Vibration Limits for Historic Buildings and Art Collections

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Which vibration limit is right for a particular historic building during a construction project, and how can it be implemented?

Fig. 1. The Saint Louis Art Museum, Saint Louis, Missouri, construction underway for expansion, 2010.

Vibration limits to prevent threshold damage to typical buildings are relatively well known. However, there is no commonly accepted standard for vibration limits to protect historic buildings, and vibration limits to protect artwork and other fragile objects within historic buildings are generally not addressed in the literature. This lack of definitive information is problematic for operators of historic buildings, such as museums, that are undertaking rehabilitations or expansions that could expose the building and its collection to vibrations (Fig. 1).

There is a plethora of guidelines for the protection of historic buildings from construction vibrations, but the recommended limits vary widely and are often presented without appropriate explanation or reference to scientific basis. Art-conservation literature shows that the vibrations that art objects commonly experience during transit between museums are several times higher than vibration limits often used to protect museum buildings and collections in situ, yet damage to art during shipment rarely occurs. This disparity suggests that the commonly used vibration limits for the protection of artwork during construction projects are overly conservative. On the other hand, the authors' experience monitoring vibrations during museum construction projects has shown that there are special risks for the artwork that need to be understood.

The objectives of this article are threefold: to provide general background information regarding vibrations in buildings, including human perception and ambient and damage levels; to synthesize the published information on vibration limits for historic buildings and provide a rational methodology to develop appropriate vibration limits for specific buildings and situations; and to provide guidance for the protection of artwork and other fragile building contents from construction vibrations.

Background Information on Vibrations

In simplified terms, vibrations originate at a source, transmit through a media, normally soil, and then reach a receiver, such as a building or other structure. Different buildings will respond quite differently to vibration input because of their differing mass, stiffness, and material composition. Moreover, different sources generate ground-borne vibrations that transmit through the soil in different ways. Transient vibrations result from ground impacts, such as from dropping heavy debris, which generate a large initial response that quickly decays (attenuates) with distance from the vibration source. Steady-state vibrations result from continuous, high-energy activities, such as vibratory pile driving or vibratory roller compaction of soil. Pseudo-steady-state vibrations are a mixture of transient and steady-state responses.

For buildings, the magnitude of vibrations is typically measured in terms of peak particle velocity (PPV) using units of inches per second (in/sec). The number of vibration cycles in a specified period of time is called the vibration frequency, typically measured in Hertz (Hz), or cycles per second.

Human perception of vibrations. The human body can perceive very low levels of vibrations (Fig. 2).[1] Steady-state vibrations become perceptible to human occupants at approximately 0.03 in/sec, depending on vibration frequency, and become disturbing to the human body at approximately 0.1 to 0.2 in/sec (at typical frequencies above approximately 10 Hz). Thresholds of perception and annoyance for transient vibrations are somewhat higher.

Table 1. Common Values of Ambient Vibrations in Buildings

Activity	Typical Vibration Amplitudes (in/sec)
Occupants walking, closing doors, other daily activities	0.02 - 0.05
Occupants running or jumping	0.05 - 0.20
Daily commuter-train traffic next to historic museum	0.03 - 0.07
Occupied floor above loading dock and trash compactor	0.03 - 0.16
Moving furniture into office in an office building	0.10 - 0.14
Moving tables and chairs after an event in historic museum	0.10 - 0.15

Ambient vibration levels in buildings. Ambient (background) levels of vibrations in buildings due to normal, day-to-day activities usually range from about 0.02 to 0.10 in/sec. Common values measured by the authors are shown in Table 1.

Ambient levels due to common occupant activities, such as walking, occasional running, and closing doors, are often 0.05 in/sec, with infrequent excursions up to 0.10 or even 0.20 in/sec. For example, vibrations in excess of 0.10 in/sec were recorded near workers taking down tables and chairs after an event at the Art Institute of Chicago. Vibrations from heel drops, a simulated activity similar to running or jumping, were recorded to be in the range of 0.05 to 0.20 in/sec at the Saint Louis Art Museum. A comparison of these values with the chart in Figure 2 clearly shows that occupants can, at times, feel background vibrations in most buildings.

Damage levels for buildings. Rigorous scientific study to determine damage thresholds for buildings exposed to vibrations was carried out by the U.S. Bureau of Mines (USBM) in the 1970s and 1980s and reported in landmark research reports.[2] Actual residences near blasting sites were carefully instrumented and documented during the course of hundreds of blasting events. Before and after each blast, condition surveys were performed to check for threshold damage. Vibration data were systematically collected and statistically analyzed to develop findings.

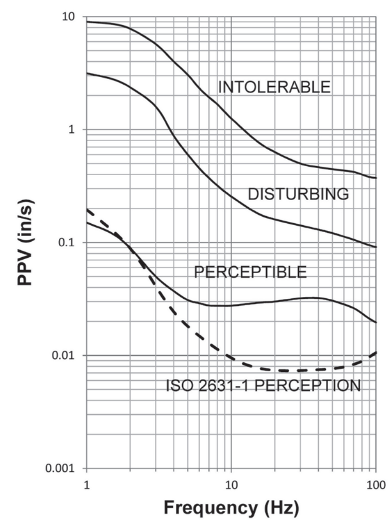

Fig. 2. Human perceptibility of vibrations. American Association of State Highway and Transportation Officials, R8-96, 2004; and John F. Wiss, "Construction Vibrations," (1981): 167-181.

A total of 76 residential buildings were included in the studies. Most buildings were relatively modern, timber-framed houses with drywall finishes; however, several were of brick and concrete masonry construction, and some were older buildings with plaster on wood-lath finishes. Pre-existing conditions in the buildings varied from good to relatively poor and distressed. One building was more than 150 years old and had significant distress (cracking) in its plaster walls before vibration exposure.[3]

Table 2. Damage Thresholds as Reported in USBM RI 8507

Conditions Observed	Typical Peak Particle Velocity (in/sec)
Threshold damage (hairline cracking in plaster, opening of old cracks, etc.)	2 - 3 Never at < 0.5
Minor damage (hairline cracking in masonry, breaking of windows)	4 - 5 Never at < 1.0
Major structural damage (cracking or shifting of foundations or bearing walls)	>5

As summarized in Table 2 and illustrated in Figure 3, the U. S. Bureau of Mines *Report of Investigations 8507*, "Structure Response and Damage Produced by Ground Vibration from Surface Mine Blasting" (USBM RI 8507), reported the following findings:

- "Threshold damage," defined as opening of old cracks, formation of new hairline cracks in drywall or plaster wall finishes, and dislodging of loose objects, typically appeared at approximately 2 to 3 in/sec and was never observed at less than 0.5 in/sec.
- "Minor damage," such as broken windows, loosened or fallen plaster, and hairline cracking of masonry, typically appeared at approximately 4 to 5 in/sec and was never observed below 1.0 in/sec.

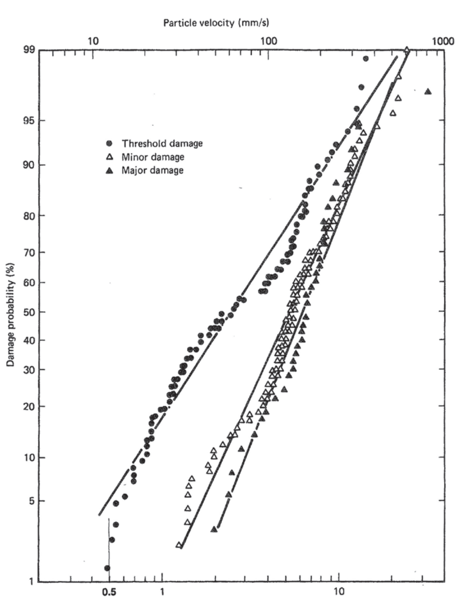

Fig. 3. Damage probability as reported in USBM RI 8507 and reproduced in C. Dowding, *Construction Vibrations*, 172.

- "Major structural damage," such as wide cracking or shifting of foundations or bearing walls, typically did not occur until levels well above 5 in/sec.[4]

The basis and limitations of the USBM RI 8507 findings should be noted. Vibrations were measured on the ground at the base of the buildings or in the basement next to the foundation walls. Supplemental instrumentation was installed at various locations inside the buildings to study dynamic amplification; amplified measurements on walls and ceilings were reported to be up to four to eight times that of the corresponding measurements at the base of the building. The study had included structures of various ages, from relatively new to quite old, and various conditions, from relatively good to already distressed. However, all of the testing was performed on low-rise residential buildings of wood and masonry construction, and the vibration type was primarily transient (from nearby blasting). Limited testing was performed on one building to study fatigue effects under sustained, steady-state excitation. With a large oscillator attached to the building and operating continuously, threshold cracking did not occur until 52,000 cycles of continuous vibration input equivalent to 0.5 in/sec at the base of the building.

The USBM RI 8507 study, as well as several other studies, compared strains in walls produced by everyday activities (walking, running, closing doors, etc.) with those needed to cause threshold cracking. Results indicated that occupants of buildings commonly produce strains in walls similar to those produced by blasting vibrations of 0.1 to 0.5 in/sec. Perhaps even more significantly, strains in walls caused by seasonal changes in temperature and humidity have been found to be several times those produced by blasting vibrations of 0.1 to 0.5 in/sec. These findings explain why wall finishes in buildings often exhibit hairline cracking in the absence of vibration exposure.[5]

Vibration Limits to Protect Buildings

Vibration limits to protect typical buildings (i.e., those without any perceived unusual sensitivity) are relatively well known and accepted. One of the most commonly cited limits in the U.S. is still based on the USBM RI 8507 study. However, there is no commonly accepted standard for vibration limits specifically to protect historic buildings, although there is a plethora of guidelines and recommendations. A 2012 National Cooperative Highway Research Program (NCHRP) report, which provides a comprehensive summary of the available literature, cites more than 20 sources for vibration limits for historic buildings, with limits ranging from as low as 0.08 to as high as 2.0 in/sec.[6] Representative references cited in the report, in addition to those referenced elsewhere in this article, are included in the bibliography.[7]

The authors have reviewed these sources, looking for commonalities and the scientific basis for the recommended limits, such as statistical analysis of actual damage data. This review indicated that many, if not most, of the recommendations are based on general experience and judgment; scientific basis and adequate explanation for the limits are often lacking. In some cases, a small number of damage incidents are reported, but these cases are difficult to interpret or make generalizations from due to the limited data and unique characteristics of the particular vibration source and structure.

This review indicated that almost all of the sources for limits at historic buildings point back to four primary sources. Careful study and comparison of these four sources reveals commonalities that can be used to formulate a rationale for developing appropriate vibration limits for particular historic buildings and situations. The following sections describe the vibration limits recommended by each of these four primary sources. The way in which each vibration limit addresses the following three key factors should be noted:

Key factor 1: building type and condition

- Responsiveness (sensitivity) of a particular structure type to vibration input
- Fragility of a particular structure, pre-existing weaknesses or distress

Key factor 2: vibration source type

- Transient (short term, impulse-type) vibrations: blasting, sudden ground impacts, and similar
- Continuous (long term, steady-state) vibrations: vibratory pile driving, vibratory compaction, and similar

Key factor 3: "importance factor"

- Reduction in the vibration limit to provide additional conservatism (less risk of damage), which may be appropriate considering the cultural or economic value of individual buildings.[8]

USBM RI 8507. Based on studies in the 1970s and 1980s, as described above, the USBM RI 8507 study recommended a "safe limit" to prevent threshold cracking of plaster in residential buildings (Fig. 4).[9] The limit has a base value of 0.5 in/sec below 10 Hz (neglecting the portion below 2.5 Hz, which is not applicable for most buildings). Above 10 Hz, the limit increases with increasing frequency up to a maximum of 2.0 in/sec. The increase recognizes the fact that higher-frequency vibrations cause less response in buildings of this type (with natural frequencies generally from 10 to 15 Hz).

The three key factors for this recommended limit can be summarized as follows:

1. Building type and condition: one- and two-story residential buildings of wood and masonry construction with building conditions ranging from relatively new structures in good condition to more than century-old structures in poor, already distressed condition.
2. Vibration source type: primarily transient from blasting; limited testing to study effects of sustained, steady-state vibrations.
3. Importance factor: not addressed.

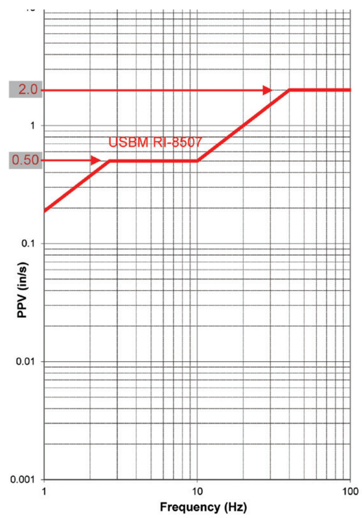

Fig. 4. "Safe limit" to prevent threshold cracking in plaster walls. From USBM RI 8507 and John F. Wiss, "Construction Vibrations," (1981): 167-181.

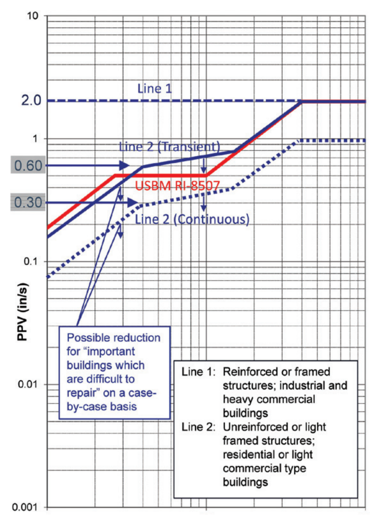

Fig. 5. Vibration limits recommended by BS 7385-2 superimposed on the USBM RI 8507 limit.

British BS 7385. The second primary source is British Standard BS 7385-2 (Fig. 5). The building types are identified on the chart. The limits shown apply for transient vibrations. As can be seen, the BS 7385-2 Line 2 limit is very similar to the USBM RI 8507 limit, which is to be expected since both relate to light-framed structures subjected to transient vibrations. Sources cited by BS 7385 include publications by the USBM researchers, as well as independent British and Swiss studies.

For continuous vibrations, the British standard states:

> The guide values . . . relate predominately to transient vibration which does not give rise to resonance response in structures, and to low-rise buildings. Where the dynamic loading caused by continuous vibration is such as to give rise to dynamic magnification due to resonance . . . then the guide values may need to be reduced by up to 50%. Note: There are insufficient cases where continuous vibration has caused damage to buildings to substantiate these guide values, but they are based on common practice.

Regarding the potential for fatigue under continuous or long-term vibration exposure, the standard states:

> There is little probability of fatigue damage occurring in residential building structures due to either blasting, normal construction activity, or vibration generated by either road or rail traffic. The increase of the component stress levels due to imposed vibration is relatively nominal and the number of cycles applied at a repeated high level of vibration is relatively low. . . . Thus, unless calculation indicates that the magnitude and the number of load reversals is significant . . . then the guide values should not be reduced from fatigue considerations.[10]

Regarding an importance factor, the standard provides a general statement: "Important buildings which are difficult to repair may require special consideration on a case-by-case basis. A building of historical value should not be assumed to be more sensitive unless it is structurally unsound." In other words, lower limits may need to be used based on professional judgment for individual cases. Dowding provides similar commentary: "Historic status does not automatically imply higher-than-usual sensitivity. . . . In a recent evaluation, several buildings on the official registry of historic structures were found to be less sensitive than typical structures. These historic structures were found to be of unusually good construction, showed few signs of distress, and withstood blast induced vibrations greater than those proposed. All structures should be evaluated on their own physical condition."[11]

Annex A of Part 1 of the British standard provides a useful matrix for classifying structures according to their type and responsiveness to vibrations. Consideration is given to soil type, foundation type, superstructure type, and "political importance factor," which includes "architectural, archeological, and historical value." However, no link is currently provided between the classifications obtained in Annex A and the limits provided in Part 2 of the standard. Development of an appropriate correlation between the classifications of Annex A and the limits of Part 2 would be very helpful.

Swiss SN 640 312. The third source commonly cited is Swiss Standard SN 640 312, which is reportedly based mainly on Swiss research, most notably that of J. Studer.[12] The standard is available only in German and French, but the authors obtained a technical translation of relevant sections from Swiss colleagues.

As for building type and condition, the standard divides structures into four classes. Figure 6 shows the limits to prevent cosmetic damage (hairline cracking) in Class 3 buildings, which includes most light-framed structures. For transient or "occasional" vibrations, which the standard defines as less than 1,000 recurrences, the Swiss limit is again similar to the USBM RI 8507 limit. For continuous or "frequent" vibrations, which the standard defines as between 1,000 and 100,000 recurrences, the standard reduces the limit by approximately 60%. Accordingly, the limit for continuous vibrations is 0.24 in/sec, whereas the limit for transient vibrations is 0.59 in/sec, both increasing at higher frequencies.

Considerations of fragility and importance are built into Class 4, which includes historic buildings. For Class 4 structures, the standard states that the guide value is a "range between the guide value for Class 3 and half thereof."[13] In other words, professional judgment is needed to choose the amount of reduction for Class 4 buildings relative to Class 3 buildings, up to a maximum reduction of 50%. As such, the limit for historic buildings subjected to transient vibrations is a range between 0.30 and 0.59 in/sec, and the limit for historic buildings subjected to continuous vibrations is a range from 0.12 to 0.24 in/sec, depending on professional judgment for the individual case. (Note that the standard applies further reductions for "permanent" vibrations with greater than 100,000 recurrences, which would be rare for construction vibrations.)

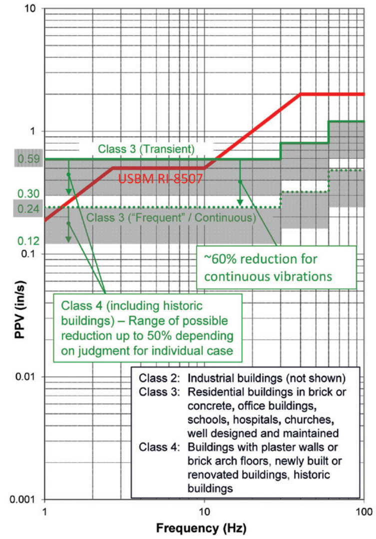

Fig. 6. Guide value vibration limits recommended by SN 640 312a for Class 3 structures, superimposed on the USBM RI 8507 limit.

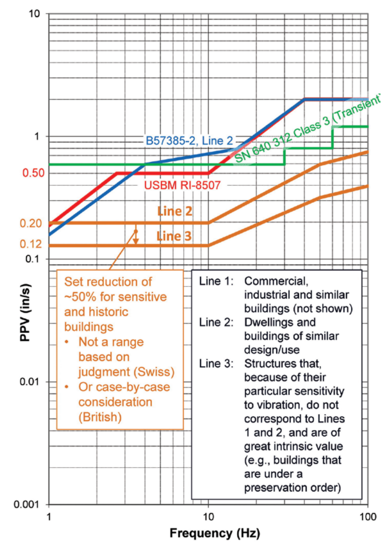

Fig. 7. Vibration limits from German DIN 4150 superimposed on the similar limits from USBM 8507, BS 7385-2, and SN 640 312a.

Section 12 of the Swiss standard, "Application of Guide Values," provides helpful commentary:

> If the velocity values occur below the guide values, then the probability of minor damage is extremely small. If the guide values are only rarely exceeded up to about 30%, then the probability that damage occurs is not increased significantly. If the values exceed twice the guide values, then damage [i.e., cosmetic cracking] is likely to occur. Cracks that penetrate through an entire wall or floor have to be expected if values exceed the guide values by several times. If conditions are very special, an expert would be allowed to define higher or lower guide values.

German DIN 4150. The fourth primary source is German Standard DIN 4150.[14] As shown in Figure 7, building type, and to some extent building fragility and condition, are addressed by different categories of buildings. Line 2 applies to dwellings and other light-framed buildings, and Line 3 applies to structures with "particular sensitivity to vibration" and those "of great intrinsic value (e.g., buildings that are under a preservation order)." The limits shown in Figure 7 are for transient, "short term" vibrations. The standard provides considerably lower limits for continuous, "long term" vibrations, but those limits apply for measurement at the top floor of the building, not at the base of the building as in the other limits, and so are not directly comparable.

The superposition of the limits in Figure 7 shows that the German standard has markedly lower limits than the other three primary sources. There is no known scientific basis for the lower nature of the German limits. Dowding notes the lack of data for the foundation of the DIN 4150 standard and states that "apparently, the DIN standard is an annoyance standard and is not based upon observed cracking."[15] This could very well be the case, as human annoyance to vibrations typically begins at 0.1 to 0.2 in/sec.

As for an importance factor, it seems that an extra degree of conservatism is already built into the German standard, although this is not transparent or explained as such in the standard. Furthermore, a flat reduction of 50% is applied for all historic buildings, not a possible range of reduction based on professional judgment as in the Swiss standard or a possible reduction based on case-by-case consideration as in the British standard.

Establishing Vibration Limits for Historic Buildings

With an appreciation for the vibration fundamentals and four primary sources of vibration limits as described above, one can begin to formulate a rational strategy to establish vibration limits for individual historic buildings and construction projects. Inasmuch as the selection of limits involves a balance between construction costs and tolerance for risk of damage, building owners, governing agencies, and the parties providing financial resources should be involved.

A sensible first step, as recommended by the 2012 NCHRP report, is to carry out an initial screening process for buildings surrounding a construction site. For the screening process, a conservative threshold for potential damage should be assumed, and simple vibration-prediction methods used to estimate levels of vibration that could occur at each building located within some assumed screening distance. The NCHRP report recommends a conservative screening distance of 500 feet for all but blasting activity, and conservative thresholds for potential damage of 0.2 in/sec for transient and 0.1 in/sec for continuous vibrations. The authors of this article agree that these are conservative initial assumptions.

If estimates of vibration are below the assumed conservative thresholds, then no further work is necessary. If not, feasible measures for reducing vibration should be evaluated. Such mitigation measures could include alternate designs or less vibratory construction methods. If it is anticipated that the conservative thresholds at a particular building would be exceeded, the next step would be to perform a higher level of review for that building. Such review should include a detailed inspection and evaluation of the building for its particular sensitivity and fragility to the vibration input; more detailed prediction of the vibration levels at the building, possibly involving field testing or structural analysis; and development of a more refined, case-specific vibration limit for the building.

The case-specific limit should be selected by assessing the three key factors identified above as they relate to the specific building and situation: building type and condition, vibration source type, and desired importance factor.[16] The limit should also consider human disturbance in any occupied buildings, as humans will often complain at levels above 0.1 in/sec and be physically disturbed at levels above 0.2 in/sec.

In the authors' estimation, the published limit that is the most comprehensive and that most sensibly reflects available research and fundamental engineering principles is Swiss Standard SN640 312. This standard provides a limit for light-framed buildings exposed to transient vibrations that closely matches scientific research (i.e., the USBM studies), a conservative reduction to account for the possible effects of continuous vibrations, and a range of possible reduction to account for cultural (i.e., historic) or economic value of the structure (i.e., the "importance factor").[17]

In the end, the limit for historic buildings will likely be in the range of 0.12 to 0.5 in/sec depending on evaluation of the key factors for the individual case. For cases of extreme fragility or where a very high importance factor is desired, the lowest vibration limit that should be set is the maximum ambient level of vibration in the building. This level can be determined by monitoring vibrations in the building for a period of time during normal, day-to-day activities before construction begins.

Protection of Artwork from Vibrations

The response and vulnerability of art objects to vibrations is extremely variable. Each object responds differently to vibration input due to its particular size, shape, material composition, and mass distribution. To further complicate matters, there is a very wide range in the possible condition of art objects: some are very sound, and others are extremely fragile and distressed.

The authors have had extensive experience with vibration control during museum construction projects and have researched the effects of vibrations on artwork in the conservation literature.[18] The following discussion summarizes the significant points of this work:

- For shipment between museums, art objects are packaged in specially designed crates to limit shock and vibration effects. However, sustained vibrations measured on the objects during truck transit are commonly from 1.5 to 3 in/sec. Much higher magnitude impulse-type vibrations occur due to crate handling, abrupt starts and stops, and other jarring transport events. Despite these very significant levels of vibration, adverse effects rarely occur.
- There is very little information on levels of vibrations that have actually caused damage to artwork, as this is obviously to be avoided. One reported case was at the British Museum in 2000, when damage occurred to twelve art objects at vibration levels in the range of 0.6 to 1.8 in/sec. All of this damage occurred in areas of preexisting weakness on relatively fragile objects.
- The authors believe that a vibration limit of approximately 0.1 in/sec (baseline) is a conservative limit to protect most art objects in reasonable condition. The following caveats apply: walking of light objects on smooth surfaces can occur at lower levels; resonance of objects or building sub-assemblies with natural frequencies similar to continuous construction vibrations can be problematic; and objects that are particularly fragile or those with serious preexisting weaknesses might be susceptible at lower levels. Measures should be taken to protect against these risks on a case-by-case basis.
- An artwork protection limit of approximately 0.1 in/sec (baseline) has been used during several recent

museum construction projects.[19] The limit proved to be achievable by the contractors without the use of extremely specialized techniques; the limit kept vibrations below levels disturbing to building occupants; and no damage to the artwork was observed.

- In the end, each museum will need to establish a vibration limit that, in the judgment of their conservation and vibration experts, is appropriate for its particular collection and construction project.

Vibration Limits as Part of an Overall Plan for Vibration Control

Selection of appropriate vibration limits is only part of a successful plan for vibration control at historic buildings. Details of other critical aspects of such a plan are provided in the following articles: "Part 3 - Recommended Methodology for Vibration Control," by Arne Johnson et. al., and "Part 4 - Protection of Adjacent Structures During Construction" by E. Hammarberg et. al.[20] The methodology will vary depending on the individual circumstances of each project. However, the following tasks should typically be included:

- Pre-construction planning and design, including prediction of vibration levels in individual buildings, assessment of building-specific vulnerabilities to vibration, selection of appropriate vibration limits, and studies of practical strategies to reduce vibration exposure.
- Development of a vibration-control specification for the project. This specification should be incorporated into the bidding and construction documents and should include requirements for pre-construction condition surveys; definition of vibration limits and locations; details of the monitoring plan to be followed; guidance and minimum requirements regarding the contractor's means and methods; and stipulation of protocols to be followed if recorded vibrations exceed the specified limits.
- Careful pre- and post-construction condition surveys of all affected buildings as a means of establishing whether any construction-related damage occurred (surveys should be repeated after any above-limit vibrations).
- Vibration monitoring throughout actual construction, as well as other monitoring that may be appropriate such as elevation surveying for settlement, crack-width measurements, and visual surveys of general building conditions.

In certain cases, other, more sophisticated tasks may be appropriate, such as pre-construction vibration testing to establish site-specific attenuation, construction-phase vibration trials using actual construction equipment, and specialized alarms and notification protocols.

Project Examples

The examples provided below, which are from the authors' project experience, illustrate selections of appropriate vibration limits for different situations involving historic buildings. For each example, note the three key factors that are identified and refer to the four primary sources for limits. Additional case studies and references to actual levels of vibrations on construction sites and associated damage observations can be found in Dowding and the 2012 NCHRP Report.[21]

Modern Wing, Art Institute of Chicago. The historic buildings on the Art Institute campus (dating from c. 1893) and the museum's extensive collections needed protection during the recent 264,000-square-foot Modern Wing addition and related construction works. The existing buildings were heavy, pile-supported, masonry buildings in very good condition (key factor 1), and most of the vibratory work near the existing buildings was transient in nature (key factor 2). With no special importance factor (key factor 3) desired, a vibration limit of 0.5 in/sec (frequency-dependent) was used for protection of the buildings. In recognition of the extreme cultural and economic value of the artwork (i.e., key factor 3), a separate limit of 0.1 in/sec (frequency-dependent) was used for locations where artwork was present. Careful pre-construction testing, construction-phase vibration trials, and an extensive system of vibration monitors with alarm and notification protocols were included in the vibration control plan. During more than three years of monitoring using over 20 seismographs, vibrations in active galleries often reached 0.05 in/sec and on two occasions reached approximately 0.2 in/sec (transient). Careful post-event and post-construction inspections revealed no damage.

Sullivan Arch, Art Institute of Chicago. This architectural element, taken from the Chicago Stock Exchange Building (c. 1893) and relocated to the Art Institute campus in 1977, presented a special case because the contractor proposed vibratory sheet pile driving (i.e., potentially continuous vibrations) within about 30 feet of the base of the arch (Fig. 8). In this case, a lower vibration limit of 0.2 in/sec (frequency-dependent) was used for any continuous vibrations (defined as cyclic vibrations with duration greater than 2 seconds) that were measured at the arch during the vibratory sheet pile installation (key factor 2). Continuous vibrations near the 0.2 in/sec limit were recorded for approximately two days. Careful pre- and post-construction surveys of the object were conducted by museum conservation staff, and no adverse effects were found.

Saint Louis Art Museum expansion. The historic museum building (c. 1904) and extensive collections needed protection during a recent 200,000-square-foot expansion (see Fig. 1). As at the Art Institute of Chicago, vibrations were typically transient in nature, and the existing buildings were massive and in good condition. The limits used were 0.5 in/sec for the buildings and 0.12 in/sec (frequency-dependent) for the artwork. Extensive field trials and multiple years of monitoring were conducted. No vibration-related damage was observed.

Fig. 8. Site-grading activities near Sullivan Arch next to the Modern Wing addition at the Art Institute of Chicago, 2005.

Taft Museum of Art. Underground tunnel construction work is underway across the street from this museum, located in Cincinnati, Ohio. Its collections include art objects and murals (c. 1850), which were painted directly on the original plaster walls. Vibrations are expected to be primarily transient (key factor 2), but the building, including the non-moveable murals, is judged more susceptible (key factor 1) due to the extreme fragility and pre-cracked condition of the very old plaster walls with the murals. A high degree of protection was desired by the museum (key factor 3) given the irreplaceable nature of the murals. Therefore, a vibration limit of 0.12 in/sec, just above maximum measured ambient levels, was selected for both the building and artwork. Construction is just beginning.

Mesopotamian Relief, Oriental Institute Museum, University of Chicago. Heavy construction was performed across the street from this museum (c. 1931), which houses eighth-century B.C. Assyrian reliefs carved from blocks of gypsum and broken in antiquity (i.e., pre-cracked). Due to the extreme fragility and value of the reliefs, which could not be moved, the museum desired a very conservative vibration limit (key factor 3), which was set to be roughly equivalent to the maximum ambient vibrations in the building, 0.06 in/sec. During construction, levels of vibrations at the relief (primarily transient) occasionally reached 0.05 in/sec and once reached 0.07 in/sec, with no damage observed.

Conclusion

Vibration limits for historic buildings, art collections, and similar environments should be established on a case-by-case basis using a rational procedure that has basis in scientific research and principles. Those responsible for establishing limits should have an understanding of human perception thresholds, ambient levels in buildings, and damage levels documented in research studies. Also critical is an understanding of the basis and provisions of the commonly cited sources for vibration limits. Assignment of an arbitrarily low vibration limit due to lack of knowledge or expediency risks unnecessary costs in lighter construction methods and greater vibration-monitoring efforts.

For each project, a case-specific vibration limit should be selected considering the following key factors: building type and condition, vibration-source type, importance factor, and the potential for human disturbance. In the authors' estimation, the currently published limit that best reflects available research and consideration of these key factors is Swiss Standard SN640 312 (as explained herein). In the end, the appropriate vibration limit for a historic building will likely be in the range of 0.12 to 0.5 in/sec, depending on evaluation of the key factors for the individual case.

Vibration limits are only part of a successful plan for vibration control at historic buildings. Other critical aspects include pre-construction planning, development of a vibration control specification, careful pre- and post-construction surveys, and monitoring during actual construction. In special cases, more sophisticated vibration-control measures such as on-site vibration testing and trials may also be appropriate in order to safeguard the resource.

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Notes

1. American Association of State Highway and Transportation Officials, "Standard Recommended Practice for Evaluation of Transportation Related Earthborne Vibrations, R8-96," *Standard Specifications for Transportation Materials and Methods of Sampling and Testing, Part I, Specifications* (Washington, D.C.: American Association of State Highway and Transportation Officials, 2004). John F. Wiss, "Construction Vibrations: State-of-the-Art," *Journal of the Geotechnical Engineering Division* 107, no. 2 (1981): 167-181.

2. D. Siskind, M. Stagg, J. Kopp, and C. Dowding, "Structure Response and Damage Produced by Ground Vibration from Surface Mine Blasting," *Report of Investigations 8507*, U.S. Bureau of Mines (Washington, D.C.: U.S. Dept. of Interior, 1980). M. Stagg, D. Siskind, M. Stevens, and C. Dowding, "Effects of Repeated Blasting on a Wood-Frame House," *Report of Investigations 8896*, U.S. Bureau of Mines (Washington, D.C.: U.S. Department of Interior, 1984).

3. Walter Konon and John Schuring, "Discussion by C. Dowding of 'Vibration criteria for historic buildings,'" *Journal of Construction Engineering and Management* 111, no. 3 (1985): 208-215.

4. See Note 2.

5. C. Dowding, "Comparison of Environmental and Vibration-Induced Crack Movement," in *Construction Vibrations*, Chapter 13 (Upper Saddle River, N.J.: Prentice Hall, 2000): 182-202. C. Dowding, D. Marron, R. Beillot, "Response of Historic Structure to Long Term Environmental and Construction Vibration Effects," documentation of construction vibrations at Blair House, *Proceedings of the 7th International Symposium on Field Measurements in Geomechanics* (Washington, D.C.: American Society of Civil Engineers: 2004): 1-13.

6. "Current Practices to Address Construction Vibrations and Potential Effects to Historic Buildings Adjacent to Transportation Projects," *National Cooperative Highway Research Program Report 25-25/Task 72* (Washington, D.C.: National Academy of Sciences, 2012).

7. Jones & Stokes, "Transportation- and Construction-Induced Vibration Guidance Manual," prepared for Noise, Vibration and Hazardous Waste Office, California Department of Transportation, 2004. C. E. Hanson, D. A. Towers, and L. D. Meister, "Transit Noise and Vibration Impact Assessment," prepared for Office of Planning and Environment, U.S. Federal Transit Administration, 2006. P. L. Kelley, S. J. DelloRusso, and C. J. Russo, "Building Response to Adjacent Excavation and Construction," *Proceedings of the American Society of Civil Engineers Annual Convention* (Boston, Mass., 1998): 80-97. W. Konon and J. R. Schuring, "Vibration Criteria for Historic and Sensitive Older Buildings," *Journal of Construction Engineering and Management* 111 no. 3 (1985): 208-215. Walter Sedovic, "Assessing the Effect of Vibration on Historic Buildings," *Association for Preservation Technology Bulletin* 16, no. 3-4 (1984): 52-61.

8. The concept of an importance factor is common in architectural/engineering practice; for example, higher importance factors (and hence higher performance expectations) are used in the design of essential facilities such as schools, prisons, hospitals, fire stations, and other emergency-response facilities.

9. See Note 2.

10. British Standards Institute, "BS 7385 Evaluation and Measurement for Vibration in Buildings, Part 1: Guide for Measurement of Vibrations and Evaluation of Their Effects on Buildings," 1990, and "Part 2: Guide to Damage Levels from Groundborne Vibration," (London: Board of British Standards Institute, 1993).

11. See Note 3.

12. Swiss Standards Association, "Effects of Vibration on Construction," SN 604 312a (2013). J. Studer and A. Suesstrunk, "Swiss Standard for Vibrational Damage to Buildings," *Proceedings of 10th International Conference of Soil Mechanics and Foundation Engineering* (Stockholm, 1981). J.A. Studer. Vibrations on Buildings; Trade Events: *Vibrations and Structure-Borne Sound: A Civil Engineering Challenge* (Zurich: Studer Engineering, 2003).

13. "Guide value" is a technical term used in Swiss engineering practice for approximate, indicatory values, benchmarks, and guidelines. Such values are not intended to be strict or mandatory but rather to call for appropriate professional judgment.

14. Deutsches Institut für Normung, "Structural Vibration, Part 3: Effects of Vibration on Structures," DIN 4150-3 (Berlin: German Institute for Standardization, 1999): 1-11.

15. C. Dowding "Frequency-based Control of Construction Vibrations," *Construction Vibrations* (Upper Saddle River, N.J.: Prentice Hall, 2000): 138.

16. Guidance in assessing building type and condition can be found in BS 7385-2, Annex A, Part 1, although a correlation between the standard's building classifications and vibration limits will need to be estimated, as a correlation is not provided in the standard.

17. Reduction in the limit to account for continuous vibrations is debated and may not be necessary. Research into damage caused by continuous vibrations is limited. Dowding and Siskind argue that the USBM RI 8507 limit already accounts for dynamic amplification and that fatigue effects are negligible on most construction projects. The British standard states that some reduction to account for dynamic amplification may be appropriate in some cases but that reduction for fatigue considerations is typically not necessary. Wiss applied a lower limit for continuous vibrations. In the absence of definitive scientific basis, the authors suggest a reduction as a conservative measure.

18. Arne Johnson, W. Robert Hannen, and F. Zuccari, "Vibration Control during Museum Construction Projects," *Journal of the American Institute for Conservation* 52 no. 1 (2013): 30-47.

19. In the project examples cited, vibrations typically originated outside the buildings, and the vibration response (where the limits apply) was measured at the base of the building or near a column or bearing wall within the building, such that dynamic amplification effects were not included. This is consistent with the four primary sources for vibration limits described in this paper, all of which assume that vibrations originate outside the building and are measured at the base of the building.

20. Johnson, Hannen, and Zuccari, 30-47. E. Hammarberg, K. Kesner, and D. Trelstad, "Protection of Historic Urban Structures During Adjacent Construction," *International Conference on Protection of Historical Buildings* (Rome, Italy, 2009). It is noteworthy that Mr. Hammarberg, when consulted during development of the present paper, commented that he has been involved in the monitoring of several hundred old (many historic) unreinforced-masonry buildings in New York City and that he has never observed damage caused by construction vibrations at levels below 0.5 in/sec, which is the stipulated limit for New York City landmark buildings (reference NYC TPPN-1088).

21. C. Dowding, *Construction Vibrations* (Upper Saddle River, N.J.: Prentice Hall, 2000).

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