Vibration Damage Claims: Ingredients for a Successful Investigation

Following procedures to predict potential ground vibrations, selecting vibration damage criteria and evaluating damage probability are key to conducting a reasonably accurate investigation.

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Many construction activities like blasting, pile driving, soil compaction and heavy equipment operation create ground vibrations. When the work is close to existing buildings, occupants will likely experience vibration levels in excess of typical ambient conditions, which often leads to an expectation of property damage and resulting insurance claims. It is almost always very difficult to determine the causal relationship of the construction activity to the alleged damage for the following reasons:

- The claimant's first inspection of the building coincides with heightened awareness created by the actual perception of noticeable or annoying vibration levels.
- The pre-construction conditions of the alleged damage are not documented.
- Vibration measurements are usually not made during construction activities, except for blasting operations.
- The alleged vibration damage is usually cosmetic and involves the cracking of brittle, fragile or aged components like roofing, flashings, plaster wall finishes and interior trim, masonry chimneys, rubble stone foundation walls and unreinforced concrete block walls.

The above conditions provide few hard facts to the engineer investigating damage claims. In the absence of hard facts — such as a pre-construction survey document — the engineer must undertake a multidimensional investigation of the interrelationship of circumstances in order to develop an opinion about the relationship between the construction vibrations and the alleged damage. In a court of law, this determination of cause must usually be expressed as "more probable than not."

A balanced, professional and multidimensional assessment of alleged vibration-re-

TABLE 1.
Vibration Damage Guideline

A. Inspect the Damaged Property
- 1. General Condition of Property
- 2. General Degree of Maintenance
- 3. Viewing of Damages
  - a. Proximity to Construction Operations
    - (1) Other Damaged Properties
- 4. Age of Damage
- 5. Credibility of Claimant
- 6. Comparative Fragility of Damaged/Undamaged Components
- 7. Identify Alternate Damage Hypotheses
- 8. Repair Concepts & Repair Costs

B. Estimate Vibration Magnitude & Frequency
- 1. Determine the Construction Parameters
  - a. Types of Equipment & Operations
  - b. Duration of Operations
  - c. Distances from Operations to Damaged Property
- 2. Determine the Site Conditions
  - a. Subsoil Conditions
  - b. Topography
  - c. Water Table
  - d. Alternate Vibration Sources
- 3. Evaluate the Maximum Potential Ground Vibration Magnitude
  - a. Published Data
  - b. Site-Specific Data
  - c. Human Perception

C. Select Appropriate Damage Threshold Criteria
- 1. Match to Structure Type
- 2. Match to Component Type
- 3. Identify Probabilistic Basis of Criteria

D. Determine Vibration Damage Probability

E. Evaluate Alternate Damage Hypotheses

F. Compare & Rank All Damage Hypotheses

lated damage claims should focus on the following three major steps:

- The prediction of potential vibration magnitudes using published data and site-specific data;
- The selection of the appropriate damage criteria; and,
- The determination of vibration damage probability.

Background

An assessment of the causal relationship of damage to architectural materials (such as plaster and wallboard) and minor cracking to relatively brittle structural materials (like concrete and brick/block/stone masonry) to ground vibrations is extremely difficult to conduct. Its difficulty is primarily due to the unknowns associated with the pre-vibration stress conditions and the fact that vibrations develop additional stresses in systems already performing under pre-vibration stresses from normal environmental loadings and aging. The problem requires determining how much additional stress from vibration is necessary to trigger failure or cracking in a material that is potentially on the verge of doing so. Because of numerous unknown factors, this type of analysis is so complex that it is generally not feasible, and empirical damage assessment methodologies must be used.

The probability of damage to a structure from ground vibrations depends on many factors, including the type and condition of the structure, the soil conditions at the site, the energy imparted to the ground, the frequency of the ground vibrations and the distance from the vibration source to the structure under consideration. Predictions or evaluations of vibration damage can be made by comparing actual site measurements with established vibration damage threshold criteria.

Guideline for a Vibration Damage Investigation

In the absence of a pre-construction survey document that can usually definitively answer the claim, there will always be one party unhappy with the report. A balanced, professional assessment will minimize the controversy. Table 1 presents an investigation guideline that is based on the assessment of numerous vibration damage claims.

Ground Vibrations From Construction Operations

Recorded vibrations, published vibration data and vibration damage criteria for structures are typically expressed as the peak vibration velocity — either measured directly or derived from an acceleration time–history record of the vibration. Vibration velocities are typically recorded in three orthogonal directions: longitudinal, transverse and vertical. Many regulatory standards and established vibration criteria relate vibrations in terms of peak particle velocity (PPV), which represents the single-direction peak. Sometimes data are reported as the peak vector sum (PVS), which is the maximum resultant of the three orthogonal components occurring at any given time. PVS will always be greater than PPV, but it is only slightly conservative to compare PVS data to PPV criteria.

Vibration measurements are typically made in the ground adjacent to the structure or on a ground-supported slab or the foundation wall. Since comparisons to the data are empirical, it is important that the site measurements be obtained in a similar fashion to the data that are the basis for the criteria. Vibration measurements on loose structural elements, even elevated floors, may amplify the ground vibration, distorting the comparison to empirical "ground" vibration criteria.

Prediction of Vibration Magnitude

It is difficult to assess the probability that construction-induced vibrations are related to alleged damage in an adjacent structure because vibration measurements are not typically recorded during construction activities, except for blasting operations. In addition, if vibrations are recorded, they are usually not recorded at the structure with the alleged damage.

The engineer investigating the claim must use published vibration data and site-specific vibration data to evaluate the potential maximum ground vibrations at the subject structure. Site-specific data include vibration measurement records taken during construction and/or vibration records made during the investigative phase with similar construction equipment.

Published Vibration Data. Several sources have compiled attenuation charts for construction-induced vibrations from a variety of construction equipment. Figure 1 shows a typical attenuation chart that illustrates the vibration-to-distance relationships for different construction equipment.

Similar ground vibration attenuation charts are available for blasting operations. Figure 2 presents an attenuation chart that illustrates the relationship between ground vibration and scaled distance, which is a function of the distance from the blast to the subject structure and the pounds of explosives per delay from the blast shot. Blasting attenuation charts use the square root scaled distance ($ft/lb^{1/2}$) or cube root scaled distance ($ft/lb^{1/3}$); Figure 2 is a square root scaled distance attenuation chart.

As indicated in the investigation guideline, it is important to identify the types of equipment and operations, as well as the approximate distances from the operations to the damaged structure. If the claim is related to a blasting operation, the blaster's log should be available and should document the amount of explosives per delay and the location of the blast shot with respect to the closest structure. Using the log data, the engineer can then determine the relative distances from each blast location to the subject structure either by field measurements or scaling techniques.

Using available vibration data for construction operations and published attenuation charts, the engineer can evaluate the potential maximum ground vibrations. The engineer should also use best judgment as to the possible impact of the soil conditions at the site.

Site-Specific Vibration Data. When vibrations from construction equipment or blasting activities are recorded at a site, they are usually not recorded at the subject structure. However, all vibration records can be used to develop a site attenuation chart, which intrinsically accounts for soil conditions. Figure 3 represents an attenuation chart for two construction equipment operations used on a site upon which ground vibrations were recorded during construction

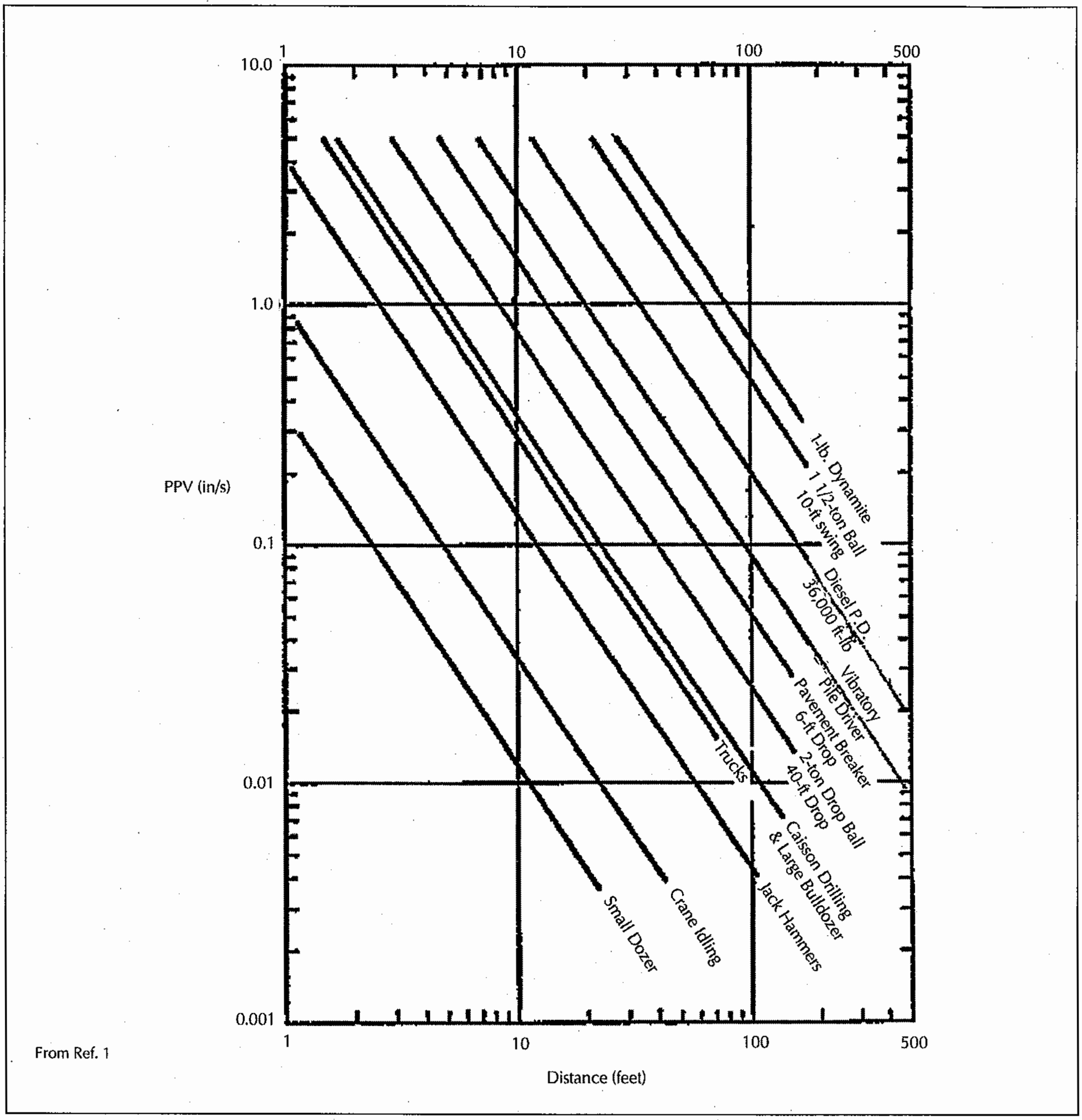

FIGURE 1. The attenuation of ground vibrations from construction equipment.

operations. The triangle-marked lines bound the test data from the vibratory compactor, and the square-marked line bound the test data from the ram-hoe. The remaining, unmarked lines are from other published construction vibration data (such as from Figure 1).

Using the site-specific attenuation lines and the approximate distances from the operations to the damaged structure, the engineer can evaluate the potential ground vibration from the construction operations to the subject structure.

For blasting operations, a site-specific attenuation chart is relatively simple to develop. A blaster's log is required to document the location of the blast shot on the site, the distance from the blast to the nearest structure, the amount of explosive per delay and the maximum ground vibration recorded at the nearest structure. In some instances, the blaster may use multiple seismographs to record simultaneous ground vibrations at numerous adjacent properties, not only the nearest properties, providing useful redundant data.

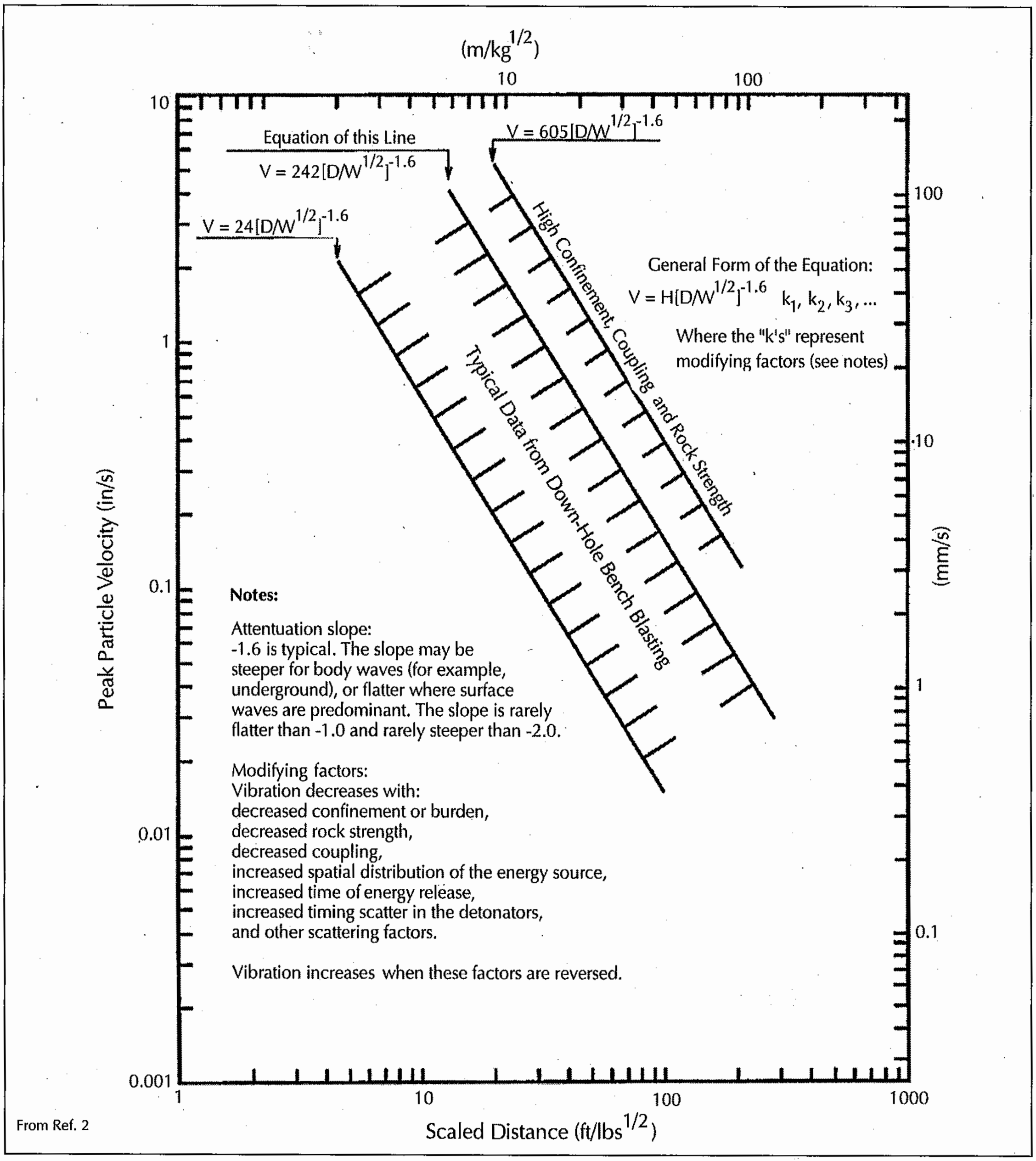

FIGURE 2. The attenuation of ground vibrations from blasting.

Using all the available vibration data, it is possible to estimate a site-specific attenuation and to determine upper and lower bounds. However, the data can be quite scattered if the blast contained variable degrees of confinement, and better predictive equations might require the segregation of data from different types of confinement (confined blast versus open-face blasts).

Selecting the Appropriate Damage Criteria

Classifications of Vibration Damage. It is important to note the relevant types of damage before using the various damage criteria. Most of the criteria use terms such as *threshold damage, minor damage* and *major damage.* A good, recent source of vibration-damage criteria

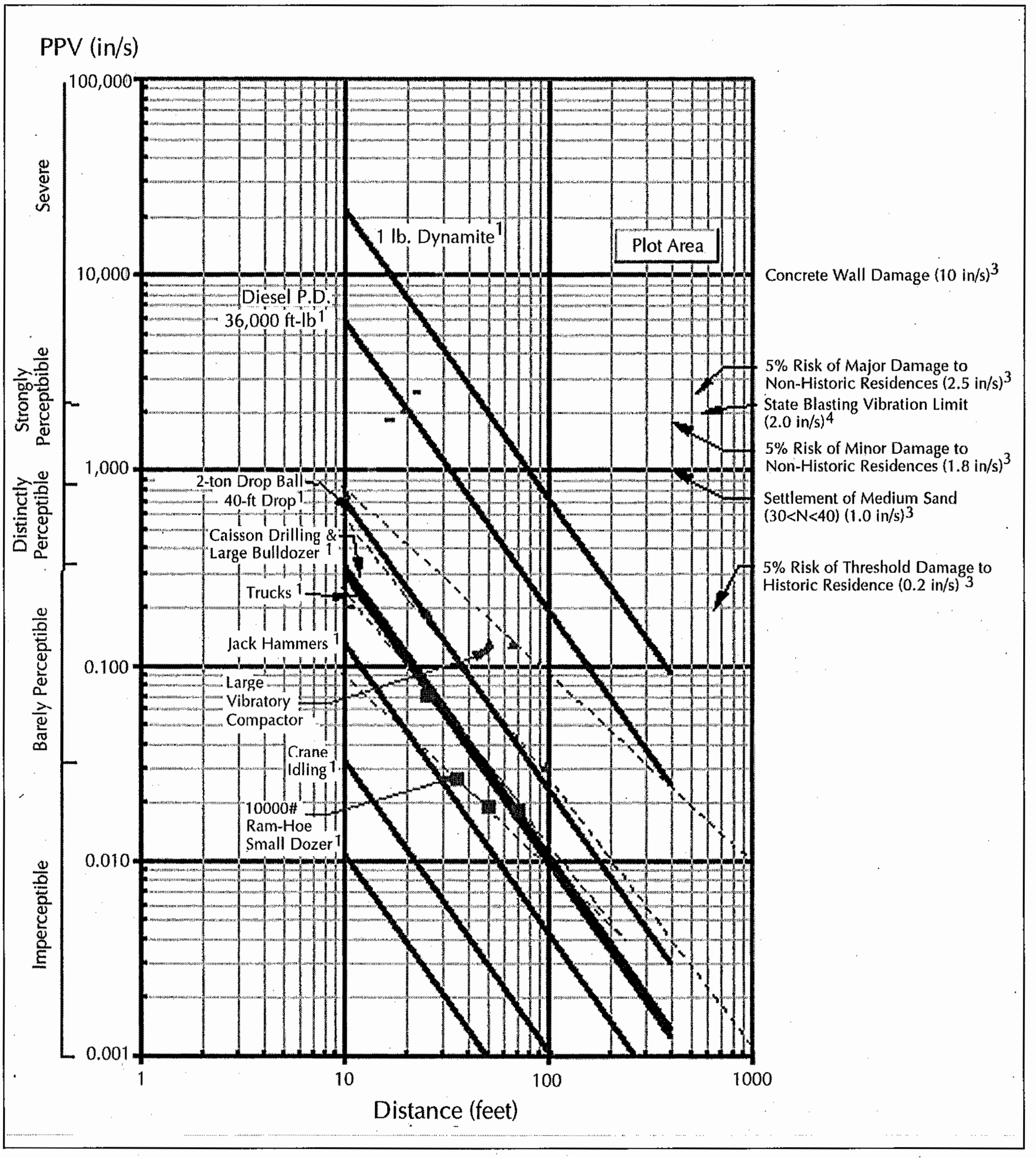

FIGURE 3. Ground vibrations from various construction equipment.

and probability is *Blast Vibration Monitoring and Control*, by Charles H. Dowding.[3] In general, the following definitions apply to these terms:

- Threshold damage: loosening of paint, small plaster cracks at joints between elements, lengthening of old cracks.
- Minor damage: loosening and falling of plaster, cracks in masonry around openings near partitions, hairline to 3-millimeter (0 to 0.125-inch) cracks, falling of loose mortar.
- Major damage: cracks of more than 3 millimeters (0.125 inches), rupture of opening vaults (arched roof chambers), fall of masonry (*e.g.*, chimneys), load support ability affected.

TABLE 2.
Swiss Standard SN 640312 Criteria for Construction Vibrations

Structural Category	PPV (in./s)							
	I — Industrial (Reinforced Concrete & Steel Construction Such as Industrial & Commercial Buildings)		**II — Concrete Framed** (Buildings With Foundation Walls & Floors in Concrete With Walls in Masonry or Concrete)		**III — Masonry or Wood Framed** (Buildings With Foundations & Basement Floors of Concrete Construction)		**IV — Vulnerable to Vibrations** (Buildings That Are Especially Sensitive or Worthy of Protection)	
Frequency	Steady-State	Transient	Steady-State	Transient	Steady-State	Transient	Steady-State	Transient
10-30	0.5	1.2	0.3	0.7	0.2	0.5	0.12	0.3
30-60	0.5-0.7	1.2-1.6	0.3-0.5	0.7-1.0	0.2-0.3	0.5-0.7	0.12-0.2	0.3-0.5

U.S. Bureau of Mines (USBM) Report of Investigation 8507/1980. This study provides an often-quoted standard damage threshold.[5] The USBM damage criteria are based on studies of first cracking in residential structures subjected to repeated blasting. The criteria are velocity based, with different allowable velocity levels over different frequency ranges to account for the likely effects of structural resonance at low frequencies. The variable velocity criteria are 0.2 inches per second at 1 herz, increasing linearly to a plateau of 0.75 inches per second (0.5 inches per second in plaster versus drywall) between 4 and 15 herz, and increasing linearly again to a 2.0 inches per second plateau starting at 40 herz. The criteria are limited because the focus is on residential buildings and because the primary basis is on the first cracking of interior plaster and drywall finishes ("minor" damage). The USBM criteria do not account for other types of construction systems that are likely in commercial construction, nor do the criteria address the age of the structure and prior deterioration of the building systems.

Swiss Standard SN 640312. A more useful approach is to categorize damage threshold criteria by the type and age of construction. One standard of this type is the "New Swiss Standard for Vibrations in Buildings," as presented by J.F. Wiss in 1980.[1] The Swiss standard is acknowledged to be conservative in deference to the importance placed on property in Switzerland. It most likely represents something on the order of a 1 to 5 percent probability of "minor" damage, based on comparisons of Dowding's damage term definitions, the Siskind blasting damage probability plots, the USBM criteria and the Swiss standard. The Swiss standard lists four building classes ranging from a Building Class IV ("very sensitive to vibrations") to Building Class I ("buildings in steel or reinforced concrete"). Table 2 presents the building classes and associated vibration criteria for both steady-state and transient vibration sources.

To use the standard, the closest comparable building class to the subject structure must be assessed to determine which criteria apply; residential structures are not specifically identified. It is interesting to note that the criteria for "steady-state" vibrations in the Swiss standard are approximately one-half of those prescribed in the same standard for impulse sources like blasting (*i.e.*, Building Class III, steady-state limiting PPV to 0.2 inches per second and transient limiting PPV to 0.5 to 0.7 inches per second). This reduction addresses the greater potential for resonance and fatigue that exists with the multiple period impulses associated with "steady-state" vibrations. This difference implies that the USBM criteria for blasting should be adjusted downward if applied to steady-state vibrations.

The Swiss standard, other similar standards and standards for particular vibration sources are presented in *Vibration Generated by Traffic and Building Construction Activities* by Roger Holmberg, *et al.*[6] One useful damage criterion noted in Holmberg is by Forssblad. The

Forssblad values are for vibratory compactors. Vibratory compaction creates steady-state vibrations, with similar frequencies to railroad traffic (10 to 40 herz). The Forssblad values indicate a 0.20 inches per second limit for "risk for cracking in normal [European] residential buildings with plastered walls and ceilings" and indicate a 0.40 inches per second limit for "risk for damage to normal residential buildings (no plastered walls and ceilings)."

Structural Damage Criteria. The above criteria generally apply to damage to architectural finishes. For the new cracking of structural walls, data from *Dynamic Strains in Concrete and Masonry Walls* by Crawford and Ward indicate a damage threshold of 3.0 inches per second for mortar and masonry (rubble) walls.[7] Data reported by Dowding indicate a damage threshold of 10.0 inches per second for concrete walls.[3] These figures are for blasting vibrations and should presumably be reduced by half for application to steady-state sources. The halving of the standard for steady-state vibrations is indirectly supported by criteria reported by Akins and Dixon.[8] Akins and Dixon address the protection of young concrete at sites where simultaneous steady-state construction activities continue. Akins and Dixon also recommend limiting vibrations in 24-hour-old concrete to 0.2 inches per second, in 1-day- to 7-day-old concrete to 0.4 inches per second, and in 8-day and older concrete to 4 inches per second (about half of 10 inches per second).

Vibration-Induced Settlements. Concerning soil settlement from vibration, studies by others reported in Dowding indicate that very loose (5< N, blow count <10) cohesionless soils (sands and gravels, with no cementing soils like clay or silt) subjected to vibratory pile driving (steady-state type source) consolidate at vibration magnitudes of 0.17 inches per second.[3] Medium-dense sands (30< N <40), under similar steady-state vibration, were shown to consolidate at vibrations of 1.0 inch per second. These soil densification data are from isolated testing, and the values are probably more indicative of a high probability of occurrence (greater than 50 percent) than the low (5 in 100) probability of the other criteria.

For blasting operations, research reported by Dowding indicates that measurable settlement occurred in loose sands from 11-pound, single-delay blasts outward to a range of 59 feet; for medium-dense sands the range is 46 feet.[3] Using the square root scaled distance technique and the attenuation chart for average peak particle velocities from blasting events produced by the International Society of Explosives Engineers,[2] this 11-pound blast corresponds to a scaled distance of 18 ft/lb$^{1/2}$ and an average peak particle velocity of 1.6 inches per second for loose sands; for medium-dense sands, the same technique and attenuation chart gives a scaled distance of 14 ft/lb$^{1/2}$ and an average peak particle velocity of 2.3 inches per second.

Buried Structures. Building structures are not the only structures where vibration damage is a concern. Underground or buried structures — such as building foundations, pipelines, culverts — should also be evaluated. Because underground structures are restrained against free response to vibration excitation, they can withstand particle velocities of much greater magnitude (at least 6 to 8 inches per second) than above ground structures without damage.[9] This restraint tends to limit dynamic displacements of the buried structural elements, which cause cracking strains in the structure, to the ground strains in the surrounding soils as opposed to the unrestrained response of above-ground structures that can selectively amplify ground-based excitation. However, any permanent deformation due to the settlement of the surrounding soils is a separate concern.

Environmental Vibrations. Many investigators believe that it is improbable that sub-0.5 inch per second vibrations can be the cause of property damage because many other environmental factors create strain levels consistent with this level of vibration and should be viewed as a "more probable" cause for cracking. *Blasting Vibrations and Their Effect on Structures* (USBM Bulletin 656) reports that studies of vibrations from normal household activities — such as walking, jumping, closing doors and operating laundry equipment like clothes dryers and washers — can create measurable vibrations sometimes approaching damaging levels, but the influence is generally very local.[10] For example, walking is reported to create vertical vibration velocity magnitudes in the range of 0.02 to 0.20 inches per second, jumping can create vertical vibration velocity magnitudes in the range of 0.23 to 5.0 inches per second and closing doors can create vertical vibration velocity magnitudes in the range of 0.01 to 0.06 inches per second.

Human Perception Levels. One major complication in the assessment of vibration damage claims is the incompatibility of the vibration intensity as perceived and reported by human witnesses to the damage criteria. It is commonly accepted that the threshold of human perception is 0.01 to 0.02 inches per second, and that steady-state exposure to vibrations greater than 0.10 inches per second causes tiredness and annoyance. With the human perception threshold one to two orders of magnitude lower than the damage criteria, and annoyance levels almost one order of magnitude lower, it is not unusual for damage claims to be accompanied by truthful testimonials of "shocking" vibration levels.

Prior to the development of a geological instrumentation network to monitor and record ground motion, the intensity of seismic events was assessed on the basis of human perception and observed building damage. The most commonly used reaction-based measure of intensity is the Modified Mercalli Intensity Scale (MMIS). The MMIS has twelve categories for ground motion intensity based on human perception and observed building damage. Table 3 is a reproduction of the MMIS with category ratings and the associated descriptions of the reactions. In addition, Table 3 presents a correlation of the MMIS to ground velocity that can be useful in trying to apply human descriptions to the puzzle of vibration-intensity information.

Determining Vibration Damage Probability

The probability of damage to a structure from ground vibrations depends on many factors, including the type and condition of the structure, the soil conditions at the site, the energy imparted to the ground, the frequency of the ground vibrations and the distance from the vibration source to the structure under consideration. Predictions or evaluations of vibration damage can be made by comparing actual site measurements with established vibration damage threshold criteria.

In addition, it must be understood that exceeding the vibration damage threshold levels does not confirm that the vibration is the cause of the damage, but only that the vibration is a measurably probable cause.

Published Damage Probability. Charles H. Dowding's book *Blast Vibration Monitoring and Control* contains a discussion of a probabilistic study by the USBM on the relationship between ground vibrations and the development of the three damage classifications discussed earlier.[3] Figure 4 represents the results of the damage probability analysis.

The probability chart can be used to evaluate the likelihood of damage for a selected damage criteria, as well as the assessment of damage probability for a given damage classification. For example, for a given blasting operation, the probability chart indicates that a 5 in 100 chance of damage requires 0.5 inches per second for "threshold" damage, 1.8 inches per second for "minor" damage and 2.5 inches per second for "major" damage. Almost four times the "threshold" damage level is required for "minor" damage. For a "more probable than not" chance of blasting damage (greater than 50 percent), the corresponding blast damage vibrations are 2.5, 4.8 and 5.9 inches per second, respectively.

Evaluation of Vibration Damage Probability. Using the predicted maximum ground vibrations, the damage probability chart and visual observations of the alleged damage, an engineer can assess the likelihood that there is a relationship between the alleged damage and the construction operations. The assessment is typically expressed terms of "improbable," "probable" and "more probable than not."

Conclusions

It is difficult to make an assessment of the causal relationship between alleged damage to architectural materials and structural components and construction-induced vibrations. The investigation usually lacks documentation of pre-existing conditions and vibration measurements at the subject property over the course of construction operations. The investigating engineer must undertake a

TABLE 3.
Modified Mercali Intensity Scale

Equivalent Magnitude[11] (Eastern North America Scale)	Equivalent Peak Ground Velocity[12] (in./s)	Modified Mercali Intensity Scale	Description of Reaction & Damage From Vibration
1.0-3.0	0.06	I	Not felt except by a very few under especially favorable conditions.
3.0-3.9	0.11	II	Felt only by a few persons at rest, especially on upper floors or buildings.
	0.22	III	Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibrations similar to the passing of a truck. Duration estimated. Hanging objects swing.
4.0-4.9	0.45	IV	Felt indoors by many; outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticebly. Hanging objects swing.
	0.90	V	Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.
5.0-5.9	1.80	VI	Felt by all; many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.
	3.60	VII	Damage negligible in buildings of good design & construction; slight to moderate in well built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken.
6.0-6.9	7.20	VIII	Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned.
	14.40	IX	Damage considerable in specially designed structures; well designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.
7.0+		X	Some well built wooden structures destroyed. Most masonry & frame structures destroyed with foundations. Rails bent.
		XI	Few, if any, (masonry) structures remain standing. Bridges destroyed. Rails bent greatly.
		XII	Damage total. Lines of sight & level are distorted. Objects thrown into the air.

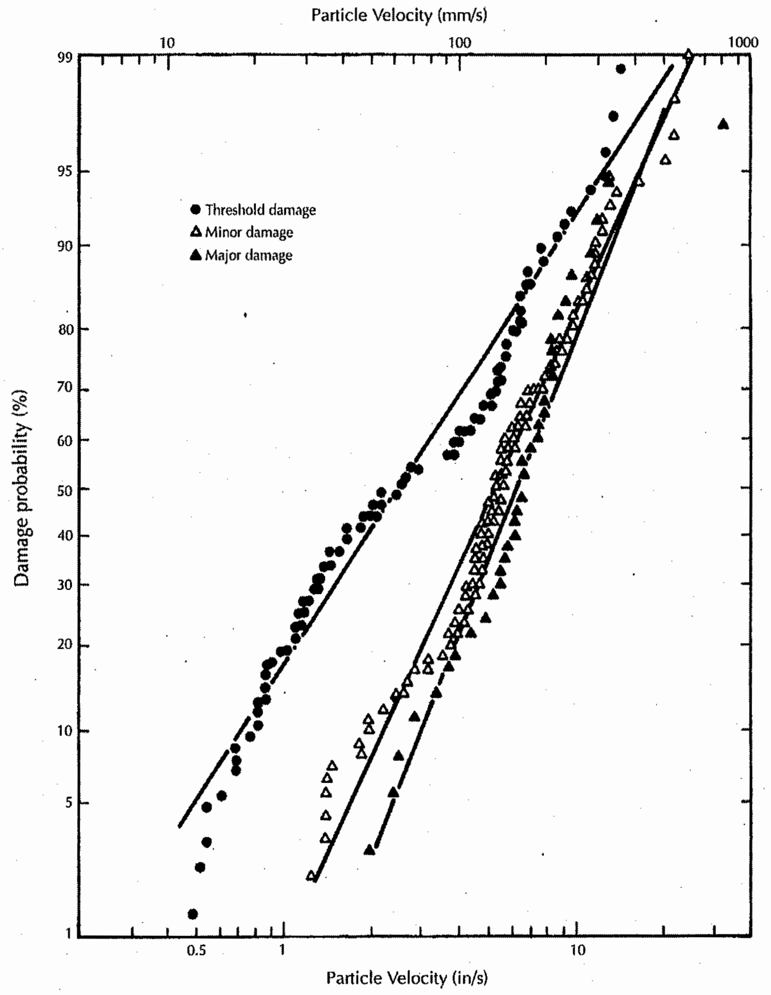

FIGURE 4. Damage probability from ground vibrations.

multidimensional assessment to evaluate the likelihood of the relationship of construction vibrations to damage.

The guideline for investigation and methodology for the prediction of potential ground vibrations (see Table 1), the selection of vibration damage criteria and the evaluation of vibration damage probability provide the investigator with a balanced and professional approach to assist clients in assessing the validity of claims.

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