter 6, "Vibration Criteria,"** summarizes various vibration criteria that have been developed over the years.

- **Chapter 7, "Vibration Screening Assessment for Construction Equipment,"** presents a simplified procedure for assessing groundborne vibration from construction equipment.

- **Chapter 8, "Methods for Reducing Vibration,"** presents approaches to reducing the adverse effects of construction vibration.

- **Chapter 9, "General Procedures for Addressing Vibration Issues,"** discusses general procedures that can be used to avoid vibration-related problems.

- **Chapter 10, "Vibration Measurement and Instrumentation,"** discusses methods and tools used to measure and analyze vibration effects.

- **Chapter 11, "Vibration and Air-Overpressure from Blasting,"** presents information on groundborne vibration and air overpressure generated by blasting.

- **Chapter 12, "References and Additional Reading,"** lists additional sources of information.

- **Appendix A, "Technical Advisory TAV-02-01-R9601."**

- **Appendix B, "Sample Vibration Screening Procedure and Vibration Complaint Form."**

- **Appendix C, "Sample Vibration Specification."**

- **Appendix D, "Sample Blasting Vibration Specifications."**

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- David M. Buehler, P.E., ICF: primary author and editor

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- Bruce Rymer, P.E., Caltrans technical review
- James Nelson, PhD, P.E., Wilson-Ihrig Associates: technical review

Chapter 2
Basic Physics of Ground Vibration

2.1 Simple Vibratory Motion

Dynamic excitation of an elastic system, such as the ground or a structure, results in movement of the particles that compose the elastic system. An idealized system of lumped parameters is commonly used to describe and evaluate the response of the elastic or vibratory system to excitation. The simplest lumped parameter system is called a "single-degree of freedom system with viscous damping." This system comprises a mass (to represent the weight of the system), a spring (to represent the elasticity of the system), and a dashpot (to represent damping in the system). Figure 1 is graphic representation of this idealized system.

The following equation, which excludes the effects of damping, can be used to describe the vibratory motion of a mass in this simple system:

$$D = D_{pk} \sin(2\pi f t) \qquad \text{(Eq. 1.)}$$

Where:

D = displacement from the at-rest position at a given point in time

D_{pk} = maximum or peak displacement amplitude from the at-rest position

π = ~3.1416

f = rate of oscillation expressed in cycles per second, or Hertz (Hz)

t = time in seconds [sec.]

Figure 2 depicts the quantities that are used to describe the vibratory motion.

As the mass oscillates up and down past the at-rest position, the motion can be described as follows. When the mass is at the maximum point of displacement with the spring either compressed or extended, the velocity of the mass is zero and the acceleration of the mass is at a maximum. Conversely, as the mass passes through the point of zero displacement, the velocity is at a maximum and the acceleration is zero.

The velocity (V) of the mass can be determined by taking the time derivative of the displacement, which is equivalent to multiplying the displacement by $2\pi f$:

$$V = 2\pi f \times D \qquad \textit{(Eq. 2)}$$

The acceleration (A) of the mass can be determined by taking the second time derivative of displacement, or the time derivative of the velocity:

$$A = 2\pi f \times V = (2\pi f)^2 \times D \qquad \textit{(Eq. 3)}$$

Therefore, if the frequency and amplitude of displacement, velocity, or acceleration are known, the remaining amplitudes can be determined by differentiation or integration. For example, if the frequency and amplitude of velocity are known, the displacement amplitudes can be determined by integration (dividing by $2\pi f$) and the acceleration amplitude can be determined by differentiation (multiplying by $2\pi f$).

2.2 Amplitude Descriptors

In describing vibration in the ground and in structures, the motion of a particle (i.e., a point in or on the ground or structure) is used. The concepts of particle displacement, velocity, and acceleration are used to describe how the ground or structure responds to excitation. Although displacement is generally easier to understand than velocity or acceleration, it is rarely used to describe ground and structureborne vibration because most transducers used to measure vibration directly measure velocity or acceleration, not displacement. Accordingly, vibratory motion is commonly described by identifying the peak particle velocity (PPV) or peak particle acceleration (PPA). This is the zero-to-peak amplitude indicated in Figure 2.

PPV is generally accepted as the most appropriate descriptor for evaluating the potential for building damage. For human response, however, an average vibration amplitude is more appropriate because it takes time for the human body to respond to the excitation (the human body responds to an average vibration amplitude, not a peak amplitude). Because the average particle velocity over time is zero, the root-mean-square (rms) amplitude is typically used to assess human response. The

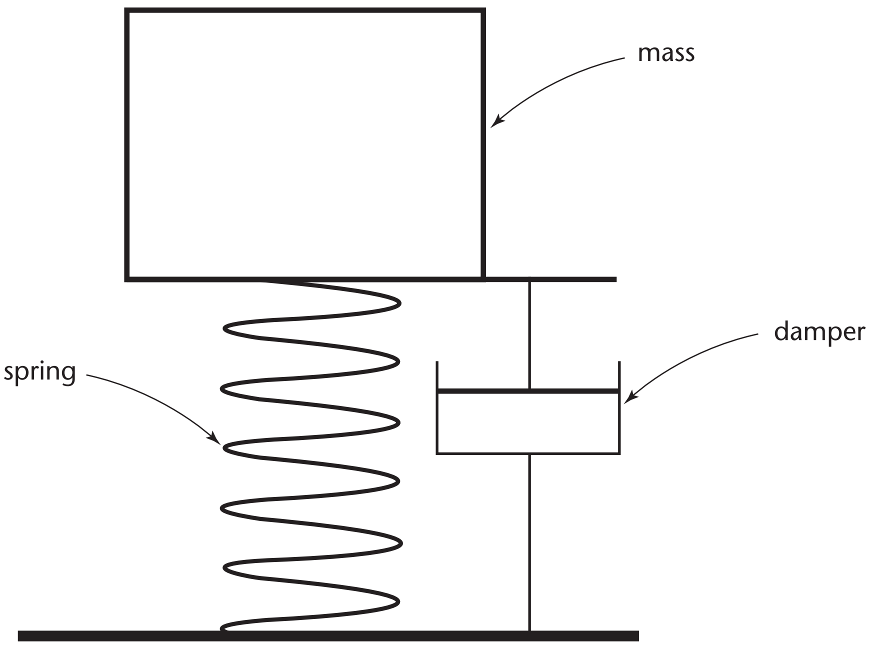

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Figure 1
Simple Lumped-Parameter Vibratory System

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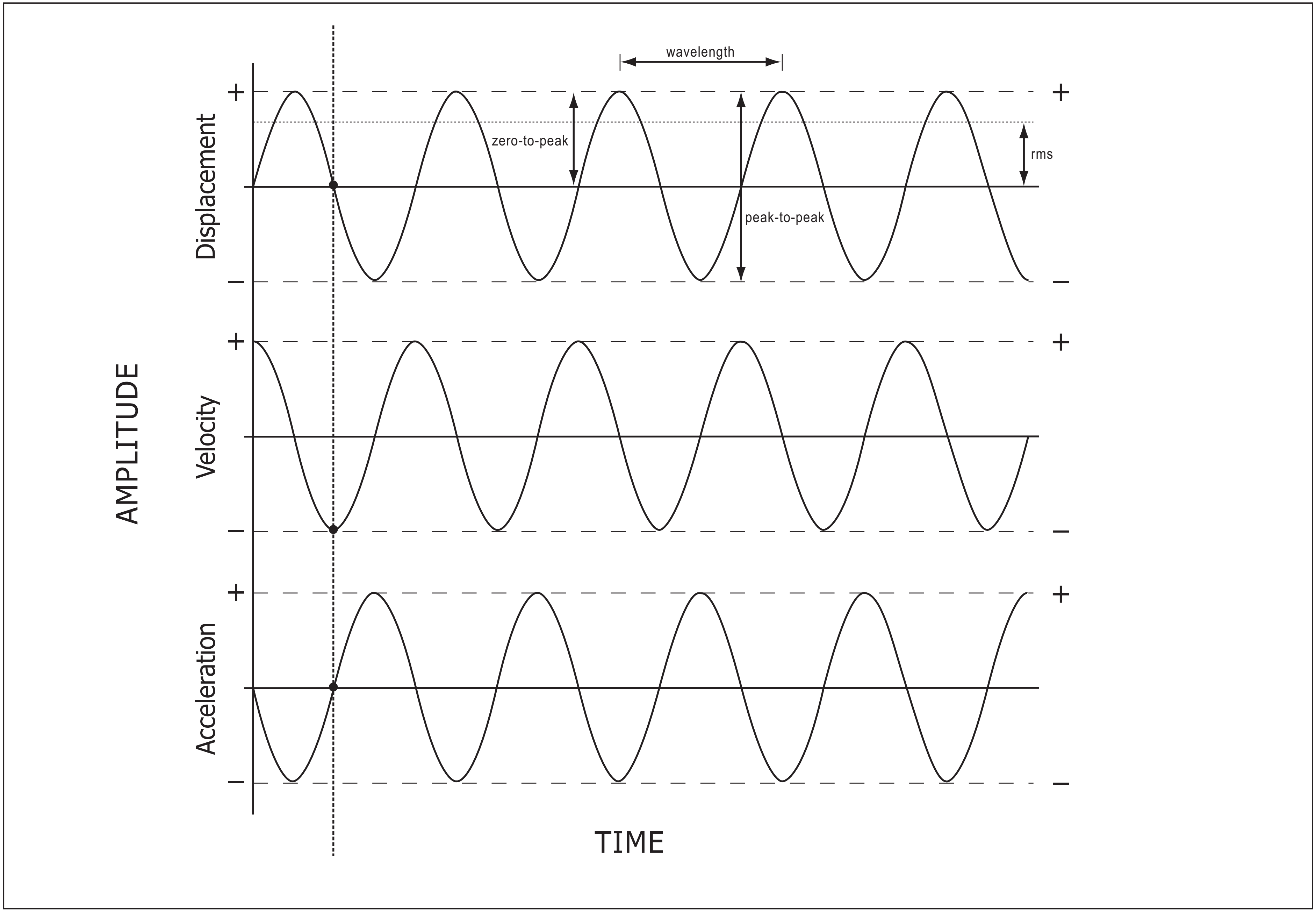

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Figure 2
Quantities Used to Describe Vibratory Motion

rms value is the average of the amplitude squared over time, typically a 1-sec. period (Federal Transit Administration 2018). The rms value is always positive and always less than PPV; for a single frequency condition, the rms value is about 70% of the PPV. The rms amplitude is indicated in Figure 2. The crest factor is the ratio of the peak amplitude to the rms amplitude. For a sine wave, the crest factor is 1.414. For random ground vibration such as vibration from trains, the crest factor is 4. For vibration from pile driving and other impact sources, the crest factor cannot be readily defined because it depends on the averaging time of the rms measurement.

Displacement is typically measured in inches (in.) or millimeters (mm). Velocity is measured in inches per second (in/sec) or millimeters per second (mm/sec). Acceleration is measured in in/sec per second (in/sec^2), mm/sec per second (mm/sec^2), or relative to the acceleration of gravity (g) (32.2 feet [ft.]/sec^2 or 9.8 meters [m]/sec^2).

Decibels (dB) are also commonly used to compress the range of numbers required to describe vibration. Vibration velocity level (L_v) in dB is defined as follows (Federal Transit Administration 2018).

$$L_v = 20 \times \log_{10}(v/v_{ref}) \qquad \textit{(Eq. 4)}$$

Where:

L_v = *velocity level in decibels (VdB)*

v = *rms velocity amplitude*

v_{ref} = *reference velocity amplitude*

In the United States, v_{ref} is usually 1 x 10^{-6} in/sec (1 μ-in/sec). For example, an rms value of 0.0018 in/sec is equal to a vibration velocity level of 65 VdB (re: 1 μ-in/sec). In this manual, all vibration velocity dB values are expressed relative to 1 u-in/sec rms. Vibration in terms of PPV is referred to as vibration velocity amplitude, whereas vibrations in terms of VdB is referred to as vibration velocity level.

When discussing vibration amplitude, the direction of the particle motion must be considered. Vibration amplitude can be described in terms a vertical component; a horizontal longitudinal component; a horizontal transverse component; and the resultant, which is the vector sum of the horizontal and vertical components. Caltrans most often uses a vertical PPV descriptor because vibration amplitude along the ground surface is usually, but not always, greatest in the vertical direction (Hendriks 2002). More importantly, the vertical component is usually representative of the vibration in all three orthogonal directions and is most easily measured.

In addition to the three translational axes discussed above, particle motion can also be rotational or angular along three rotational axes. Rotational particle motion is generally not a concern with regard to human or structure response. However, certain semiconductor tools, radar antennas, and telescopes are sensitive to rotational vibration. A detailed discussion of rotational particle motion is beyond the scope of this manual.

Chapter 3
Vibration Sources

The duration and amplitude of vibration generated by construction and maintenance equipment varies widely depending on the type of equipment and the purpose for which it is being used. The vibration from blasting has a high amplitude and short duration, whereas vibration from grading is lower in amplitude but longer in duration. In assessing vibration from construction and maintenance equipment, it is useful to categorize the equipment by the nature of the vibration generated. Various equipment categories according to type of vibration and/or activities in each category are discussed below.

Equipment or activities typical of continuous vibration include:

- excavation equipment,
- static compaction equipment,
- tracked vehicles,
- traffic on a highway,
- vibratory pile drivers,
- pile-extraction equipment, and
- vibratory compaction equipment.

Equipment or activities typical of single-impact (transient) or low-rate repeated impact vibration include:

- impact pile drivers,
- blasting,
- drop balls,
- “pogo stick” compactors, and

- crack-and-seat equipment.

Equipment typical of high-rate repeated impact vibration includes jackhammers, hoe rams, and some types of pavement breakers.

Because vehicles traveling on highway are supported on flexible suspension systems and pneumatic tires, these vehicles are not an efficient source of ground vibration. They can, however, impart vibration into the ground when they roll over pavement that is not smooth. Continuous traffic traveling on a smooth highway creates a fairly continuous but relatively low level of vibration. Where discontinuities exist in the pavement, heavy truck passages can be the primary source of localized, intermittent vibration peaks. These peaks typically last no more than a few seconds and often for only a fraction of a second. Because vibration drops off rapidly with distance, there is rarely a cumulative increase in ground vibration from the presence of multiple trucks. In general, more trucks result in more vibration peaks, though not necessarily higher peaks. Automobile traffic normally generates vibration amplitudes that are one-fifth to one-tenth the amplitude of truck vibration amplitudes. Accordingly, ground vibration generated by automobile traffic is usually overshadowed by vibration from heavy trucks.

Freight trains, commuter rail trains, mass-transit trains, and light-rail trains can also be significant sources of ground vibration in the environment. Although Caltrans is usually not involved in the construction of rail projects, there are instances in which construction or modification of a roadway requires the relocation or existing rail lines. In these cases, Caltrans must consider the effects on ground vibration associated with relocated existing tracks. Factors that affect the amount of vibration generated by a train include:

- stiffness of the vehicle suspension systems,
- unsprung mass of the wheel sets and trucks,
- roundness of the wheels,
- roughness of the rails and wheels,
- rail support system,
- mass and stiffness of the guideway structure, and
- stiffness and layering of soils supporting the rails.

For a detailed discussion of vibration effects from trains, refer to Federal Transit Administration 2018, Nelson 1987, and U.S. Department of Transportation 1982.

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Chapter 4
Vibration Propagation

4.1 Vibration Wave Types

When the ground is subject to vibratory excitation from a vibratory source, a disturbance propagates away from the vibration source. The ground vibration waves created are similar to those that propagate in water when a stone is dropped into the water. To assess ground vibration propagation over distance, the ground is modeled as an infinite elastic halfspace. The body of this type of medium can sustain two types of waves: “compression” or “primary” waves (P-waves), and “secondary” or “shear” waves (S-waves). These waves are called “body waves.” The particle motion associated with a P-wave is a push-pull motion parallel to the direction of the wave front, whereas particle motion associated with an S-wave is a transverse displacement normal to the direction of the wave front.

In 1885, Lord Rayleigh discovered a third type of wave that can propagate in a halfspace. The motion of this wave, called a Rayleigh wave (R-wave), is confined to a zone near the surface or boundary of the halfspace. The R-wave consists of horizontal and vertical components that attenuate rapidly with depth (Richart 1970). Figure 3 depicts the deformation characteristics of P-, S-, and R-waves.

P-, S-, and R-waves travel at different speeds. The P-wave is the fastest, followed by the S-wave, then the R-wave. For a single short-duration disturbance, the characteristic wave system is shown in Figure 4 (Richart 1970). About 67% of energy is transmitted in the R-wave, 26% in the S-wave, and 7% in the P-wave (Richart 1970). As shown in Figure 5, the P-wave arrives first, followed by the S-wave, then the R-wave, with most of the energy in the R-wave. Along the surface of the ground, the P- and S-waves decay more rapidly than the R-wave. Therefore, the R-wave is the most significant disturbance along the surface of the ground, and it may be the only clearly distinguishable wave at large distances from the source (Richart 1970). However, at higher frequencies the R-wave may not be identifiable because inhomogeneities and layering complicate the propagation of these waves.

4.2 Vibration Propagation Models

When the ground is subject to vibratory excitation, body waves propagate outward radially from the source along a hemispherical wave front, while the R-wave propagates outward radially along a cylindrical wave front. All of these waves encounter an increasingly large volume of material as they travel outward, and the energy density in each wave decreases with distance from the source. This decrease in energy density and the associated decrease in displacement amplitude is called spreading loss. The amplitudes of body waves decrease in direct proportion to the distance from the source, except along the surface, where their amplitudes decrease in direct proportion to square of the distance to the source. The amplitude of R-waves decreases in direct proportion to the square root of the distance from the source.

The general equation for modeling spreading loss (often called “geometric attenuation”) is as follows:

$$v_b = v_a \, (r_a/r_b)^{\gamma} \qquad \textit{(Eq. 5)}$$

Where:

v_a = vibration amplitude of the source at distance r_a

v_b = vibration amplitude at distance r_b

γ = geometric attenuation coefficient

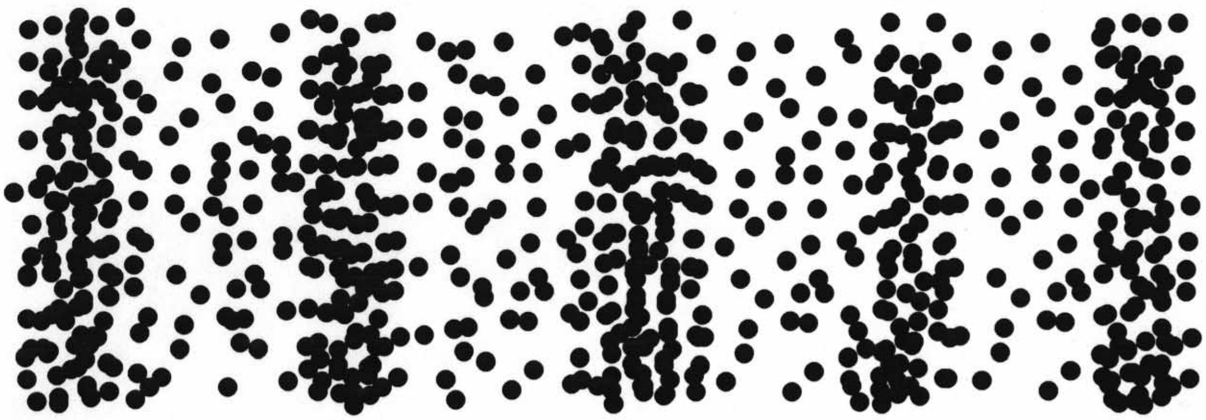
As implied above, the geometric attenuation exponent depends on the wave type and propagation path. Table 1 summarizes the geometric attenuation coefficient by wave type and propagation path.

Table 1. Geometric Attenuation Coefficients

Source	Wave Type	Measurement Point	γ
Point on surface	R	Surface	0.5
Point on surface	Body (P or S)	Surface	2
Point at depth	Body (P or S)	Surface	1
Point at depth	Body (P or S)	Depth	1

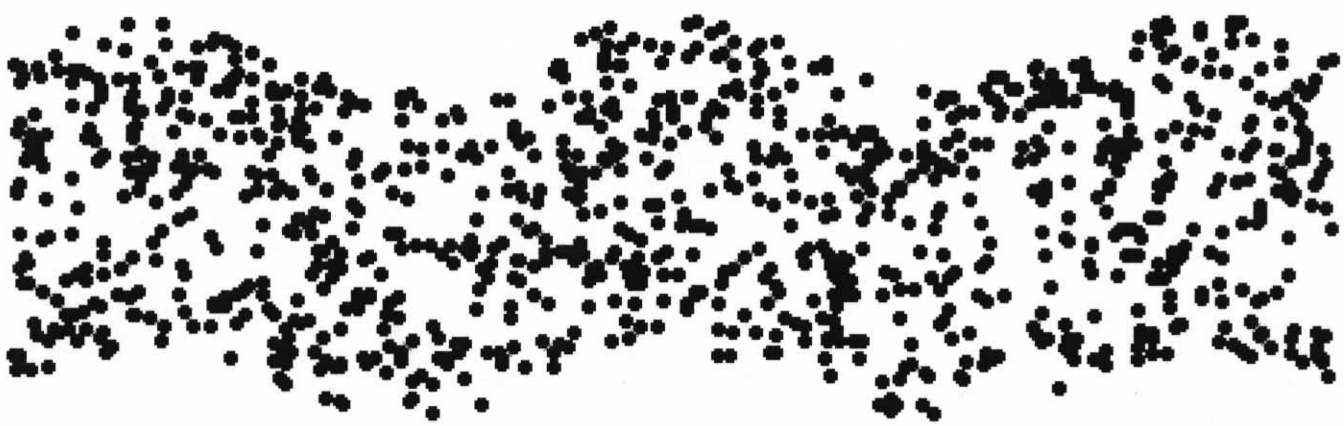
Source: Amick 2000.

Given that two-thirds of the total input energy is transmitted away from a vertically oscillating source by the R-wave and that the R-wave decays much more slowly with distance than body waves, the R-wave is of primary concern for foundations on or near the ground surface (Richart 1970). Most construction settings involve surface or near-surface sources



Compression or Primary Wave (P-Wave)

direction of wave propagation



Shear or Secondary Wave (S-Wave)

Figure 3
Body Wave Types

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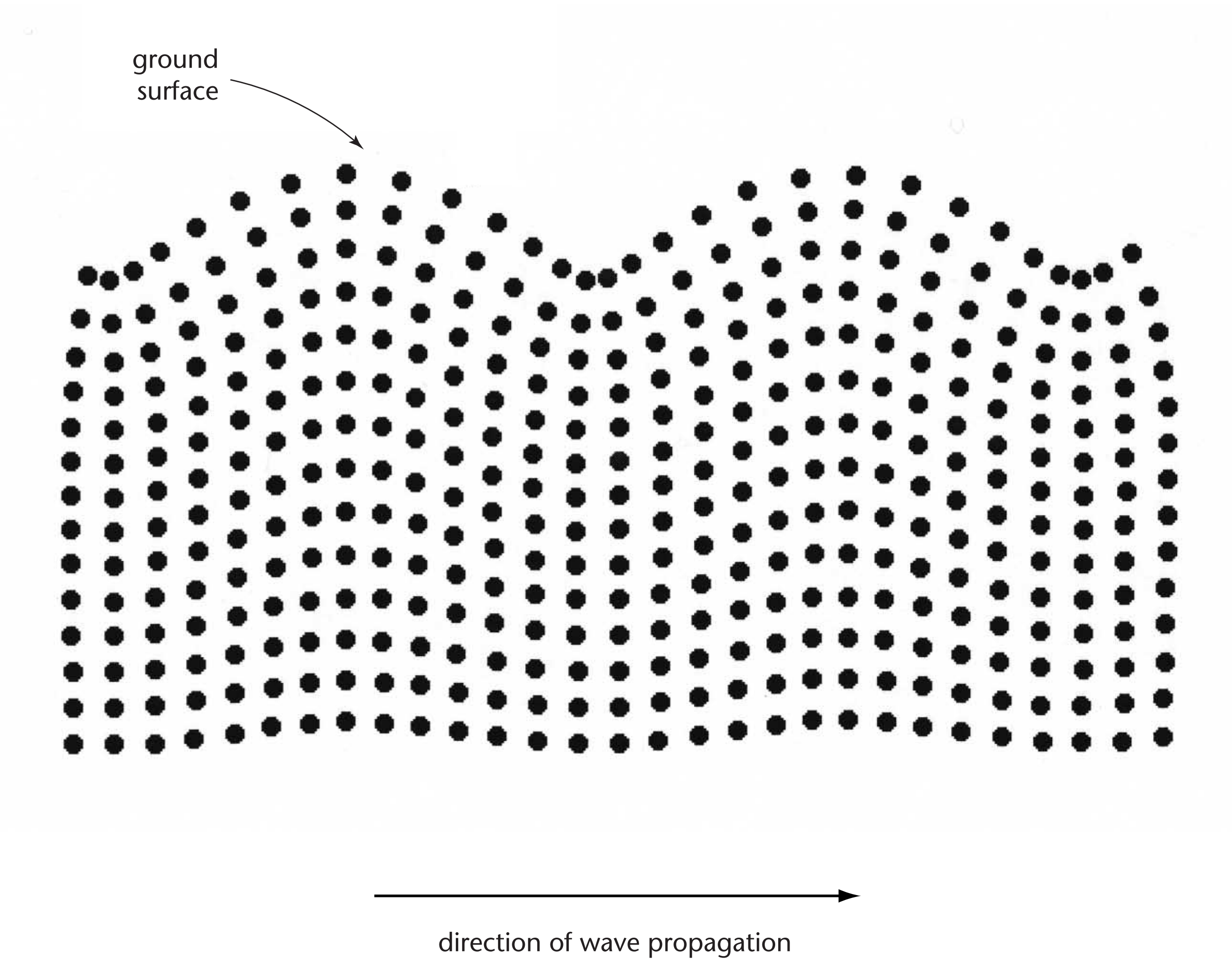

Figure 4
Rayleigh Surface Wave

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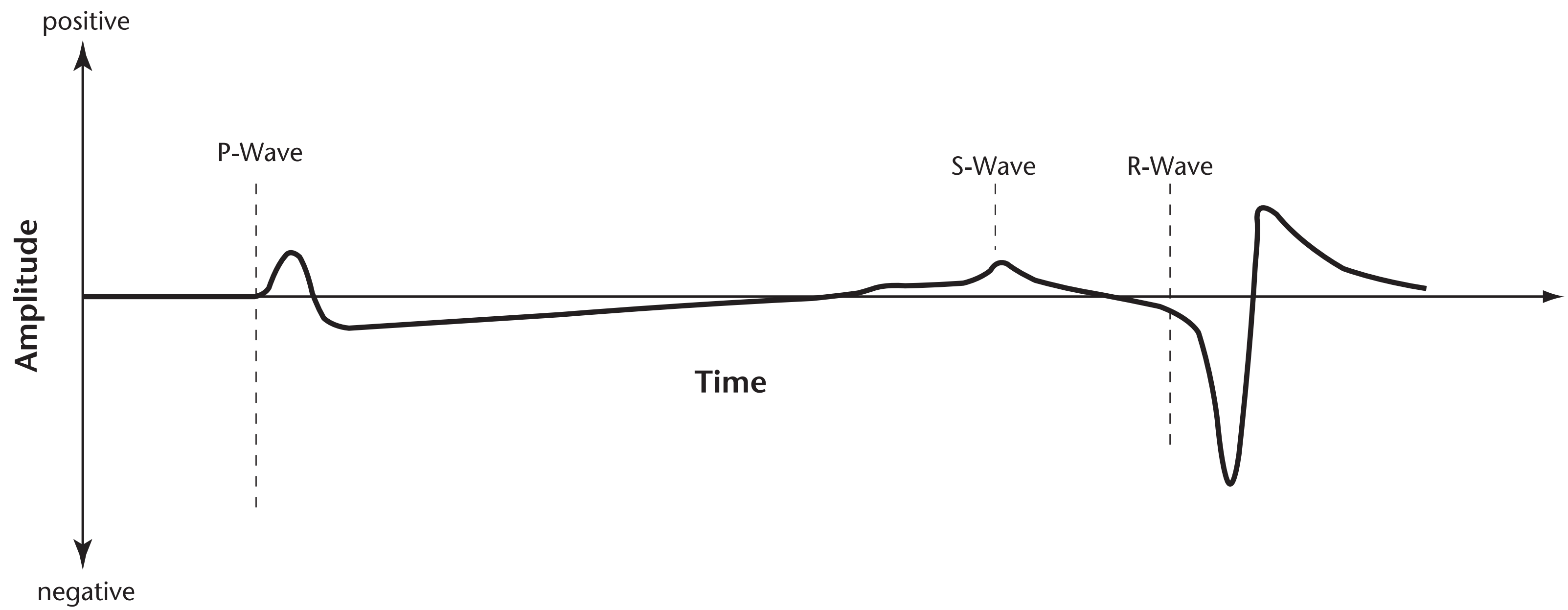

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Figure 5
Wave System from a Surface Point Source

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and receivers, making the R-wave the primary wave of concern. Even when the actual vibration source is below the surface, as with pile driving, R-waves are formed within a few meters of the point on the surface directly above the source (Dowding 1996). Accordingly, propagation of vibration from construction sources, including pile driving, is typically modeled in terms of R-waves (i.e., $\gamma = 0.5$). For a buried source, the R-wave emerges at a distance of about five times the depth from the source.

Because soil is not perfectly elastic, another attenuation factor influences attenuation of R-waves. In real earth materials, energy is lost by material damping (Richart 1970). Material damping is generally thought to be attributable to energy loss due to internal sliding of soil particles. Fluid motion in pores may also produce attenuation. Assuming R-waves are of primary consideration, the effect of material damping can be added to Eq. 5 as follows (Richart 1970):

$$v_b = v_a \, (r_a/r_b)^{0.5} \, e^{a(ra - rb)} \qquad \textit{(Eq. 6)}$$

Where:

α = *material damping coefficient*

Many factors affect material damping in soil, including soil type, moisture content, temperature, and the frequency of the vibration sources. Clays tend to exhibit higher damping than sandy soils (Wiss 1967). Wet sand attenuates less than dry sand because the combination of pore water and sand particles in wet sand does not subject compressional waves to as much attenuation by friction damping as does dry sand. Propagation of R-waves is moderately affected by the presence or absence of water (Richart 1970). Frozen soil attenuates less than thawed soil (Barkan 1962). Table 2 summarizes material damping coefficients for various soil types.

Table 2. Summary of Material-Damping Coefficients (Applies to Both P- and S-Waves)

Investigator	**Soil Type**	**α feet^{-1}**	**α meter^{-1}**
Forssblad	Silty gravelly sand	0.04	0.13
Richart	4-in. concrete slab over compact granular fill	0.006	0.02
Woods	Silty fine sand	0.079	0.26
Barkan	Saturated fine grain sand	0.003	0.010
	Saturated fine grain sand in frozen state	0.018	0.06
	Saturated sand with laminae of peat and organic silt	0.012	0.04
	Clayey sand, clay with some sand, and silt above water level	0.012	0.04
	Marly chalk	0.03	0.1
	Loess and loessial soil	0.03	0.1
	Saturated clay with sand and silt	0.0–0.037	0.0–0.12
Dalmatov	Sand and silt	0.079–0.11	0.026–0.36
Clough, Chameau	Sand fill over bay mud	0.015–0.061	0.05–0.2
	Dune sand	0.076–0.2	0.025–0.65
Peng	Soft Bangkok clay	0.079–0.13	0.026–0.44
Hendriks	Sand-silt, clayey silt, silty sand	0.006	0.021

Sources: Amick 2000, Hendriks 2002 (for Hendricks only).

A more simplified model has been suggested by Wiss (1981), who obtained a best fit of field data with the following equation:

$$V = kD^{-n} \qquad \textit{(Eq. 7)}$$

Where:

V = PPV of the seismic wave

k = value of velocity at one unit of distance

D = distance from the vibration source

n = slope or attenuation rate

The "n" value in this case is not equivalent to the material damping coefficient, but rather is a composite value or pseudo-attenuation coefficient that accounts for both geometric and material damping. Woods and Jedele (1985) developed values for "n" from field construction data. These values were related to generic soil types as indicated in Table 3.

Table 3. "n" Values Based on Soil Classes

Soil Class	Soil Type	"n" Value for Eq. 7
Class I	*Weak or soft soils:* lossy soils, dry or partially saturated peat and muck, mud, loose beach sand, dune sand, recently plowed ground, soft spongy forest or jungle floor, organic soils, topsoil (shovel penetrates easily)	None identified
Class II	Competent soils: *most sands, sandy clays, silty clays, gravel, silts, weathered rock (can dig with a shovel)*	1.5
Class III	*Hard soils:* dense compacted sand, dry consolidated clay, consolidated glacial till, some exposed rock (cannot dig with a shovel, need a pick to break up)	1.1
Class IV	*Hard, competent rock:* bedrock, freshly exposed hard rock (difficult to break with a hammer)	None identified

Source: Wood 1997.

There is a relationship between vibration amplitude and the energy of the driving force (Hendriks 2002). In general, if the energy of the driving force changes from E_1 to E_2, the vibration amplitude changes from V_1 to V_2 according to the following equation:

$$V_2 = V_1(E_2/E_1)^{0.5} \qquad \text{(Eq. 8)}$$

In general, if the vibration amplitude of a source at a given distance is known, Eq. 6 or Eq. 7 can be used to estimate the resulting amplitude at various distances. This methodology, which does not account for the frequency dependence of the material-damping coefficient, provides a convenient and reasonable means of assessing vibration impact on structures and people. This method does not, however, have enough detail to be particularly useful for impact assessment for vibration-sensitive research or advanced technology facilities (Amick 2000). There is a significant body of knowledge that relates human response and building damage to the peak velocity amplitude measured in the time domain. Essentially, this is the function of Eq. 6 and Eq. 7. However, most assessment of the impact of vibration on research and advanced technology facilities is based on measurement and analysis in the frequency domain using frequency spectra (typically one-third octave spectra). The assessment of frequency-dependent vibration propagation is beyond the scope of this guidance manual.

For the purposes of assessing vibration effects on people and structures, use of a frequency- independent material-damping coefficient is supported by the fact that damage levels in terms of velocity in the frequency range of 1–80 Hz tend to be independent of frequency. This is also true for complaint levels in a frequency range of 8–80 Hz. Typical vibration from transportation and construction sources typically falls in the range of 10–30 Hz and usually centers around 15 Hz (Hendriks 2002). Within the narrow range of frequencies associated with most sources, frequency independence is a reasonable assumption.

Chapter 7 discusses a suggested method for applying propagation models to the assessment of groundborne vibration from construction equipment. Chapter 8 discusses a method relating to blasting.

Chapter 5
Vibration Receivers

There are three primary types of receivers that can be adversely affected by ground vibration: people, structures, and equipment.

Ground vibration can be annoying to people. The primary effect of perceptible vibration is often a concern. However, secondary effects, such as the rattling of a china cabinet, can also occur, even when vibration levels are well below perception. Any effect (primary perceptible vibration, secondary effects, or a combination of the two) can lead to annoyance. The degree to which a person is annoyed depends on the activity in which they are participating at the time of the disturbance. For example, someone sleeping or reading will be more sensitive than someone who is running on a treadmill. Reoccurring primary and secondary vibration effects often lead people to believe that the vibration is damaging their home, although vibration levels are well below minimum thresholds for damage potential.

Vibration generated by construction activity has the potential to damage structures. This damage could be structural damage, such as cracking of floor slabs, foundations, columns, beams, or wells, or cosmetic architectural damage, such as cracked plaster, stucco, or tile.

Ground vibration also has the potential to disrupt the operation of vibration-sensitive research and advanced technology equipment. This equipment can include optical microscopes, cell probing devices, magnetic resonance imaging (MRI) machines, scanning electron microscopes, photolithography equipment, micro-lathes, and precision milling equipment. The degree to which this equipment is disturbed depends on the type of equipment, how it used, and its support structure. For example, equipment supported on suspended floors may be more susceptible to disturbance than equipment supported by an on-grade slab.

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Chapter 6
Vibration Criteria

Over the years, numerous vibration criteria and standards have been suggested by researchers, organizations, and governmental agencies. There are no Caltrans or Federal Highway Administration standards for vibration, and it is not the purpose of this manual to set standards. Rather, the following discussion provides a summary of vibration criteria that have been reported by various researchers, organizations, and governmental agencies. The information is used in this chapter to develop a synthesis of these criteria that can be used to evaluate the potential for damage and annoyance from vibration-generating activities. In addition to the criteria discussed in this chapter, additional criteria that apply specifically to blasting are provided in Chapter 11.

6.1 People

Numerous studies have been conducted to characterize the human response to vibration. Table 4 summarizes the results of an early study (Reiher 1931) on human response to steady-state (continuous) vibration. Human response to vibration generated by blasting is discussed in Chapter 8.

Table 4. Human Response to Steady State Vibration

PPV (in/sec)	**Human Response**
3.6 (at 2 Hz)–0.4 (at 20 Hz)	Very disturbing
0.7 (at 2 Hz)–0.17 (at 20 Hz)	Disturbing
0.10	Strongly perceptible
0.035	Distinctly perceptible
0.012	Slightly perceptible

Table 5 summarizes the results of another study (Whiffen 1971) that relates human response to vibration from traffic (continuous vibration).

Table 5. Human Response to Continuous Vibration from Traffic

PPV (in/sec)	Human Response
0.4–0.6	Unpleasant
0.2	Annoying
0.1	Begins to annoy
0.08	Readily perceptible
0.006–0.019	Threshold of perception

Table 6 summarizes the results of another study (Wiss 1974) that relates human response to transient vibration.

Table 6. Human Response to Transient Vibration

PPV (in/sec)	Human Response
2.0	Severe
0.9	Strongly perceptible
0.24	Distinctly perceptible
0.035	Barely perceptible

The results in Tables 4–6 suggest that the thresholds for perception and annoyance are higher for transient vibration than for continuous vibration.

In 1981, the International Standards Organization (ISO) published *Guide to the Evaluation of Human Exposure to Vibration and Shock in Buildings (1 Hz to 80 Hz)* (ISO 2631). This document, based on the work of many researchers, suggested that humans are sensitive to particle velocity in the range of 8–80 Hz. This means that the same velocity at different discrete frequencies will elicit the same response, such as detection or discomfort. Below 8 Hz, the body is less sensitive to vibration, and therefore responds more uniformly to acceleration (i.e., higher velocities are needed to elicit the same response). Table 7 summarizes the vibration criteria in ISO 2631 for vibration sources with predominant frequencies in the range of 8–80 Hz. It is recommended in ISO 2631 that one-third octave band filtering be used when the vibration source has many closely spaced frequencies or contains broadband energy.

Table 7. ISO 2631 Vibration Criteria

Building Use	Vibration Velocity Level (VdB)	Vibration Velocity rms Amplitude (in/sec)
Workshop	90	0.032
Office	84	0.016
Residence	78 day/75 night	0.008
Hospital operating room	72	0.004

Also, FTA (2018) has developed vibration criteria based on building use. These criteria, shown in Table 8, are based on overall rms vibration levels expressed in VdB.

Table 8. Federal Transit Administration Vibration Impact Criteria

Land Use Category	Vibration Impact Level for Frequent Events (VdB)	Vibration Impact Level for Occasional Events (VdB)	Vibration Impact Level for Infrequent Events (VdB)
Category 1: Buildings where low ambient vibration is essential for interior operations	65	65	65
Category 2: Residences and buildings where people normally sleep	72	75	80
Category 3: Institutional land uses with primarily daytime use	75	78	83

Note: "Frequent events" is defined as more than 70 events per day. "Occasional events" is defined as 30 to 70 events per day. "Infrequent events" is defined as fewer than 70 events per day.

6.2 Structures

The effects of vibration on structures has also been the subject of extensive research. Much of this work originated in the mining industry, where vibration from blasting is a critical issue. The following is a discussion of damage thresholds that have been developed over the years. Mining industry standards relating to structure damage thresholds are presented in Chapter 7.

A study by Chae (1978) classifies buildings in one of four categories based on age and condition. Table 9 summarizes maximum blast vibration amplitudes based on building type. (The study recommends that the categories be lowered by one if the structure is subject to repeated blasting.)

Table 9. Chae Building Vibration Criteria

Class	PPV (Single Blast) (in/sec)	PPV (Repeated Blast) (in/sec)
Structures of substantial construction	4	2
Relatively new residential structures in sound condition	2	1
Relatively old residential structures in poor condition	1	0.5
Relatively old residential structures in very poor condition	0.5	—

The Swiss Association of Standardization has developed a series of vibration damage criteria that differentiates between single-event sources (blasting) and continuous sources (machines and traffic) (Wiss 1981). The criteria are also differentiated by frequency. Assuming that the frequency range of interest for construction and traffic sources is 10–30 Hz, Table 10 shows criteria for 10–30 Hz.

Table 10. Swiss Association of Standardization Vibration Damage Criteria

Building Class	Continuous Source PPV (in/sec)	Single-Event Source PPV (in/sec)
Class I: buildings in steel or reinforced concrete, such as factories, retaining walls, bridges, steel towers, open channels, underground chambers and tunnels with and without concrete alignment	0.5	1.2
Class II: buildings with foundation walls and floors in concrete, walls in concrete or masonry, stone masonry retaining walls, underground chambers and tunnels with masonry alignments, conduits in loose material	0.3	0.7
Class III: buildings as mentioned above but with wooden ceilings and walls in masonry	0.2	0.5
Class IV: construction very sensitive to vibration; objects of historic interest	0.12	0.3

Konan (1985) reviewed numerous vibration criteria relating to historic and sensitive buildings, and developed a recommended set of vibration criteria for transient (single-event) and steady-state (continuous) sources. Konan recommended that criteria for continuous vibration be about half the amplitude of criteria for transient sources. Table 11 summarizes the recommended criteria.

Table 11. Konan Vibration Criteria for Historic and Sensitive Buildings

Frequency Range (Hz)	Transient Vibration PPV (in/sec)	Steady-State Vibration PPV (in/sec)
1–10	0.25	0.12
10–40	0.25–0.5	0.12–0.25
40–100	0.5	0.25

Whiffen (1971) presents additional criteria for continuous vibration. These criteria are summarized in Table 12.

Table 12. Whiffen Vibration Criteria for Continuous Vibration

PPV (in/sec)	Effect on Buildings
0.4–0.6	Architectural damage and possible minor structural damage
0.2	Threshold at which there is a risk of architectural damage to normal dwelling houses (houses with plastered walls and ceilings)
0.1	Virtually no risk of architectural damage to normal buildings

0.08	Recommended upper limit of vibration to which ruins and ancient monuments should be subjected
0.006–0.019	Vibration unlikely to cause damage of any type

Siskind et al. (1980) applied probabilistic methods to vibration damage thresholds for blasting. Three damage thresholds have been identified and are described in Table 13 in terms of PPV for probabilities of 5, 10, 50, and 90%.

Table 13. Siskind Vibration Damage Thresholds

	PPV (in/sec)			
Damage Type	**5% Probability**	**10% Probability**	**50% Probability**	**90% Probability**
Threshold damage: loosening of paint, small plaster cracks at joints between construction elements	0.5	0.7	2.5	9.0
Minor damage: loosening and falling of plaster, cracks in masonry around openings near partitions, hairline to 3-mm (0–1/8-in.) cracks, fall of loose mortar	1.8	2.2	5.0	16.0
Major damage: cracks of several mm in walls, rupture of opening vaults, structural weakening, fall of masonry, load support ability affected	2.5	3.0	6.0	17.0

Dowding (1996) suggests maximum allowable PPV for various structure types and conditions. Table 14 summarizes these values.

Table 14. Dowding Building Structure Vibration Criteria

Structure and Condition	Limiting PPV (in/sec)
Historic and some old buildings	0.5
Residential structures	0.5
New residential structures	1.0
Industrial buildings	2.0
Bridges	2.0

The American Association of State Highway and Transportation Officials (AASHTO) (1990) identifies maximum vibration levels for preventing damage to structures from intermittent construction or maintenance activities. Table 15 summarizes the AASHTO maximum levels.

Table 15. AASHTO Maximum Vibration Levels for Preventing Damage

Type of Situation	Limiting Velocity (in/sec)
Historic sites or other critical locations	0.1
Residential buildings, plastered walls	0.2–0.3
Residential buildings in good repair with gypsum board walls	0.4–0.5
Engineered structures, without plaster	1.0–1.5

The National Cooperative Highway Research Program (NCHRP) published a report in September 2012 entitled "Current Practices to Address Construction Vibration and Potential Effects to Historic Buildings Adjacent to Transportation Projects." This report summarizes a detailed literature search on the topic of construction vibration effects on historic building along with information from a survey of state departments of transportation on the topic. The report also provides a suggested guideline approach to assessing these effects. The report can be found at the following NCHRP website:

http://onlinepubs.trb.org/onlinepubs/nchrp/docs/NCHRP25-25(72)_FR.pdf

6.3 Equipment

The operation of equipment for research, microelectronics manufacturing, medical diagnostics, and similar activities can be adversely affected by vibration. For the purposes of designing facilities to house this equipment, vibration criteria that are generic (i.e., applicable to classes of equipment or activity) rather than specific have been developed (Amick et al. 2005). These criteria are expressed in terms of one-third octave band velocity spectra and are summarized in Table 16.

Table 16. Vibration Criteria for Sensitive Equipment

Criterion Curve (see Figure 1)	Max Level[1] (microinches/sec) (dB)	Detail Size[2] (microns)	Description of Use
Workshop (ISO)	32,000	NA	Distinctly perceptible vibration. Appropriate to workshops and nonsensitive areas.
Office (ISO)	16,000	NA	Perceptible vibration. Appropriate to offices and nonsensitive areas.
Residential Day (ISO)	8,000	75	Barely perceptible vibration. Appropriate to sleep areas in most instances. Usually adequate for computer equipment, semiconductor probe test equipment, and microscopes less than 40x.
Op. Theatre (ISO)	4,000	25	Vibration not perceptible. Suitable in most instances for surgical suites, microscopes to 100x and for other equipment of low sensitivity.
VC-A	2,000	8	Adequate in most instances for optical microscopes to 400x, microbalances, optical balances, proximity and projection aligners, etc.
VC-B	1,000	3	Appropriate for inspection and lithography equipment (including steppers) to 3 μ line widths.
VC-C	500	1-3	Appropriate standard for optical microscopes to 1,000x, lithography and inspection equipment (including moderately sensitive electron microscopes) to 1 μ detail size, TFT-LCD stepper/scanner processes.
VC-D	250	0.1-0.3	Suitable in most instances for the most demanding equipment including many electron microscopes (SEMs and TEMs) and E-Beam systems.
VC-E	125	<0.1	A challenging criterion to achieve. Assumed to be adequate for the most demanding of sensitive systems including long path, laser-based, small target systems, E-beam lithography systems working at nanometer scales, and other systems requiring extraordinary dynamic stability.
VC-F	62.5	N/A	Appropriate for extremely quiet research spaces; generally difficult to achieve in most instances, especially cleanrooms. Not recommended for use as a design criterion, only for evaluation.
VC-G	31.3	N/A	Appropriate for extremely quiet research spaces; generally difficult to achieve in most instances, especially cleanrooms. Not recommended for use as a design criterion, only for evaluation.

[1] As measured in one-third octave bands of frequency over the frequency range 8 to 80 Hz (VC-A and VC-B) or 1 to 80 Hz (VC-C through VC-G).

[2] The detail size refers to the line width in the case of microelectronics fabrication, the particle (cell) size in the case of medical and pharmaceutical research, etc. It is not relevant to imaging associated with probe technologies, AFMs, and nanotechnology.

The information given in this table is for guidance only. In most instances, it is recommended that the advice of someone knowledgeable about the applications and vibration requirements of the equipment and process be sought.

Source: Amick et al. 2005.

Chapter 7
Vibration Prediction and Screening Assessment for Construction Equipment

To assess the potential for vibration to annoy people and damage structures, a reasonable means must be available for estimating or predicting the PPV from various sources at various distances. This section describes a simple method for predicting vibration amplitudes from construction equipment, in terms of PPV, for a variety of vibration sources and soil types. A method for evaluating vibration from blasting is provided in Chapter 8. The evaluation of potential vibration impacts on research and advanced technology production equipment is beyond the scope of this manual. Individuals with specialized expertise in the evaluation of these impacts should be contacted in cases where research and advanced technology equipment could be affected.

This assessment of effects relates to the direct effects of vibration on people and structures. For pile driving, there are few cases of direct damage to structures located farther from a pile than the length of that pile. Settlement of soil as the result of pile driving, however, has potential to damage surface and buried structures at greater distances. Assessment of effects related to vibration-related soil settlement is beyond the scope of this manual. Individuals with specialized expertise in vibration-related soil settlement should be consulted in cases where construction-induced vibration could result in soil settlement or liquefaction.

The method presented in this chapter uses reference vibration source amplitudes and the simplified Wiss propagation model (Eq. 7) described in Chapter 4. The following discussion is separated into the following equipment categories: pile drivers, hydraulic breakers, and other construction equipment. Vibration amplitudes estimated using the method presented in this chapter are expected to be *typical worst-case values* and should be viewed as guidelines only. Actual values from equipment used by a contractor may result in vibration amplitudes that exceed or are lower than the estimated values.

7.1 Pile Driving Equipment

A wide variety of impact and vibratory pile driving hammers is used for driving or extracting various types of piles. Commonly used types of pile drivers are described below.

- **Drop hammer:** The simplest form of pile driving hammer is a falling weight called a gravity or drop hammer. In this case, a weight is raised to the desired height by an attached crane hoist line and dropped directly or indirectly onto the pile. The weight can be enclosed in a steel cylinder.

- **Pneumatic hammer:** A pneumatic impact hammer, also called a compressed-air hammer, is essentially a drop hammer in which a ram/piston in a cylinder is propelled upward by compressed air. The ram strikes the pile cap at the end of a downward stroke, which may be in a free fall under gravity (single-acting) or assisted in downward stroke by pressurized air over the piston head to accelerate the ram (double-acting).

- **Diesel hammer:** Diesel impact hammers are similar to pneumatic hammers. However, whereas pneumatic hammers are one-cylinder drivers that require compressed air from an external source, diesel hammers carry their own fuel, from which they generate their power internally. The falling ram compresses the air in the cylinder, and the impact atomizes a pool of diesel fuel at the end of the cylinder. The atomized fuel ignites with the compressed air and propels the ram upward, ready for the next downward stroke. The burnt gases are scavenged from the cylinder on the upward stroke of the ram. Some diesel hammers are provided with an adjustable fuel pump that serves to regulate the jumping height, and thereby the impact energy.

- **Hydraulic hammer:** Hydraulic impact hammers are a relatively new type of hammer. They are similar to the pneumatic impact hammers, except that the ram is lifted hydraulically, using an external hydraulic source, and then is left to fall freely or is accelerated downward by pressurized gas above the piston.

- **Vibratory pile driver:** Vibratory pile drivers advance the pile by vibrating it into the ground. They are especially effective for soils that are vibratorily mobile, such as sands and silts. Vibration is created in the gear case by rotating eccentric weights powered by hydraulic motors, and sometimes by electric motors. Only vertical vibration is created in the gear case. Horizontal vibration is canceled by the paired eccentrics, which are interconnected with gears to maintain synchronization. The vibration created in the gear case is transmitted into the pile being driven or extracted by means of a hydraulic clamp attached to the bottom of the gear case. The complete vibrator assembly is held by crane. To prevent the vibration created in the gear case from affecting the crane line, a vibration suppresser assembly is attached to the top of the gear case.

The rated energies of most pile drivers are in the range of about 20,000–300,000 foot-pounds (ft-lbs.) (Woods 1997). One very large driver, the Vulcan 6300, has a rated energy of 1,800,000 ft-lbs. Smaller drivers have rated energies as low as 300 ft-lbs. (Woods 1997.)

7.1.1 Vibration Amplitudes Produced by Impact Pile Drivers

An extensive review of the available literature (Martin 1980; Wood and Theissen 1982; Wiss 1967, 1974, 1981; Dowding 1996; Federal Transit Administration 2018; Woods 1997; Schexnayder and Ernzen 1999) and information provided by the manufacturers (Preston 2002; Morris 1991, 1996, 1997) indicates that the PPV from impact pile drivers can be estimated by the following equation:

$$PPV_{Impact\ Pile\ Driver} = PPV_{Ref}\ (25/D)^n \times (E_{equip}/E_{Ref})^{0.5} \quad (in/sec) \quad (Eq.\ 9)$$

Where:

PPV_{Ref} = 0.65 in/sec for a reference pile driver at 25 ft.

D = distance from pile driver to the receiver in ft.

n = 1.1 is a value related to the vibration attenuation rate through ground

E_{Ref} = 36,000 ft-lb (rated energy of reference pile driver)

E_{equip} = rated energy of impact pile driver in ft-lbs.

The above equation is based on extensive review of the actual data points at various distances, measured for a wide range of impact pile drivers. The data were measured at the ground surface outside or within various types of buildings.

Literature indicates that the value of “n” in the above equation is generally 1 to 1.5. The suggested value for n is 1.1. The use of values greater than

1.1 would likely result in overestimation of amplitudes at distances closer than 25 ft and would be slightly conservative at distances beyond 25 ft.

If vibration impacts, based on the above approach, are expected to exceed the vibration assessment criteria, vibration estimates may be refined further by using values of “n” that are based on soil type classification, ranging from Class I–IV soils as outlined in the National Cooperative Highway Research Program (NCHRP) Synthesis 253 (Woods 1997), and based on data developed by Woods and Jedele (1985). This step would require detailed information on soil conditions at the site. Table 17 describes soil materials, soil classes, values of “n” determined by Woods and Jedele (1985), and suggested values for “n” for the purposes of estimating vibration amplitude.

Table 17. Measured and Suggested “n” Values Based on Soil Class

Soil Class	Description of Soil Material	Value of “n” measured by Woods and Jedele	Suggested Value of “n”
I	Weak or soft soils: loose soils, dry or partially saturated peat and muck, mud, loose beach sand, and dune sand, recently plowed ground, soft spongy forest or jungle floor, organic soils, top soil. (shovel penetrates easily)	Data not available	1.4
II	Competent soils: most sands, sandy clays, silty clays, gravel, silts, weathered rock. (can dig with shovel)	1.5	1.3
III	Hard soils: dense compacted sand, dry consolidated clay, consolidated glacial till, some exposed rock. (cannot dig with shovel, need pick to break up)	1.1	1.1
IV	Hard, competent rock: bedrock, freshly exposed hard rock. (difficult to break with hammer)	Data not available	1.0

As indicated by Wood and Theissen (1982), the use of published attenuation relationships, based primarily on Wiss (1967) and Attewell and Farmer (1973), relating hammer energies, scaled distances, and PPVs to predict vibration levels in moderately large commercial buildings or in buried structures would probably result in overly conservative estimates. Wiss (1967, 1974, 1981) does not report data points for complete evaluation, but rather presents only generalized curves.

Research by Wood and Theissen (1982) and an evaluation of the available literature indicate that predictions based on Wiss and Attewell and Farmer are likely to be overly conservative. Therefore, it is prudent to be cautious about the upper range of values presented in FTA’s *Transit Noise and Vibration Impact Assessment* guidance manual (Federal Transit Administration 2018) and the NCHRP Synthesis 218 (Schexnayder and Ernzen 1999) for the impact pile drivers, because these higher values appear to be based on Wiss's curves. The typical values for impact pile drivers, reported in these publications, appear to be based on the actual measured data reported by Martin (1980) and form the basis for Eq. 9 above.

7.1.2 Vibration Amplitudes Produced by Vibratory Pile Drivers

Information regarding vibration amplitudes produced by vibratory pile drivers is scarce in published literature. However, Wood (1982) presents some data for vibratory pile drivers. International Construction Equipment (ICE) has also provided some data for the vibratory pile drivers (Morris 1991, 1996, 1997). ICE conducted tests in 1991 with three different vibratory pile drivers and measured vibration levels at several distances between 3 and 100 ft. Wiss (1967, 1974, 1981) also presents some data curves for vibratory pile drivers. A lack of actual data points and inconsistency in the curves presented in different publications suggests that some caution be applied in evaluating the data.

Based on review of the available literature (Wood and Theissen 1982; Wiss 1967, 1974, 1981) and information provided by ICE (Morris 1991, 1996, 1997), vibration amplitudes produced by vibratory pile drivers can be estimated by the following equation:

$$PPV_{Vibratory\ Pile\ Driver} = PPV_{Ref}\,(25/D)^{n} \quad (in/sec) \qquad (Eq.\ 10)$$

Where:

PPV_{Ref} = 0.65 in/sec for a reference pile driver at 25 ft

D = distance from pile driver to the receiver in ft.

n = 1.1 (the value related to the attenuation rate through ground)

The suggested value for "n" is 1.1, the same value used for impact pile drivers. If desired and if soil information is available, the value of "n" may be changed to reflect soil type classification, as shown in Table 17.

Vibratory pile drivers generate the maximum vibration levels during the start-up and shut-down phases of the operation because of the various resonances that occur during vibratory pile driving (Woods 1997). Maximum vibration occurs when the vibratory pile driver is operating at the resonance frequency of the soil-pile-driver system. The frequency depends on properties of the soil strata being penetrated by the pile.

As indicated in the NCHRP Synthesis 253 (Woods 1997), vibration from vibratory pile drivers is related to the centrifugal force, which is proportional to the mass of the rotating eccentric elements, the radius of eccentricity of rotating elements, and the frequency of the rotating elements. Because of the scarcity of available data, the effect of centrifugal force on vibration from vibratory pile drivers could not be evaluated. In the absence of any reliable data, it is recommended that vibration from vibratory pile drivers be estimated by using Eq. 10 above.

Eq. 10 can be used to estimate the vibration amplitude during the resonant start-up and shut-down phases of the pile driving operation. Although there are no actual data that show the relative magnitude of vibration during the primary driving phase, away from the resonance effects, it is estimated that it could be 50% or less of the maximum levels that may occur during the start-up and shut-down phases. The maximum levels during the start-up and shut-down phases are the important values that should be evaluated when assessing potential impacts. Vibration generated during these start-up and shut-down phases is often very perceptible and is the source of most complaints from vibratory pile driving activity.

The FTA's *Transit Noise and Vibration Impact Assessment* (Federal Transit Administration 2018) and NCHRP Synthesis 218 (Schexnayder and Ernzen 1999) state that continuous operation at a fixed frequency may be more noticeable to nearby residents, even at lower vibration levels. In addition, the steady-state excitation of the ground may increase the response at the resonance frequency of building components. Response may be unacceptable in cases of fragile historical buildings or vibration-sensitive manufacturing processes. Impact pile drivers, conversely, produce high vibration levels for a short duration (0.2 second) any may have sufficient time between impacts to allow any resonant response to decay.

Wood and Theissen (1982) state that vibration levels from vibratory pile drivers may be at least as severe as those from impact pile drivers, and that the potential for damage from vibratory pile drivers may be greater than that from impact hammers because of sustained vibration levels. Vibration data provided by ICE (Morris 1991, 1996, 1997) support the fact that vibratory pile drivers generate vibration levels that are somewhat similar to those produced by impact pile drivers. The use of resonance-free vibratory pile drivers may be an exception to this inference (see "Vibration Mitigation Measures for Pile Drivers" section below).

7.1.3 Vibration Amplitudes Produced by Hydraulic Breakers

Review of available literature indicates that there is no information available about measured vibration amplitudes from hydraulic breakers used in pavement and concrete demolition projects. Hydraulic breakers (also called hoe-rams, hydraulic hammers, or mounted impact hammers) are generally rated by the amount of energy being delivered, typically in the range of 70–15,000 ft-lbs. Because the breakers are rated in a similar manner to impact pile drivers, it is reasonable to assume that the approach presented in Eq. 9 can be used for estimating vibration amplitude from hydraulic breakers. Because hydraulic breakers generally have much lower energy ratings than impact pile drivers, Eq. 9 should be adjusted for typical reference energy of only 5,000 ft-lbs. for hydraulic breakers.

Based on the above discussion, vibration produced by hydraulic breakers can be estimated by the following formula:

$$PPV_{Hydraulic\ Breaker} = PPV_{Ref}\,(25/D)^n \times (E_{equip}/E_{Ref})^{0.5} \quad (in/sec) \quad (Eq.\ 11)$$

Where:

PPV_{Ref} = 0.24 in/sec for a reference hydraulic breaker at 25 ft.

D = distance from hydraulic breaker to the receiver in ft.

n = 1.1 (the value related to the attenuation rate through ground)

E_{Ref} = 5,000 ft-lbs. (rated energy of reference hydraulic breaker)

E_{equip} = rated energy of hydraulic breaker in ft-lbs.

The suggested value for "n" is 1.1. Because vibration from the hydraulic breakers originates primarily near the ground surface, a value of "n" based on soil classification may not necessarily be applicable; however, a higher value of "n" based on site-specific soil conditions could be used for a less-conservative estimation of vibration amplitude.

7.2 Vibration Produced by Other Construction Equipment

Review of available literature indicates that there is limited information available on vibration source levels from general construction equipment. The most comprehensive list of vibration source amplitudes is provided in the document entitled *Transit Noise and Vibration Impact Assessment* (Federal Transit Administration 2018). This document lists vibration source amplitudes at 25 ft. for various types of construction equipment. Table 18 summarizes these and other source levels.

Caltrans has conducted several studies related to ground vibration produced by crack-and-seat operations. A study conducted by Caltrans (2000) measured and evaluated ground vibration generated by crack-and-seat operations along State Route 101 near Santa Maria. A Walker Megabreaker Model 8-13000 was used. This machine drops an 8-ft-wide by 10-ft-tall steel plate weighing 13,000 lbs. approximately 4 ft. Operation of this machine produced the following results:

- At 12 m, PPV = 1.25 in/sec.
- At 27 m, PPV = 0.422 in/sec, 0.62 in/sec, and 0.412 in/sec.
- At 34 m, PPV = 0.290 in/sec.
- At 63 m, PPV = 0.083.

Another study (Ames et al. 1976) conducted in 1972 produced the following results:

- At 10 ft., PPV = 2.99 in/sec.
- At 38 ft., PPV = 0.275 in/sec.

The Santa Maria data has been used to develop a reference vibration amplitude for crack-and-seat operation. Using the measurement at 12 m as the reference distance, the data corresponds to Eq. 12 with N = 1.5. The reference amplitude at 25 ft. extrapolated from this is 2.4 in/sec and is shown in Table 18.

Table 18. Vibration Source Amplitudes for Construction Equipment

Equipment	Reference PPV at 25 ft. (in/sec)
Vibratory roller	0.210
Large bulldozer	0.089
Caisson drilling	0.089
Loaded trucks	0.076
Jackhammer	0.035
Small bulldozer	0.003
Crack-and-seat operations	2.4

Sources: Federal Transit Administration 2018 (except Hanson 2001 for vibratory rollers) and Caltrans 2000 for crack-and seat-operations.

Using these source levels, vibration from this equipment can be estimated by the following formula:

$$PPV_{Equipment} = PPV_{Ref}\,(25/D)^{n} \quad (in/sec) \qquad (Eq.\ 12)$$

Where:

PPV_{Ref} = reference PPV at 25 ft.

D = distance from equipment to the receiver in ft.

n = 1.1 (the value related to the attenuation rate through ground)

The suggested value for "n" is 1.1. Because vibration from this equipment originates primarily near the ground surface, modifying the value of "n" based on soil classification may not necessarily be applicable; however, a higher value of "n" based on site-specific soil conditions could be used for a less-conservative estimation of vibration amplitude. FTA recommends a value of "n" of 1.5 for vibration assessment. Using a value of 1.5 is less conservative than using a value of 1.4 or less (as indicated in Table 17) because it assumes that vibration will attenuate at a greater rate.

7.3 Evaluating Potential Vibration Impacts

As shown in Chapter 6, there is limited consistency between the categorization of effects and damage thresholds; however, it is apparent that damage thresholds for continuous sources are less than those for single-event or transient sources. It is also apparent that the vibration from traffic is continuous and that vibration from a single blasting event is a single transient event; however, many types of construction activities fall between a single event and a continuous source. An impact pile driver, for example, continuously generates single transient events. As a practical matter and based on the nature of available criteria, the criteria can only be reasonably separated into two categories: continuous and transient.

To assess the damage potential from ground vibration induced by construction equipment, a synthesis of various vibration criteria presented in Chapter 6 has been developed. This synthesis of criteria essentially assumes that the threshold for continuous sources is about half of the threshold for transient sources. A vibration amplitude predicted using Eqs. 9–12 can be compared the criteria in Tables 19 and 20 to evaluate the potential for damage.

Table 19. Guideline Vibration Damage Potential Threshold Criteria

Structure and Condition	Maximum PPV (in/sec) Transient Sources	Maximum PPV (in/sec) Continuous/Frequent Intermittent Sources
Extremely fragile historic buildings, ruins, ancient monuments	0.12	0.08
Fragile buildings	0.2	0.1
Historic and some old buildings	0.5	0.25
Older residential structures	0.5	0.3
New residential structures	1.0	0.5
Modern industrial/commercial buildings	2.0	0.5

Note: Transient sources create a single isolated vibration event, such as blasting or drop balls. Continuous/frequent intermittent sources include impact pile drivers, pogo-stick compactors, crack-and-seat equipment, vibratory pile drivers, and vibratory compaction equipment.

A similar synthesis of criteria relating to human perception has also been developed and is summarized in Table 19. A vibration amplitude predicted with Eqs. 1–4 can be compared to the criteria in Table 20 for a simple evaluation of the potential for annoyance and adverse impact. Some individuals may be annoyed at barely perceptible levels of vibration, depending on the activities in which they are participating.

Table 20. Guideline Vibration Annoyance Potential Criteria

Human Response	Maximum PPV (in/sec) Transient Sources	Maximum PPV (in/sec) Continuous/Frequent Intermittent Sources
Barely perceptible	0.04	0.01
Distinctly perceptible	0.25	0.04
Strongly perceptible	0.9	0.10
Severe	2.0	0.4

Note: Transient sources create a single isolated vibration event, such as blasting or drop balls. Continuous/frequent intermittent sources include impact pile drivers, pogo-stick compactors, crack-and-seat equipment, vibratory pile drivers, and vibratory compaction equipment.

7.3.1 Example Calculations

Example 1: An 80,000 ft-lb. pile driver will be operated at 100 ft. from a new office building and 100 ft. from a historic building known to be fragile. Evaluate the potential for damage to the buildings and annoyance to the building occupants. No information on the soil conditions is known.

Use Eq. 10 to estimate the PPV from the pile driving at 100 ft. In the absence of soil information, use N = 1.1.

$$PPV = 0.65\ (25/100)^{1.1}\ X\ (80{,}000/36{,}000)^{0.5} = 0.21\ in/sec$$

Table 19 suggests that an appropriate damage potential threshold for new commercial buildings is 0.5 in/sec when the source is continuous. The predicted vibration amplitude of 0.21 in/sec is well below this value, indicating low potential for structural damage to the building.

Table 19 suggests that an appropriate damage potential threshold for a fragile building is 0.1 in/sec when the source is continuous. The predicted vibration amplitude of 0.21 in/sec exceeds this value, indicating potential for structural damage to the building.

Table 20 suggests that a transient vibration amplitude 0.21 in/sec would be strongly perceptible, indicating that pile driving could lead to annoyance of building occupants.

Example 2: A vibratory roller will be operated 50 ft. from residences constructed in the 1940s. A detailed soil study is available indicating that the soil is hard competent rock. Evaluate the potential for damage to the buildings and annoyance to the building occupants.

Use Eq. 12 and data from Table 18 to estimate the vibration amplitude. Hard competent rock is in Soil Class IV. Therefore, N = 1.0 should be used.

$$PPV = 0.210\ (25/50)^{1} = 0.11\ in/sec$$

Table 19 suggests that an appropriate damage potential threshold for older residential structures is 0.3 in/sec when the source is continuous. The predicted vibration amplitude of 0.11 in/sec does not exceed this value, indicating low potential for structural damage to the building.

Table 20 suggests that a continuous vibration amplitude 0.11 in/sec would be strongly to severely perceptible, indicating that operation of the roller could lead to a high level of annoyance of residences.

Example 3: Crack-and-seat operations will be conducted on a freeway located 75 ft. from newly constructed residences and residences constructed in the 1940s. Soil conditions are known to be dense, compacted sand. Evaluate the potential for damage to the residences and annoyance to the building occupants.

Use Eq. 12 to estimate the PPV from the pile driving at 120 ft.. Dense, compacted sand is in Soil Class IV. Therefore, N = 1.1 should be used.

$$PPV = 2.4\ (25/120)^{1.1} = 0.43\ in/sec$$

Table 19 suggests that an appropriate damage potential threshold for older residential structures is 0.3 in/sec when the source is continuous. The threshold for new residential construction is 0.5 in/sec. The predicted vibration amplitude of 0.43 in/sec is below the 0.5 in/sec threshold for new residential construction but above the threshold of 0.3 for older construction, indicating low potential for structural damage to the newer residences but potential for damage to the older structures.

Table 20 suggests that a transient vibration amplitude 0.43 in/sec would be severely perceptible, indicating that pile driving could lead to annoyance of residents.

Chapter 8
Methods for Reducing Vibration

This chapter discusses methods for reducing ground vibration. For the most part, the methods involve reducing vibration at the source. Wave barriers treat the transmission path between the source and the receiver. Once ground vibration is transmitted to a receiver, there are few, if any, means for reducing the vibration.

8.1 Wave Barriers

The following discussion is a summary of the discussion of wave barriers provided in NCHRP Synthesis 253 (Woods 1997). Richart (1970) also provides useful information on this subject.

The purpose of a barrier is to reflect or absorb wave energy, thereby reducing the propagation of energy between a source and a receiver. A wave barrier is typically a trench or a thin wall made of sheet piles or similar structural members. The depth and width of a wave barrier must be proportioned to the wavelength of the wave intended for screening. The wavelength of a seismic wave is a function of propagation velocity and frequency. Pile driving typically generates ground vibration with frequencies in the range of 4–30 Hz. With common wave velocities in the range of 61–610 m/s, typical wavelengths can be in the range of 3–152 m.

Studies indicate that the depth of a wave barrier must be at least two-thirds of the seismic wavelength to be screened and that the length of the barrier must be at least one wavelength to screen even a small area. In one case, a trench wave barrier that was 1.19 wavelengths deep by 1.79 wavelengths long resulted in an 88% reduction in amplitude in two small areas behind the trench. Wave barriers must be very deep and long to be effective, and they are not cost effective for temporary applications such as pile driving vibration mitigation.

8.2 Vibration Reduction for Impact Pile Drivers

Impact pile driving can be the most significant source of vibration at construction sites. The principal means of reducing vibration from impact pile driving are listed below. Some of these methods may not be appropriate in specific situations, but where they are practical, they can often be used to reduce vibration to an acceptable level.

- **Jetting:** Jetting is a pile driving aid in which a mixture of air and water is pumped through high-pressure nozzles to erode the soil adjacent to the pile to facilitate placement of the pile. Jetting can be used to bypass shallow, hard layers of soil that would generate high levels of vibration at or near the surface if an impact pile driver was used.

- **Predrilling:** Predrilling a hole for a pile can be used to place the pile at or near its ultimate depth, thereby eliminating most or all impact driving.

- **Using cast-in-place or auger cast piles:** Using cast-in-place or auger cast piles eliminates impact driving and limits vibration generation to the small amount generated by drilling, which is negligible.

- **Using nondisplacement piles:** Use of nondisplacement piles such as H piles may reduce vibration from impact pile driving because this type of pile achieves its capacity from end bearing rather than from large friction transfer along the pile shaft.

- **Using pile cushioning:** With pile cushioning, a resilient material is placed between the driving hammer and the pile to increase the period of time over which the energy from the driver is imparted to the pile. Keeping fresh, resilient cushions in the system can reduce the vibration generated by as much as a factor of 2 (Woods 1997).

- **Scheduling for specific times to minimize disturbance at nearby vibration-sensitive sites:** Adverse effects can be avoided if pile driving is not scheduled for times at which vibration could disturb equipment or people. For example, if pile driving near a residential area can be scheduled during business hours on weekdays, many people will be at work and will therefore not be affected.

- **Using alternative nonimpact drivers:** Several types of proprietary pile driving systems have been designed specifically to reduce impact-induced vibration by using torque and down-pressure or hydraulic static loading. These methods would be expected to significantly reduce adverse vibration effects from pile placement. The applicability of these methods depends in part on the type of soil. The following information is provided for informational purposes only. This discussion is not intended to favor any commercial product; inclusion of information on these products does not constitute endorsement or approval by Caltrans.

- The first nondynamic system is the Fundex Tubex piling system, manufactured by Fundex in the Netherlands and marketed by American Piledriving in California. Tubex piles are installed with minimal vibration by using torque and down-pressure to produce true soil displacement piles. A patented cast-steel boring drill tip is welded to the pipe casing; then, the Tubex machine installs the pile by gripping the outside of the pipe casing with hydraulic clamps and, in essence, screwing the pile into the ground. Grout injection ports are located at the base of the tip, which allows for the injection of water as a drilling medium and for the injection of grout to produce a soil-cement mixture around the steel casing. Once the steel shell is installed and grouted, concrete and reinforcing are conventionally placed inside the pipe as structurally required by design, or the pile is left unfilled as a simple pipe pile.

  Based on vibration tests performed in 2001 by American Piledriving, the vibration amplitude generated by the Tubex system is expected to be about 0.05 in/sec at 25 ft. This amplitude is significantly lower than vibration generated by conventional impact or vibratory pile drivers. Tubex piles were evaluated by Caltrans in a test project conducted near Interstate 280 in the San Francisco Bay Area. The ultimate capacity of the Tubex pile in terms of tension and compression exceeded all other pile types evaluated.

- The second nondynamic system is the Still Worker (Liddy 2002), a static load piling system, marketed by the Ken-Jet Corporation in New Jersey. This system hydraulically installs and retrieves H-piles, pipe, and sheet piles, generating significantly less vibration than is generally associated with conventional impact and vibratory pile drivers. The system uses hydraulics to push in piles in a smooth, fluid motion that virtually eliminates vibration commonly associated with the installation of piling. Although there are no available vibration data for the system, it appears to substantially reduce vibration from pile driving. A product developed by Giken Engineering Group called the "Silent Piler" operates in a similar fashion.

- Using a vibratory pile driver instead of an impact pile driver can reduce some vibration problems, but vibration amplitudes are similar to those of an impact pile driver because a resonance can occur as the vibratory pile driver starts up and shuts down. One alternative to conventional vibratory pile drivers is a resonance-free vibrator, or variable eccentric moment vibrator. ICE manufactures two such models. These vibrators do not vibrate during start up and shut down, thereby avoiding the excessive vibrations that are commonly associated with traditional vibratory units. By changing the static moment, these vibrators can vary the frequency of operation and the force amplitude. Before the vibrator is started, two parallel rows of eccentric weights are shifted out of phase, resulting in no vibration during start up. By changing the relative orientation of the two rows of parallel eccentric masses, the static moment is changed. After the vibrator reaches full speed, the eccentric masses are shifted into phase, resulting in maximum eccentric moment and maximum amplitude to drive the pile efficiently. Before shut down, the two rows of eccentric weights are again shifted out of phase, resulting in no vibration during shut down.

8.3 Vibration Reduction for Hydraulic Breakers

If vibration levels from hydraulic breakers are expected to exceed applicable vibration limits, the following vibration-reducing measures can be considered. Some of these methods may not be appropriate in particular situations, but they can often be used to reduce vibration levels to an acceptable limit where they are practical.

- A hydraulic crusher (also called smasher, densifier, processor, or pulverizer) can be used to break up the material. A hydraulic crusher is an attachment that is generally mounted on the end of a backhoe, excavator, or skid-steer. It has large jaws that open and close. When closed, the attachment can cut through and crush concrete and any rebar used in the concrete. The attachment can be used for demolition of concrete dividers, such as those used between roadways, and at locations where the concrete can be placed between the jaws. For demolition of a sidewalk or pavement, digging or breaking up of the surface may be required to allow the concrete to be placed between the jaws.

- Saws or rotary rock-cutting heads can be used to cut bridge decks or concrete slabs into small sections that can be loaded onto trucks for disposal.

- Hydraulic splitters can be used to break up concrete. These devices apply lateral force against the inside of holes drilled into the concrete.

- Chemicals can be used to split concrete.

- Pavement and concrete demolition can be scheduled for certain times to minimize the disturbance at the nearby vibration-sensitive sites.

8.4 Vibration Reduction Measures for Other Construction Equipment

In most cases, vibration induced by typical construction equipment does not result in adverse effects on people or structures. Noise from the equipment typically overshadows any meaningful ground vibration effects on people. Some equipment, however, including vibratory rollers and crack-and-seat equipment, can create high vibration levels.

Because of the nature of these types of devices, the options for reducing vibration are limited. Maximizing the distance between the source and receiver might be possible, but there is usually little or no flexibility in this regard. Conducting work when most people are not in the area (e.g., at work) or when sensitive equipment is not operating can avoid or minimize adverse impacts with this type of equipment, but pavement crack-and-seat operations often must be conducted at night to avoid disrupting traffic. As such, little can be done to avoid adverse impacts on people. In some circumstances, temporary relocation of residents during these operations may be appropriate; this is often done by offering hotel vouchers to potentially affected residents.

In the absence of measures than can physically reduce induced ground vibration, informing the public about the project and the potential effects of construction activities is, in many cases, the best way to avoid adverse reactions from the public. The suggested process for engaging the public is discussed in Chapter 9.

8.5 Vibration Reduction for Vehicle Operations

Vehicles traveling on a smooth roadway are rarely, if ever, the source of perceptible ground vibration. However, discontinuities in roadway pavement often develop as the result of settling of pavement sections, cracking, and faulting. When this occurs, vehicles passing over the pavement discontinuities impart energy into the ground, generating vibration. In most cases, only heavy trucks, not automobiles, are the source of perceptible vibration. Trucks traveling over pavement discontinuities also often rattle and make noise, which tends to make the event more noticeable when the ground vibration generated may only be barely noticeable.

Because vibration from vehicle operations is almost always the result of pavement discontinuities, the solution is to smooth the pavement to eliminate the discontinuities. This step will eliminate perceptible vibration from vehicle operations in virtually all cases.

8.6 Vibration Reduction for Train Operations

Methods for reducing ground vibration generated by rail operations are described in FTA 2018. These methods include:

- maintaining wheel and rail smoothness;
- locating special trackwork for turnouts and crossovers away from vibration-sensitive areas;
- specifying vehicles with low unsprung weight, soft primary suspension, minimum metal-to-metal contact between moving parts of the truck, and smooth wheels; and
- use of special track-support systems such as:
    - resilient fasteners,
    - ballast mats,
    - resiliently supported ties,
    - floating slabs, and
    - speed reduction.

Special track support systems require engineering to ensure optimal effectiveness in reducing vibration.

Chapter 9
General Procedures for Addressing Vibration Issues

Concerns about vibration generally arise because of complaints about existing operations or construction and maintenance activities. (Construction and maintenance activities are collectively referred to here as “construction activities.”) Concerns can also arise in response to planned activities, such as the construction and operation of a new facility or the modification of an existing facility. This chapter discusses the recommended procedures for addressing vibration concerns about both existing and planned activities and operations.

9.1 Vibration Concerns about Existing Activities and Operations

Pile driving and crack-and-seat operations near homes or businesses are the primary subjects of vibration complaints. Vibration complaints can also be generated in response to traffic operations if pavement is in poor condition. Increases in traffic, heavy truck, or bus operations resulting from opening of new transportation facilities or the redirection of traffic can also trigger complaints. Although complaints can come from any type of receiver, most are from occupants of residences and from businesses that have vibration-sensitive equipment or operations. Complaints about vibration require a response from Caltrans.

The first step in investigating complaints is to interview the individuals making the complaints (i.e., the complainants) and to assess the severity of the vibration concern. A list of questions, a screening procedure to determine the severity of the concern, and a vibration complaint form are provided in Appendix B for this purpose. In assessing the severity of a vibration concern, the most important issues are:

- The type and location of the vibration source(s)

- The complainant’s concerns (e.g., annoyance, damage, disruption of operations)
- The location that is most sensitive, or where vibration is most noticeable

The screening procedure may indicate that vibration monitoring should be conducted. Vibration monitoring of existing operations or construction activity can range from simple, single-location measurements to more complex, simultaneous, multi-instrument measurements. The simple approach consists of taking measurements at the most sensitive location or the location perceived by the complainant to have the worst level of vibration. Sufficient data should be collected for each location of interest. For highway traffic vibrations, 10 heavy-truck pass-bys (preferably worst-case combinations of several trucks) for each location should be measured. For pile driving or crack-and-seat operations, several minutes of equipment operation should be monitored at each location of interest. The measurement results can then be compared to the applicable vibration criteria.

If the simple measurement indicates that vibration approaches or exceeds applicable criteria, a more detailed study should be conducted. This study involves placing a sensor close to the source as a reference and one or more sensors at the critical locations. The reference sensor remains fixed in one location near the source, whereas the response sensors may be moved to different locations. The simultaneous measurements can then be used to positively identify the vibration source, the drop-off rate, and the response (i.e., vibration level) at the locations of interest. This information can be used to identify unusual conditions that may be contributing to the high vibration condition and to identify a course of action to reduce the impact.

9.2 Vibration Concerns about Planned Activities and Operations

Avoiding adverse vibration effects regarding planned construction activities and facility operations involves using physical methods to reduce the actual vibration and good public relations to ensure that the public is well informed about the work and its potential effects. In general, literature on the subject shows that only blasting, pile driving, and pavement breaking have documented examples of potential damage to buildings (American Association of State Highway and Transportation Officials [AASHTO] 1990). For pile driving and pavement breaking, the potential for damage from vibration is at locations in relatively close proximity to the activity. However, because the threshold of perception for vibration is much lower than the threshold for damage, claims of damage often arise because of perceptible vibration and not because of actual damage.

Chapter 11 outlines a process for avoiding and addressing potential problems from the public related to blasting. The following process, which focuses on vibration from construction activities and facility operations, is modeled after that process. Every attempt should be made to mitigate the adverse vibration effects from construction activities through the use of modern techniques, procedures, and products. It is equally important to develop a process to avoid and, if necessary, address problems identified by the public that can arise from construction activities, even when the levels of vibration are well below the levels at which damage to structures or excessive annoyance to humans are expected to occur. The following steps should be taken:

1. Identify potential problem areas surrounding the project site
2. Determine conditions that exist before construction begins
3. Inform the public about the project and potential vibration-related consequences
4. Schedule work to reduce adverse effects
5. Design construction activities to reduce vibration
6. Notify nearby residents and property owners that vibration-generating activity is imminent
7. Monitor and record vibration from the activity
8. Respond to and investigate complaints

These steps are described below.

9.2.1 Step 1. Identify Potential Problem Areas Surrounding the Project Site

The first step is to identify the types of dynamic equipment that will be used on the project. As previously discussed, pile drivers and crack-and-seat equipment tend to be the most common source of vibration concerns. In some cases, vibration from the operation of a new or modified highway may need to be evaluated. Prediction methods discussed in Chapter 7 should then be used to estimate distances at which vibration could exceed perception thresholds and structural damage thresholds.

A question that must be answered before determining a preconstruction survey radius is whether the intent is to prevent structural damage or to prevent the perception that structural damage is occurring. In general it is impractical to survey all locations where vibration could be perceptible or where there could be the perception of damage. Regardless of the radius selected for preconstruction surveys, there have been numerous instances where claims of damage came from locations far beyond the surveyed areas. Hence, there is no reasonable standard distance beyond which no complaints can be assured.

Bearing in mind human perceptions and economic considerations, the best solution might be to select structures for preconstruction surveys as follows:

- those structures or groups of structures closest to the vibration source,
- structures within a radius where the effects are estimated to be strongly perceptible and,
- any structures at greater distances that, because of historic value or special conditions, are deemed to deserve special attention.

If the surrounding residents do not view the project as necessarily beneficial to them, or if the project is otherwise unpopular, the distances should probably be increased accordingly.

After the decision has been made as to the limit of preconstruction surveys, anticipate that damage claims may come from residents outside the limit that would have to be resolved through forensic investigation. This is discussed in Step 8.

In some special circumstances, an assessment of the vibration propagation characteristics of the project site may be warranted to improve the accuracy of the vibration predictions. These special circumstances may include situations with special receivers, such as a hospital, research facility, or high-technology facility with vibration-sensitive equipment. Other circumstances might include situations where vibration is known to propagate efficiently though the soil on the site.

A method that Caltrans has used to determine site-specific vibration drop-off characteristics involves the generation of vibration on the site and measurement of the response of the ground at various distances. To generate a strong vibration signal, Caltrans has driven a heavily loaded water truck or dump truck at high speed over a series of five 2- by 4-in. or 2- by 6-in. wood boards spaced 25 ft. apart. This method has been proven to generate a recognizable signal at 90 m (300 ft.). Other methods of generating vibration are also available and include drop-balls, impact hammers, and vibratory rollers.

With this method, a minimum of two sensors must be used simultaneously: one reference sensor and one or more response sensors. Refer to Chapter 10 for a discussion of vibration measurement instrumentation. The reference sensor remains fixed at 5 m (16 ft.) from the centerline of travel (or any convenient distance near the source) opposite the last board to be run over (most forward in line with the direction of travel). The response sensors are positioned at various distances from the source. Because of the steepness of the drop-off curve near the source, it is a good idea to cover shorter-distance intervals near the source and longer ones away from the source. To adequately cover the entire range of the drop-off curve, six to eight locations should be monitored and at least five truck pass-bys measured at each location. Frequently, simulations are not possible on the site of interest because of space limitations. Nearby empty lots or open fields, or data from other sites known or judged to have similar soil conditions, can then be used. However, care must be exercised in choosing a representative site because subsurface conditions can vary substantially.

Once the measurements have been made, the data at each location should be averaged. Using the reference position and at least two others (including the farthest one), the soils coefficient of attenuation (or alpha value, α) can be calculated using Eq. 6. Ideally, the alpha value should remain constant for each location, but in reality it will vary as a function of frequency and position. The average of several values can then be used to develop a drop-off curve. The vibration amplitudes at all measured locations should then be plotted to determine how well they fit this curve. Assuming they fit reasonably well, a normalized drop-off curve can be developed and used with any source reference level, to predict the future level at any distance within the range of the curve.

Another method that can be used to determine vibration propagation characteristics on a site involves measuring the transfer mobility of the ground. This procedure involves dropping a heavy weight on the ground, and then measuring the forces into the ground and the response at several distances from the impact. This procedure is discussed in detail in Federal Transit Administration 2018.

If it is possible to do the simulations at the site, measurement locations both inside and outside the buildings of concern should be included to measure the effects of building amplification or attenuation. Ambient vibration should also be measured both inside and outside the building to document vibration before the construction activity. Any claims that a Caltrans activity or project has increased ground vibration can then be assessed by comparing project-related vibration compared to the existing vibration.

Using the information collected from this study, future vibration can be predicted and compared to existing ambient vibration, perception and damage thresholds, or any other applicable criteria. In some cases where disturbance thresholds for sensitive equipment are not known, vibration measured near the sensitive equipment can be correlated with the disturbance of the equipment to establish a threshold.

The methods described here are generally sufficient for identifying the potential for adverse effects on sensitive equipment. Most situations involving construction operations near sensitive equipment will require consulting experts with specialized expertise in this area.

9.2.2 Step 2. Determine Conditions That Exist Before Construction Begins

There are various methods that can be used to conduct preconstruction surveys, but all must meet the primary purpose of documenting all the defects and existing damage in the structures concerned. An inadequate preconstruction survey can be worse than no preconstruction survey at all. Preexisting defects that are not listed in the preconstruction survey will probably then be attributed to the construction by the property owner. Unless these can be refuted through forensic investigation, the complainant will probably be successful.

Secondary purposes of the preconstruction survey include answering any questions the homeowner may have regarding the project and looking for anything that might require correcting before construction starts or that may place an unexpected limit on blast design. Examples include antique plates that are leaning against a wall or precariously balanced figurines. These should be secured for the duration of the project if there is any concern.

Surveys can consist of drawings on paper, high-resolution video, black and white photography, or any other method that adequately documents existing defects and damage. It is also helpful if the possible cause of the defect can be determined and listed. Oriard (1999) and Dowding (1996) describe preconstruction survey methods in detail.

In some instances, homeowners will prefer that their homes not be surveyed. This is usually for the sake of the owners' privacy, and a notation should be made for that structure as to the time and date, the specific comment made and the person who made it. On some occasions, a homeowner may terminate a preconstruction survey before it is complete. Again, the survey should be annotated accordingly.

It is usually advantageous to conduct postconstruction surveys to verify that no additional damage has been caused by the construction activity.

All residential structures suffer from normal shrinkage of materials caused by diurnal thermal strains and possible settling that start to occur soon after construction. This can present a problem on long-term projects when relatively new homes are included in the preconstruction survey. The normal shrinkage cracks and defects may not show up before the preconstruction survey, but may be there for any postconstruction inspection. The only solution is to investigate them thoroughly to determine whether it was possible that construction activity caused the defect. This will normally require the services of an experienced forensic investigator.

It is also good practice to examine homes both near and far from the construction activity. If cracks or other defects are consistent throughout the area, they are likely the result of thermal stresses or settlement. Cracks or defects that diminish with distance from the vibration source may be indicative of effects caused by the source. Cracks that occur only on surfaces exposed to the sun are indicative of thermal cracking.

There is a tendency for insurance companies to settle smaller claims rather than pay the cost involved in determining the actual cause. This is not only technically and philosophically unsound, but also an open invitation for additional claims from surrounding neighbors.

9.2.3 Step 3. Inform the Public about the Project and Potential Construction-Related Consequences

Good public relations with the neighbors nearest the project, as well as all interested parties, are always beneficial. Most homeowners do not have experience with construction vibration, and may have concerns about their own safety and the safety of their homes.

If the situation warrants, a meeting should be held and a presentation made that explains the reason for the project, that construction will be necessary, what the residents can expect to hear and feel from the construction, any specific warning signals that will be used, and the intent of the preconstruction survey. Knowledgeable persons should attend to answer questions. There should be a handout that explains all of the above information and includes phone numbers to call if there are problems or questions. The person or company that will conduct the preconstruction surveys should be introduced. The main purpose of such a meeting is to educate the neighbors and to put their minds at ease. Such a meeting, conducted properly, can greatly reduce the potential for problems with neighboring property owners.

Another opportunity to conduct good public relations is during the preconstruction survey. The informational sheet from the meeting should be distributed during the survey. The person or persons that conduct the survey should be conversant enough about the project to answer any questions that homeowners might have.

Homeowners should be provided with a procedure for registering complaints with Caltrans in the event that vibration is found to be excessive. This procedure should identify a contact person and phone number or email address.

9.2.4 Step 4. Schedule Work to Reduce Adverse Effects

As long as safety considerations can be met, construction activity should be scheduled to occur during times of maximum human activity, rather than during times of extreme quiet. In some cases, nearby sources of noise and/or vibration can be used to mask the noise from construction activities. For example, if highway work can be conducted during daytime hours, normal traffic noise may mask much of the construction noise. Night work should be avoided, although night work is required to avoid disruption of commute traffic flows in many cases.

Other factors may need to be considered as well. A survey of the area should disclose locations with critical activities that might require close coordination. For example, if a hospital where surgery is conducted or other facilities with equipment highly sensitive to vibration are nearby, coordination is necessary so that construction does not interfere with operations of those facilities. Medical equipment that is particularly sensitive to vibration include magnetic resonance imaging (MRI) systems, scanners, and microscopes.

9.2.5 Step 5. Design Construction Activities to Minimize Vibration

Where adverse vibration effects are anticipated, reasonable efforts should be made to reduce those effects. Chapter 8 discusses methods to reduce vibration from construction.

9.2.6 Step 6. Notify Nearby Residents and Property Owners That Vibration-Generating Activity Is Imminent

Once work has been scheduled, nearby residents and property owners should be notified about the specific times and dates that vibration-generating activity will occur. Many complaints occur because a resident or property owner was not aware that the construction activity would occur.

9.2.7 Step 7. Monitor and Record Vibration Effects from Construction

Although it is possible to estimate the levels of construction-induced vibration with some confidence, field monitoring and recording of vibration effects is sometimes warranted. Monitoring records provide excellent tools for evaluating the potential for damage from construction activities. The monitoring and recording should be conducted with equipment specifically intended for this purpose, including accelerometers, velocity sensors, and data-recording or data-logging devices. Equipment used to collect and evaluate vibration data is discussed in Chapter 10.

In situations in which there is considerable opposition to a project and damage claims are anticipated, monitoring and recording should be conducted by a third party. In situations in which there is little chance for claims or where monitoring is being done solely to ensure that specifications are being met, the construction contractor could conduct the monitoring, although it is advisable for the contractor to have a third-party vibration consultant oversee and approve the monitoring and recording process.

9.2.8 Step 8. Respond to and Investigate Complaints

An adequate process for handling complaints should be established. Neighboring residents should know whom to contact with a concern or complaint, regardless of whether it involves a claim of damage. In all instances, a form that documents the details should be initiated on receipt of a complaint. A sample construction vibration complaint form is provided in Appendix B.

For minor complaints, responsible, knowledgeable contractor personnel might conduct the investigation. It is advisable to have a qualified forensic investigator look into claims of damage. The investigator might be the same party that conducted the preconstruction survey or conducted the monitoring. Prompt investigation is advisable. Correction of the problem, if caused by the construction activity, should also be handled promptly.

A vibration specification can be valuable in avoiding problems resulting from construction vibration. Because it is impossible to foresee all variables that may be encountered on various project sites, specifications should be developed specifically for each construction site. A sample vibration specification developed for a construction site with nearby historic structures is provided in Appendix C.

9.3 Vibration Study Reports

Any time a vibration field study is conducted, the results should be documented in a report. Depending on the number of sites measured, amount of data collected, methodologies used, and the importance of the study, the report may range from a simple one or two paged memo, to a report of twenty or more pages long. A vibration study can be considered a mini-research project, and should contain enough information for the reader to independently come to the same conclusions.

Normally, a vibration report should contain the following topics:

- project title and description;
- introduction;
- objectives;
- background;

- study approach;
- instrumentation;
- measurement sites;
- measurements;
- data reduction;
- measurement results;
- data analysis;
- results and comparison with criteria;
- conclusions and recommendations;
- tables showing all measured data, summaries of results, analysis, and standards;
- figures showing site layouts and cross sections, instrument setups, drop-off curves, and other pertinent illustrations; and
- references cited.

In short and simple vibration studies, the above topics may be described within a few sentences in a memorandum. In more complex studies, a fairly extensive report is usually required. Refer to Appendix A for more detailed information on vibration study reports.

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Chapter 10
Vibration Measurement and Instrumentation

10.1 Vibration Measurement Equipment

Ground vibration is typically measured with a sensor that produces an electrical signal that is proportional to amplitude amplitude of the ground motion. These sensors are called transducers because they "transduce" the ground motion into an analogous electronic signal. Transducers can be designed to produce a signal that is analogous to the displacement, velocity, or acceleration of the ground motion. Velocity transducers (seismometers) and acceleration transducers (accelerometers) are the most widely used transducers for measuring ground motion. Vibration transducers measure vibration in one axis. These transducers can be combined into a triaxial array to simultaneously measure vibration in three orthogonal axes.

During the period between 1958 and 1994, all vibration monitoring conducted by Caltrans was performed by staff from the Caltrans Translab. A transducer calibration system consisting of a shaker table mounted on a concrete vibration isolation pad and a camera/amplifier system that measured displacement allowed Translab to calibrate its own transducers with traceability to the National Institute of Standards and Technology (NIST), formerly known as the National Bureau of Standards (NBS). Transducers were calibrated by mounting them on the shaker table and running the table at a known frequency and displacement. Translab is no longer responsible for vibration studies. These studies are now conducted by Caltrans headquarters staff and vibration consultants retained by Caltrans.

Historically, Caltrans used both seismometers and accelerometers to measure ground motion. Seismometers used by Caltrans measure vibration at relatively low frequencies, usually between 1 and 200 Hertz (Hz), through magnetic induction that produced a voltage proportional to velocity. Because seismometers are typically large and can weigh as much as about 7 kilograms (kg) (15 pounds [lbs]), they typically can be placed directly on the ground without special mounting attachments if the mounting surface is stiff, such as hard soil, a concrete sidewalk, flagstone, or asphalt. If used on soil, the seismometer should be firmly embedded in the soil by embedding the entire base in the soil.

An accelerometer measures acceleration directly. When used with an integrator, an accelerometer can also measure velocity and displacement. Accelerometers used by Caltrans have piezoelectric (charge-generating) crystals. As the transducer vibrates with the surface it is mounted on, acceleration changes the compression of the crystal, which in turn causes variations in the electrical charge across the crystal faces. These charge variations are proportional to acceleration.

Accelerometers are typically small and not as sensitive as seismometers. The advantage is that they have a wider frequency range, typically from 1 Hz to several kilo-Hertz (kHz). Because of their small size and lack of mass, accelerometers should not be placed directly on the ground, floor, or other vibrating surface without proper mounting. Accelerometers can be mounted in various ways, depending on the surface. Accelerometers can be adhered to a vibrating surface such as floors, sidewalks, or walls using scientific wax, beeswax, or other special wax provided by the accelerometer manufacturer can be used. Threaded studs adhered to the surface with epoxy can also be used. For good high frequency (up to 100 Hz) coupling to soil, accelerometers should be mounted to an aluminum spike.

An accelerometer can also be mounted via a magnet (or adhesive) to a heavy block of steel weighing 5–10 kg (10–20 lbs). The steel block can then be placed directly on the ground or other surface if the steel block does not rock. The mass of the steel block provides adequate coupling of the accelerometer with the ground for the low-frequency, low-level vibrations generated by transportation facilities and construction activities. Other mounting options are also available. Refer to the accelerometer manufacturer's recommendations for other mounting options.

The signal from a vibration transducer can be directly conditioned and displayed with stand-alone equipment or it can be recorded with an analog or digital recording device for subsequent analysis. Stand-alone or software-based digital fast fourier transform (FFT) analyzers are commonly used to evaluate the recorded signal. Most analyzers can integrate the signal so that velocity and displacement values can be determined from an acceleration signal. Overall peak amplitudes (i.e., PPV) in the time domain can be displayed or, if desired, the frequency spectrum of the signal can be evaluated in the frequency domain (i.e., one-third octave band or narrow band spectrum). A variety of averaging methods is often available.

Chapter 11
Vibration and Air Overpressure from Blasting

11.1 Introduction to Blasting

Often, the only means of loosening a rock mass and reducing it to a material of manageable size is to blast using explosives placed within drilled holes. Many variables relate to the execution of a blast, only some of which are within the control of the blaster. Some of these variables are difficult, if not impossible, to adequately define. As such, blasting is still part "science" and part "art," based on the laws of physics and the capability and experience of the blaster.

11.1.1 Blasting Terminology

The following terms are commonly used in blasting and should be understood by anyone involved in the subject.

- **Downhole blasting:** Downhole blasting is a type of blasting in which explosives are loaded into drilled holes, as opposed to charges being placed on the surface. Surface charges do not have application in conventional construction blasting situations, especially in urban settings.

- **Burden:** Burden represents that volume of material that a detonating hole or holes are expected to fragment and shift. There are two types of burdens: drilled burden and shot burden. Drilled burden is the distance between a row of holes and the nearest free face, and is measured perpendicular to the row of holes. It is also the distance between two rows of holes. Shot burden represents the distance between a hole that is detonating and the nearest free face that is developing in the blast. Unless otherwise specified, the term usually refers to the drilled burden.

- **Spacing:** Spacing represents the distance between holes in a row. A drill pattern is always described in terms of (in order) burden and spacing (e.g., a 6-foot by 8-foot pattern has a burden of 6 ft. and a spacing of 8 ft.)

- **Subdrilling:** Subdrilling is the amount of hole that is drilled below the intended floor of the excavation. Except in situations in which the rock is in flat bedding planes, the detonating charge usually leaves a crater at the bottom of the hole rather than shearing the rock on a horizontal plane. Accordingly, it is not uncommon to subdrill a distance that approaches half of the burden distance to be able to excavate to the intended depth.

- **Stemming:** To confine the energy from the explosive, the top portion of the hole is stemmed (back-filled) with inert material. Because of their proximity to the hole, drill cuttings are usually used, although other material such as stemming plugs can be used. Crushed stone chips are superior to drill cuttings for stemming material because they tend to lock in place under pressure.

- **Decks or decking:** Decks or decking is a means of separating two or more charges within a hole. This step is usually taken to (1) reduce the amount of explosive detonating in a given instant by having the decks fired on different delays, or (2) to avoid loading explosives in weak zones or mud seams in the rock. Decks are separated by inert stemming material and require some means of initiating each deck. Most blasters prefer to avoid the use of decking, however, because it increases the chances for misfired holes and is fairly labor intensive.

- **Primary (production) blast:** A primary (or production) blast is intended to adequately fragment a given volume of rock. The rock may be removed in one or more primary blasts. If the depth of an excavation is sufficient to require removal in more than one lift, each lift would be removed using one or more primary blasts.

- **Secondary blast:** Secondary blasts may be required to remove or reduce material that is not adequately fractured in primary blasts (i.e., trimming blasts or removing high bottom). Also secondary blasts are used for boulders whether or not primary blasting was conducted.

- **Powder factor:** The powder factor is the ratio between explosives consumed and material blasted, usually defined in pounds per cubic yard for construction blasts. When discussing powder factors, it is important to know whether one is using "shot powder factor" or "pay [or yield] powder factor." Shot powder factor includes the material in the subdrilling zone in the calculations, while pay powder factor does not.

- **Detonator:** Detonators are devices, either electric or nonelectric, that are used to detonate the explosive charges.

- **Delay:** The delay is the time interval between detonators (and their corresponding explosive charges) exploding. Because modern initiation systems provide for further subdividing of the delay times in conventional detonators, delay times can be tuned for specific blasting needs.

- **Initiation system:** The initiation system is the entire system for initiating the blast, including the blasting machine or starter, detonators, delay devices, and interconnecting parts.

- **Dynamite:** Dynamite was one of the earliest explosive charges. It was originally sensitized with nitroglycerin, but now uses other sensitizers.

- **Slurry, watergel, emulsion:** These products are modern explosive products in which portions of the ingredients have been replaced with water and various emulsifiers, gums, and other substances. These products come in either packaged or free-flowing form, and poured or pumpable forms.

- **ANFO:** ANFO is an inexpensive blasting agent consisting of 94% prilled ammonium nitrate and 6% #2 diesel fuel (by weight). There are variations of this product in which other materials are added to increase the energy yield. Because of the reduced sensitivity of this material, it requires the use of a more-sensitive explosive for initiation.

- **Booster:** A booster is a fairly sensitive charge that is used to initiate less-sensitive explosive charges. A booster is often in a cast form with a detonator well or detonating cord tunnel, but it can also be a cartridge product.

- **Detonating Cord:** Detonating Cord consists of a core charge of pentaerythritol tetranitrate (PETN) wrapped with layers of plastics and textiles. It is available in various core loadings, all of which detonate at approximately 23,000 ft/sec. Originally developed as an initiation system, it has also been used in specialized blasting situations as the primary charge. Because of the extremely high noise level, this product is not normally used on urban blasting projects. (PETN is also the base charge in most detonators and is an ingredient in most cast boosters.)

- **Presplitting:** Presplitting is a procedure in which a row of lightly loaded holes is detonated ahead of the main production blast. It is intended to propagate a crack along the row of holes to protect the final perimeter wall by allowing expanding gases to vent and preventing back-break from subsequent detonating production holes. It has been shown that a presplit crack has little or no effect in reducing vibration from subsequent blasts; in fact, a presplitting blast creates more vibration per unit of explosive than other forms of blasting.

- **Smooth blasting:** Smooth blasting is similar to presplitting, except that the holes are detonated after the production holes in the main blast. The intent is not to form a crack, but to blast loose the remaining burden with the lighter charges without causing excessive damage to the perimeter wall. In this instance, the charge weights in the nearest production holes are usually reduced.

- **Sinking cut:** A sinking cut is a blast in which no free vertical (or sloped) face exists and in which it is necessary to ramp down into a horizontal surface. In this type of blast, a portion of the blasted material must be expelled upward to make room for the expanding material from subsequent holes detonating. Some flyrock may occur and must be taken into account.

- **Throw or heave:** Throw or heave is movement or shifting of the blasted material an intended distance and direction.

- **Flyrock:** Flyrock is material that is expelled from the blast and travels farther than expected or intended.

- **Blasting mats:** Blasting mats are mats used to cover a blast in an urban situation where flyrock cannot be tolerated and where the situation dictates that explosives be loaded fairly high in the holes. (It is not practical to cover large blast areas, and prevention of flyrock is best addressed in blast design for those situations.) Blasting mats are usually fabricated from sections of rubber tires, manila rope, used conveyor belting, or other similar materials. Many contractors cover the blast with soil, sand, or other fine material; this step can be successful, but it is necessary to use a sufficient amount of covering and to use covering that does not contain rock or other projectiles. Blast covering with any of these materials or devices must be done carefully so that the initiation system is not damaged.

- **Scaled distance (square root or cube root):** Scaled distance is a means of scaling a ratio of distance and charge weight so that effects from various blasts can be compared or estimated. Once a blaster has recorded data from a given blast site, scaled distance can be used as a tool to assist in designing future blasts. Square-root scaled distance is derived by dividing the distance between the detonating charge and the object of interest by the square root of the charge weight. Square root scaling is used for vibration estimations where linear charges (length is more than twice the diameter) are used. Cube-root scaled distance is derived similarly, using the cube root of the charge weight instead of the square root. It is conventional to use cube root scaling for estimating air overpressure and for infrequent instances in which vibration estimations involve a spherical charge (diameter is greater than half the length).

- **Overburden:** Overburden is soil and other materials that overlay the rock to be blasted. Overburden is usually removed before drilling, but it is occasionally left in place to confine the blast and to allow loading explosives higher in the hole (nearer to the top of the rock).

11.1.2 Blasting Process

After the decision has been made to conduct blasting at a construction site, the necessary permits obtained, and arrangements made for explosives storage, the first consideration is usually the size of the drill that will be used. For large excavations, large-diameter drills (4–6 in.) will provide better production than smaller drills, but will result in larger material. A larger number of smaller holes (2–3 in.) will take longer to drill and load, but will provide better fragmentation and easier handling of material. Other considerations are the size of the digging and hauling equipment, the location of any local utilities, nearby structures, vibration and air overpressure or airblast limitations for the specific site, and the lengths of drill steel available.

The blaster uses the borehole diameter and the considerations above to formulate blast designs—laying out burden and spacing, depth of hole (including subdrilling), type of initiation system, explosive products, and sequence of initiation. The blaster often uses timing and the sequence of initiation to control the direction of heave and to allow time for the earlier rows' burden to begin to move before the later rows detonate.

At this point, the blaster can document his intentions on a blasting plan, but he must have the latitude to make changes as drilling progresses and more is learned about the site geology. One or more test blasts are not unusual. The rock from a preceding blast will usually be removed before the succeeding blast is loaded and shot, thus providing a space for the expansion, or swell, of the material in the succeeding blast. If circumstances dictate, however, a portion of the shot rock may be left in place to help contain the material in the front row of the succeeding blast.

The actual loading process will depend on the type of explosives to be used, but will generally consist of the following. (Please note that only the blaster and those persons necessary for the loading process are allowed within 50 ft. of a blast while it is being loaded.)

1. The detonators are laid out near the holes according to the desired initiation sequence.

2. The primer is made up by inserting the detonator securely into the priming charge and is lowered to the bottom of the hole.

3. A denser bottom charge (if desired) is loaded. If there is water in the holes, a water-resistant explosive is loaded until the column builds up out of the water. The main explosive charge then is loaded. Holes are normally loaded to a specific height; however, in cases where the exact quantity of explosive is critical, holes might be loaded with a specific number of cartridges or containers of bulk product. If bulk loading equipment is used, the density of the product and the quantity loaded can be controlled by the operator.

4. A second primer is added, if desired.

5. After a hole is loaded with the desired quantity of explosive, the remainder of the hole is stemmed or backfilled with inert material.

6. After all holes are loaded and stemmed, the initiation system, except for the starter or blasting machine, is connected and checked. In the case of electric detonators, a Blaster's Galvanometer or Blaster's Multimeter is used to check the resistance of the system. Other systems are usually checked visually.

7. Blasting mats or other coverings are put in place, if they are to be used.

8. When the blast is ready to be detonated, the area is cleared, the blasting signals are initiated, and the blaster prepares to connect the starter or blasting machine.

9. Just before initiation, the blaster connects the starter or blasting machine, then detonates the blast at the proper time.

10. During and immediately following the blast, the blaster and his crew watch for any sign of a possible misfire. If a misfire is suspected, the area remains secured and no one, including the blaster, is allowed to approach the blast for at least 30 minutes. (This is a California Occupational Health and Safety Administration–mandated time period. Although seldom used in construction blasting, the use of cap and fuse would mandate a 60-minute wait.)

11. As soon as it is safe to do so (and following the mandatory wait if a misfire is suspected), the blaster inspects the site.

12. After any misfires are cleared and the site inspection is complete, the "all clear" signal can be given and personnel are allowed back into the blast area.

As blasting proceeds through the project, the blaster can fine-tune his blast designs. Quite often, the best blasts will occur near the end of the blasting program because the blaster will have gradually increased his or her knowledge of how the rock on the site breaks.

11.2 Vibration and Air Overpressure Concerns that Arise from Blasting

When a blast is detonated, only a portion of the energy is consumed in breaking up and moving the rock. The remaining energy is dissipated in the form of seismic waves expanding rapidly outward from the blast, either through the ground (as vibration) or through the air (as air overpressure or airblast). While a blaster can quite easily design his blasts to stay well below any vibration or air overpressure levels that could cause damage, it is virtually impossible to design blasts that are not perceptible by people in the vicinity.

As seismic waves travel outward from a blast, they excite the particles of rock and soil through which they pass, causing them to oscillate. Spherical spreading, imperfect coupling, and other factors cause seismic waves to dissipate rapidly with distance, normally by two-thirds for each doubling of distance from the source. The motion of particles at a given point in the earth is measured when blast vibration is recorded. Blast vibration is described using the following terms.

- **Displacement:** Displacement is the farthest distance that the ground moves before returning to its original position. For blasting, displacement is usually only a few thousandths or ten-thousandths of an inch.

- **Particle velocity:** Particle velocity is the velocity at which the ground moves.

- **Peak particle velocity (PPV):** PPV is the greatest magnitude of particle velocity associated with an event.

- **Acceleration:** Acceleration is the rate at which particle velocity changes. Acceleration is measured in in/sec^2, mm/sec^2, or g.

- **Frequency:** Frequency is the number of oscillations per second that a particle makes when under the influence of seismic waves. Frequency is measured in Hz.

- **Propagation velocity:** Propagation velocity is the speed at which a seismic wave travels away from the blast. Propagation velocity is measured in ft/sec. (Please note that propagation velocity is several orders of magnitude greater than particle velocity.)

When blast vibration is recorded with a seismograph, three mutually perpendicular sensors record particle velocities in longitudinal (radial), transverse, and vertical axes; the PPVs recorded for each axis are the main data of interest for comparison with damage criteria. Because the data are recorded against a time base, other information such as frequency, displacement, acceleration, and true vector sum (resultant) can be calculated and included on the record.

The resultant particle velocity is the highest particle velocity in any direction. Although the resultant particle velocity is the highest particle velocity in any direction, the conventions and standards currently in use are based on data that were gathered when it was impractical to obtain true resultant data. Resultant values have become easily obtainable since the development of the digital seismograph and digital recording techniques. Therefore, when using modern prediction curves or blasting level criteria that are based on older data, one should use individual axis peaks rather than the resultant. If it is desirable to use the resultant instead of individual peaks, allowances need to be made that consider the higher numbers that would be obtained. (The true resultant PPV could be as much as 1.73 times the highest individual peak, although in actual practice it is usually only about 10–20% greater.)

In all instances, body waves (compression and shear waves that pass through the ground) and surface waves (waves that travel along the surface of the ground) diminish with distance, although they dissipate at differing rates. Body waves typically have a higher frequency than surface waves and are dominant close to the blast; therefore, the frequencies of the PPVs closer to the blast will be higher. As the distance from the blast increases, body waves dissipate faster than surface waves; therefore, the surface waves become dominant and the frequencies (and intensities) of the PPVs are lower. Exceptions can occur when waves propagate in underlying stiff soil or rock, and emerge as the dominant wave at large distances.

When the distance between the recording point and the blast is large enough, waves that have traveled different paths arrive at different times with spreading and some overlap. Recorded at greater distances, the entire blast begins to take on the characteristics of a single point detonation of relatively long duration.

Although residential structures may not be as strongly constructed as engineered structures, it is unusual to find damage to them from blast vibration. In numerous instances, vibration levels far greater than the maximum levels recommended by the U.S. Bureau of Mines (USBM) or Office of Surface Mining and Reclamation Enforcement (OSMRE) failed to cause damage. With regard to residences, the main issue with blast vibration is the perception of some residents that, because they could hear and feel the blast vibration, the vibration must have caused some damage to their residence. It is not unusual for a homeowner to be unaware of cracks or other defects in his or her residence that have developed slowly because of settlement or thermal strains. When a nearby blast is detonated and the homeowner examines his or her structure more closely, it is not surprising that defects are attributed to the event.

Homeowners with wells, especially in times of drought, can have major concerns over the effects of blast vibration on their water source, although vibration alone would not be expected to damage a well. If a blast was detonated in close enough proximity that rock-block movement pinched off a well, the well could sustain damage, but it would not have been caused by vibration (Robertson 1980; Rose 1991). In some situations, vibration is used by the oil industry to enhance permeability and well production.

11.3 Methods of Predicting Blast Vibration and Air Overpressures

To predict the intensities of blast-induced vibration and air overpressures from blasting, a scaling method is usually used that considers the energy released, the distance to the blast, and their relationship to the intensities derived. Other variables affect the intensities to a lesser extent.

11.3.1 Predicting Blast Vibration

Square-root scaled distance is a scale that divides the distance from the point of interest to the blast by the square root of the largest charge weight detonated on one delay period. All explosives detonating within any given 8-millisecond (ms) time period are typically counted as having been detonated on the same delay. (The blaster may be separating his detonating charges by more or less than 9 ms. In any case, all explosives detonating within any 8-ms period are combined for typical prediction calculations.)

The most commonly accepted blast vibration prediction curves in use were developed by Lewis L. Oriard, a noted seismologist from Huntington Beach, California (now retired), and are based on data gathered from a large number of blasts in various geological settings. Other researchers have come to similar conclusions, with their estimations falling within Oriard's parameters.

Figure 6 contains curves representing Oriard's upper and lower bounds for typical down-hole blasting, with a higher approximation for those instances where there is very high confinement, such as in presplitting. Because of the many variables involved in blast design and site-specific geology, data points could fall above or below the bounds for typical data shown on the graph.

Oriard's basic formula for predicting blast vibration is:

$$PPV = K\,(D_S)^{-1.6} \qquad \textit{(Eq. 13)}$$

Where:

PPV = peak particle velocity (in in/sec),

D_S = square-root scaled distance (distance to receiver in ft. divided by square root of charge weight in lbs.)

K = a variable subject to many factors, as described below

This equation is similar to Eq. 7 presented in Chapter 4 and Eqs. 1–4 in Chapter 2. The K factor (and the resulting PPV) decreases with the following:

- decreased confinement of energy,
- decreased elastic moduli of the rock,
- increased spatial distribution of the energy sources,
- increased time of energy release or timing scatter, and
- decreased coupling of the energy sources.

PPV increases when these changes are reversed. Of the factors listed above, confinement of the explosive energy will probably be the most-

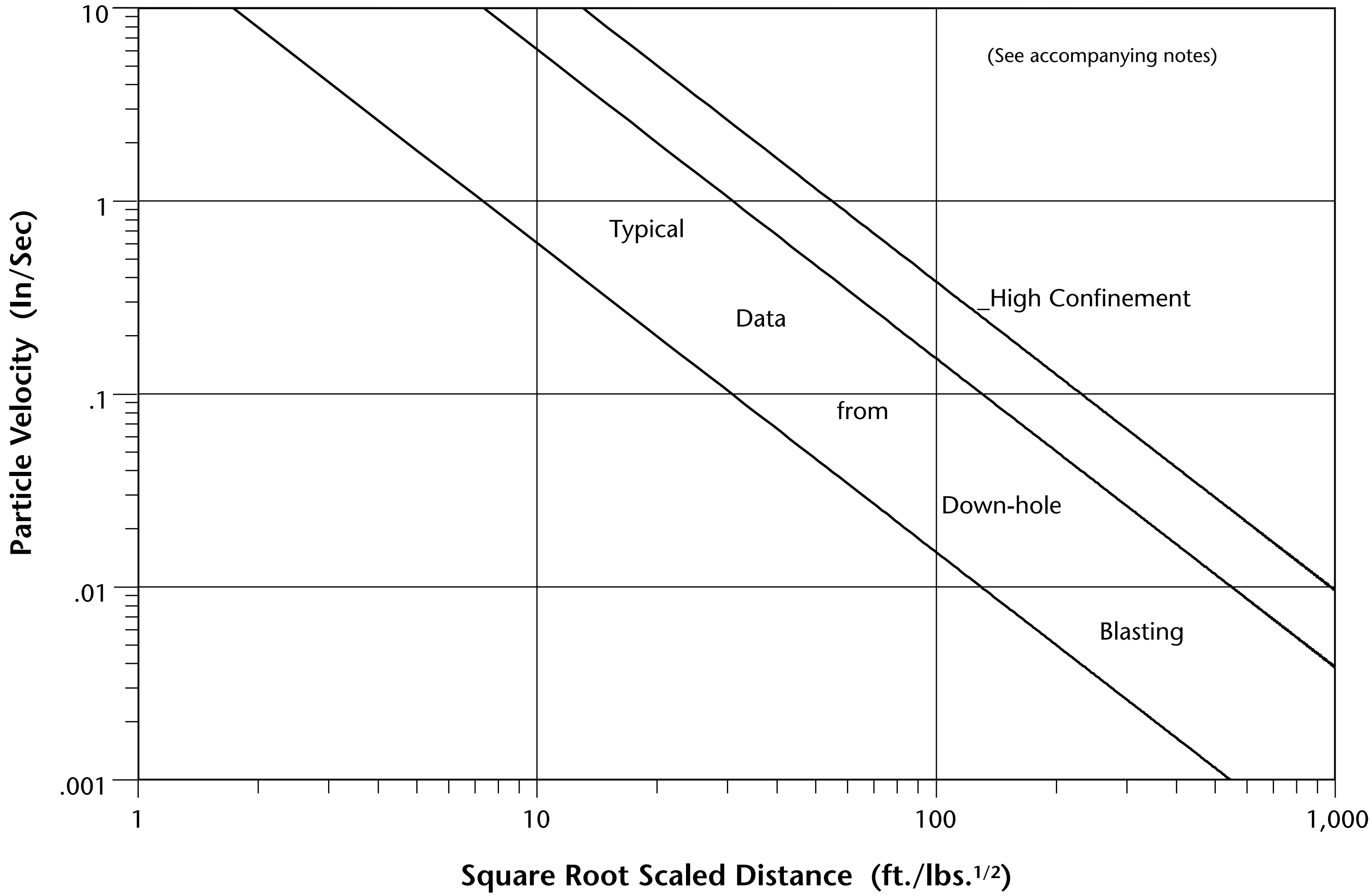

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Figure 6
Blast Vibration Prediction Curves (Oriard, 1999,2000)

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important factor after charge weight and distance. Confinement of the energy is increased as the burden, depth of burial, and quality of rock increase. The combined K factor for Oriard's upper and lower bounds are 242 and 24, respectively. Most conventional blasts will fall between these bounds. The combined K factor for a blast under extremely high confinement is 605.

An exponent of –1.6 is typical. This exponent may be more negative for body waves in very close proximity to the blast or less negative where surface waves dominate.

The exponent –1.6 is more negative than the value of –1.0 to –1.4 recommended for construction equipment in Table 17. This suggests that blast vibration amplitudes in general attenuate at a higher rate than vibration from construction equipment. Persons experienced in blast vibration prediction will use the range given in the curves (or formulas) as a basis and adjust them for any blast-specific variables that they can quantify through experience. They will need information from the blaster (or the blaster's records) regarding charge weights per delay, timing schemes, and other factors.

In addition to ensuring that the charge weights obtained from the blaster are accurate, the correct number of holes per delay should be verified and, if more than one hole or deck will detonate simultaneously, the spatial separation of those holes or decks should be noted. Two holes that detonate simultaneously will not generate the same vibration as a single hole containing the same weight as the two holes combined; the greater the distance between holes detonating simultaneously, the less they cooperate in increasing vibration.

With regard to distance measurements, blast-induced ground vibration can travel only through the ground; it cannot jump across an open space. The shortest path through the ground between the detonating hole and the object of interest should be the distance used. The correct square-root scaled distance is the lowest number calculated for various configurations within the blast and will more closely relate to the intensity of vibration. Technically speaking, there are as many square-root scaled distances as there are holes detonating. If all the holes are loaded identically and are detonated on individual delays, the closest hole will naturally yield the lowest number. If the blast has varying charge weights (the shot may be deeper in some areas), the lowest square-root scaled distance may actually be calculated from a hole that is farther away.

A site-specific prediction curve is initiated when results from several recorded blasts have been plotted on a graph, although it should not be assumed that all future blasts will follow the results of just a few blasts. The confidence level increases as additional data are added, although some scatter in the data points can be expected. It is also helpful to have PPV readings over a wide range of distances (and square-root scaled distance) to provide linearity to the plot. If all recordings are made at one distance, the data points will be clustered in a general zone on the chart and it will be difficult to obtain a reasonable regression plot.

11.3.2 Predicting Air Overpressures from Blasting

Air overpressures from blasting can be predicted by using curves in a manner similar to vibration prediction; however, cube-root distance scaling, not square-root distance scaling, is normally used. Figure 7 depicts curves that are based on data gathered from blasts in various locations and from research conducted by various individuals and organizations, including USBM. Again, because of the variables, many of which are difficult to quantify, data points for a given event may fall above or below the bounds shown on the graph. The prediction curves were established using the basic formula for estimating air overpressures:

$$\text{Peak air overpressure (in pounds per square inch [psi])} = K\,(D_S)^{-1.2} \qquad \text{(Eq. 14)}$$

Where:

D_S = *cube-root scaled distance (distance to receiver in ft, divided by cube root of charge weight in lbs.)*

The curves representing the normal upper and lower bounds for confined charges use combined K factors (intercepts at a D_s of 1) of 2.5 and 0.78, respectively. The curve for unconfined charges uses a combined K factor of 82.

The attenuation slope of –1.2 is typical for static conditions and represents a reduction of approximately 7.2 dB for each doubling of distance. Some researchers have used attenuation slopes as flat as –1.0 (corresponding to 6 dB per doubling of distance), but the difference does not become a major factor until a considerable distance has been reached. Atmospheric variables such as wind and temperature inversions have a greater effect on attenuation.

In addition to charge weight and distance (which affect the cube-root scaled distance), the following factors affect air overpressure intensity.

- depth of burial of the charge;
- terrain features, trees, foliage, and other screening;

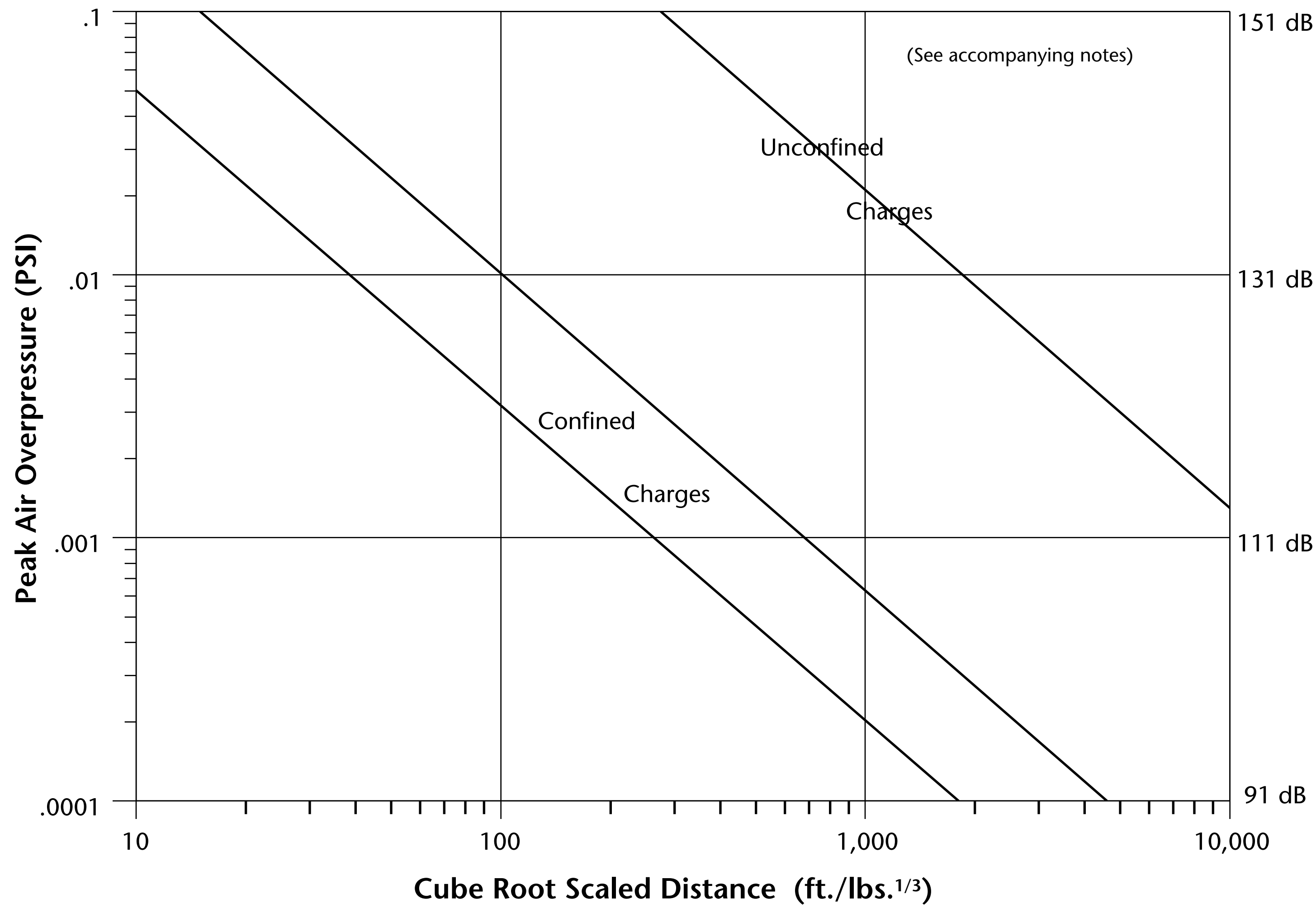

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Figure 7
Air Overpressure Prediction Curves

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- orientation of the blast face (facing toward the recording point increases intensity);

- velocity of blast progression (across the face or along the surface);

- explosive composition (elapsed time of energy release, a minor effect that can normally be disregarded for conventional explosive products);

- atmospheric conditions:

    - changes in barometric pressure (a minimal effect normally disregarded), and

    - humidity (normal daily fluctuations may be disregarded, but the difference between a very dry day and a rainy one can be quite noticeable); and

- temperature gradients:

    - normal or lapse conditions (temperature decreases with elevation; sound energy is refracted upwards and the air overpressure will attenuate at a greater rate than isothermal conditions),

    - inversion conditions (temperature decreases with elevation; sound energy is refracted downwards and air over pressure will attenuate at a lower rate than for isothermal conditions; a temperature inversion has little effect in the immediate area of the blast and usually only affects air overpressure beyond a radius equal to the height of the inversion layer), and

    - wind direction and velocity (wind can have a major impact on air overpressure; downwind from the blast, the overpressure will not attenuate as rapidly as it would upwind from the blast because the wave front and the sound energy is being refracted or bent downward; this can add from several to as much as about 20 dB to the overpressure).

If it is desirable to convert psi to decibels, the following formula can be used:

$$dB = 20 \log (psi / 2.9 \times 10^{-9}) \qquad (Eq.\ 15)$$

In addition to the cautions concerning charge weights and delays discussed above, the shortest distance through the air should be used. Depending upon terrain, this may not always be a straight line.

The estimation of air overpressures is more difficult than estimating vibration due to variables that can change from moment to moment. For this reason, allow a greater margin of error when estimating air overpressures. Gathering data for specific sites and accurately noting weather conditions at blast times can assist in building prediction curves for specific operations or specific sites.

11.4 Criteria for Assessing Human Response to Blasting and Potential for Structural Damage

11.4.1 Human Response

Human response to blast vibration and air overpressures from blasting is difficult to quantify. Ground vibration and air overpressures can be felt at levels that are well below those required to produce any damage to structures. The duration of the event has an effect on human response, as does the frequency. Events are of short duration, 1–2 seconds, for millisecond-delayed blasts. Typically, the longer the event and the higher the frequency, the more adverse the effect on human response. Factors such as frequency of occurrence, fright or “startle factor,” level of personal activity at the time of the event, health of the individual, time of day, orientation of the individual (standing up or lying down), the perceived importance of the blasting operation, and other political and economic considerations also affect human response.

Although the duration of an event affects human response, some researchers have found that fewer blasts of a longer duration are preferable to many blasts with shorter durations. There would be fewer times of perceived disturbance. Fixed locations such as quarries may be able to take advantage of this. Construction projects, however, usually have constraints such as smaller volumes of material to be blasted and sequence of the work that would preclude this.

Table 21 indicates the average human response to vibration and air overpressures that may be anticipated when the person is at rest, situated in a quiet surrounding.

Table 21. Human Response to Blasting Ground Vibration and Air Overpressure

Average Human Response	PPV (in/sec)	Airblast (dB)
Barely to distinctly perceptible	0.02–0.10	50–70
Distinctly to strongly perceptible	0.10–0.50	70–90
Strongly perceptible to mildly unpleasant	0.50–1.00	90–120
Mildly to distinctly unpleasant	1.00–2.00	120–140
Distinctly unpleasant to intolerable	2.00–10.00	140–170

In reviewing the above responses, one must distinguish between the average individual and those who may reside at either end of the human response spectrum. At one end are persons who might perceive some financial benefit or common good from the project. Although they may not appreciate the inconvenience of the blasting, unless they are physically damaged in some manner, they may not complain. At the other end of the spectrum, individuals who do not want the project to take place may be disturbed by the slightest inconvenience and will generally make their feelings known.

The listing of vibration levels and air overpressure levels on the same comparison chart above does not indicate that there is any connection between the two, except as the particular levels apply to human response. In blasting, an increase in vibration can often be accompanied by a decrease in air overpressures, and vice versa.

11.4.2 Effect of Blast Vibration on Materials and Structures

Table 22 summarizes the effects of peak particle velocities on structures and materials that have been documented by various researchers and organizations. The listing is intended to provide some idea of what various particle velocities represent and the effects that might be expected. This listing is not intended to be used to establish specific limits. In some instances equivalent velocity levels were derived from strain measurements.

Several valuable points can be drawn from review of Table 22 and associated references:

- Concrete is difficult to damage with normal construction blast vibration, although unsupported concrete slabs can eventually crack from their own weight. Extremely close blasts could damage concrete from rock block movement, but this would not be considered vibratory damage.

- The average residence experiences far greater stress from daily environmental changes than from construction blasting if blast vibration intensities are kept at or below USBM or OSMRE limits.

- Water wells and buried pipelines can survive rather high-vibration intensities because they are constrained by the soil and bedding materials surrounding them.

Table 22. Effect of Blasting Vibration on Materials and Structures

PPV (in/sec)	Application	Effect	Reference
600	Explosives inside concrete	Mass blowout of concrete	Tart et al. 1980
375	Explosives inside concrete	Radial cracks develop in concrete	Tart et al. 1980
200	Explosives inside concrete	Spalling of loose/weathered concrete skin	Tart et al. 1980
>100	Rock	Complete breakup of rock masses	Bauer and Calder 1978
100	Explosives inside concrete	Spalling of fresh grout	Tart et al. 1980
100	Explosives near concrete	No damage	Oriard and Coulson 1980
50–150	Explosive near buried pipe	No damage	Oriard 1994
25–100	Rock	Tensile and some radial cracking	Bauer and Calder 1978
40	Mechanical equipment	Shafts misaligned	Bauer and Calder 1977
25	Explosive near buried pipe	No damage	Siskind and Stagg 1993
25	Rock	Damage can occur in rock masses	Oriard 1970
10–25	Rock	Minor tensile slabbing	Bauer and Calder 1978
24	Rock	Rock fracturing	Langefors et al. 1948
15	Cased drill holes	Horizontal offset	Bauer and Calder 1977
>12	Rock	Rock falls in underground tunnels	Langefors et al. 1948
12	Rock	Rock falls in unlined tunnels	E. I. du Pont de Nemours & Co. 1977
<10	Rock	No fracturing of intact rock	Bauer and Calder 1978
9.1	Residential structure	Serious cracking	Langefors et al. 1948
8.0	Concrete blocks	Cracking in blocks	Bauer and Calder 1977
8.0	Plaster	Major cracking	Northwood et al. 1963
7.6	Plaster	50% probability of major damage	E. I. du Pont de Nemours & Co. 1977
7.0–8.0	Cased water wells	No adverse effect on well	Rose et al. 1991
>7.0	Residential structure	Major damage possible	Nichols et al. 1971
4.0–7.0	Residential structure	Minor damage possible	Nichols et al. 1971
<6.9	Residential structure	No damage observed	Wiss and Nichols 1974
6.3	Residential structure	Plaster and masonry walls crack	Langefors et al. 1948
5.44	Water wells	No change in well performance	Robertson et al. 1980
5.4	Plaster	50% probability of minor damage	E. I. du Pont de Nemours & Co. 1977
4.5	Plaster	Minor cracking	Northwood et al. 1963
4.3	Residential structure	Fine cracks in plaster	Langefors et al. 1948
>4.0	Residential structure	Probable damage	Edwards and Northwood 1960
2.0–4.0	Residential structure	Plaster cracking (cosmetic)	Nichols et al. 1971
2.0–4.0	Residential structure	Caution range	Edwards and Northwood 1960
2.8–3.3	Plaster	Threshold of damage (from close-in blasts)	E. I. du Pont de Nemours & Co. 1977
3.0	Plaster	Threshold of cosmetic cracking	Northwood et al. 1963
1.2–3.0	Residential structure	Equates to daily environmental changes	Stagg et al. 1980
2.8	Residential structure	No damage	Langefors et al. 1948
2.0	Residential structure	Plaster can start to crack	Bauer and Calder 1977
2.0	Plaster	Safe level of vibration	E. I. du Pont de Nemours & Co. 1977
<2.0	Residential structure	No damage	Nichols et al. 1971
<2.0	Residential structure	No damage	Edwards and Northwood 1960
0.9	Residential structure	Equivalent to nail driving	Stagg et al. 1980
0.5	Mercury switch	Trips switch	Bauer and Calder 1977

PPV (in/sec)	Application	Effect	Reference
0.5	Residential structure	Equivalent to door slam	Stagg et al. 1980
0.1–0.5	Residential structure	Equates to normal daily family activity	Stagg et al. 1980
0.3	Residential structure	Equivalent to jumping on floor	Stagg et al. 1980
0.03	Residential structure	Equivalent to walking on floor	Stagg et al. 1980

11.4.3 Government-Published Vibration Limits

11.4.3.1 U.S. Bureau of Mines

In 1974, USBM began a study to gather and update available blast vibration data. Work was included in the area of structural and human response to vibration. This resulted in the publishing in 1980 of USBM RI 8507, "Structure Response and Damage Produced by Ground Vibration From Surface Mine Blasting." Some of the conclusions contained in the report are as follows:

- PPV is the most practical descriptor of vibration as it applies to the damage potential for residential structures.
- The potential for damage to residential structures is greater with low-frequency blast vibration (below 40 Hz) than with high frequency blast vibration (40 Hz and above).
- The type of residential construction is a factor in the vibration amplitude required to cause damage.
- For low-frequency blast vibration, a limit of 0.75 in/sec for modern drywall construction and 0.50 in/sec for older plaster-on-lath construction was proposed. For frequencies above 40 Hz, a limit of 2.0 in/sec for all types of construction was proposed.
- Alternative blasting-level criteria were also proposed that used the above limits over a wide range of frequencies and included some limits on displacement.

Figure 8 depicts the alternative blasting level criteria proposed by USBM. (These curves also have been applied to impact rate driving vibration.)

11.4.3.2 Office of Surface Mining and Reclamation Enforcement

In 1983, OSMRE established regulations controlling vibration at all surface coal mining operations. Three optional methods of limiting vibration are allowed:

1. The first option limits PPV based on the distance to the nearest protected structure. Each blast must be monitored by a seismograph. With this option, velocities must be kept at or below the following levels:
    - Distances up to 300 ft.: 1.25 in/sec
    - Distances of 301–5,000 ft.: 1.00 in/sec
    - Distances beyond 5000 ft.: 0.75 in/sec
2. The second option does not require monitoring, but requires the operator to design his blasts utilizing Square-Root Scaled Distances (D_s). The calculated Scaled Distances must not fall below the following values:
    - Distances up to 300 ft.: 50
    - Distances of 301–5000 ft.: 55
    - Distances beyond 5000 ft.: 65
3. The third option requires an operator to monitor his blasts with a seismograph and use PPV limits that vary with frequency, similar to the alternative blasting level criteria proposed in USBM Report of Investigations (RI) 8507. The OSMRE option differs from RI 8507 in two areas: (1) it does not differentiate between drywall and plaster-on-lath construction, allowing 0.75 in/sec in the medium frequencies for either case, and (2) it allows a particle velocity of 2.0 in/sec down to a frequency of 30 Hz rather than 40 Hz.

Figure 9 depicts OSMRE optional criteria. An analysis of the OSMRE options discloses the following:

- Option 1 is reasonable for mine-type blasts, which are usually larger than construction blasts and generally result in larger charge weights and lower frequencies. The nearest structures of concern are usually at greater distances than would be expected in construction blasts where

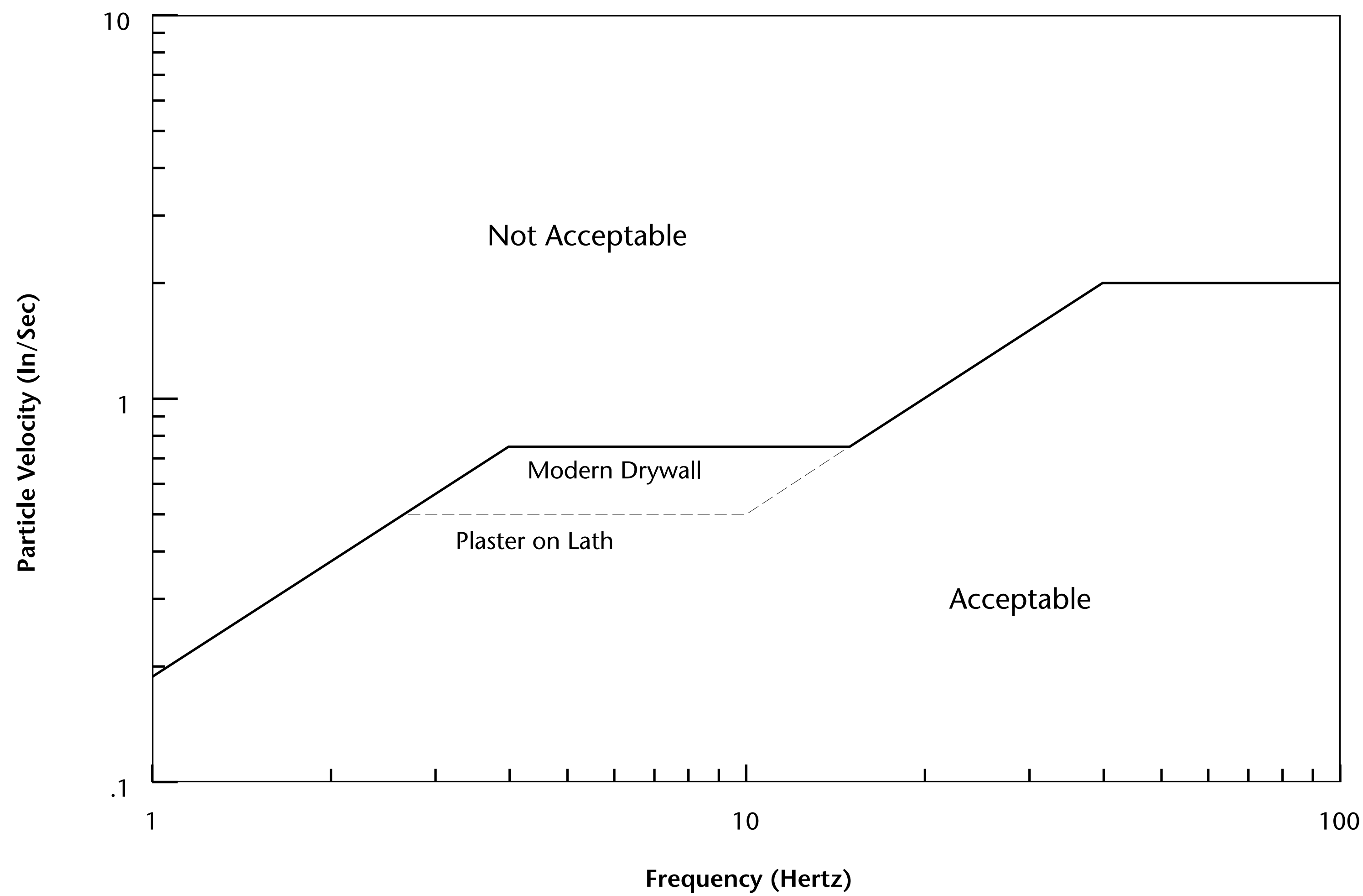

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Figure 8
R18507 Alternative Blasting Level Criteria

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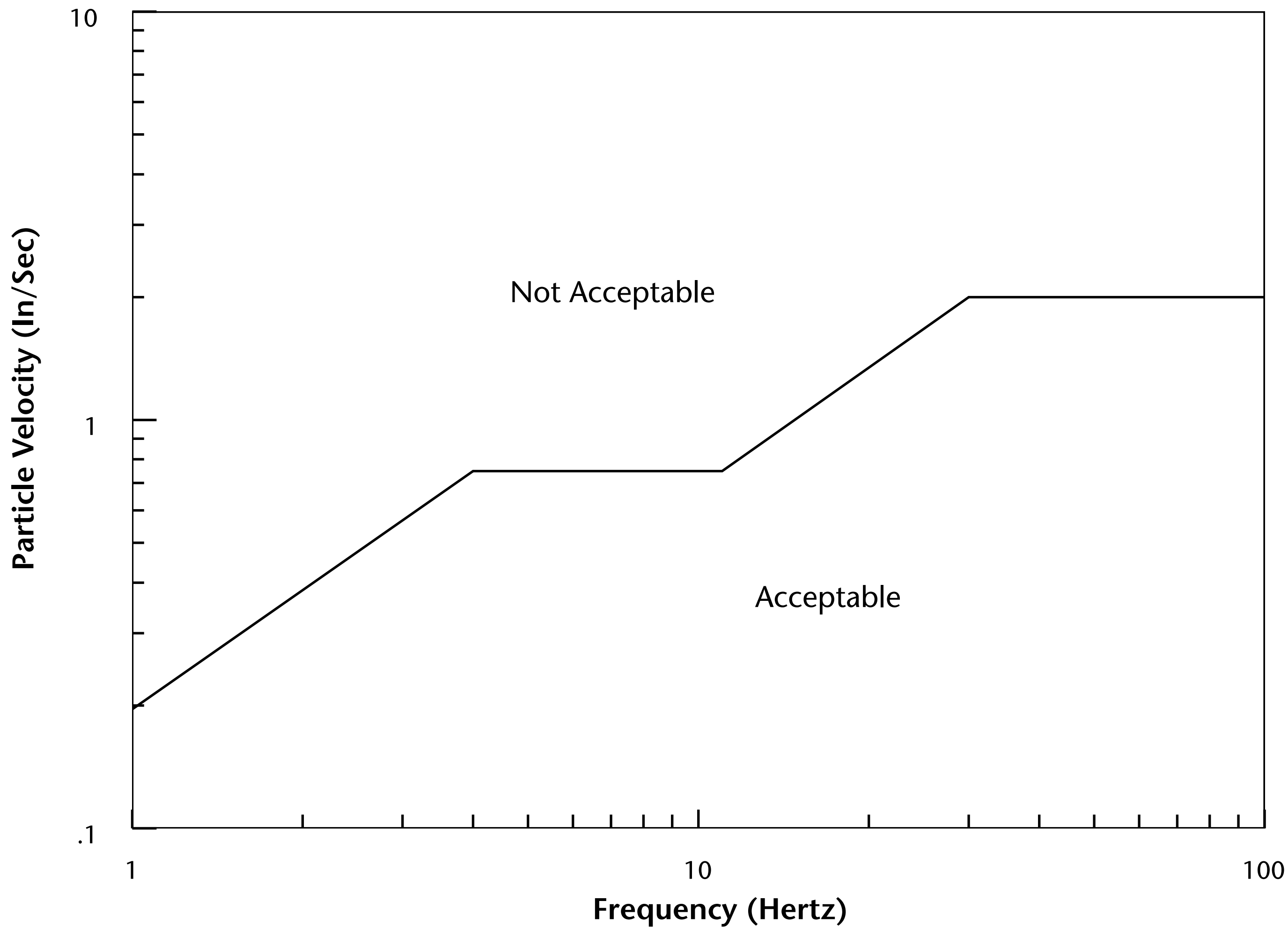

Figure 9
OSMRE Alternative Blasting Criteria
(30 CFR Part 816.67(d)(4)

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charges are usually smaller and frequencies higher. Option 1 would be somewhat conservative for construction blasts.

- Option 2 is quite conservative and uses blast design criteria rather than limiting the effects of the blast. Because no recording is required, a larger safety factor is built into this option. Unfortunately, this option also has the unintended effect of limiting the blaster's use of modern technology to improve blast efficiency while at the same time keeping adverse effects within acceptable limits.

- Option 3, which requires vibration recording with a capability of determining frequencies, is a more practical limit and can be equally applied to both mine and construction blasting.

11.4.3.3 Vibration Limits for Other than Residential Structures

Massive concrete structures, bridges, and other well-engineered structures are far more capable of withstanding blast vibration intensities than residential structures. Massive structures do not respond adversely to the relatively high-frequency and low-displacement vibration waves that result from nearby construction blasting. (On the other hand, the large displacements and low frequencies encountered in earthquakes must always be considered when designing these structures.) A PPV limit of 4.0–10.0 or 12.0 in/sec is not uncommon where the mass of a structure precludes it from being damaged by blast vibration, and it is unusual to find situations in which rock has been blasted away at the base of such structures without causing damage. Blast vibration limits are best addressed for engineered structures on a case-by-case basis.

Buried pipelines, being constrained by the bedding material and soil surrounding them, can also withstand high-vibration intensities (Oriard 1994; Siskind and Stagg 1993). When blasting in close proximity to these pipelines or in close proximity to most structures, rock block movement and cracks emanating from the crater zone toward the object can become more of a concern than vibration.

Special care should be taken when blasting in close proximity to historically important structures. Such structures are usually of older, less-competent construction, and lower vibration limits for them are often justified. These should be addressed on a case-by-case basis.

11.4.4 Effects of Air Overpressure (Airblast)

Although the term "airblast" has been used to describe all air overpressures from blasting, it is more correctly applied only to high-frequency air overpressures resulting from the detonation of explosives on the surface or in the air and that result in high intensities in close proximity to the detonation. Detonation of such charges should not have a part in construction blasting, especially in urban settings. Air overpressures from fully confined charges in normal down-hole blasting are lower-frequency pressure pulses that result from movement or bulking of the blasted material, bench-face movement, and the vertical component of ground vibration waves in the vicinity of an air overpressure recording device. All blasting involves expanding cases that induce a positive pressure pulse (hence the term "overpressure").

Overpressure at higher frequencies can be startling in a quiet surrounding, but it will not normally cause damage unless it exceeds approximately 150 dB (linear, unweighted). Low-frequency overpressures, although they might be below the range of human hearing, can impact the side of a residential structure, resulting in windows rattling and other noise. On hearing this noise, the average homeowner will not be able to distinguish between air overpressure or ground vibration as the source but will generally incorrectly attribute the effect to the latter.

11.4.5 Government-Published Air Overpressure Limits

USBM RI 8485 (1980), "Structure Response and Damage Produced by Airblast From Surface Mining," generally recommends a maximum safe overpressure of 0.014 psi (134 dB, linear, unweighted) for residential structures. The first occurrence of airblast damage is usually the breakage of poorly mounted windows at approximately 152 dB (0.11 psi). A limit of 134 dB is sufficiently low to prevent damage but may not address the annoyance of individuals.

OSMRE also addressed air overpressure limits in its 1983 regulations. It considered the characteristics of the recording systems and established the following limits:

Table 23. OSMRE Overpressure Limits

Recording Device Characteristics	Limit
Lower Limit of 0.1 Hz*	134 dB
Lower Limit of 2.0 Hz	133 dB
Lower Limit of 6.0 Hz	129 dB
C-weighted, slow response*	105 dBC

* To be used only with prior approval of OSMRE.

Most modern seismographs with air overpressure recording capability have a frequency response of from 2–250 Hz; hence, the 133-dB limit would be appropriate where they were used for recording.

For several years, an air overpressure limit of 140 dB was used primarily to prevent injury to workmen's' hearing; it also successfully prevented damage to structures. In recent times, lower limits have been used, mostly in attempts to reduce annoyance.

11.5 Procedures for Mitigating Blast Vibration and Air Overpressures from Construction Blasting

Every attempt should be made to mitigate the adverse effects from blasting on construction projects by using modern techniques, procedures, and products. It is equally important to put in place a process to avoid and, if necessary, deal with problems from the public that can arise from blasting, even when the levels of vibration and air overpressure are well below the levels at which damage to structures or excessive annoyance to humans is expected to occur. Taking the following steps is suggested to avoid and/or deal with potential problems from the public.

1. Identify potential problem areas surrounding the project site
2. Determine the conditions that exist prior to commencement of construction
3. Inform the public about the project and potential blasting-related consequences
4. Schedule the work to reduce adverse effects
5. Design the blast to reduce vibration and air over pressure
6. Use blast signals to notify nearby residents that blasting is imminent

7. Monitor and record the vibration and air overpressure effects of the blast

8. Respond to and investigate complaints

Steps 1–3 are closely related. Step 1 involves determining the radius within which a preblast survey should be conducted. Step 2 involves the actual preblast survey. Step 3 is related to the preblast survey but incorporates a larger radius and should be offered to all interested parties.

A blasting specification is a tool that can be used to identify blast vibration limits, surveys, monitoring instruments, and other key methods to avoid and minimize the effects of blasting. This chapter concludes with a discussion of blasting specifications.

11.5.1 Step 1. Identify Potential Problem Areas Surrounding the Project Site

The scope of blasting anticipated for a project will be part of the process of identifying potential problem areas. If only a very small portion of rock would be blasted at one end of the project, for example, there may be no need for a preblast survey of structures at the other end. Therefore, it must be determined how far away from the proposed blasting the surveys must be conducted. There is no standard distance that would be appropriate for all projects or all locations.

One method of determining the preblast survey radius is to estimate the blast vibration and survey to a radius at which the anticipated vibration levels drop below the threshold of human detection (0.01–0.02 in/sec PPV). This method would be economically feasible in rural areas where such a radius might include only a few structures, but may not be economically feasible in more densely populated areas. In a study conducted by Caltrans (Egan et al. 2001), it was suggested that a preblast survey radius of 100 m (328 ft.) appeared to be reasonable to take in all structures susceptible to blast vibration damage. Any distance selected must consider the volume of material to be blasted and the probable charge weights to be used.

One question that must be answered before any preblast survey radius is mandated is whether the intent is to prevent structural damage or to prevent the perception that structural damage is occurring. Egan (2001) notes in his study that structures beyond 35 m (115 ft.) would not have experienced blast vibration in excess of 2.0 in/sec, the Caltrans threshold for damage prevention at the time. Although this may have served well to prevent damage to structures, such vibration levels will usually result in claims of perceived damage from nearby neighbors. It would not prove excessively costly to base the preblast survey radius on preventing actual damage, but it could be very expensive if the radius were based on preventing human perception.

Regardless of the radius selected for preblast surveys, there have been numerous instances in which claims of damage came from locations far beyond the surveyed areas. Therefore, there is no reasonable standard distance beyond which no complaints can be assured.

Bearing in mind human perceptions and economic considerations, the best solution might be to select structures for preblast surveys as follows:

1. those structures or groups of structures closest to the blasting,

2. structures within a radius where the effects are estimated to be strongly perceptible and,

3. any structures at greater distances that, because of historic value or precarious condition, are deemed to deserve special attention (if the project is viewed by the surrounding residents as not necessarily being to their benefit or is otherwise unpopular, the distances should probably be increased accordingly).

After a decision has been made about the limit of preblast surveys, damage claims should be anticipated from residents in other structures that will probably need to be resolved through forensic investigation. This is discussed in Step 8.

11.5.2 Step 2. Determine the Conditions That Exist Before Construction Begins

Oriard (1999) and Dowding (1996) describe preblast survey methods in detail. Various methods can be used to conduct preblast surveys, but all must meet the primary purpose of documenting all defects and existing damage in the structures concerned. Secondary purposes of preblast surveys are to answer any questions homeowners have about the project, and to look for anything that might require correction before construction begins or that may unexpectedly limit blast design, such as antique plates that are leaning against a wall or precariously balanced figurines (which could probably be secured for the duration of the project). It is usually advantageous to conduct postblast surveys to verify that no additional defects have been caused by the blasting.

Surveys can be documented using drawings on paper, high-resolution video, black-and-white photography, or any other method that adequately documents existing defects and damage. It is also helpful if the possible causes of defects can be determined and listed. All residential structures suffer from normal shrinkage of materials, possible settling, and thermal stresses, which start to occur soon after their construction. Both factors can present problems on long-term projects for which relatively new homes are included in the preblast survey. Normal shrinkage cracks and defects might not be apparent during the preblast survey while being apparent during a postblast inspection. To determine whether it is possible that blasting caused the defect, the only solution is to investigate the defects thoroughly, which will normally require an experienced forensic investigator.

It is also good practice to examine homes both near and far from the construction activity. If cracks or other defects are consistent throughout the area, they are likely the result of regional settlement. Cracks or defects that diminish with distance from the vibration source may be indicative of effects caused by the source.

An inadequate preblast survey can be worse than no preblast survey at all; preexisting defects not listed in the preblast survey will likely be attributed to the blasting by the property owner. Unless such claims can be refuted through forensic investigation, the complainant will probably be successful. Insurance companies tend to settle smaller claims rather than pay the costs involved in determining the actual cause. Such action is technically and philosophically flawed, and is effectively an open invitation for additional claims from surrounding neighbors.

Homeowners will sometimes prefer that their homes not be surveyed, usually for the sake of privacy. A notation should be made for that structure as to the time and date, the specific comment made, and the person who made it. A homeowner might also terminate a preblast survey before it is complete. Again, the survey should be annotated accordingly.

11.5.3 Step 3. Inform the Public about the Project and Potential Blasting-Related Consequences

Establishing good public relations with those nearest the project and any other interested parties is always beneficial. Most homeowners do not have experience with blasting or its effects (other than spectacular events on television) and may have concerns for the safety of themselves and their homes.

A meeting should be held and a presentation made that explains the reason for the project, the necessity of blasting, the effects that the residents might experience (hear and/or feel), the specific blasting signals that will be used, and the intentions of the preblast survey. Knowledgeable persons should attend to answer questions. A handout should be provided that explains all of the above and includes phone numbers in case of a problem or questions. The person or company that will conduct the preblast surveys should be introduced. The main purpose of this meeting is to educate the neighbors, but it also tends to put their minds at ease. Such a meeting, conducted properly, can greatly reduce the potential for problems with neighboring property owners.

Another opportunity to establish good public relations is the preblast survey. The informational sheet that was used in the meeting should be distributed in the course of the survey. The person or persons conducting the survey should be conversant enough about the project to answer any questions from homeowners.

Homeowners should be provided with a procedure for registering complaints with Caltrans in the event that vibration is found to be excessive. This procedure should identify a contact person and phone number or email address.

11.5.4 Step 4. Schedule the Work to Reduce Adverse Effects

As long as safety considerations can be met, blasting should be scheduled for times of maximum human activity rather than times of extreme quiet. In some cases, other nearby sources of noise and/or vibration can be used to mask construction activities. (In one case, blasting complaints on a project near Reno were eliminated by detonating blasts only when planes were taking off from the nearby airport. Although this is an extreme example, it illustrates the concept well.)

In situations where only one blast is needed on a project (which are infrequent), providing a safe viewing location and invite neighboring residents to view the event can be beneficial. The residents will appreciate being included and will better understand the blasting process. A safe viewing location is key; there cannot be any chance that flyrock could reach the spectators.

There are other considerations in scheduling blasting. A survey of the area should disclose locations that might require close coordination. If hospitals where surgery is conducted or other facilities with equipment highly sensitive to vibration are nearby, coordination is necessary so that blast effects do not interfere with the operations of these facilities. Also, in areas prone to lightning storms, blasting schedules must be adjusted so that there is minimal interruption to the work. Blasts may need to be loaded and detonated during times when thunderstorms are not likely to occur.

11.5.5 Step 5. Design the Blast to Minimize Vibration and Air Overpressure

Most of the factors involved in blast design are interrelated or interactive; correcting one problem may prompt others. Safety is paramount. The first consideration in blast design must be the safety of all personnel and surrounding structures and objects.

Blast vibration is affected by the following list of variables. These are in turn affected by blast design factors as indicated. Fixed variables, which cannot be controlled by the blaster, are listed below.

- **Distance:** As the distance from the blast increases, the vibration decreases. However, the blasting must be conducted where it is needed, and smaller charge weights may be necessary if blasting is needed in close proximity to structures.

- **Site geology:** As the distance between the blast and the recording point increases, geology plays a more dominant role in determining the frequency of the blast vibration and the speed at which the vibration dissipates.

- **Weather:** The blaster cannot control the weather, but can work to avoid blasting when windy conditions might increase the intensity of air overpressures at nearby residences.

Variables that the blaster can control are listed below.

- **Quantity of explosive per delay:** The quantity of explosive per delay is one of the major variables in blast design for mitigating vibration. Blast design factors that can affect this include hole diameter and depth, the number of explosive decks, and the method of initiation. Generally, reducing this quantity will reduce the vibration generated, but the powder factor must remain high enough to adequately fracture the material (see third item in list below).

- **Confinement of the explosive energy:** Confinement is affected by burden and spacing, the quantity (and quality) of stemming, amount of subdrilling, and the location of the initiating device. Highly confined blasts, such as presplitting, generate higher vibration levels per unit weight of explosive. If a certain amount of throw or heave is acceptable or if means are employed to prevent excessive throw, reducing burdens can lower vibration levels appreciably. If confinement is reduced to any great extent, one must be careful of increased air overpressures. Bottom initiation will generally result in slightly more vibration than top initiation. However, any vibration benefit that might be gained from shooting from the top down or from reducing the amount of subdrilling can be offset by any additional blasts that may be required if the primary blast does not fracture rock to the full depth.

- **Powder factor:** The powder factor is affected by almost all blast design factors. The keys are to use as close to the optimum amount of explosive as possible and to distribute it through the material to be blasted in such a way that it will adequately fracture and shift the mass. If the powder factor is too low, it will not adequately fragment the material and a large portion of the available energy will be lost as seismic energy, resulting in excessive blast vibration. If the powder factor is too high, it can result in flyrock and excessive air overpressures, as well as increased vibration intensities.

- **Explosive/borehole coupling:** Although explosive/borehole coupling can affect vibration, the effect is minimal. For example, presplitting uses decoupled charges (there is an annular space between the charge and the wall of the borehole), but results in high vibration levels because the increased burden has a greater impact than the decoupling. Decoupling of explosive charges normally is not used to reduce vibration.

- **Spatial distribution of the energy source:** The spatial distribution of the energy source can affect vibration in terms of intensity and frequency. There are two examples of this. In the first example, two holes separated by a reasonable distance and detonated simultaneously will generate less vibration than one hole containing as much explosive as the two holes combined. The resulting vibration will also be of a higher frequency. The extent of this effect depends largely on the separation distance between the two holes. In a second example, a long column of explosive will generate less vibration than a spherical charge of the same weight. Although the detonation velocity of a column of explosive has some effect on the spatial distribution of energy (and time of energy release), it is not usually a large enough factor to consider in blast design. The explosive properties are usually selected to match the rock conditions. As stated above, it is not wise to select a low-energy explosive to reduce adverse effects if more blasts would be needed to excavate the material to grade.

- **Timing of detonating charges:** Some regulatory agencies specify a minimum of 9 ms between detonating charges and consider all explosives detonating in any given 8-ms period to have detonated in the same instant; this is done solely for determining explosive weight for scaled distance calculations and has no basis in reducing vibration. In actual practice, while 9 ms may be used in some situations, various delay intervals may be appropriate depending on the conditions. It is not unusual for delay intervals of as little as 5 ms to be used in very close-in blasting situations. When the nearest structures are at greater distances, longer delay periods are often used. After first considering safety issues, the blaster should try to determine a delay timing scheme that would minimize vibration or air overpressures, although this might not always be possible. Extending the delay time can reduce the amount of energy released per unit of time, reducing vibration to some extent.

- **Timing of blast progression:** Air overpressures from blasting can be excessive when the velocity of initiation along a free face meets or exceeds the speed of sound; this occurs to a lesser extent on the surface of the blast. Reducing the velocity of the blast progression along the face to half the speed of sound reduces the effect considerably. The delay timing must not be increased, thereby reducing the blast progression, to the point of causing misfires through cutoff in initiation systems or explosive columns. The blaster must incorporate into the design a buffer zone that consists of several or more rows of holes between a hole that is detonating and detonators in holes in which the initiation signal has not been received. If this step is not taken, misfires often result. Although not required, many successful blasters prefer to use delay timing between holes in a row of 2–5 ms per foot of burden. Many also prefer to use delay timing from row to row that is double (or nearly double) the delay timing in a row.

- **Blast orientation:** Blast orientation is usually mandated by terrain and the physical layout of the rock. As a general rule, the highest vibration amplitudes will usually be in a direction opposite of that in which the rock is being heaved or thrown, although local geology may affect the actual direction of maximum intensity. In side-hill situations, the rock movement would be downhill or along the side-hill, almost never uphill. Site safety conditions will dictate the actual design, but blasting against gravity can increase problems for flyrock and vibration.

11.5.6 Step 6. Use the Blast Signals to Notify Nearby Residents That Blasting Is Imminent

Although blasting signals were originally intended to provide a means of clearing a blast site before the blast is detonated, they also serve to alert nearby residents that a blast is about to occur. This helps to reduce the "startle" effect. After hearing 5- and 1-minute warnings, the average resident will anticipate the event and the intensities will not appear as severe as they would have if the person had not been warned. The blasting signals currently mandated by the California Occupational Safety and Health Administration for blasting on construction sites are contained under "Sample Specifications" in Appendix D.

11.5.7 Step 7. Monitor and Record the Vibration and Air Overpressure Effects of the Blast

Although blast-induced vibration and air overpressures can be estimated with some confidence, monitoring and recording these effects is far more effective. Records from blasting seismographs, when combined with the written blaster's report, provide excellent tools for evaluating the potential for damage from blast-induced vibration and air overpressure. Recording should be conducted with calibrated seismographs specifically intended for the purpose. Such instruments include a microphone channel for recording air overpressures; most have the ability to print a graph that compares vibration magnitudes and frequencies against accepted national standards.

In situations where there is considerable opposition to a project and damage claims are anticipated, third-party monitoring should be conducted. In situations where there is little chance for claims or where monitoring is being done solely to ensure that specifications are being met, the contractor might conduct his or her own monitoring. In such a case, a third-party vibration consultant is advisable to oversee and approve the contractor's monitoring and recording process. Damage claims should always be anticipated.

11.5.8 Step 8. Respond to and Investigate Complaints

An adequate process for handling complaints should be established. Neighboring residents should know whom to contact with a concern or complaint, whether or not it involves a claim of damage. In all instances, a form that documents the details of a complaint should be initiated when the complaint is received. A sample construction/blast complaint form is provided in Appendix B.

For minor complaints, responsible, knowledgeable contractor personnel might conduct the investigation. A qualified forensic investigator is advisable to look into claims of damage. The investigator could be the same person that conducted the preblast survey, the monitoring, or both. A prompt investigation is advisable. If the problem was caused by the blasting, correction of the problem should also be handled promptly.

11.6 Blasting Specifications

Anticipation of all variables that may be encountered on various project sites is not possible. For each project, a site-specific blasting specification should be developed that considers the peculiarities of the project location. In particular, the areas of blast vibration limits, preblast surveys, the number of recording instruments and their locations, the times and days of scheduled blasting, and cautious blasting techniques (if any) should be addressed. A sample blasting specification has been developed to provide a starting point for writing a blasting specification for construction blasting; the sample is provided in Appendix D.

Chapter 12
References and Additional Reading

American Association of State Highway and Transportation Officials. 1990. *Standard recommended practice for evaluation of transportation-related earthborne vibrations.* Washington, DC.

Ames, W. H., W. Chow, A. Sequeira, and R. Johnson. 1976. *Survey of earth-borne vibrations due to highway construction and highway traffic.* (Report CA-DOT-TL-6391-1-76-20.) Sacramento, CA: California Department of Transportation.

Amick, H. 2000. *Construction vibrations and their impact on vibration-sensitive facilities*. San Mateo, CA: Colin Gordin & Associates.

Amick, H. et al. 2005. Evolving criteria for research facilities: I–Vibration. San Bruno, CA: Colin Gordin & Associations.

Attewell, P. B., and I. W. Farmer. 1973. Attenuation of ground vibrations from pile driving. *Journal of Ground Engineering* 6(4):26–29.

Barkan, D. D. 1962. *Dynamics of bases and foundations.* New York: McGraw-Hill Co.

Bauer, A., and P. N. Calder. 1977. *Pit slope manual.* Ottawa: CANMET.

———. 1978. *Open pit and blast seminar.* Kingston, Ontario, Canada.

California Department of Transportation. 1976. *Survey of earthborne vibrations due to highway construction and highway traffic.* (Report CA-DOT-TL-6391-1-76-20.) Sacramento, CA.

———. 2000. *State Route 101 crack-and-seat vibration study.* Sacramento, CA.

———. 2002. *Transportation-related earthborne vibrations.* (Technical Advisory TAV-02-01-R9601.) Sacramento, CA.

Chae, Y. S. 1978. Design of excavation blasts to prevent damage. *Civil Engineering—American Society of Civil Engineers* 48(4):77–79.

Dowding, C. H. 1985. *Blast vibration monitoring and control.* Prentice-Hall. Englewood Cliffs, NJ.

———. 1996. *Construction vibrations*. Prentice-Hall. Englewood Cliffs, NJ.

———. 2000. *Construction vibrations.* Second edition. Prentice-Hall. Englewood Cliffs, NJ.

Edwards, A. T., and T. D. Northwood. 1960. Experimental studies of the effects of blasting on structures. *The Engineer* 210:538–546.

Egan, J., J. Kermode, M. Skyrman, and L. Turner. 2001. *Ground vibration monitoring for construction blasting in urban areas*. (Report FHWA/CA/OR-2001/03.) California Department of Transportation. Sacramento, CA.

E. I. du Pont de Nemours & Co. 1977. *Blasters' handbook.* Wilmington, DE.

Federal Transit Administration. 2018. *Transit noise and vibration impact assessment.* DOT-T-95-16. Office of Planning. Washington, DC. Prepared by Harris Miller Miller & Hanson, Inc., Burlington, MA.

Gordon, C. 1991. Generic criteria for vibration-sensitive equipment. *Proceedings of International Society of Optical Engineering* 1619.

Hanson, Carl. Personal communication with David Buehler—October 24, 2001.

Hendriks, R. 2002. *Transportation related earthborne vibrations (Caltrans experience).* California Department of Transportation. Sacramento, CA.

International Society of Explosives Engineers. 1998. *Blasters' handbook.* Cleveland, OH.

International Standards Organization. 1989. *Guide to the evaluation of human exposure to vibration and shock in buildings (1 Hz to 80 Hz).*

Konon, W. 1985. Vibration criteria for historic buildings. *Journal of Construction Engineering and Management* 111(3):208–215.

Langefors, U., and B. Kihlstrom. 1958. Ground vibrations in blasting. *Water Power*. September.

Liddy, M. 2002. Information provided by Ken-Jet Corporation.

Martin, D. J. 1980. *Ground vibrations from impact pile driving during road construction*. (Supplementary Report 544.) London: United Kingdom Department of Environment, Department of Transport, Transport and Research Road Laboratory.

Medearis, K. 1976. *The development of rational damage criteria for low-rise structures subjected to blasting vibrations*. Prepared for National Crushed Stone Association, Washington, DC.

Morris, R. S. 1991. *Surface vibration measurements for vibratory pile drivers.* Tests conducted by International Construction Equipment.

———. 1996. Letter dated June 20, 1996.

———. 1997. Letter dated April 2, 1997.

Nelson, P. M. (ed.). 1987. *Transportation noise reference book.* London: Butterworths.

Nichols, H. R., C. F. Johnson, and W. I. Duvall. 1971. *Blasting vibrations and their effects on structures.* (Bulletin 656.) Washington, DC: U.S. Bureau of Mines.

Northwood, T. D., R. Crawford, and A. T. Edwards. 1963. Blasting vibrations and building damage. *The Engineer* 215(5601).

Oriard, L. L. 1970. *Dynamic effect on rock masses from blasting operations.* Slope Stability Seminar, University of Nevada.

———. 1994. Vibration and ground rupture criteria for buried pipelines. In *Proceedings of the Twentieth Annual Conference on Explosives and Blasting Techniques*. Cleveland, OH: International Society of Explosives Engineers.

———. 1999. *Effects of vibrations and environmental forces.* Cleveland, OH: International Society of Explosives Engineers.

———. 2002. *Explosives engineering, construction vibrations and geotechnology.* Cleveland, OH: International Society of Explosives Engineers.

Oriard, L. L., and J. H. Coulson. 1980. *TVA blast vibration criteria for mass concrete.* Reston, VA: American Society of Civil Engineers.

Preston, M. 2002. Information provided by American Piledriving, Inc.

Pugliese, J. M. 1972. *Designing blast patterns using empirical formulas*. (Information Circular IC8550.) U.S. Bureau of Mines. Washington, DC.

Reiher, H., and F. J. Meister. 1931. The effects of vibration on people. *Forshung auf dem Gebeite der Ingenieurwesens* 2(2).

Richart, F. E. 1970. *Vibrations of soil and foundations.* Englewood Cliffs, NJ: Prentice-Hall.

Robertson, D. A., J. A. Gould, J. A. Straw, and M. A. Dayton. 1980. *Survey of blasting effects on ground water supplies in Appalachia*. (Contract Report J-0285029.) Washington, DC: U.S. Bureau of Mines.

Rose, R., B. Bowles, and W. Bender. 1991. Results of blasting in close proximity to water wells at the sleeper mine. In *Proceedings of the Seventeenth Conference on Explosives and Blasting Technique*. Cleveland, OH: International Society of Explosives Engineers.

Schexnayder, C .J., and J. E. Ernzen, 1999. *Mitigation of nighttime construction noise, vibration, and other nuisances.* (Synthesis of Highway Practice 218.) Washington, DC: National Academy Press.

Siskind, D. E. and M. S. Stagg. 1993. *Response of pressurized pipelines to production-size mine blasting*. Minneapolis, MN: U.S. Bureau of Mines, Twin Cities Research Center.

Siskind, D. E., V. J. Stachura, M. S. Stagg, and J. W. Kopp. 1980. *Structure response and damage produced by airblast from surface mining*. (Report of Investigations 8485.) Washington, DC: U.S. Bureau of Mines.

Siskind, D. E., M. S. Stagg, J. W. Kopp, and C. H. Dowding. 1980. *Structure response and damage produced by ground vibration from surface mine blasting*. (Report of Investigations 8507.) Washington, DC: U.S. Bureau of Mines.

Stagg, M. S. and A. J. Engler. 1980. *Measurement of blast-induced ground vibrations and seismograph calibration*. (Report of Investigations 8506.) Washington, DC: U.S. Bureau of Mines.

Stagg, M. S., D. E. Siskind, M. G. Stevens, and C. H. Dowding. 1984. *Effects of repeated blasting on a wood-frame house*. (Report of Investigations 8896.) Washington, DC: U.S. Bureau of Mines.

Tart, R. G., L. L. Oriard, and J. H. Plump. 1980. *Blast damage criteria for massive concrete structure.* (American Society of Civil Engineers Preprint 80–175.) Portland, OR: ASCE National Meeting, Specialty Session on Minimizing Detrimental Construction Vibrations.

U.S. Department of Transportation. 1982. *Urban rail noise and vibration control.* Washington, DC.

Whiffen, A. C. 1971. *A survey of traffic-induced vibrations.* (Report LR419.) Crowthorne, Berkshire, England: United Kingdom Department of Environment, Road Research Laboratory.

Wiss, J. F. 1967. *Damage effects of pile driving vibration*. Pages 14–20 in *Structural Construction: Five Reports*, (Highway Research Record 155). Washington, DC.

———. 1974. Vibrations during construction operations. *Journal of the Geotechnical Division* 100(CO3):239–246.

———. 1981. Construction vibrations: state-of-the-art. *Journal of the Geotechnical Division* 107(GT2):167–181.

Wiss, J. F., and H. R. Nichols. 1974. *A study of damage to a residential structure from blast vibrations.* New York: American Society of Civil Engineers.

Wood, W. C., and J. R. Theissen. 1982. Variations in adjacent structures due to pile driving. Pages 83–107 in H. W. Hunt (ed.), *Geopile Conference ’82: San Francisco, May 19–21, 1982*. Clifton, NJ: Associated Pile and Fitting Corp.

Woods, R. D. 1997. *Dynamic effects of pile installations on adjacent structures.* (Synthesis of Highway Practice 253.) Washington, DC: National Academy Press.

Woods, R. S., and L. P. Jedele. 1985. Energy-attenuation relationships from construction vibrations. Pages 187–202 in G. Gazetas and E. T. Selig (eds.), *Vibration Problems in Geotechnical Engineering: Proceedings of a Symposium*. Sponsored by the Geotechnical Engineering Division, in conjunction with the American Society of Civil Engineers Convention, Detroit, MI, October 22, 1985. New York: American Society of Civil Engineers.

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Appendix A. Technical Advisory TAV-02-01-R9601

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California Department of Transportation
Division of Environmental Analysis
Office of Noise and Hazardous Waste Management
Sacramento, CA

TRANSPORTATION RELATED EARTHBORNE VIBRATIONS

(Caltrans Experiences)

Technical Advisory, Vibration
TAV-04-01-R0201

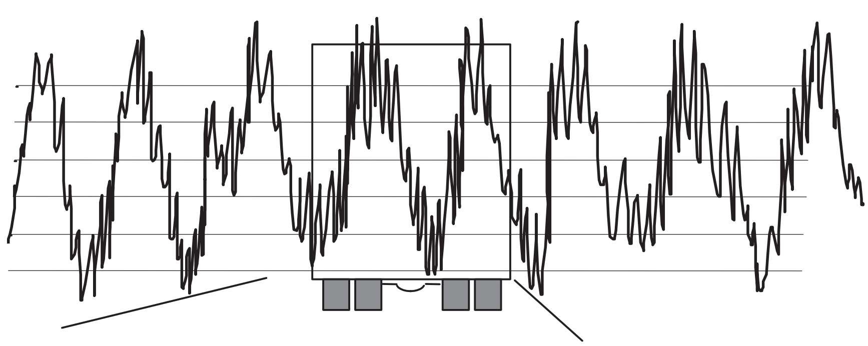
January 23, 2004

Prepared by Rudy Hendriks – Caltrans Retired Annuitant

NOTICE:

This document is a revision of technical advisory TAV-02-01-R9601 with the same title, prepared by the same author, dated February 20, 2002. As a result of a final review, minor editorial changes were made and a cautionary note was added to a method of coupling an accelerometer to the measuring surface. The basic information was not changed from the earlier version. This version of the technical advisory is included as Appendix A in the Transportation and Construction-Induced Vibration Guidance Manual, prepared by Jones & Stokes, Sacramento, CA, for Caltrans.

<u>This document is not an official policy, standard, specification or regulation and should not be used as such.</u> Its contents are for informational purposes only. Any views expressed in this advisory reflect those of the author, who is also responsible for the accuracy of facts and data presented herein. The latter were derived from Caltrans vibration studies from 1958 to 1994, and the author's vibration experiences from 1980 to 1994 at the Caltrans Transportation Laboratory (Translab) in Sacramento, CA.



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INTRODUCTION

This Technical Advisory is intended to give district environmental, materials, design, construction and other concerned personnel a basic understanding of transportation related earthborne vibrations. The advisory covers general vibration principles, vibrations caused by construction and operation of transportation facilities, criteria used by the California Department of Transportation (Caltrans), impacts, vibration study approaches, possible mitigation, and screening procedures to identify potential vibration problems in the field.

District personnel are usually the first to be contacted by the public when vibration problems occur. Until 1994, the district personnel in turn contacted the Caltrans laboratory (TransLab) and requested either an assesment of the problem or a vibration field study. In 1994, Translab discontinued the field studies because of a reorganization. Presently, HQ Division of Environmental Analysis, Noise, Air Quality and Hazardous Waste Management Office, Noise and Vibration Branch is responsible for providing guidance on potential vibration problems.

The information in this advisory will enable district personnel to participate in assessing and screening routine vibration complaints as well as provide background information for the oversight of more complex studies. This advisory will also be a useful source of information for developing contract specifications and oversight.

BACKGROUND

Caltrans has performed earthborne vibration studies since 1958. In 1976, a landmark TransLab vibration research report titled "Survey of Earth-borne Vibrations due to Highway Construction and Highway Traffic", Report No. CA-DOT-TL-6391-1-76-20, compiled a summary of results, findings, and conclusions of 23 studies completed in the 17 year period between 1958 and 1975. Since then many more studies have been performed. Most of these fall into the following three categories:

- Highway traffic vibrations
- Construction vibrations
- Train/light rail vibrations

The main concerns of vibrations involve:

- Annoyance
- Damage
- Disruption of vibration sensitive operations or activities
- Triggering of land slides

The sites investigated included private residences, factories, aerospace and defense plants, electronic laboratories, radio station, movie studio, etc., and even a major cake and pastry bakery.

Because of similarities between the disciplines of noise and vibrations, the former Noise Section took over the responsibilities for vibration studies from the Electrical Instrumentation Testing and Research Section in July, 1980. Almost two-thirds of the above mentioned studies were performed by the Noise Section, which, in 1994 was absorbed by the newly created Office of Environmental Engineering of the Environmental Program. The individual study reports are on file at the Office of Environmental Engineering. This advisory incorporates information and experience gained in all Caltrans vibration studies from 1958-1994.

FUNDAMENTALS OF EARTHBORNE VIBRATIONS

Vibration Sources

Sources of earthborne vibrations include natural phenomena (earthquakes, volcanic eruptions, sea waves, landslides, etc.), or manmade causes (explosions, machinery, traffic, trains, construction equipment, etc.). Vibration sources may be continuous such as factory machinery, and transient, such as explosions.

A distinction must be made between earthborne and airborne vibrations. Some sources, such as jet aircraft, rockets, explosions, sonic booms, locomotives, and even trucks under certain conditions, can create low frequency airborne noise of enough intensity to be felt, as well as heard. These low frequency airborne blasts or rumbles are often erroneously perceived as earthborne vibrations.

As is the case with airborne sound, earthborne vibrations may be described by amplitude and frequency.

Amplitude and Frequency

In airborne sound, amplitude is described by common logarithm of the square of the ratio of pressure fluctuations around mean air pressure divided by a reference pressure, and is expressed in logarithmic units of decibels. The pressure fluctuations propagate in waves of alternating compressed and rarefied air. The rate at which these waves radiate outward from their source is called the speed of sound, which is the wave velocity. Air is an elastic medium through which the waves travel.

In earthborne vibrations, amplitude is described by the local movement of soil particles. This movement must not be confused with wave velocity.

To distinguish between wave velocity and particle motion, consider the analogy of ripples on a lake and a floating cork. Wave velocity (in air, speed of sound) is analogous to the velocity of the ripples. Particle motion may be compared to the bobbing of the cork as the ripples pass by. The bobbing of the cork represents the local movement of the soil particles as earthborne vibration waves pass through the soil. The soil acts as an elastic medium.

The amplitude of particle motion may be described three ways:

1. **Particle displacement** - the distance the soil particles travel from their original position. Units are millimeters (mm). inches (in)

2. **Particle velocity** - the velocity of the soil particles. Units are inches per second (in/sec) or millimeters per second (mm/sec). Sometimes expressed logarithmically in decibels (dB) with reference to a specified unit of velocity such as .001 in/sec (1μ in/sec), or 0.001 mm/sec.

3. **Particle acceleration** - the acceleration of the soil particles. Units are inches per second per second (in/sec^2), millimeters per second per second (mm/sec^2), or g-force (g = acceleration of gravity = 32.2 feet per second per second (ft/sec^2) = 9.81 meter per second per second (m/sec^2). Sometimes expressed logarithmically in decibels (dB) with reference to a specified unit of acceleration, such as 1 g, or 0.001g (1μg).

For a perfect sine wave produced by a single vibration frequency there exists a simple relationship between the above three measures of amplitude (see Appendix). If the frequency and amplitude of one descriptor is known, the other two can easily be calculated. For waves consisting of many frequencies, and therefore not sine waves, the relationships become much more complicated.

There is a 90 degree phase shift between the three descriptors, i.e. velocity is 90 degrees out of phase with displacement, acceleration is 90 degrees out of phase with velocity, and acceleration is 180 degrees out of phase with displacement. To illustrate this, we might imagine a pendulum just released from a point furthest away from its stationary position. If we arbitrarily call this position the extreme positive (+) position of the pendulum, the stationary point 0, and the region beyond the stationary point a negative (-) position, we observe the following:

- at the point of release, the displacement (distance from stationary or 0 displacement position) is maximum and positive (+).
- the velocity at the point of release is 0.
- the acceleration at the point of release is at its maximum, in the direction towards the negative (-).

This can be worked out the same for other pendulum positions. For instance, as the pendulum swings through the stationary position, the displacement is 0, the velocity is maximum in the negative (-) direction, and the acceleration is 0. Once past the stationary point the pendulum decelerates in the negative (-) direction which is the same as increasing acceleration in the positive (+) direction.

Vibration amplitudes are usually expressed as either "peak", as in peak particle velocity, or "rms" (root mean square), as in rms acceleration. The relationship between the two is the same as with noise. The rms value is approximately 0.71 x the peak value for a sine wave representing either displacement, velocity, or acceleration.

Finally, the direction in which vibrations are measured, analyzed or reported should be specified (vertical, horizontal longitudinal, horizontal transverse, or the resultant of all three motions). For example, Caltrans most often uses a peak vertical particle velocity descriptor, because vibrations along the ground surface are most often (although not always) greatest in the vertical direction.

Propagation

Propagation of earthborne vibrations is complicated because of the endless variations in the soil through which waves propagate.

The relationship between frequency (f), period (T), wave length (λ), and wave velocity (c) is the same as that in noise, that is:

$f=1/T$ and $f=c/\lambda$

However, the wave velocity (c, sometimes also called the phase velocity) in soils varies much more than the speed of airborne sound does, and is often also frequency dependent (in the atmoshere, the speed of sound only varies with temperature). As a consequence, wavelength cannot readily be calculated when frequency is known and vice versa, unless the wave velocity happens to be known also.

There are three main wave types of concern in the propagation of earthborne vibrations:

1. **Surface or Rayleigh waves**, which as the name implies, travel along the ground surface. They carry most of their energy along an expanding cylindrical wave front, similar to the ripples produced by throwing a rock into a lake. The particle motion is retrograde elliptical, more or less perpendicular to the direction of propagation.
2. **P-waves, or compression waves.** These are body waves that carry their energy along an expanding spherical wave front. The particle motion in these waves is longitudinal, "push-pull". P-waves are analogous to airborne sound waves.
3. **S-waves, or shear waves.** These are also body waves, carrying their energy along an expanding spherical wave front. Unlike P-waves, however, the particle motion is transverse, or perpendicular to the direction of propagation.

As wave fronts move outward from a vibration source, their energy is spread over an ever increasing area. The more rapidly this area increases, the more quickly the energy intensity (energy per unit area) decreases. The areas of cylindrical Raleigh wave fronts do not increase as rapidly with distance as do the body (P- and S-) waves. Consequently, the energy intensities of Raleigh waves attenuate at a lesser rate with distance than those of body waves.

The spreading of energy over ever increasing areas is called geometric spreading (geometric attenuation) and the difference in attenuation rates between surface and body waves is analogous to that of line sources and point sources, respectively, in airborne sound. Geometric attenuation also results of encountering more soil mass as the area of the wave front increases.

Geometric attenuation is not the only attenuation encountered with distance. Hysteretic attenuation, or material damping, results from energy losses due to internal friction, soil layering, voids, etc. The amount of hysteretic attenuation varies with soil type, condition, and frequency of the source.

These variations make it much more difficult to predict vibration amplitudes at specific locations, than it is to predict noise levels.

In general, manmade earthborne vibrations attenuate rapidly with distance from the source. Even the more persistent Rayleigh waves decrease relatively quickly. Manmade vibration problems are therefore confined to short distances from the source.

In contrast, natural vibration problems are often wide spread. An obvious example is an earthquake which can cause damage over large areas, due to the release of enormous quantities of energy at longer wavelengths.

TRANSPORTATION RELATED EARTHBORNE VIBRATIONS

Sources

Caltrans is most commonly concerned with three types of transportation related earthborne vibration sources:

- Normal highway traffic - heavy trucks, and quite frequently buses, generate the highest earthborne vibrations of normal traffic. Vibrations from these vary with pavement conditions. Pot holes, pavement joints, differential settlement of pavement, etc., all increase the vibration amplitudes.
- Construction equipment - pile driving, pavement breaking, blasting, and demolition of structures generate among the highest construction vibrations.
- Heavy and light rail operations - diesel locomotives, heavily loaded freight cars, and operations such as coupling create the highest rail traffic vibrations.

Of the above three types, construction vibrations are of greatest concern. The four operations mentioned under construction vibrations are potentially damaging to buildings at distances of less than 7.5 m (25 ft) from the source.

Descriptor Used By Caltrans

With the exception of some construction operations such as pile driving, pile hole drilling, and perhaps some deep excavations, all vibrations generated by construction or operation of surface transportation facilities are mainly in the form of surface or Raleigh waves. Studies have shown that the vertical components of transportation generated vibrations are usually the strongest and that peak particle velocity correlates best with damage and complaints. For these reasons, Caltrans adopted the Peak Vertical Particle Velocity descriptor, with units of mm/sec or in/sec.

A great advantage of using this descriptor is that for a frequency range of 1 - 80 Hz damage amplitudes in terms of velocity tend to be independent of frequency. The same is true for complaint amplitudes within a range of 8 - 80 Hz. Velocity is the product of frequency, displacement and a constant (see appendix). It appears that within the above frequency ranges a doubling of frequency will offset a halving of displacement and vice versa; i.e. the effects of the product of the two tend to remain equal. Typical transportation and construction vibrations fall within the above frequency ranges. They typically range from 10 - 30 Hz, and usually center around 15 Hz.

From the above we can surmise that not only the effects of displacement are frequency dependent, but also those of acceleration. The latter is related to the former by the frequency times a constant squared (see appendix). Thus, criteria amplitudes in terms of displacement or acceleration need to be accompanied by a frequency.

Propagation of Transportation Related Vibration

Raleigh (Surface) Wave Drop-off - Surface waves generated by traffic, trains, and most construction operations tend to attenuate with distance according to the following equation:

$$V = V_0(D_0/D)^{0.5} e^{\alpha(D0-D)} \qquad \text{(eq. 1)}$$

where: V = Peak particle velocity at distance D
V_0 = Peak particle velocity at reference distance D_0
D_0 = Reference distance
D = Distance for which vibration amplitude needs to be calculated
e = Base of natural logarithm = 2.718281828
α = Soil parameter

The soil parameter α can be determined by simultaneous vibration measurements at a minimum of two different distances from a source. One distance should be near the source, ideally between4.5 and 7.5 m (15 -25 ft). The other should be farther away from the source, ideally at or beyond the farthest point of interest, but at a location where the source is still measurable and not contaminated by other vibrations. A third point in between is recommended for confirmation. Note that the value of α depends on the distance units used. The reason for this is that the exponential $(D_0 - D)\ \alpha$ needs to be a constant value while the value of $(D_0 - D)$ changes with the units used (normally, m or ft). Therefore, the relationship between α (based on m) and α (based on ft) is:

α (based on m) = 3.281α (based on ft), and
α (based on ft) = 0.305 α (based on m)

α can be calculated from the vibration measurements by rewriting eq. 1 as:

$$\alpha = (\ln V^2 + \ln D - \ln V_0{}^2 - \ln D_0)/2(D_0 - D) \qquad \text{(eq. 2)}$$

where "ln" denotes "natural logarithm"

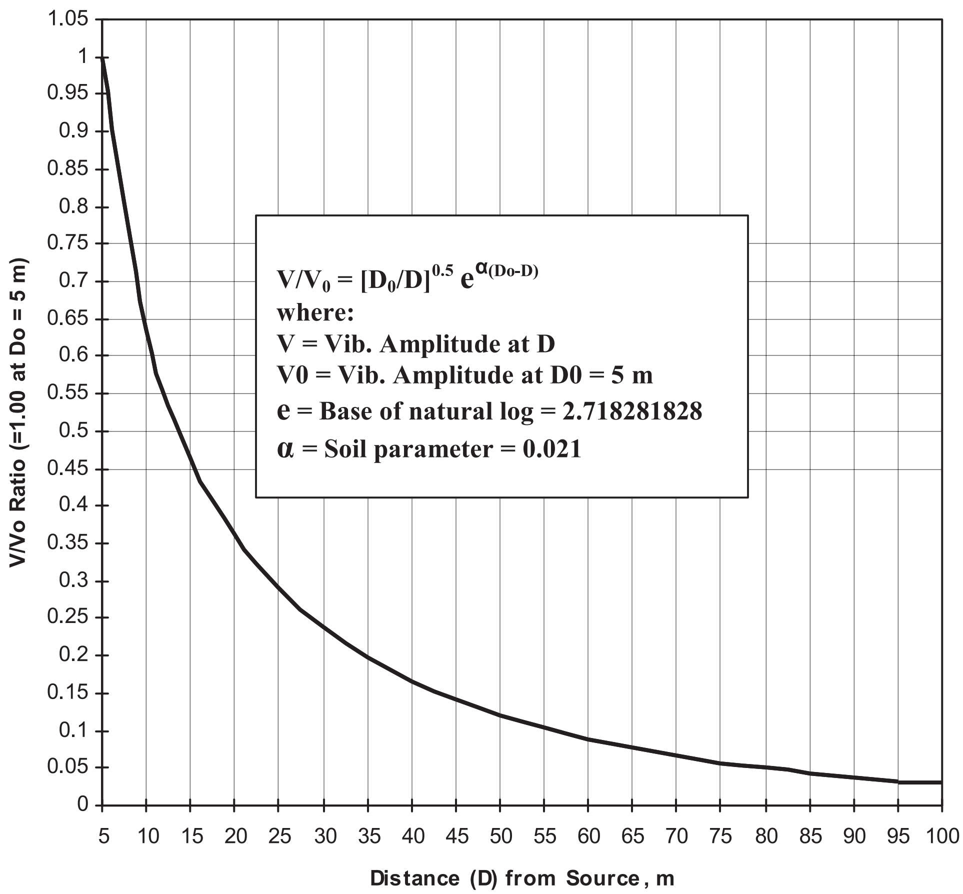
Once α is calculated from the measurements it can be used in eq. 1 to calculate vibrations for any other distance, given the same reference source.

Figure 1 shows a drop-off curve expressed as a ratio of V/V_0, using a reference distance D_0 of 5 m (16 ft). This is a normalized curve for α = 0.021 (distance in m), or α = 0.006 (distance in ft), derived from data measured in the City of Lynwood to calculate α for the LA-105 Alameda Viaduct vibration study, involving traffic effects on Westech Gear Corporation (formerly Western Gear) close tolerance manufacturing operations. The attenuation curve in Figure 1 is valid for the soils stratification derived from Caltrans boring logs for the Alameda Viaduct, shown in Table 1.

Table 1. - Soils Classifictaions for Figure 1.

Depth, m (ft)	Soil Description
0	
	Sand-Silt
1.5 (5)	
	Clayey Silt
9 (29)	
	Silty Sand
12 (40)	
	Sandy Silt
15.5 (51)	
	Sand
19.5 (64)	

Figure 1. Typical Normalized Distance Attenuation Ratio Curve of Earthborne Surface Vibrations (Reference Distance, Do = 5 m)



The curve is representative of many locations in the L.A. Basin, and also of various locations in Sacramento, and can be used for estimating traffic, train, and most construction vibration drop-offs with distance. To use the curve, the vibration amplitude V_1 must be known at a given distance D_1 near the source, preferably between 5 and 15 m (16 and 50 ft). The vibration amplitude V_2 at the distance of interest D_2 can then be calculated as follows:

$$V_2 = (V_2/V_0)/(V_1/V_0) \cdot V_1$$

(the ratio's V_2/V_0 and V_1/V_0 can be obtained from Figure 1)

For example, if the vibration amplitude is known to be 3.2 mm/s (peak particle velocity) at a distance of 12 m, the vibration amplitude at 58 m can be estimated from (0.09/0.55) x 3.2 mm/s = 0.5 mm/s.

Pile Driving Vibration Drop-off - During pile driving, vibration amplitudes near the source depend mainly on the soil's penetration resistance. In soils such as sand and silt, this resistance is relatively low with the result that a large portion of the impact energy is used to advance the pile. Less energy is then available for generating ground vibrations. In clay soils, however, the penetration resistance is higher and more energy is available for ground vibrations. The resistance provided by the soils consists of friction along the sides of the pile as well as compressional resistance due to the transfer of energy of the pile tip to the soil. This appears to generate body waves as opposed to surface waves by other construction operations.

The energy of a pile driver is of course also influential on the vibration amplitude at the source. There is a relationship between vibration amplitude and energy. If pile driver energy changes from E_1 to E_2, the vibration amplitude at a certain location changes from V_1 to V_2, where:

$$V_2 = V_1\left(\sqrt{\frac{E_2}{E_1}}\right) \qquad \text{(Eq. 3)}$$

Example: E_1 = 68,000 J (50,000 ft lbf)

E_2 = 111,900 J (82,500 ft lbf)

V_1 = 2.8 mm/s

Then: $V_2 = 2.8\left(\sqrt{\frac{111{,}900}{68{,}000}}\right)$ = 3.6 mm/sec

Vibrations of pile driving appear to drop off differently than the Raleigh waves, probably due to the presence of a significant proportion of body waves. Pile driving vibrations tend to drop off with distance according to the following equation:

$$V = V_0.(D_0/D)^k \qquad \text{(Eq. 4)}$$

where: V, V_0, D_0, and D are same as defined in Eq. 1, and
k = soil parameter (no units)

(Note that α and k are different parameters; whereas the value of α is dependent on the distance units used (m or ft), the value of k - which depends only on the ratio of distances - is independent of distance units used.)

Generally, the values of "k" lie between 1 to 1.5 (approaching 1 for sandy soils and 1.5 for clay soils), although values < 1 and > 1.5 have been encountered.

The value of "k" can be determined experimentally at different distances from a pile driver, similarly to the previously described derivation of α. For this purpose, Eq. 4 can be rewritten as:

$$k = (\text{Log}V - \text{Log}V_0)/(\text{Log } D_0 - \text{Log}D) \qquad \text{(eq. 5)}$$

Caltrans Vibration Criteria

There are no FHWA or state standards for vibrations. The traditional view has been that highway traffic and construction vibrations pose no threat to buildings and structures, and that annoyance to people is no worse than other discomforts experienced from living near highways.

Damage - A considerable amount of research has been done to correlate vibrations from single events such as dynamite blasts with architectural and structural damage. The U.S. Bureau of Mines has set a "safe blasting limit" of 50 mm/s (2 in/sec). Below this amplitude there is virtually no risk of buiding damage.

“Safe” amplitudes for continuous vibrations from sources such as traffic are not as well defined. The Transport and Road Research Laboratory in England has researched continuous vibrations to some extent and developed a summary of vibration amplitudes and reactions of people and the effects on buildings (Table 2). These are the criteria used by Caltrans to evaluate the severity of vibration problems. Traffic, train, and most construction vibrations (with the exception of pile driving, blasting, and some other types of construction/demolition) are considered continuous. The "architectural damage risk amplitude" for continuous vibrations (peak vertical particle velocity of 5 mm/sec or 0.2 in/sec) shown in Table 2 is one tenth of the maximum “safe” amplitude of 50 mm/sec (2 in/sec) for single events.

All damage criteria for buildings are in terms of ground motion at the buildings' foundations. No allowance is included for the amplifying effects of structural components. Obviously, the way a building is constructed and the condition it is in determines how much vibration it can withstand before damage appears. Table 2 shows a recommended upper amplitude of 2.0 mm/s (0.08 in/sec) for continuous vibrations to which "ruins and ancient monuments" should be subjected. This criterion amplitude may also be used for historical buildings, or buildings that are in poor condition.

Relatively little information is available concerning the damaging effects of pile driving. Although technically a series of single events, pile driver blows occuring often enough in a confined area could cause damage at a lower amplitude than the single event criterion of 50 mm/s (2 in/sec). Caltrans has experienced minor damage from sustained pile driving at about 7.5 - 9 mm/s (0.30 - 0.35 in/sec) peak vertical particle velocity vibration on the ground next to an existing parking structure. The extent of the damage was some crumbling of mortar used to fill wall joints. In that instance the

Table 2 - Reaction of People and Damage to Buildings at Various Continuous Vibration Amplitudes

Vibration Amplitude (Peak Particle Velocity)*			
mm/s	**in/sec**	**Human Reaction**	**Effect on Buildings**
0.15-0.30	0.006-0.019	Threshold of perception; possibility of intrusion	Vibrations unlikely to cause damage of any type
2.0	0.08	Vibrations readily perceptible	Recommended upper amplitude of the vibration to which ruins and ancient monuments should be subjected
2.5	0.10	Amplitude at which continuous vibrations begin to annoy people	Virtually no risk of “architectural” damage to normal buildings
5.0	0.20	Vibrations annoying to people in buildings (this agrees with the amplitudes extablished for people standing on bridges and subjected to relative short periods of vibrations)	Threshold at which there is a risk of “architectural” damage to normal dwelling - houses with plastered walls and ceilings Special types of finish such as lining of walls, flexible ceiling treatment, etc., would minimize “architectural” damage
10-15	0.4-0.6	Vibrations considered unpleasant by people subjected to continuous vibrations and unacceptable to some people walking on bridges	Vibrations at a greater amplitude than normally expected from traffic, but would cause “architectural” damage and possibly minor structural damage.

** The vibration amplitudes are based on peak particle velocity in the vertical direction. Where human reactions are concerned, the value is at the point at which the person is situated. For buildings, the value refers to the ground motion. No allowance is included for the amplifying effect, if any, of structural components.*

Source: “A Survey of Traffic-induced Vibrations” by Whiffen and Leonard, Transport and Road Research Laboratory, RRL Report LR418, Crowthorne, Berkshire, England, 1971.

distance to the pile driving was slightly greater than 5 m (17 ft). The pile driver energy and the soil conditions were unknown. It is likely that the ground vibrations were amplified by the structure, causing the damage.

On the whole, the architectural damage criterion for continuous vibrations, 5 mm/s (0.2 in/sec) appears to be conservative even for sustained pile driving. Pile driving amplitudes often exceed 5 mm/s (0.2 in/sec) at distances of 15 m (50 ft), and 13 mm/s (0.5 in/sec) at 7.5 m (25 ft). Pile driving has been done frequently at these distances without apparent damage to buildings (with the previously mentioned exception). The criterion amplitude for pile driving is therefore somewhere between 5 and 50 mm/s (0.2 and 2 in/sec). The 50 mm/s (2 in/sec) single event criterion is still being used by some organizations and engineering firms as a safe amplitude for pile driving. Although never measured by Caltrans, calculations show that this amplitude will be probably exceeded within 2 m (6 ft) from a 68,000 J (50,000 ft lbf) pile driver. This amplitude is probably a "safe" criterion to use for well engineered and reinforced structures. For normal dwellings, however, pile driving peaks should probably not be allowed to exceed 7.5 mm/s (0.3 in/sec). In any case, extreme care must be taken when sustained pile driving occurs within 7.5 m (25 ft) of <u>any</u> building, and 15-30 m (50-100 ft) of a historical building, or building in poor condition.

When high amplitudes of construction vibrations (such as from pile driving, demolition, and pavement breaking) are expected at residences or other buildings, it is recommended that a detailed "crack survey" be undertaken BEFORE the start of construction activities. The survey may be done by photographs, video tape, or visual inventory, and should include inside as well as outside locations. All existing cracks in walls, floors, driveways, etc. should be documented with sufficient detail for comparison after construction to determine whether actual vibration damage has occurred.

<u>Annoyance</u> **-** The annoyance amplitudes in Table 2 should be interpreted with care. Depending on the activity (or inactivity) a person is engaged in, vibrations may be annoying at much lower amplitudes than those shown in Table 2. Elderly, retired, or ill people staying mostly at home, people reading in a quiet environment, people involved in vibration sensitive hobbies or other activities are but a few examples of people that are potentially annoyed by much lower vibration amplitudes. Most routine complaints of traffic vibrations come from people in these categories. To them, even vibrations near the threshold of perception may be annoying.

Frequently, low amplitude traffic vibrations can cause irritating secondary vibrations, such as a slight rattling of doors, windows, stacked dishes, etc. These objects are often in a state of neutral equilibrium and readily respond to very low amplitudes of vibrations. The rattling sound gives rise to exaggerated vibration complaints, even though there is very little risk of damage.

Other criteria - At times, other criteria may be necessary to address very specific concerns. For example, vibration sensitive manufacturing or calibration processes, such as close tolerance machining, laboratories calibrating sensitive electronic equipment, use of electron microscopes, etc. often require vibration criteria that are much lower than the threshold of perception amplitude.

Determining the specific criterion amplitude for such sites is no easy task, and requires the cooperation of the engineers, technicians, or managers involved with the operations. Frequently, even those experts do not know at what amplitude of vibrations their operations will be disturbed, and tests involving generation of vibrations (such as running a heavy truck over 2"x4" wooden boards outside the plant), vibration monitoring equipment, and a test operation must be performed.

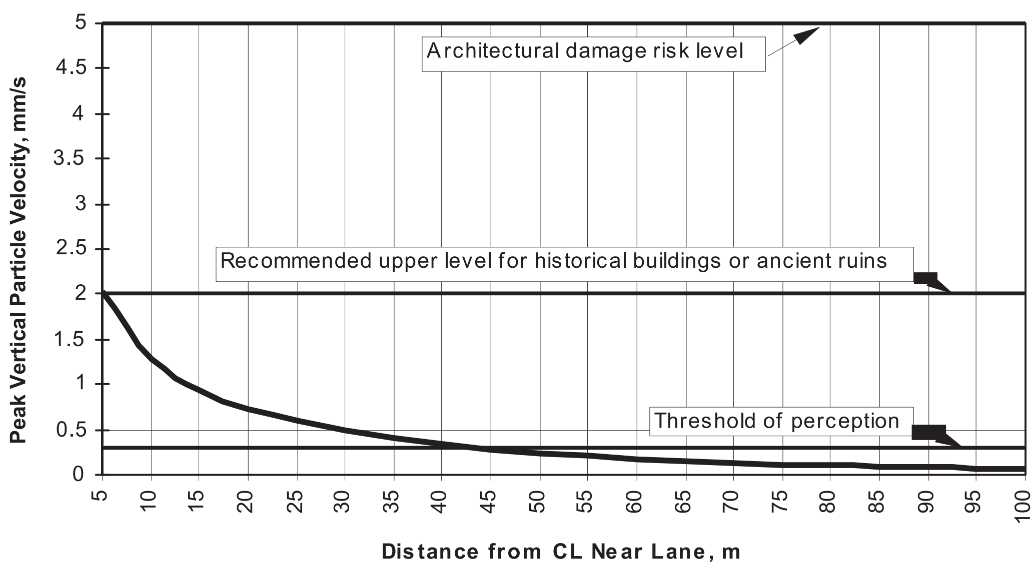
Typical Traffic Vibration Amplitudes

From Figure 1 typical relationships of traffic vibrations vs. distance from a freeway can be developed. For instance, vibration data of truck passbys are characterized by peaks that are considerably higher than those generated by automobiles. These peaks last no more than a few seconds and often only a fraction of a second, indicating a rapid drop-off with distance. Figure 1 showed that at 15 m (50 ft) from the centerline of the nearest lane, truck vibrations are about half of those measured near the edge of shoulder (5 m, or about 15 ft from the centerline of the near lane). At 30 m (100 ft) they are about one fourth, at 60 m (200 ft) about one tenth, and at 90 m (300 ft) less than one twentieth. These rough estimates are supported by years of measurements throughout California.

Because of the rapid dropoffs with distance, even trucks traveling close together often do not increase peak vibration amplitudes substantially. In general, more trucks will show up as more peaks, not necessarily higher peaks. Wavefronts emanating from several trucks closely together may either cancel or partially cancel (destructive interference), or reinforce or partially reinforce (constructive interference) each other, depending on their phases and frequencies. Since traffic vibrations can be considered random, the probabilities of total destructive or constructive interference are extremely small. Coupled with the fact that two trucks cannot occupy the same space, and the rapid drop-off rates, it is understandible that two or more trucks normally do not contribute significantly to each other's peaks. It is, however, good practice to try and include the worst combinations of truck clusters with heavy loads in traffic passby vibration measurements. This obviously requires a good view of the traffic, or an observer who is in communication with the instrument operator.

Figure 2 is a plot of maximum highway truck traffic vibrations vs. distance from the centerline of the nearest freeway lane. The curve was compiled from the highest measured vibrations available from previous studies. Some of the Table 2 criteria are also plotted, for comparison. The graph indicates that the highest traffic generated vibrations measured on freeway shoulders (5 m from center line of nearest lane) have never exceeded 2.0 mm/s, with worst combinations of heavy trucks. This amplitude coincides with the maximum recommended "safe amplitude" for ruins and ancient monuments (and historical buildings). The graph illustrates the rapid attenuation of vibration amplitudes, which dip below the threshold of perception for most people at about 45 m (150 ft).

Figure 2. Maximum Highway Truck Traffic Vibration Levels vs. Distance



Automobile traffic normally generates vibration peaks of one fifth to one tenth of truck vibrations. Traffic vibrations generally range in frequencies from 10-30 Hz, and tend to center around 15 Hz. However, it is not uncommon to measure lower frequencies, even down to 1-2 Hz. Due to their suspension systems, city buses often generate low frequencies around 3 Hz, with high velocities (indicating high displacements). It is more uncommon, but possible, to measure frequencies above 30 Hz for traffic.

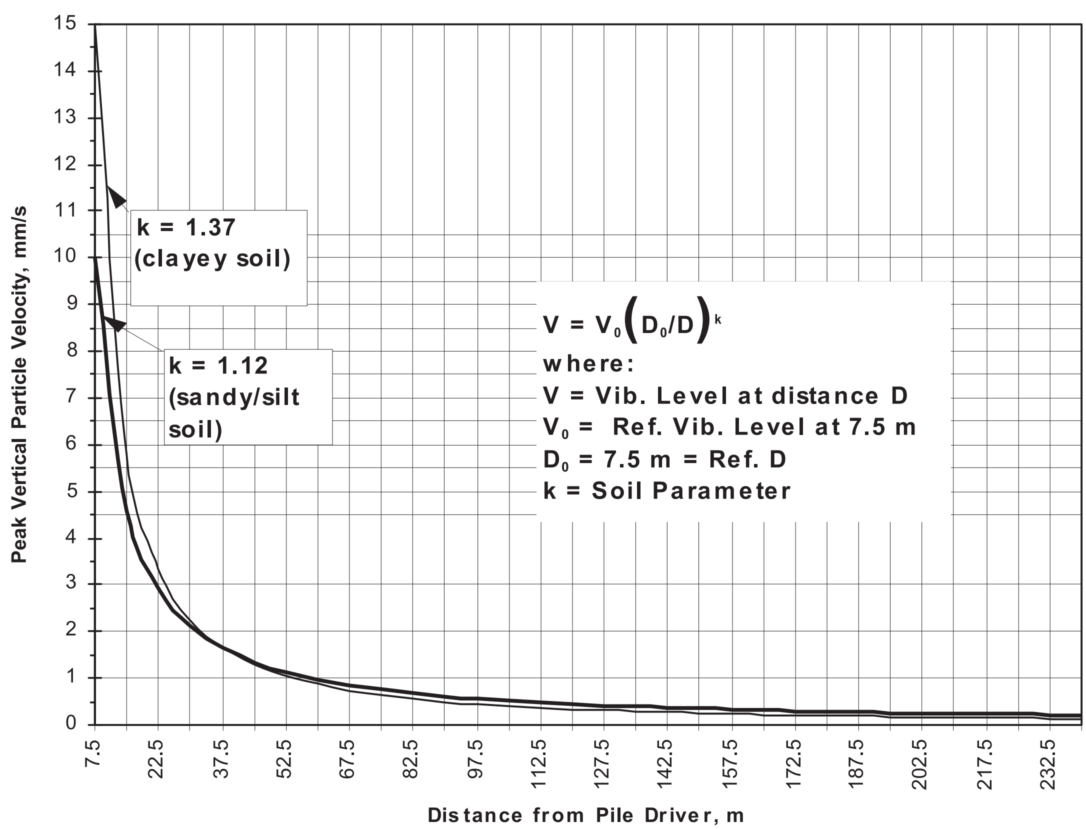
Construction Vibration Amplitudes

With the exception of a few instances involving pavement breaking, pile driving, all Caltrans construction vibration measurements have been below the 5 mm/s (0.2 in/sec) architectural damage risk amplitude for continuous vibrations. The highest measured vibration amplitude was 73.1 mm/s (2.88 in/sec) at 3 m (10 ft) from a pavement breaker. This instance marked the only time that the single event safe amplitude of 50 mm/s (2 in/sec) was exceeded during vibration monitoring by Caltrans.

Other construction activities and equipment, such as D-8 and D-9 Caterpillars, earthmovers and haul trucks have never exceeded 2.5 mm/s (0.10 in/sec) or one half of the architectural damage risk amplitude, at 3 m (10 ft)). Depending on the activity and the source, construction vibrations vary much more than traffic vibrations.

Figure 3 shows typical pile driving vibrations with distance, for a 68,000 J (50,000 ft lbf) energy impact pile driver, for two different soils (clayey and sandy with silt). Clay

Figure 3. Expected Vibration Levels Generated by a 68,000 J (50,000 ft lbf) Impact Pile Driver



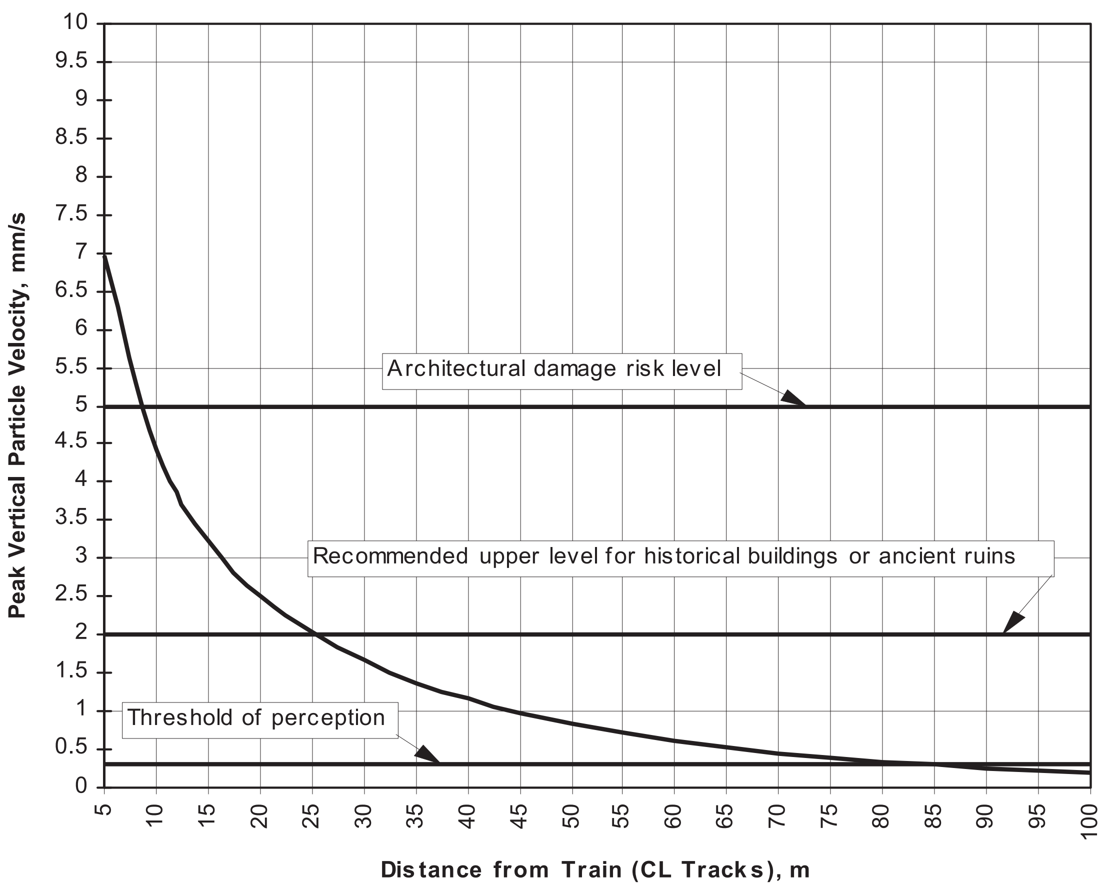
soils provide more resistance to advancing piles and therefore generate higher vibration amplitudes near the source than those in sandy soils. Vibrations in clay soils, however, tend to drop off more rapidly with distance than those in sandy soils.

Frequency ranges of construction vibrations, (including pile driving) tend to be the same as for traffic vibrations, mostly in the 10-30 Hz range, centered around 15 Hz, once in a while lower than 10 Hz, and rarely higher than 30 Hz.

Train Vibration Amplitudes

Train vibration amplitudes may be quite high, depending on the speeds, load, condition of track, amount of ballast used to support the track, and the soil. The highest train vibration measurement was 9.1 mm/s (0.36 in/sec) at 3 m (10 ft), in Sacramento. Using this information with the drop-off curve in Figure 1, we can construct a train vibration curve vs. distance. This is shown in Figure 4, beginning at 5 m (16 ft) where

Figure 4. Maximum Train Vibration Levels vs. Distance



the vibration amplitude is calculated at 7 mm/s. The curve represents maximum expected amplitudes from trains, and thus is very conservative. Measurements at various distances at other locations and different freight trains averaged about two-thirds of those shown in the curve.

Train vibrations tend to be in the same frequency ranges as traffic and construction vibrations. In some cases higher frequencies are encountered, especially in curves, caused by wheel chatter and squeal.

Impacts

Architectural and Structural Damage - The above discussions indicate that in any situation the probability of exceeding architectural damage risk amplitudes for continuous vibrations from construction and trains is very low and from freeway traffic practically non-existent. However, if vibration concerns involve pavement breaking, extensive pile driving, or trains, 7.5 m (25 ft) or less from normal residences, buildings, or unreinforced structures, damage is a real possibility. This may also be true if these operations occur within 15 m – 30 m (50 ft- 100 ft) from historical buildings, buildings in poor condition, or buildings previously damaged in earthquakes.

Pile driving in close proximity (say within 3 m or 10 feet) of structures can cause additional problems, depending on the soils and configurations of substructures. An example was the reconstruction of San Francisco-Oakland Bay Bridge Toll Plaza in June 1987. A number of piles were driven in soft clay soils ("bay mud") close to the existing booth access tunnel underneath the freeway. Due to the large number of piles, and the proximity and configuration of the old substructure, the lateral soil movement, caused by piles permanently displacing the clay, was resisted. The resulting conflict of forces was relieved by structure uplift and damage (cracks in the reinforced concrete tunnel).

Annoyance **-** As was discussed before, the annoyance amplitude shown in Table 2 is highly subjective, and does not take into consideration elderly, retired, ill, and other individuals that may stay home more often than the "average" person. Nor does it account for people involved in vibration sensitive hobbies or activities, and people that like to relax in quiet surroundings without noticing vibrations. The threshold of perception, or roughly 0.25 mm/s (0.01in/sec) may be considered annoying by those people. Low amplitude vibrations may also cause secondary vibrations and audible effects such as a slight rattling of doors, windows and dishes, resulting in additional annoyance. Annoying low frequency airborne noise can sometimes accompany earthborne vibrations.

Vibration Sensitive Operations - Aerospace and electronic laboratories, close tolerance manufacturing, calibration of sensitive instruments, radio & TV stations, recording studios, etc., require additional attention. Shutting down their operations, even temporarily, could be extremely costly to the state. As was previously discussed vibration criteria for these operations are not well defined, for two main reasons. First, the operations are often classified and their precise nature is therefore not always known. Secondly, the engineers involved in the critical operations often do not know how much vibration can be tolerated, or what operations they may be involved with in the future.

Heavy truck traffic on freeways within 30 m (100 ft), major construction within 60 m (200 ft), freight trains within 90 m (300 ft) and pile driving within 180 m (600 ft) may be potentially disruptive to sensitive operations.

Mitigation

Unlike with noise, there are no easy ways to mitigate earthborne vibrations. There are, however, a limited number of options available.

When designing new transportation facilities, reasonable amounts of care should be taken to keep these facilities away from vibration sensitive areas.

When dealing with existing transportation facilities, obvious vibration causes, such as pot holes, pavement cracks, differential settlement in bridge approaches or individual pavement slabs, etc., may be eliminated by resurfacing. In certain situations a ban of heavy trucks may be a feasible option.

The use of alternate construction methods and tools may reduce construction vibrations. Examples are predrilling of pile holes, avoiding cracking and seating methods for resurfacing concrete pavements near vibration sensitive areas, using rubber tired as opposed to tracked vehicles, placing haul roads away from vibration sensitive areas.

Scheduling construction activities (particularly pile driving) for times when it does not interfere with vibration sensitive operations (e.g. night time) may be another solution, especially in industrial areas.

Train vibrations may be reduced by using continuous, welded rails, vibration damping pads between rails and ties, and extra ballast.

Link With Historical Data

A considerable amount of effort has gone into the field measurements, reduction, documentation and reporting of vibration data since 1958. As data sets are accumulated with each vibration study, a more complete picture emerges of the generation and propagation of vibration waves under various conditions of geometry, soil, and source types.

Due to the lack of accurate subsurface information, empirical data is of utmost importance and can be used for future estimates when conditions are alike. Historical data that can be linked to the present and future play a very important role in estimates and predictions of future vibrations.

Present and future personnel charged with the responsibility of performing vibration studies and maintaining vibration files should make every effort necessary to maintain a good correlation between any new and old instrument systems, calibration procedures, and measuring methods. The link between present and valuable historical data must be preserved.

Vibration Monitoring Equipment

During the period of 1958 - 1994 all of Caltrans vibration monitoring was performed by Translab. A transducer calibration system consisting of a shake table mounted on a concrete vibration isolation pad, and an Optron camera/amplifier system, measuring displacement allowed Translab to calibrate its own transducers with traceability to the National Institute of Standards and Technology (NIST), formerly known as the National Bureau of Standards (NBS). Transducers were calibrated by mounting them on the shake table and running the latter at a known frequency and displacement.

Two types of sensors (transducers) were used by Caltrans. The first type was the seismometer. A seismometer measures vibrations at relatively low frequencies usually 1 - 200 Hertz (Hz), is very sensitive to low amplitudes of vibrations and, through magnetic induction produces a voltage proportionally to velocity. It measures velocity directly via a signal conditioner, and is therefore called a velocity transducer. It is large, weighs about 7 kg (15 lbs), and, because of its mass, can be placed directly on the ground without further mounting attachments.

The second type of transducer was an accelerometer. As the name implies, this type of transducer measures acceleration directly. Used with an integrator it can also measure velocity and displacement.

The type of accelerometer used by Caltrans has a piezoelectric (pressure sensitive) crystal. As the transducer vibrates with the surface it is mounted on, acceleration changes the compression of the crystal, which in turn causes variations in the electrical charge across the crystal faces. These charge variations are proportional to acceleration.

An accelerometer is small, not as sensitive as the seismometer and has a wide frequency range, from 1 Hz to several KHz (1 KHz = 1000 Hz). Larger, more sensitive accelerometers, weighing about 1 lb, are available with a narrower frequency range from 0.1 Hz to 1KHz. Due to their small size and lack of mass, accelerometers should not be placed directly on the ground, floor, or other vibrating surface without proper mounting. When properly mounted, accelerometers are excellent transducers for vibration monitoring. They can be mounted various ways, depending on the surface.

For earthborne vibration work an accelerometer can be mounted via a magnet (supplied with it) to a block of steel of, say 5-10 kg (10-20 lbs). The steel block can then be placed directly on the ground, or other surface. However, the steel block should be firmly embedded in loose soil. On harder surfaces such as pavements, the block can only be used on friction surfaces that are perfectly amplitude without high spots to avoid rocking of the block. Correlation tests conducted by Caltrans using this method and the heavy seimometers, concluded that the mass of the steel block provided adequate coupling of the accelerometer with the ground for the low frequency, low amplitude vibrations generated by transportation facilities and construction.

Vibration Study Approach and Instrument Setup

Vibration studies can be classified into two main categories:

1. Studies involving existing transportation operations and facilities
2. Studies involving future transportation operations and facilities

Vibration Studies for Existing Construction Operations and Transportation Facilities - These studies consist of mainly addressing vibration complaints due to existing traffic, or construction operations. Understandably, pile driving near homes or businesses will normally generate many noise and vibration complaints. Other construction operations can also be responsible. Traffic vibration complaints are often due to poor pavement conditions. Other reasons may be increases in traffic, heavy trucks, buses, etc. Sudden increases in traffic vibrations may be due to opening of new transportation facilities, or redirecting traffic.

Although complaints can originate from the entire spectrum of receptors, most are from residences, or businesses that have vibration sensitive equipment or operations.

The first step in investigating complaints should be interviewing the complainant(s). The screening procedures outlined later in this document cover the most important questions to ask. For the purposes of performing a vibration study, the most important issues are:

- The type and location of the vibration source(s)
- The complainant(s)' concerns, i.e., annoyance, damage, disruption of operations.
- The location that is most sensitive, or where vibrations are most noticeable.

Vibration monitoring of existing operations or facilities ranges from simple, single location measurements to more complex multi-instrument, simultaneous measurements. The former consists of taking measurements at the most sensitive location, or location perceived by the complainant to have the worst vibrations. The latter usually involves placing a sensor close to the source as a reference, and one or more sensors at the critical location(s) ("response sensors"). Simultaneous measurements will then positively identify the vibration source, the drop-off and the response (vibration amplitude) at the location(s) of interest. The reference sensor remains fixed in one location near the source, while the response sensor(s) may be moved to different locations.

Sufficient data should be collected for each location. For highway traffic vibrations, 10 passbys of heavy trucks (preferably worst case combinations of several trucks) for each location should be sufficient. For pile driving, at least one pile closest to the receptor should be monitored at each location of interest.

The highest vibration amplitude at each location can then be compared to Caltrans or other appropriate criteria.

Vibration Studies for Future Construction Operations and Transportation Facilities - Studies involving predictions of construction and operation vibrations of future transportation facilities often require vibration simulations to determine a site-specific drop-off curve. In order to generate vibrations that can still be measured at 60-90 m (200 to 300 ft) to develop the curve, the site must be free of high ambient vibrations (preferably less than 0.13 mm/s or 0.005 in/sec at the 90 m or 300 ft distance), and the generated vibrations must be relatively high. From Figure 1 we can calculate approximately how high the reference vibration V_0 at 5 m should be to detect the vibrations at 90 m. The V/V_0 ratio at that distance = 0.038; assuming we want V to be at least 0.13 mm/s; then V_0 = 1/0.038 x 0.13 = 3.4 mm/s (0.13 in/sec). If a low-vibration site cannot be found, either the distance for the drop off curve must be shortened, or the reference vibrations increased. Caution must be used to apply the drop-off curve to pile driving projections, due to the previously discussed differences in propagation characteristics.

To generate data for the drop-off curve, a heavily-loaded water truck, or dump truck (preferably 25 tons or greater GVW) is run at high speed over 2" x 4", or 2" x 6" wooden boards. Normally, five boards are laid perpendicular to the direction of travel, and spaced 7.5 m (25 ft) apart along the direction of travel. The advantage of this arrangement is that the generated vibration "signature" is normally recognizable at 90 m (300 ft).

A minimum of two sensors must be used simultaneously: one reference sensor, and one or more response sensors. The reference sensor remains fixed at 5 m (16 ft) from centerline of travel, (or any convenient distance near the source) opposite the last board to be run over (most forward in line with the direction of travel). The response sensor(s) is (are) positioned at various distances away from the source. Because of the steepness of the curve near the source it is a good idea to cover shorter distance intervals near the source and longer ones away from the source. To adequately cover the entire range of the drop-off curve, 6 to 8 locations must be monitored, and at least 5 truck passbys per location.

Frequently it is not possible to do the simulations on the site of interest, because of space limitations. Nearby empty lots or open fields, or data from other sites known or judged to have similar soil conditions can then be used.

Once the measurements have been made, the data at each location should be averaged. Using the reference location, and at least two others (including the furthest one), the soil parameter “α” can be calculated using equation 2. Ideally, “α” should remain constant for each location, but in reality it will vary. The average of several values can then be used to develop a drop-off curve. The vibration amplitudes at all measured locations should then be plotted to determine how well they fit this curve. Assuming they fit reasonably well, a normalized drop-off curve using V/V_0 ratios and distances (similar to Figure 1) can then be developed and used with any source reference amplitude, to predict the future amplitude at any distance within the range of the curve.

If it is possible to do the simulations at the site, inside/outside building locations should be included to measure the building amplification or attenuation ratio.

The next step is to measure ambient amplitudes at the site. Outside as well as inside building locations should be included for these measurements.

Using all the above information, future amplitudes can be predicted and compared to existing ambient amplitudes, Caltrans guidelines, or any other appropriate or required standard.

Concerns for vibrations of future transportation facilities are usually raised by vibration sensitive factories, laboratories, or other vibration sensitive sites. Unless construction activities are expected to occur very close to residential or other structures, or near historical buildings, these receptors are not routinely included in vibration studies for future facilities.

Vibration field studies including simulations are expensive. Unless the consequences of transportation and construction generated vibrations may be costly to Caltrans, the curves and techniques described in this document can be used to estimate "ball park" vibration amplitudes, in lieu of field studies.

Vibration Reports

Each vibration field study should be documented in a report. Depending on the amount of sites measured, amount of data collected, methodologies used, and the importance of the study, the report may range from a simple one or two paged memo, to a report of twenty or more pages. A vibration study can be considered a mini-research project, and should contain enough information for the reader to independently come to the same conclusions.

As a norm, vibration reports contain the following topics, which will be described in greater detail:

* Project title and description
* Introduction
* Objectives
* Background
* Study Approach
* Instrumentation
* Measurement Sites
* Measurements
* Data Reduction
* Measurement Results
* Data Analysis
* Results and Comparison with Standards
* Conclusions and Recommendations
* Tables showing all measured data, summaries of results, analysis and standards
* Figures showing site layouts and cross sections, instrument setups, drop-off curves, and other pertinent illustrations
* References cited

In short, simple vibration studies, the topics may be described in a few sentences in a memo. In more complex studies, a fairly extensive report is usually required.

Project Title and Description - If the report consists of a short memo this info. can be put in the "Subject:" space. In a long report it should be put on a separate title page, with the date, who did the study (Div.or District, Branch, and personnel involved), and author of report.

Introduction - Typical opening sentences: "This report (memo) presents the results of a vibration study at …….. The study was requested by ……, in response to concerns by ………… that vibrations of …….. would interfere with ………operations. The study was performed by ….. (branch or section) on ……. (dates)."

Objectives - This is often combined with the introduction. Example: "The purpose of the study was to provide baseline data for estimating vibration amplitudes in sensitive areas of Hughes Aircraft facility generated by construction and traffic of the proposed LA-105 Freeway."

Background - Used only when there is a long and complicated history connected with the reasons for the studies. Useful for documenting all the facts leading up to the study for litigation purposes. Dates first contacted, correspondence, actions taken, and other pertinent details may be appropriate in this section. Not necessary in most studies.

Study Approach - May be combined with other sections. A short description of how the study was done. Example:

"First, vibrations generated by a 25 ton GVW three-axle water truck driven over five 2"x4" wooden boards …….. were measured at various distances to measure the vibration attenuation with distance. This info. was then used to develop a drop-off curve….., etc." For simple studies, such as residential complaints: "The sensor was set up at four different locations where, according to the homeowner, vibrations were most noticeable. Five heavy truck passbys on Route ….. were measured at each of the locations. …"

Instrumentation - Always include description, manufacturer, model, serial no. of each vibration equipment components used. It is also extremely important to include the date instruments were last calibrated, by whom, where the records are on file, and whether calibration was traceable to the NIST (National Institute of Standards and Technology, formerly NBS). Essential in court cases!

Measurement Sites - Include a sketch, preferably to scale, of the relationship between source and measurement locations. Plot and number the sites on the sketch. Include typical cross sections if there are significant elevation differences between source and receptors. Plot significant structures. Show enough dimensions to pinpoint each measurement location. Show detailed descriptions, and instruments or sensors used at each location in the text, or in a separate table if there are many. Once locations are numbered and described, they can be referred to by number only.

Measurements - This section may also include the study approach. Basically explains the methods used, how sensors were mounted, number of measurements taken, what sources were measured (e.g. heavy trucks on Route 5), descriptor used and why, and other pertinent information concerning the vibration measurements. When possible, include a description of soil type and structure. This info. can often be extracted from nearby boring logs. Be sure to include ambient or background measurements.

Data Reduction - A short description of how the data was reduced can effectively be combined with the measurement section. Only if the reduction method is unusual or complex should it be discussed in a separate section.

Measurement Results - May also be combined with the measurement section. Briefly summarize data in the text by giving highest values, ranges, and averages. Should be accompanied by a table summarizing measurement run No. (or just Run No.), date and time, measurement location, source (heavy truck in N/B lane No.4), distance, vibration amplitude, dominant frequency, and optional remarks. This table may be put in the text or in an appendix with all other tables and figures. All individual measurements should be included as part of the report, for possible future use. Ambient or background vibration measurements can be expressed as a range of vibrations, typical frequency ranges, time period during which they were measured, and if possible the range of sources and distances.

Data Analysis - Developing drop-off curves, predicting future amplitudes, calculating amplitudes at specific distances not measured, etc. all should be in this section. May not be necessary for simple studies involving residential complaints, monitoring for compliance with a standard, or any other study involving vibration measurements only.

Results and Comparisons to Standards - Existing measured, projected, and predicted vibration amplitudes and frequencies are summarized and compared to pertinent standards in this section. This is usually done in tabular form, and accompanied by Table 1, which shows the vibration criteria used by Caltrans.

Conclusions and Recommendations - Conclusions are drawn from the previous comparisons with standards. Typically for highway vibration complaints would be: "Although vibrations generated by heavy trucks on I-5 may at times be felt, they are far below the 'architectural damage risk amplitude' criterion of 0.2 in/sec used by Caltrans."

Recommendations for mitigation are rather limited (see "Mitigation" section). However, in some cases strategies such as pile driving at night may solve interference with vibration sensitive manufacturing processes during day time. When ever possible, such recommendations should be included.

References - In complex reports, relying partly on previously gathered data, it may be beneficial to cite other reports or references by number. A listing of these references should then be included at the end of the report.

Field Review and Screening of Possible Vibration Problems

The following procedures were designed to screen vibration complaints near existing transportation facilities. They are intended to accomplish two things: 1) to evaluate the severity of the vibration problem, and 2) obtain preliminary information for a vibration study, should one be necessary.

The procedures are divided in two parts: problem definition and actions to take. An outline of the steps in each part follows:

I. Problem Definition

A. Interview resident at the site of concern. Ask the following questions:

1. What is the exact problem in the resident's opinion?

Many people confuse low frequency airborne noise with earthborne vibrations.

2. What are the sources in the resident's opinion?

Trucks on freeway?; city traffic?; trains? (sources may not be our jurisdiction.)

3. What are the specific concerns?

Annoyance?, interference with activities?, damage to the residence? If damage is the main concern, ask for evidence look for stucco cracks, cracks in driveways, walkways, walls, stucco, etc. Compare with other residences further away from the transportation facility. If these also have cracks, then it is safe to assume that the facility is not responsible.

4. Where are the vibrations most noticeable?

Which room?; which part of the yard? (Let resident point out the critical locations.)

5. What time of the day and/or what day of the week does the resident feel vibrations the most?

6. When did the resident become aware of the vibrations?

Try to correlate with changes in nearby traffic patterns, due to truck bans elsewhere, new industrial development, or other reason for truck increases.

B. Feel the vibrations

1. Stand at critical locations and try to feel vibrations when trucks pass by.

Place finger tips on furniture, walls, uncarpeted floor, ground outside the residence, patio floor, etc.

2. Have someone walk nearby; feel these vibrations and compare with the traffic vibrations. Also compare other in-house generated vibrations.

Walking, air conditioners, heater blowers, and garbage disposals, etc. often generate more vibrations than traffic.

3. Stand on freeway shoulder, sidewalk next to highway, or anywhere close to the suspect source. Feel vibrations and compare with those felt at the receptor.

Place finger tips on ground or pavement surface.

4. Look for obvious causes of excessive vibrations.

Pot holes, pavement joints, sag, and pavement cracks, or anything that could cause above normal vibrations; also look for drainage or other structures transmitting vibrations to the receptor without benefit of soil attenuation.

C. Evaluate severity of the problem.

The graphs in Figures 1 - 4 show typical vibration attenuations with distance for various sources. Use these to evaluate typical relationships of near and far source vibration amplitudes. If vibrations appear to dropoff at a significantly lesser rate, then suspect that something unusual is going on. For instance, vibrations may be transmitted by underground structures, which can cause problems at the receptor.

1. If vibrations feel as strong (or almost as strong) at the receptor as they do near the source (such as on a freeway shoulder), consider problem severe.

2. If vibrations at the receptor are readily noticeable and appear to interfere with activities or vibration sensitive operations, consider problem severe.

3. If vibrations of any amplitude are an issue in litigation, consider the problem severe.

4. If after this screening procedure uncertainty still exists, consider problem severe.

II. Actions To Take

A. If problem is not severe:

1. If there are obvious causes for excessive vibrations, such as pot holes, etc., contact Maintenance or other departments and find out if scheduled for repair or resurfacing.

2. Write memo to resident explaining your findings.

If there are obvious solutions such as patching or resurfacing, tell the resident. If there are no obvious solutions, explain to the resident that although vibrations may be felt, they are not damaging. Use background info. in this document.

B. If problem is considered severe, or if the resident keeps insisting on actual monitoring, consider contracting out vibration monitoring or a complete vibration study.

APPENDIX
BASIC VIBRATION FORMULAE

APPENDIX

BASIC VIBRATION FORMULAE

Symbols

A = Zero-to-Peak, or Peak Acceleration (Units: m/sec^2, mm/sec^2, ft/sec^2, in/sec^2)

A_g = Zero-to-Peak, or Peak Acceleration (Units: "g" = acceleration of gravity), where:

1 g = $9.807\ m/sec^2$

= $9807\ mm/sec^2$

= $32.174\ ft/sec^2$

= $386.102\ in/sec^2$

D = Peak-to-Peak Displacement (Units: m, mm, ft, in) (Normally of interest)

$D/2$ = Zero-to-Peak, or Peak Displacement (Units: m, mm, ft, in)

f = Frequency (Units: Hertz)

V = Zero-to-Peak, or Peak Particle Velocity (Units: m/sec,mm/sec, in/sec)

π = 3.14159etc.....

Formulae for Sinusoidal Waves

Units need to be consistent; for example, if D is in mm, then V must be in mm/sec, and A either in mm/sec^2 or units of "g" ($9807\ mm/sec^2$).

With displacement, we are normally interested in the peak-to-peak value or in other words, the total displacement (distance between the + peak and - peak) soil particles travel. Sometimes, however we may also be interested in the zero-to-peak displacement, or displacement relative to a stationary (zero) reference position. For sinusoidal waves, the + side of reference and the - side are symmetrical, and zero-to-peak values are D/2.

With velocity and acceleration, however, we are always interested in the zero-to-peak values. These give an indication of maximum value, without regard of the direction.

Acceleration is most commonly used in units of g.

Following are formulae expressing the relationships between displacement, velocity, and acceleration for sinusoidal vibration waves.

Velocity and Displacement:

$V = 2\pi f(D/2)$ (Eq.A-1)

$V = \pi fD$ (Eq.A-2)

$D/2 = V/(2\pi f)$ (Eq.A-3)

$D = V/(\pi f)$ (Eq.A-4)

Acceleration and Displacement:

$A = (2\pi f)^2(D/2)$ (Eq.A-5)

$A = 2\pi^2 f^2 D$ (Eq.A-6)

$A_g = (2\pi^2 f^2 D)/g$ (Eq.A-7)

If D is in inches:

$A_g = (2\pi^2 f^2 D)/386.102 = 0.0511 f^2 D$ (Eq.A-8)

If D is in mm:

$A_g = (2\pi^2 f^2 D)/9807 = 0.00201 f^2 D$ (Eq.A-9)

Acceleration and Velocity:

$A = 2\pi fV$ (Eq.A-10)

$A_g = (2\pi fV)/g$ (Eq.A-11)

If V is in inches per second:

$A_g = (2\pi fV)/386.102 = 0.0163 fV$ (Eq.A-12)

If V is in mm per second:

$A_g = (2\pi fV)/9807 = 0.000641 fV$ (Eq.A-13)

Acceleration or Velocity in Decibels:

$A(dB) = 20 Log(A/A_0)$; $V(dB) = 20 Log(V/V_0)$ (Eq.A-14)

where A = acceleration, A_0 = reference acceleration,

V = velocity, and V_0 = reference velocity (units must be consistent)

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Appendix B. Sample Vibration Screening Procedure and Vibration Complaint Form

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Vibration Screening Procedure

The vibration screening procedure is divided in two parts: problem definition and actions to take.

I. Problem Definition

A. Interview resident at the site of concern. Ask the following questions.

1. *What is the exact problem, in the resident's opinion?*
   Confirm that the vibration is from a Caltrans facility or activity and that vibration is really the issue. Many people confuse low frequency airborne noise with earthborne vibrations.

2. *What are the sources of vibration, in the resident's opinion?*
   Identify the sources of vibration (e.g., trucks on freeway, city traffic, trains, construction equipment). Sources such as trains may not be within Caltrans' jurisdiction.

3. *What are the specific concerns?*
   Identify the specific concern (e.g., annoyance, interference with activities, damage to the residence). If damage is the main concern, ask for evidence and look for cracks in driveways, walkways, walls, stucco, etc. Compare these conditions with other residences farther away from the transportation facility or construction activity. If distant locations have similar conditions, it is likely that the damage is not the result of the facility or construction activity.

4. *Where is the vibration most noticeable?*
   Identify where the vibration is most noticeable (e.g., specific rooms, yard outside). Let resident point out the critical locations.

5. *What time of the day and what day of the week does the resident feel vibrations the most?*
   Identify when the vibration is most noticeable.

6. *When did the resident become aware of the vibrations?*
   Try to correlate the detection of vibration with changes in nearby traffic patterns, changes in heavy truck percentages, or the presence of new vibration sources.

B. Feel the vibrations.

1. *Stand at critical locations and try to feel vibrations when trucks pass by.*

   Place fingertips on furniture, walls, uncarpeted floor, ground outside the residence, patio floor, etc., to sense where vibration is most noticeable.

2. *Have someone walk nearby; feel these vibrations and compare with the traffic vibrations. Also compare other vibrations generated in-house.*

   People walking, air conditioners, heater blowers, garbage disposals, etc. often generate more vibrations than traffic. Try to see how vibration from these sources compares to vibration from the sources identified by the resident.

3. *Stand on freeway shoulder, sidewalk next to highway, or anywhere close to the suspected source. Feel vibrations and compare with those felt at the receptor.*

   Place fingertips on ground or pavement surface to sense vibration near the source of concern.

4. *Look for obvious causes of excessive vibrations.*

   Identify potholes, pavement joints, sag, pavement cracks, or anything that could cause above-normal vibration. Also look for drainage pipes or other structures that can transmit vibration directly to the receptor without benefit of soil attenuation.

C. Evaluate the severity of the problem.

If the vibration level appears to drop off at a significantly lower rate than would be expected, something unusual may be occurring on the site. For example, vibration may be transmitted by underground structures, which can cause vibration to be transmitted over longer-than-normal distances. A vibration problem should be considered severe if:

1. vibration feels as strong (or almost as strong) at the receptor as it does near the source (such as on a freeway shoulder),

2. vibration at the receptor is readily noticeable and appears to interfere with activities or vibration-sensitive operations,

3. vibration at the receptor is readily noticeable and appears to have resulted in structural or cosmetic damage,

4. vibration of any amplitude is an issue in litigation, or

5. uncertainty still exists as to the source of vibration.

II. Actions to Take

A. If problem is not severe:

1. *Identify the obvious causes for excessive vibrations.* These causes could include pavement imperfections that result in vibration from truck pass-bys or unusual building resonances that amplify vibration at the receiver. For issues within Caltrans' control, such as pavement conditions, contact the appropriate Caltrans department and find out whether the pavement is scheduled for repair or resurfacing.

2. *Prepare a memo to explain your findings.* If there are obvious solutions, such as pavement patching or resurfacing, explain these, along with actions that will or will not be taken to address the issue. If there are no obvious solutions, explain that, although vibration may be felt, it is not enough to cause damage.

B. If problem is considered severe, or if the resident keeps insisting on actual monitoring, conduct a vibration monitoring study to further investigate the issue.

Vibration Complaint Report

Complaint received: Date: ________________ Time: _______________

Complainant's name: ____

Address: ____ Phone: ______________

Specific complaint: ____

____

____

____

Date and specific time of occurrence (as reported by Complainant):

Date: _______________ Time: ________________

Complaint received by: ____

Results of Investigation: ____

____

____

____

____

____

Investigated by: ____

Disposition of Complaint: ____

____

____

____

Appendix C. Sample Vibration Specifications

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VIBRATION MONITORING

DESCRIPTION

1.01 GENERAL

A. The Work of this Section includes furnishing, installing and maintaining vibration-monitoring instrumentation; collecting vibration data; and interpreting and reporting the results. The Contractor shall implement required remedial and precautionary measures based on the vibration-monitoring data.

B. The purpose of the vibration-monitoring program is to protect the following properties from excess vibration during demolition and construction activities associated with the ___________________________ Project:

1. Building name and address

2. Building name and address

3. Building name and address

4. Building name and address

C. Caltrans is not responsible for the safety of the Work based on vibration-monitoring data, and compliance with this Section does not relieve the Contractor of full responsibility for damage caused by the Contractor's operations.

1.02 RESPONSIBILITIES OF CONTRACTOR

A. Furnish and install vibration-monitoring instrumentation.

B. Protect from damage and maintain instruments installed by the Contractor and repair or replace damaged or inoperative instruments.

C. Collect, interpret and report data from instrumentation specified herein.

D. Implement response actions.

1.03 QUALIFICATIONS OF VIBRATION MONITORING PERSONNEL

A. The Contractor's vibration-monitoring personnel shall have the qualifications specified herein. These personnel may be on the staff of the Contractor or may be on the staff of a specialist subcontractor. However, they shall not be employed nor compensated by subcontractors, or by persons or entities hired by subcontractors, who will provide other services or material for the project.

B. The Contractor's vibration-monitoring personnel shall include a qualified Vibration Instrumentation Engineer who is a registered Professional Engineer in the State of California, who has a minimum of a Bachelor of Science degree in civil engineering, and who has at least 4 years of experience in the installation and use of vibration-monitoring instrumentation and in interpreting instrumentation data. The Vibration Instrumentation Engineer shall:

1. Be on site and supervise the initial installation of each vibration-monitoring instrument.

2. Supervise interpretations of vibration-monitoring data.

C. The Contractor's vibration-monitoring personnel shall be subject to the review of the Engineer.

1.04 QUALITY ASSURANCE

A. A record of laboratory calibration shall be provided for all vibration-monitoring instruments to be used on site. Certification shall be provided to indicate that the instruments are calibrated and maintained in accordance with the equipment manufacturer's calibration requirements and that calibrations are traceable to the U. S. National Institute of Standards and Technology (NIST).

1.05 SUBMITTALS

A. As soon as feasible after the Notice to Proceed, submit manufacturer's product data describing all specified vibration-monitoring instruments to the Engineer for review, including requests for consideration of substitutions, if any, together with product data and instruction manuals for requested substitutions.

B. Within 3 weeks after the Notice to Proceed, submit to the Engineer for review the resumes of the Vibration Instrumentation Engineer and any vibration monitoring technical support personnel, sufficient to define details of relevant experience.

C. Within 5 Workdays of receipt of each instrument at the site, submit to the Engineer a copy of the instruction manual and the laboratory calibration and test equipment certification.

D. Prior to the start of construction and prior to performing any vibration monitoring, the Contractor shall submit to the Engineer for review a written plan detailing the procedures for vibration monitoring. Such details shall include:

1. The name of the Firm providing the vibration monitoring services.

2. Description of the instrumentation and equipment to be used.

3. Measurement locations and methods for mounting the vibration sensors.

4. Procedures for data collection and analysis.

5. Means and methods of providing warning when the Response Values, as specified in Article 3.07, are reached.

6. Generalized plans of action to be implemented in the event any Response Value, as specified in Article 3.07, is reached. The generalized plans of action shall be positive measures by the Contractor to control vibrations (e.g. using alternative construction methods).

E. Submit data and reports as specified in Article 3.04.

MATERIALS

2.01 GENERAL

A. Whenever any product is specified by brand name and model number, such specifications shall be deemed to be used for the purpose of establishing a standard of quality and facilitating the description of the product desired. The term "acceptable equivalent" shall be understood to indicate a product that is the same or better than the product named in the specifications in function, quality, performance, reliability, and general configuration. This procedure is not to be construed as eliminating other manufacturers' suitable products of equal quality. The Contractor may, in such cases, submit complete comparative data to the Engineer for consideration of another product. Substitute products shall not be used in the Work unless accepted by the Engineer in writing. The Engineer will be the sole judge of the suitability and equivalency of the proposed substitution.

B. Any request from the Contractor for consideration of a substitution shall clearly state the nature of the deviation from the product specified.

C. The Contractor shall furnish all installation tools, materials, and miscellaneous instrumentation components for vibration monitoring.

2.02 SEISMOGRAPHS

A. Provide portable seismographs for monitoring the velocities of ground vibrations resulting from construction activities. Provide model DS-477 Blastmate II as manufactured by Instantel Inc., Kanata (Ottawa), Ontario, Canada, model VMS-500 as manufactured by Thomas Instruments, Inc., Spofford, NH, or model NC5310/D, as manufactured by Nomis Inc., Birmingham, AL, or acceptable equivalent. The seismograph shall have the following minimum features:

1. Seismic range: 0.01 to 4 inches per second with an accuracy of ±5 percent of the measured peak particle velocity or better at frequencies between 10 Hertz and 100 Hertz, and with a resolution of 0.01 inches per second or less.

2. Frequency response (±3 dB points): 2 to 200 Hertz.

3. Three channels for simultaneous time-domain monitoring of vibration velocities in digital format on three perpendicular axes.

4. Two power sources: internal rechargeable battery and charger and 115 volts AC. Battery must be capable of supplying power to monitor vibrations continuously for up to 24 hours.

5. Capable of internal, dynamic calibration.

6. Direct writing to printer and capability to transfer data from memory to 3-1/2 inch magnetic disk. Instruments must be capable of producing strip chart recordings of readings on site within one hour of obtaining the readings. Provide computer software to perform analysis and produce reports of continuous monitoring.

7. Continuous monitoring mode must be capable of recording single-component peak particle velocities, and frequency of peaks with an interval of one minute or less.

CONSTRUCTION METHODS

3.01 INSTALLATION OF SEISMOGRAPHS

A. The Contractor shall install seismographs at four points near the corners of the buildings that are closest to the project site; these points are denoted as locations 1 through 4 in Figure 1.

B. The seismograph vibration sensors shall be located at points on the ground between 3 and 6 feet from the building facades.

C. The seismograph vibration sensors shall be firmly mounted on the surface slab of concrete or asphalt, or firmly set in undisturbed soil

3.02 FIELD CALIBRATION AND MAINTENANCE

A. The Contractor's instrumentation personnel shall conduct regular maintenance of seismograph installations.

B. All seismographs shall have been calibrated by the manufacturer or certified calibration laboratory within one year of their use on site. A current certificate of calibration shall be submitted to the Engineer with the Contractor's data.

3.03 DATA COLLECTION

A. The Contractor shall collect seismograph data prior to any vibration-producing demolition or construction activities to document background vibrations at each monitoring location. This monitoring shall consist of a continuous recording of the maximum single-component peak particle velocities for one-minute intervals, which shall be printed on a strip chart. The background monitoring shall be performed for a minimum of two non-consecutive workdays, spanning the hours during which demolition and construction activities will take place.

B. The Contractor shall monitor vibration during demolition and other significant vibration-producing construction activities as determined by the Engineer. This monitoring shall consist of a continuous recording of the maximum single-component peak particle velocities for one-minute intervals, which shall be printed on a strip chart. During the monitoring, the Contractor shall document all events that are responsible for the measured vibration levels, and submit the documentation to the Engineer with the data as specified in Article 3.04. A record form for documenting these events is included herein as Figure 2.

C. All vibration monitoring data shall be recorded contemporaneously and plotted continuously on a graph by the data acquisition equipment. Each graph shall show time-domain wave traces (particle velocity versus time) for each transducer with the same vertical and horizontal axes scale.

D. The Contractor shall notify the Engineer at least 24 hours prior to starting a new vibration-producing construction task, and shall have the seismographs in place and functioning properly prior to any such activity within 200 feet of the monitoring locations. No significant vibration-producing activity shall occur within this zone unless the monitoring equipment is functioning properly.

E. The equipment shall be set up in a manner such that an immediate warning is given when the peak particle velocity in any direction exceeds the Response Values specified in Article 3.07. The warning emitted by the vibration-monitoring equipment shall be instantaneously transmitted to the responsible person designated by the Contractor by means of warning lights, audible sounds or electronic transmission.

3.04 DATA REDUCTION, PROCESSING, PLOTTING AND REPORTING

A. Within 10 working days after the completion of the background vibration monitoring, the Contractor shall submit to the Engineer a hard copy report documenting the results at each of the monitoring locations.

B. During bridge demolition and construction, the Contractor shall provide weekly, hard copy reports summarizing any vibration monitoring data collected at the specified vibration-monitoring locations. The reports for each week shall be submitted on or before the end of the following week.

C. All reports shall be signed by the approved Vibration Instrumentation Engineer, and shall include the following:

1. Project identification, including District, County, Route, Post Mile, Project Name and Bridge number as shown on the project plans.

2. Location of the monitoring equipment, including address of adjacent building.

3. Location of vibration sources (e.g. traffic, demolition equipment, etc.)

4. Summary tables indicating the date, time and magnitude and frequency of maximum single-component peak particle velocity measured during each one-hour interval of the monitoring period.

5. Field data forms (construction vibration monitoring only).

6. Appendix graphs of the strip charts printed during the monitoring periods.

D. In addition to the hard copy data specified herein, the Contractor shall provide data on 3.5-inch diskettes with each report. Electronic data files for all instrument data shall be provided in dBASE IV (.DBF) format.

3.05 DAMAGE TO INSTRUMENTATION

A. The Contractor shall protect all instruments and appurtenant fixtures, leads, connections, and other components of vibration-monitoring systems from damage due to construction operations, weather, traffic, and vandalism.

B. If an instrument is damaged or inoperative, the Contractor's instrumentation personnel shall repair or replace the damaged or inoperative instrument within 72 hours at no additional cost to Caltrans. The Contractor shall notify the Engineer at least 24 hours prior to repairing or replacing a damaged or inoperative instrument. The Engineer will be the sole judge of whether repair or replacement is required.

3.06 DISCLOSURE OF DATA

A. The Contractor shall not disclose any instrumentation data to third parties and shall not publish data without prior written consent of Caltrans.

3.07 DATA INTERPRETATION AND IMPLEMENTING PLANS OF ACTION

A. The Contractor shall interpret the data collected, including making correlations between seismograph data and specific construction activities. The data shall be evaluated to determine whether the measured vibrations can be reasonably attributed to construction activities.

B. The Response Values for vibration include a Threshold Value of 0.2 inches per second and a Limiting Value of 0.3 inches per second. The actions associated with these Response Values are defined below. Plans for such actions are referred to herein as plans of action, and actual actions to be implemented are referred to herein as response actions. Response Values are subject to adjustment by the Engineer as indicated by prevailing conditions or circumstances.

C. If a Threshold Value is reached, the Contractor shall:

1. Immediately notify the Engineer.

2. Meet with the Engineer to discuss the need for response action(s).

3. If directed by the Engineer during the above meeting that a response action is needed, submit within 24 hours a detailed specific plan of action based as appropriate on the generalized plan of action submitted previously as part of the vibration-monitoring plan specified in Article 1.05.

4. If directed by the Engineer, implement response action(s) within 24 hours of submitting a detailed specific plan of action, so that the Limiting Value is not exceeded.

D. If a Limiting Value is reached, the Contractor shall:

1. Immediately notify the Engineer and suspend activities in the affected area, with the exception of those actions necessary to avoid exceeding the Limiting Value.

2. Meet with the Engineer to discuss the need for response action(s).

3. If directed by the Engineer during the above meeting that a response action is needed, submit within 24 hours a detailed specific plan of action based as appropriate on the generalized plan of action submitted previously as part of the vibration-monitoring plan specified in Article 1.05.

4. If directed by the Engineer, implement response action(s) within 24 hours of submitting a detailed specific plan of action, so that the Limiting Value is not exceeded.

3.08 DISPOSITION OF INSTRUMENTS

A. The Contractor shall remove salvageable instruments only when directed by the Engineer.

B. All salvaged instruments shall become the property of the Contractor.

COMPENSATION

4.01 BASIS OF PAYMENT

A. The contract lump sum price paid for vibration monitoring shall include full compensation for furnishing all labor, materials, tools, equipment, and incidentals and for performing all work involving vibration monitoring, as specified in the Standard Specifications and these special provisions, and as directed by the Engineer.

B. Any additional areas where vibration monitoring is required will be paid for as extra work as provided in the Standard Specifications.

[Show vibration monitoring locations here.]

FIGURE 1. VIBRATION MONITORING LOCATIONS

CONSTRUCTION VIBRATION MONITORING FIELD DATA FORM

Contract Number: ______________________________

Contract Name: ______________________________

Contractor: ______________________________

Observer: ______________________________

Seismograph Information

Manufacturer and Model: ______________________________

Serial Number: ______________________________

Current Calibration Date: ______________________________

Monitoring Location

Building: ______________________________

Address: ______________________________

Sensor Location (describe location and attach sketch)

____

Data Collection: 1-minute ppv Strip Chart (attach data)

Monitoring Period (date and time) Start: ______________ End: ______________

Observed Events

Date	Time	Source of Vibration (e.g. demolition, pile driving, compaction, excavation, tracked vehicles, etc.)	Distance From Sensor (ft)	Peak Particle Velocity (in./sec)	Frequency (Hz)

Attach additional sheets as necessary

FIGURE 2. CONSTRUCTION VIBRATION MONITORING DATA FORM

Appendix D. Sample Blasting Vibration Specifications

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Sample Blasting Specifications

It is impossible to foresee all of the variables that may be encountered on various project sites. A site-specific Blasting Specification should be developed for each project that takes into consideration the peculiarities of that project location. In particular, the areas of blast vibration limits, pre-blast surveys, the number of recording instruments and their locations, the times and days of scheduled blasting, and cautious blasting techniques (if any) should be addressed.

Considering the foregoing, the following represents a generic blasting specification that provides a starting point for writing a blasting specification for construction blasting.

1. GENERAL

All blasting operations on this project, including the storage, on-site transportation, loading and firing of explosives, shall be in strict compliance with this section.

2. PERMITS AND LICENSES

A. All blasting operations shall be conducted under the direct supervision of a blaster holding a current license issued by the California Division of Occupational Safety and Health (CALOSHA). The class of license held by the blaster shall include the type of blasting that is to be accomplished. Prior to commencing blasting operations, a copy of the Blaster's License shall be provided to the Engineer.

B. The Contractor shall be responsible for obtaining any explosives or blasting permits that may be required by state or local laws.

3. STORAGE OF EXPLOSIVES

Storage of explosives, if anticipated, shall comply with the applicable provisions of CALOSHA's Construction Safety Orders and with Title 27 CFR 181, Part 55, Subpart K, Commerce in Explosives. Adequate magazine records shall be maintained for stored explosives.

4. TRANSPORTATION OF EXPLOSIVES

A. Transportation of explosives to the project site shall be in accordance with current Federal Department of Transportation and California Highway Patrol regulations.

B. Transportation of explosives on the project site shall comply with provisions of the CALOSHA Construction Safety Orders.

5. BLASTING OPERATIONS

A. All blasting operations shall be conducted in compliance with the CALOSHA Construction Safety Orders and the provisions of this Section.

B. The time and date of blasting shall be coordinated in advance with the Engineer in order to minimize the impact on traffic and nearby residents.

C. Due to the potential presence of RF emitting devices in the vicinity, only initiation systems that are not affected by stray current or RF energy shall be utilized. Initiation systems consisting solely of cap and fuse shall not be used. Procedures in the use of the initiation system selected shall conform to the system manufacturer's recommendations. Regardless of other exclusions in this section, if deemed safe by the Contractor, an electric detonator may be utilized to start the initiation system. The electric cap or other starter shall not be brought onto the blast site nor shall it be connected to the initiation system until the area has been cleared and the blast is ready to be detonated.

D. Before commencing loading operations, warning signs shall be posted at points of access to the blasting site. Only the blaster, his loading crew and necessary supervisory personnel shall be allowed within 50 feet of the blast site during loading.

E. Only a reasonable quantity of explosives for each blast shall be brought to the blast loading site. When loading is complete, all excess explosive materials shall be removed from the site and returned to the storage magazine or the supplier's storage facility. In no instance shall explosives, blasting agents, detonators or loaded holes be left unguarded or unattended.

F. A lightning detector of a type approved by CALOSHA shall be utilized to detect the presence of lightning immediately prior to and during blast loading operations. Prior to commencing loading operations, if an electrical storm is detected whose approach is estimated to interfere with loading operations, loading shall not commence and the blast shall be rescheduled. If an approaching electrical storm is detected during loading that will present a hazard to loading operations, loading shall be discontinued and all personnel moved to a safe area. All approaches to the blast site shall be guarded and no one shall be allowed to return to the blast site until the storm has passed safely out of range.

G. All refuse from explosives loading such as empty boxes, bags, plastic, paper and fiber packing shall be removed from the project site and destroyed in accordance with the provisions of the Construction Safety Orders.

H. Prior to firing a blast, all personnel shall be cleared to a safe distance and all approaches to the blast site shall be guarded. Traffic shall be stopped at a safe distance and held until the all-clear signal. The blaster firing the blast shall be in a position where he can see the blast site and approaches and shall not detonate the blast until he is certain that no one remains in a hazardous location.

I. Blasting signals shall be conspicuously posted at the site. The signaling device shall be sufficiently loud so that the signals can be heard throughout the area to be cleared. The following blasting signals shall be used:

WARNING SIGNAL
5 minutes prior to the blast...a 1-minute series of long signals

BLASTING SIGNAL
1 minute prior to the blast.....a series of short signals

ALL-CLEAR SIGNAL
Following inspection of the blast....a prolonged signal

J. Misfires.

1. After the blast has been fired, an inspection shall be made by the blaster to determine that all charges have detonated. Only after the blaster is satisfied that the area is safe shall the ALL-CLEAR signal be given.

2. If, after a blast has been fired, the blaster suspects that a misfire has occurred, the Engineer shall be notified. The ALL CLEAR signal shall NOT be given, traffic shall not be released and the blast site shall continue to remain guarded. The blaster shall be in charge of investigating the misfire. He shall do so in accordance with the Construction Safety Orders.

3. If no misfire is found to exist after adequate inspection by the blaster, he shall so notify the Engineer and the ALL CLEAR signal can be sounded.

4. If a misfire is found to exist, the blaster shall immediately notify the Engineer and he shall then proceed to clear the misfire. While this is being accomplished, the blast site shall remain guarded.

5. Following the successful clearing of the misfire and a subsequent inspection of the blast site by the blaster, he shall give the order to sound the ALL CLEAR signal.

6. BLAST DOCUMENTATION (BLAST REPORT)

A. At least 24 hours prior to the loading of a blast, the Contractor shall submit to the Engineer a copy of the proposed blasting scheme for that particular blast. As a minimum, the Blast Report shall include:

1. A plan view of the blast showing the number and location of all holes.

2. The hole diameter(s) and depth(s).

3. The burden and spacing dimensions.

4. The type(s) of explosive to be used and the anticipated total quantity of each.

5. The quantity of explosive to be loaded in each hole and in each deck if decking of charges is anticipated.

6. The type and depth(s) of stemming material to be used.

7. The type, layout and timing of the initiation system to be used.

8. The method of starting the initiation system.

9. The maximum quantity of explosive that will be detonated within any 8 millisecond time period during the blast.

10. The name of the licensed blaster and his license number.

B. It is anticipated that minor changes could be necessary during loading of the blast due to lost holes, etc. Immediately following the blast, the blaster shall annotate a copy of the Blast Report with such changes, if any, and shall sign the Report and deliver it to the Engineer.

7. PROTECTION OF NEIGHBORING FACILITIES

A. The Contractor shall conduct his blasting operations in a manner that will preclude his causing damage to neighboring facilities. Compliance with the provisions of these specifications or acceptance by the Engineer of any blasting procedures or techniques shall not absolve the Contractor from full responsibility for any damage that may result from his blasting operations.

B. Blasts shall be designed so that vibration and air overpressure levels and flyrock do not exceed the limits stated in this Section.

C. All blasts shall be monitored by the Contractor with ___(qty)___ blast vibration seismograph(s). Each seismograph shall record blast-generated vibration in three mutually perpendicular axes and have a frequency response range of from 2 to 250 Hertz.

D. The seismograph(s) shall have received a factory calibration within the 12 month period preceding the blast recorded. Each seismograph shall produce a real-time graphical depiction of the particle velocities recorded for each individual axis for the duration of the event. The seismograph(s) shall also produce a numeric record of the peak particle velocities and principle frequencies of the vibration recorded for each axis during the event.

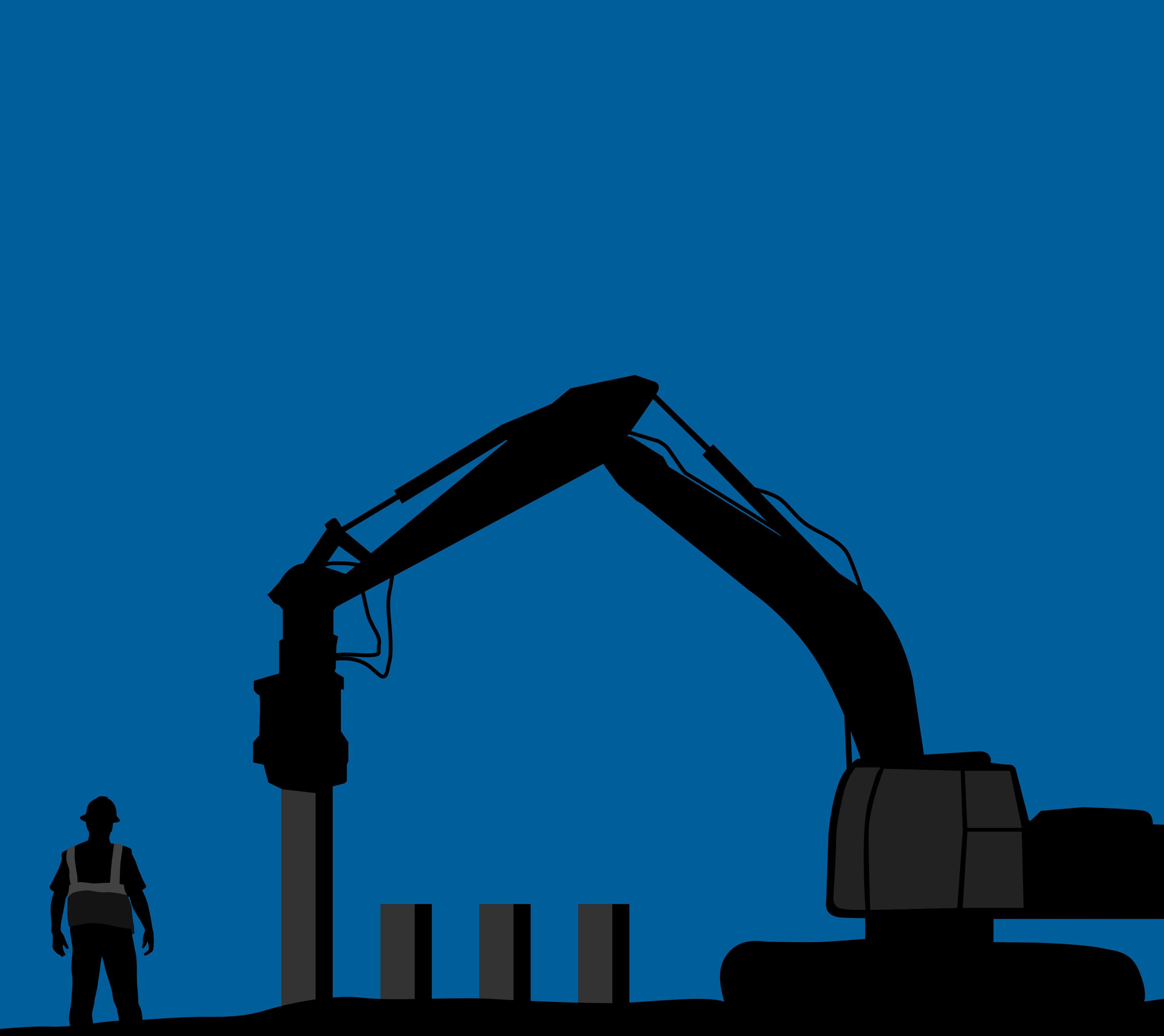
E. For each blast, the seismograph(s) shall be located in accordance with instructions from the Engineer. As a minimum, one seismograph shall be located at the nearest critical structure.

F. The peak particle velocities recorded on each of the three axes shall not exceed the frequency-dependent limits contained in Bureau of Mines RI 8507 Alternative Blasting Level Criteria (Figure _____) at any of the monitoring locations.

G. Air overpressures from each blast shall be recorded at the monitoring locations using the airblast channel of the blasting seismographs or with other suitable means. Readings shall be in decibels or in pounds per square inch (psi) and shall be recorded as a linear, unweighted value.

H. Air overpressures from blasting shall not exceed 133 dB (0.013 psi) at any of the monitoring locations.

I.   Flyrock will not be tolerated and shall be controlled through proper blast design. If flyrock occurs, the cause shall be investigated by the blaster. Blasting shall not continue until satisfactory corrective measures have been taken to preclude further flyrock incidents.



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