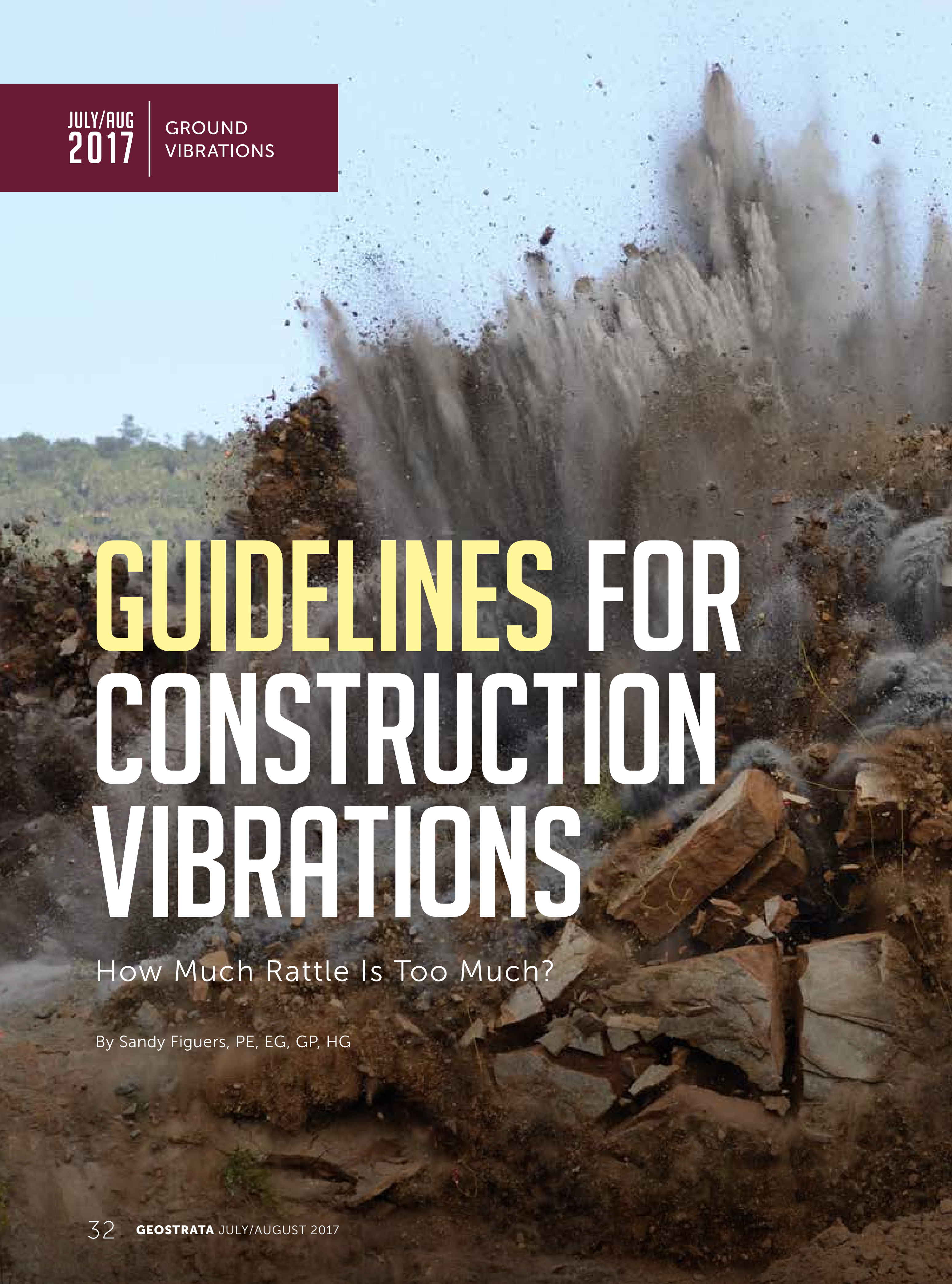

GUIDELINES FOR CONSTRUCTION VIBRATIONS

How Much Rattle Is Too Much?

By Sandy Figuers, PE, EG, GP, HG

The study of construction/blast-related ground vibrations on structures, people, and objects is a surprisingly diverse field. Vibration sources vary from blasting, all types of construction equipment, tunneling, trains, trucks, and even pipe bursting. These vibrations can damage structures, annoy people, kill fish, and disturb sensitive equipment. Evaluating the effects of these vibrations is complicated by the existence of multiple guidelines, difficulty in documenting low-level damage, human response to vibrations, separating long-term environmental effects, geology, and wide variations in building design, construction, and their condition.

The challenge is the inherent conflict between the statistical nature of the monitoring data reflecting potential damage, and the human fear that their structure will be damaged. This conflict is amplified by the fact that a person's home, a corporation's office building, or an agency's dam is a major asset. The link between vibrations and damage is damage guidelines. As described later, these guidelines are not exact because they are defined based on limited building types, various sources of vibrations, and human responses to vibrations.

What's Measured?

Peak particle velocity (PPV) has been found to be the best indicator of building damage. Typically, the largest vibrations are from surface waves (Raleigh waves), but sometimes compression (P) or shear (S) waves control. Ground vibrations are recorded using a 3-axis geophone attached to a stand-alone recording/analysis unit. Proper geophone installation is critical. Improper geophone installation or placement can lead to over or underestimating actual vibration levels.

The standard in the U.S. is to use the highest measured PPV from the three axes. Occasionally, a contract will require, or a consultant may use, a root mean squared (RMS) method to calculate PPV. There are two types of RMS, true and pseudo. A true-RMS is based on the largest PPV and the PPVs from the other two axes measured at the same time. A pseudo-RMS is based on the largest PPVs from each axis, irrespective of time. Either RMS value will be larger than a single-axis PPV. This has the effect of increasing the factor of safety by 15 to 40 percent, and possibly restricting contractor activities.

A PPV damage guideline is an intensity scale and can be compared with earthquake Mercalli scales. The relationship between PPV and Modified Mercalli Intensity in California is presented in Table 1.

Modified Mercalli Intensity	I	II-III	IV	V	VI	VII	VIII	IX	X+
Peak Acc. (%g)	<0.17	0.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PPV (ips)	<0.004	0.004-0.43	0.43-1.3	1.3-3.2	3.2-6.3	6.3-12	12-24	24-46	>46

Source: Yaghmaei-Sabegh, Tsang, and Lam, 2011, *Journal of Earthquake Engineering*.

Table 1. Conversion between peak ground-motion parameters and modified Mercalli intensity values.

The Guidelines

Three vibration guidelines have developed:

- U.S. Bureau of Mines (USBM)
- European (exemplified by the German DIN)
- Railroad

There is a fundamental philosophical difference between them. All are frequency-based, but the difference is how human response is accounted for. Residential threshold vibration limit curves for these guidelines are shown in Figure 1. Users should be aware of the guideline differences because U.S. agencies have begun creating hybrid guidelines. For example, the Florida Department of Transportation uses the USBM guidelines, but added a German DIN curve.

USBM Guidelines

Beginning in the late 1960s, the USBM began evaluating the effects of blast vibrations on buildings. Over the next 15 years, more than 70 buildings were tested. Building types included one- and two-story wood and masonry buildings. Building ages ranged from more than 100 years old to new. The results of this testing program were published in *USBM RI 8507, Structure Response and Damage Produced by Ground Vibration from Surface Mine Blasting*. A key finding was that building damage best correlated with PPV and frequency.

Three damage levels were defined in *RI 8507*: threshold, minor, and major. Threshold damage included the opening of old cracks, formation of new hairline cracks in drywall or plaster, and dislodging of loose objects. Threshold cracking occurred above 0.75 in./sec (ips), but not below 0.5 ips (depending on frequency). Minor damage included broken windows, loosened or fallen plaster, and hairline cracks in masonry (developing between 1 to 2 ips, again depending on frequency). Major damage included development of larger cracks, and shifting of foundations or bearing walls. Similar testing by the Australian Coal Association (C9040) in 2003 confirmed the USBM findings.

The data were also presented in a frequency/velocity graph (Figure 1) that included a safe limit below which threshold damage did not develop in the buildings studied. This graph, used in conjunction with vibration monitoring data, forms the technical basis used to determine if and what level of damage is likely to be caused by construction vibrations. Despite some objections over 30 years of use, the graph has proven to be an excellent predictor of damage.

The safe limit curve is derived from the following assumptions:

1. The safe limit was based on vibration monitoring of buildings built to central U.S. construction standards at that time (mid-1970s). The extension of the safe limit curve to newer or other types of structures, including underground structures/utilities, should not be assumed. Changes in building codes since the 1980s (from life safety to building survivability) have created buildings better able to withstand vibrations without damage.
2. The safe limit does not vary with the type, age, or condition of buildings. Soil deformation was not considered.
3. The safe limit is not applicable to human annoyance or damage to household goods.
4. The vibration sources were single-event coal mine blasts. These events have lower frequency content than construction blasts, and construction blasts have lower frequency content than construction equipment. Geology has a far-field effect. If unexpected high-vibration levels are noted at long distances, geologic variations could be a cause.
5. Continuous vibrations were not evaluated until a later study (*USBM RI 8896, Effects of Repeated Blasting on a Wood-Frame House*). Threshold cracking developed after about 56,000 cycles at 0.5 ips.
6. If attenuation curves are developed, they should show that predicted PPV levels will not exceed the maximum allowable PPV within a 95 percent confidence level.

The safe limit values are based on a statistical analysis. Threshold damage will eventually occur when vibration levels exceed the safe limit, but the study does not indicate how much the vibration level must exceed the safe limit before threshold damage occurs. At 10 Hz, damage could develop just at the safe limit, or when vibration levels are as large as 2 ips. There is a small chance (5 percent) that damage will occur below the safe limit. The probability decreases to near zero at 0.5 ips (at 10 Hz). Over 35 states have adopted vibration guidelines, mostly based on the USBM study. The current *AASHTO R8-96* vibration limits, *Standard Practice for Evaluation of Transportation-Related Earthborne Vibrations*, appear to be the same as the USBM guidelines.

British Commonwealth and European Guidelines

The British residential guideline (*BS 7385-2*) is similar to the USBM guideline except the British threshold level stops at 4 Hz. Below 4 Hz, peak displacement levels control (<¼ in.). Their threshold vibration levels are based on transient vibrations, ones that do not cause resonant response in buildings. The British guidelines do not disagree with the USBM finding that the probability of damage goes to zero at 0.5 ips, and state that the British data is consistent with USBM data. They also state: "Minor damage is possible at vibration magnitudes greater than twice those given. A building of historical value should not (unless it is structurally unsound) be assumed to be more sensitive."

The German (*DIN 4150-3*) guideline is the most restrictive. Short-term residential vibration limits range from 0.2 to 0.8 ips, depending on frequency. Short-term is defined as vibrations that do not occur often enough to cause structural fatigue or produce building resonance. Geophones have to be attached to the inside of the foundation or mounted on the top floor. Building damage is any permanent effect of vibration that reduces the serviceability of a structure, including plaster cracks or enlargement of existing cracks (minor damage). There is a straight 50 percent reduction in the vibration limit for historic buildings. A key point is that compliance with their threshold values ensures that damage will not occur. If damage is found, assume that it was caused by something else until proven otherwise. It appears that the German limits were set to eliminate the possibility of even minor building damage or human complaints.

The Swiss guideline (*SN 640-312a*) is frequency-based, but is unusual in that threshold values are controlled by the number of vibrations that a building experiences. The 0 to 30Hz limit for Class 3 buildings (houses) is 0.6 ips as long as the number of 0.6 level (or greater) vibrations is less than 1,000 (transient vibrations). If the number of vibrations exceeds 1,000, the vibration limit drops to 0.24 ips (frequent vibrations). When the number of vibrations exceeds 100,000 events, the limit drops to 0.12 (continuous vibrations). No historic building vibration level is provided. Instead, the guideline suggests that the Class 3 vibration limits can be reduced by up to 50 percent based on professional judgment. The text says that if the vibration levels remain below the Class 3 values, the probability of minor damage is extremely small. If the guide values are occasionally exceeded by up to 30 percent, then the probability of damage does not significantly increase. If vibration levels are double the guide values, minor damage will likely occur. This is similar to USBM limits.

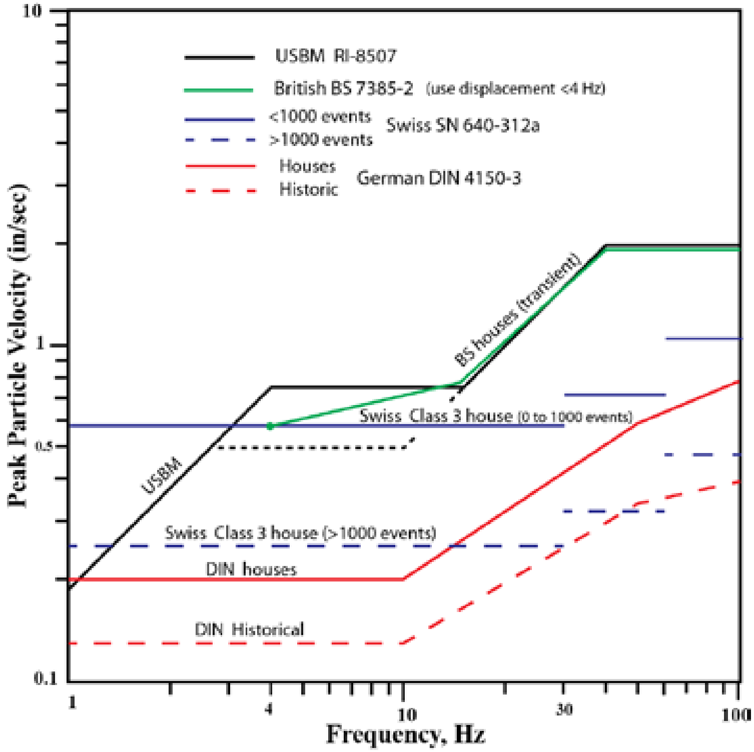

Figure 1. Comparison of major vibration guidelines for threshold cracking in houses under impulse/transient vibrations.

Railroad Guidelines

Velocity Decibels

Evaluation of ground vibrations from trains developed independently of blasting and construction vibration analyses. The initial concerns were the rumbles and rattles generated by trains. Sound engineers analyzed such sounds using decibel (db) scales. As train-generated ground vibrations became more worrisome, decibel scales began to be used to describe ground vibrations. Decibel scales can be converted to PPV, but one must know conversion factors, such as which db scale was used, an RMS value, and the reference velocity amplitude. Evaluation of train-generated sounds and ground vibrations is codified in a report by the Federal Railroad Administration in 1998 (*High-Speed Ground Transportation Noise and Vibration Impact Assessment*). This report adopted a 0.5 ips PPV (about 102 Vdb, or vibration velocity level) for threshold damage to fragile buildings, and 0.12 ips PPV (about 90 Vdb) for extremely fragile historical buildings. These values were derived from Swiss vibration standards, but are not frequency-dependent. The State of New Hampshire has adopted this standard, and New York City used this standard to monitor historic buildings during reconstruction of the World Trade Center.

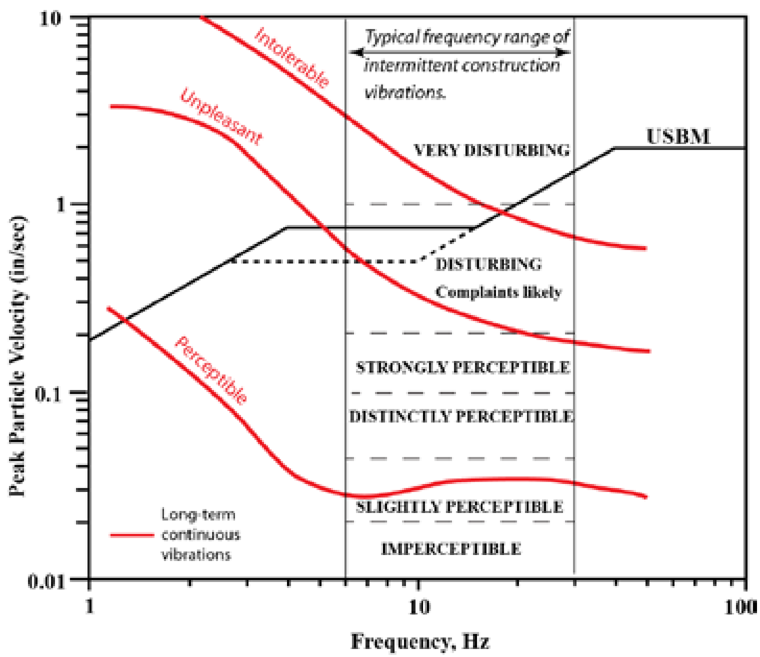

Figure 2. **Human perception of vibrations. (From Foster, 1981, "Structural Response and Human Response to Blasting Vibration Effects."** ***Proceedings, 7th Conference on Explosives and Blasting Techniques*****. p. 19.)**

Low-Level Vibrations

Low-level vibrations, <0.5 ips, cause many complaints, but little damage. Not only are people sensitive to low-level vibrations, but they typically can only describe vibration strength using fuzzy terms such as "annoying," "disturbing," or "weak." Human perception varies with frequency and duration. Context matters. Vibrations under 0.1 ips might be ignored during the day, but can wake someone up at night. Low-level vibrations can cause glassware to rattle, pictures to tilt, and small items to dance around or off tables, giving audible and visual reinforcement to the perceived vibration strength. Even vibration consultants with years of monitoring experience find it difficult to quantify vibration levels by feel. People also tend to distrust technical guidelines when their senses tell them that something scary has happened. Figure 2 shows the range of human vibration annoyance plotted on the USBM graph.

Where vibrations are concerned, the best defenses to human annoyance are forewarning, education, and response. Although residents may not like the vibrations, if they understand what is going to occur, who they can talk to, and when it will end, they will be better prepared to tolerate them. An extreme example occurred during blasting near a hospital. The vibration levels were not large enough to cause damage to the building or hospital equipment, but the hospital specialized in heart patients. The doctors feared that even low-level vibrations (~0.1 ips) could startle a fragile heart patient, possibly causing additional injury or death. The solution was to notify the hospital staff prior to a blast so they could inform the patients. Everyone survived.

There are no universally agreed guidelines for setting vibration limits for historic/fragile buildings and objects. The problem is the incredible range in age, type, construction, and condition of historic/fragile buildings, along with the difficulty in separating environmentally-caused damage from vibration causes. Numerous studies throughout the world have converged on a vibration range between 0.1 and 0.5 ips. In practice, vibration limits for historic/fragile buildings are set with a combination of experience and caution.

What's Next?

The expansion of objects being monitored is calling into question the use of current guidelines for non-residential objects. The problem is the difference in natural frequencies and amplification factors between those objects and residential buildings. Using existing guidelines for some objects may actually allow damage to occur.

Threshold limit development for other objects is ongoing. Aimone-Martin is helping develop a strain-based damage criterion for blasting near mid- and high-rise buildings in New York City, along with a modified PPV-frequency curve. Brune, King, and others evaluated vibration stability of precarious rocks throughout the western U.S. The Southwest Research Institute evaluated how to determine vibration effects on gas pipelines. Amick developed vibration standards for the effects of very low vibrations (0.002 to 0.00001 ips) on equipment. Multiple studies have evaluated the effect of vibrations on green concrete, fish, historical buildings, and museum objects. These studies have yet to be incorporated into guidelines.

Monitoring equipment is changing. Precision is increasing, and multiple sensor types can be attached to an instrument. Real-time, remote monitoring of instrument networks is becoming common. Computational advancements are changing how objects are evaluated and monitored. On larger projects, detailed vibration histories (background or induced), strain gauge, and crack-monitoring networks are used to gather data about buildings or object responses prior to construction. This data are then analyzed to define amplification factor curves that are then used to define vibration/strain limits. As costs reduce, these types of analyses will become more common.

Even with future advances, the current guidelines and monitoring techniques are cost effective and still useful. They will be in use for many years. Just make sure you understand their limitations. GS

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