Vibration Fundamentals, Vibration Criteria, Typical Effects of Construction Equipment

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Iowa DOT Workshop, October 29, 2015

References

- *Vibration Control During Museum Construction Projects*, Arne Johnson, Bob Hannen and Frank Zuccari, Journal of the American Institute for Conservation, 2013
- *Vibration Limits for Historic Buildings and Art Collections*, Arne Johnson and Bob Hannen, APT Bulletin - Journal of Preservation Technology, 2015
- NCHRP 25-25/Task 72, *Current Practices to Address Construction Vibrations and Potential Effects to Historic Buildings Adjacent to Transportation Projects*, 2012

VIBRATION CONTROL DURING MUSEUM CONSTRUCTION PROJECTS

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As vibrations caused by heavy construction at museums are potentially harmful to museum buildings and artwork, the protection of museum objects calls for a reliable method of vibration control. This article provides background information on vibrations and their effects on humans, buildings, and artwork, along with recommending conservative limits for protection of buildings and artwork from construction vibrations. Humans can perceive low levels of vibration before damaging levels are reached, and typical ambient (background) vibrations in museums can approach recommended limits. Research also shows that during transit, art objects are exposed to vibration levels much higher than recommended limits and damage rarely occurs. The greatest risks for damage to art objects during construction are from light objects "walking" on smooth surfaces; from the resonance of objects with natural frequencies similar to construction vibrations; and from vibratory motion of extremely fragile objects or those with serious pre-existing weaknesses. On the basis of research and the authors' experience, a general methodology for vibration control during museum construction projects is introduced—a methodology that reliably protects the museum while not unduly constraining the construction. Two examples of large-scale implementations are described to illustrate this methodology.

KEYWORDS: *vibration, shock, construction, museums, artwork, monitoring, vibration limits*

1. INTRODUCTION

With virtually any kind of construction project, especially with the heavy construction such as selective demolition and foundation installation commonly associated with museum expansions, significant levels of vibrations will be transmitted into the existing buildings. Such vibrations can be damaging to irreplaceable collections as well as to adjacent galleries, which might themselves be aging structures, susceptible to transmitted vibrations.

Artwork left in place near the construction will likely be subjected to greater-than-background levels of vibrations. By their nature, aged and delicate art objects can be very sensitive to damage from vibrations and movement. But while the safety of the art is paramount and the elimination of risk imperative, relocation of artwork poses its own set of risks to collections and is disruptive to the operation of the museum.

Hence, among the difficult questions that museums must address before embarking on major construction projects, the following considerations must be taken into account: what are safe and acceptable vibration levels, what materials should be relocated, what, if any, protective measures should be employed for the artwork that remains in-place near the construction, and what protective measures should be taken to safeguard the museum buildings themselves?

Approaches taken in response to these difficult questions are:

1. A conservative approach, in which any and all artwork that could possibly be affected by the nearby construction is relocated in advance of the construction. This approach should avert construction-related damage, but it will most likely add unnecessary cost and be disruptive to the operation of the museum.
2. A judgment-based approach, in which the museum staff decides, based on their judgment and experience, what levels of vibration are safe, which artwork can remain, and which artwork must be proactively de-installed. If, based on the staff's judgment, objectionable vibrations occur during the construction, steps are taken to mitigate damage. This approach is not only subjective and risks short-term exposure of artwork to potentially damaging vibrations, but it also risks costly construction stoppages while artwork is relocated. In addition, it fails to provide clear, quantifiable operational limits to which the contractor can be held accountable and

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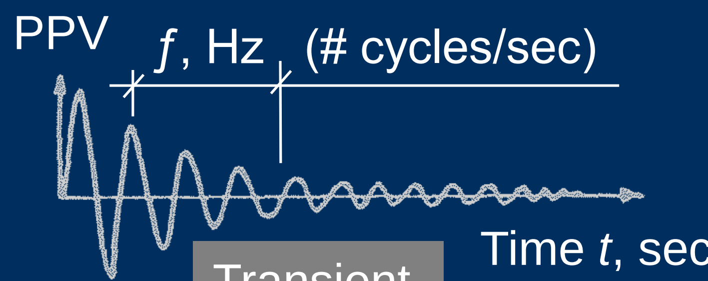
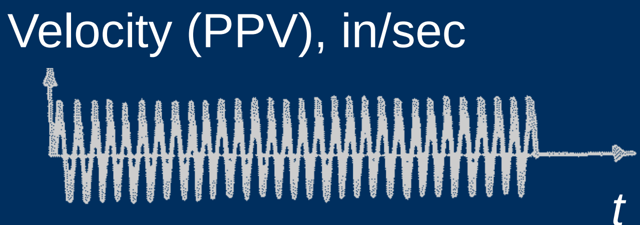
Outline

1. Vibration fundamentals
   - Human perception
   - Ambient levels
   - Building damage
   - Contents (art)
2. Vibration criteria
   - Historic buildings
   - Art objects and other fragile building contents
3. Effects of construction equipment
   - Wiss/FTA/CALTRANS/NCHRP
   - Vibration Type
   - Magnitude

Source → Media (Soil) → Receiver



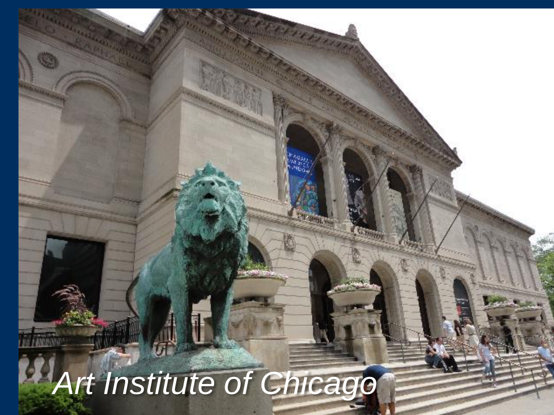
Transient



Steady-State

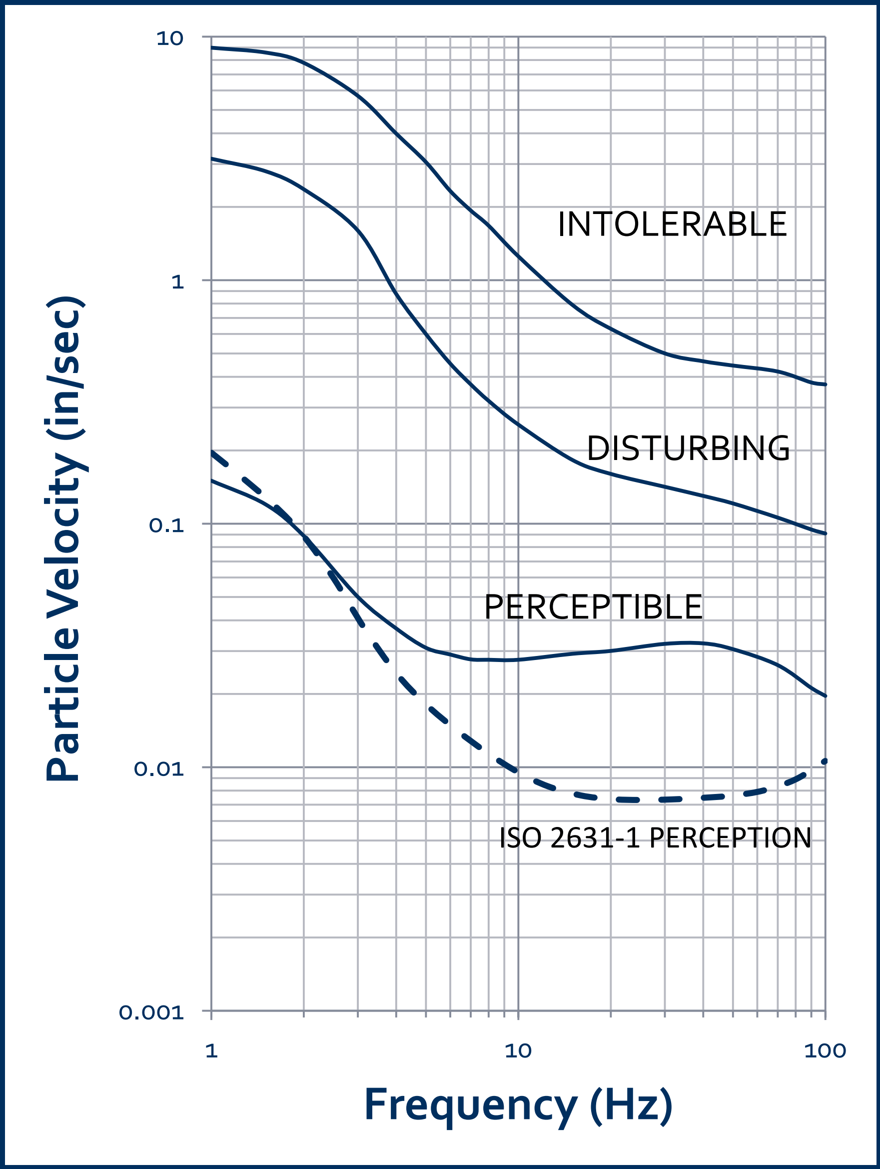
Pseudo Steady-State


Robie House, Chicago, IL


Art Institute of Chicago

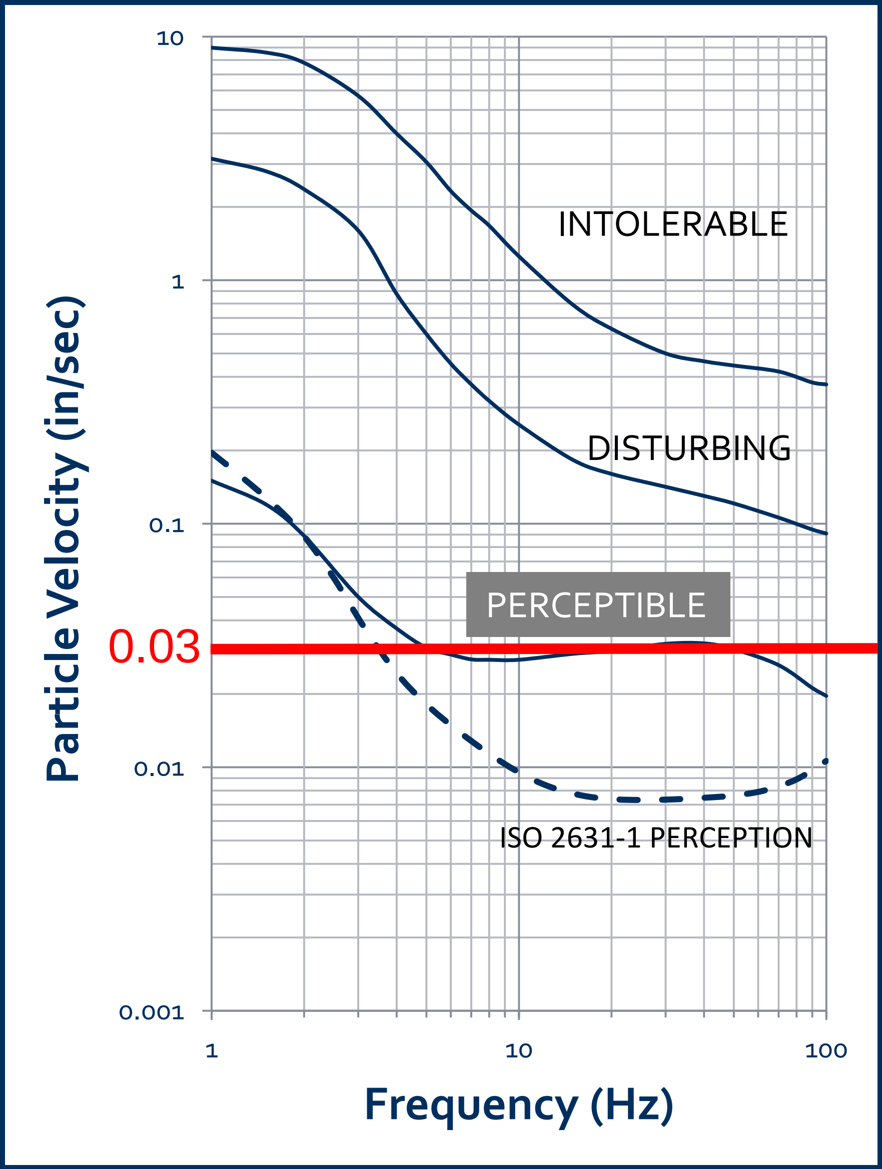

Edgar Co. Courthouse, Paris, IL

Human Perception



The human body can **perceive very low levels** of vibrations

Human Perception

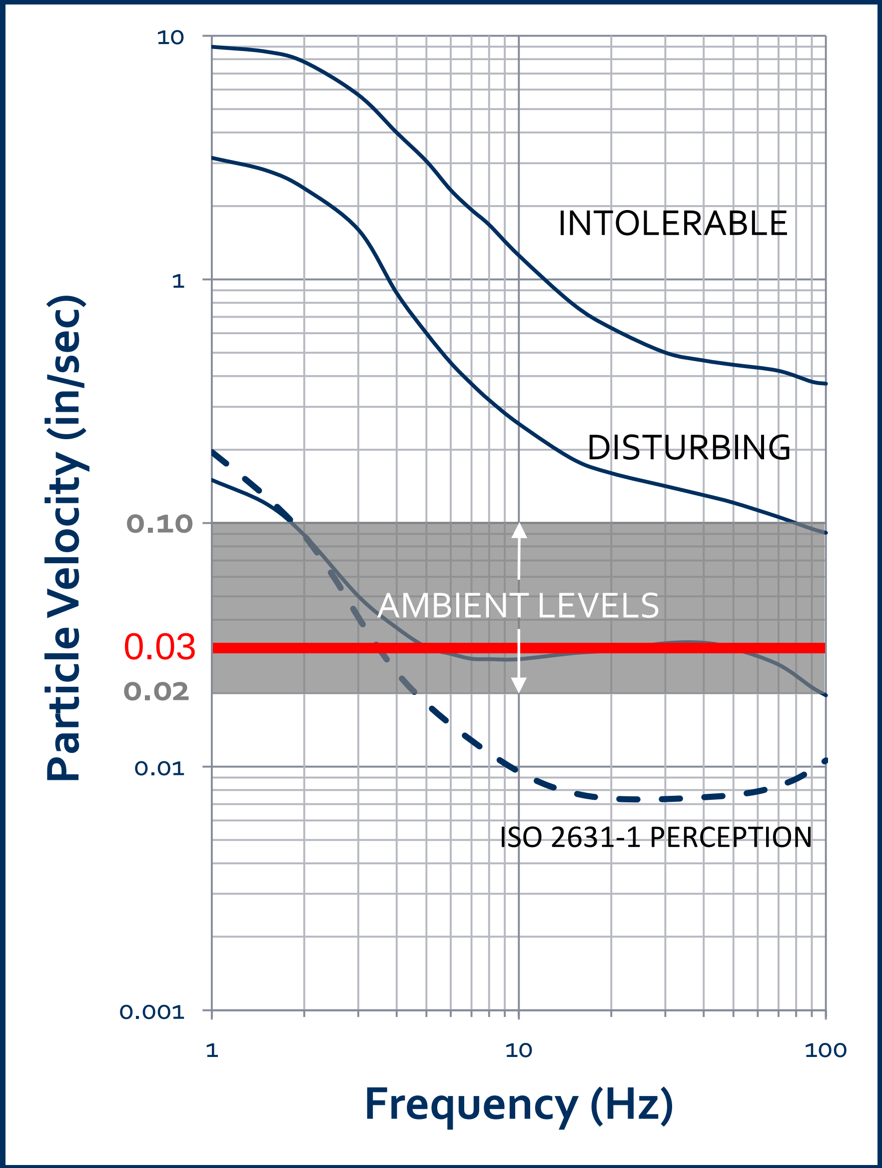


The human body can **perceive very low levels** of vibrations

Roughly, perception threshold for <u>steady-state</u> vibrations is **0.03 in/sec**

Vibrations become <u>disturbing</u> at **0.1-0.2 in/sec**

Ambient (Background) Levels in Buildings



Common Values:

- Closing doors, crowds walking: **~0.02 to 0.05 in/sec**
- Running, jumping: **~0.05 to 0.10 in/sec**
- Trains next to AIC: **~0.03 to 0.07 in/sec**
- Moving tables and chairs for event: **~0.10 to 0.15 in/s**

Vibration Criteria to Protect Historic Buildings

Table 1. Summary of Vibration Limits (NCHRP 25-25 Task 72, 2012)

	Reference Source	Remarks on Vibration Source	Remarks on Building or Structure	Remarks on Type of Damage	Vibration Limit - PPV (inches/sec)
1	British Standards Institute (1993)	All (including blasting)	Unreinforced or light framed structures	Cosmetic	0.6 to 2.0† (historic buildings may require special consideration)
	Sedovic (1984)	All	Historic buildings in good state of maintenance	--	0.5
	City of New York City (1988); Esrig and Ciancia (1981)	Blasting, pile driving and vehicular traffic	Structures which are designated NYC landmarks, or located within an historic district or listed on the NHRP	--	0.5
	Whiffin and Leonard (1971)	Traffic	Buildings with plastered walls and ceilings	Architectural damage and risk of structural damage	0.4 to 0.6
	Rudder (1978)	Traffic	All	Structural damage possible	0.4
	City of Toronto (2008)	All (blasting not mentioned)	All buildings	--	0.3 to 1.0† (lower limits may be identified by professional engineer)
	Konon and Schuring (1985)	Transient	Historic buildings	Cosmetic	0.25 to 0.5†
2	Swiss Standards Association (1992)	All (blasting, construction equipment, and road traffic)	Historic and protected buildings	--	0.2 to 0.5†
	Federal Transit Administration (2006)	All	Non-engineered timber and masonry buildings	--	0.2
	Sedovic (1984)	All	Historic or architecturally important buildings in deteriorated state of maintenance	--	0.2
	Whiffin and Leonard (1971)	Traffic	Buildings with plastered walls and ceilings	Threshold of risk of architectural damage	0.2
	Feilden (2003)	All	All buildings	Threshold for structural damage	0.2
	Rudder (1978)	Traffic	All	Minor damage possible	0.2
	Konon and Schuring (1985)	Steady state	Historic buildings	Cosmetic	0.13 to 0.25†
3	Deutsches Institut für Normung DIN 4150-3 (1999)	All	Buildings of great intrinsic value	Any permanent effect that reduces serviceability	0.12 to 0.4†
	Federal Transit Administration (2006)	All	Buildings extremely susceptible to vibration	--	0.12
	American Association of State Highway and Transportation Officials (2004)	All	Historic sites and other critical locations	Threshold for cracks (cosmetic)	0.12
	Esteves (1978)	Blasting	Special care, historical	--	0.1 to 0.4††
	Rudder (1978)	Traffic	All	Threshold of structural damage	0.1
	Whiffin and Leonard (1971)	Traffic	Buildings with plastered walls and ceilings	Virtually no risk of architectural damage	0.1

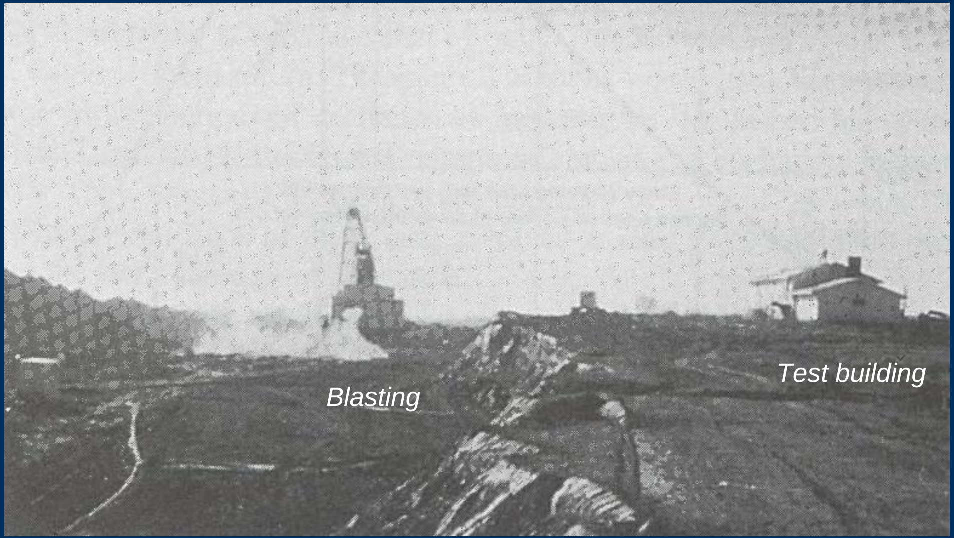
4 *USBM RI-8507, Siskind, Stagg, Kopp, and Dowding, "Structure Response and Damage Produced By Ground Vibration from Surface Mine Blasting," 1980*

- No commonly accepted standard
- NCHRP 2012 report identifies 20+ possible references with limits
- Four primary sources:
  - British standard
  - Swiss standard
  - German standard
  - USBM RI-8507

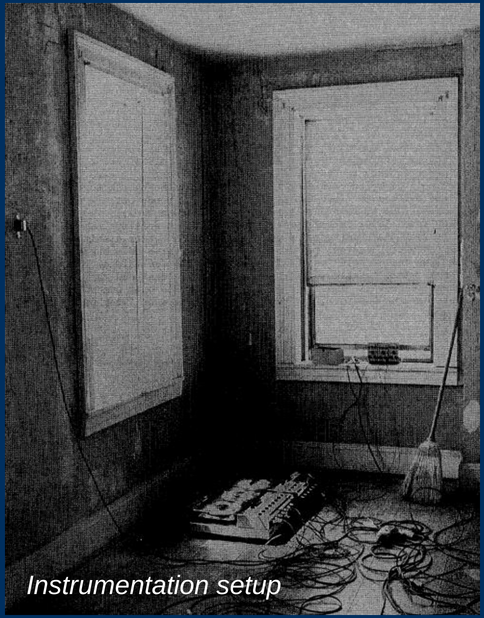
3 Key Factors (in Selecting Appropriate Criteria)

1. Building Type and Condition
   - Responsiveness (sensitivity) to vibration input
   - Fragility
2. Vibration Type
   - Transient / Short Term: Blast, impacts
   - Steady-State / Continuous: Vibratory pile driving, vibratory compaction
     - Potential for <u>resonance</u> (dynamic amplification) and <u>fatigue</u>
3. Importance Factor
   - Additional conservatism, cultural or economic value

1. USBM RI-8507, 1980

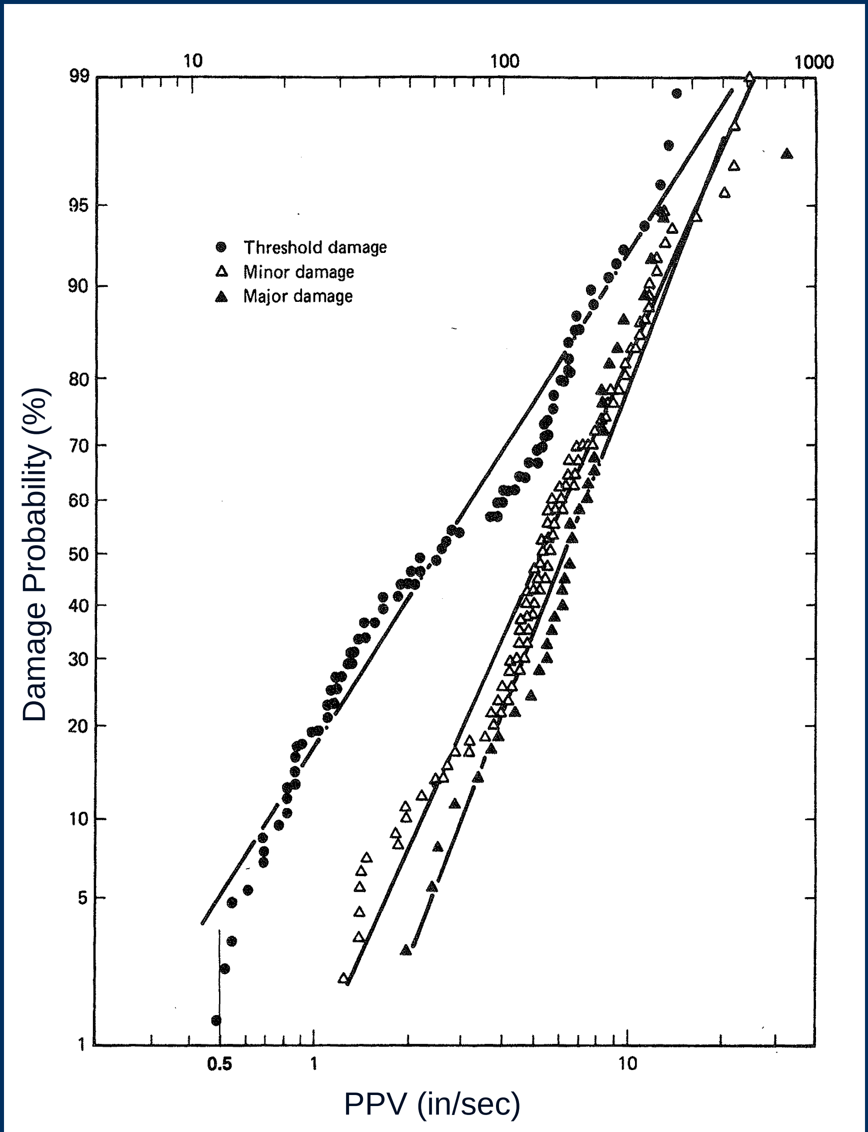



John F. (Jack) Wiss

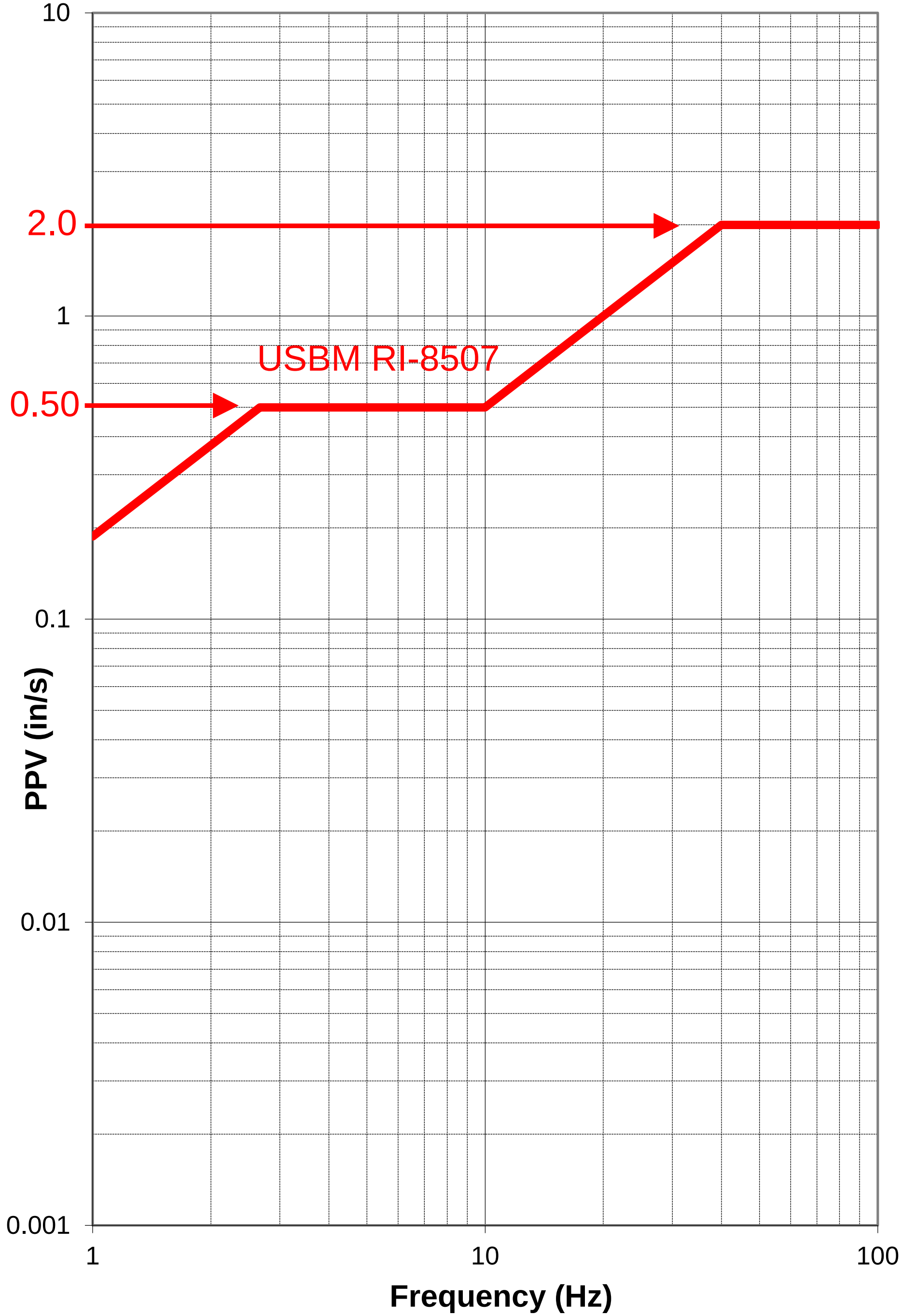

Instrumentation setup

- Rigorous scientific testing over many years
  - Pre- and post-blast surveys
  - Statistical analysis of damage data
- 76 residential buildings
  - Most timber framed, drywall
  - Some brick, concrete block
  - Some 100+ years old with plaster on wood lathe
- Blast loading, but also explored fatigue and resonance

USBM RI-8507 Damage Levels for Buildings



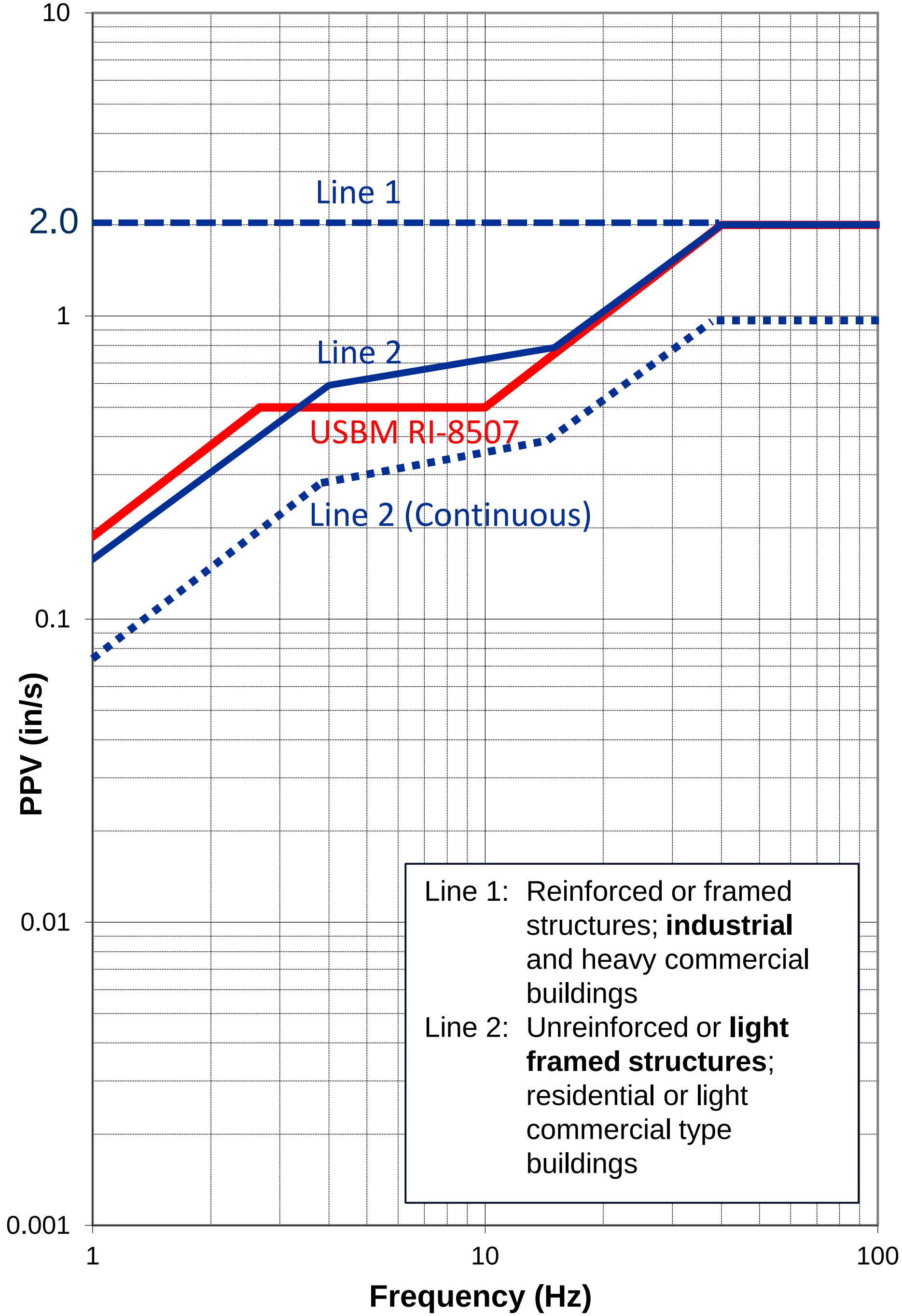
Damage Observed	PPV (in/sec)
Threshold damage (hairline cracking in plaster, opening of old cracks, etc.)	3.0 <0.5 (never)
Minor damage (hairline cracking in masonry, breaking of windows)	4.5
Major structural damage (cracking or shifting of foundations or bearing walls)	8.0



USBM RI-8507

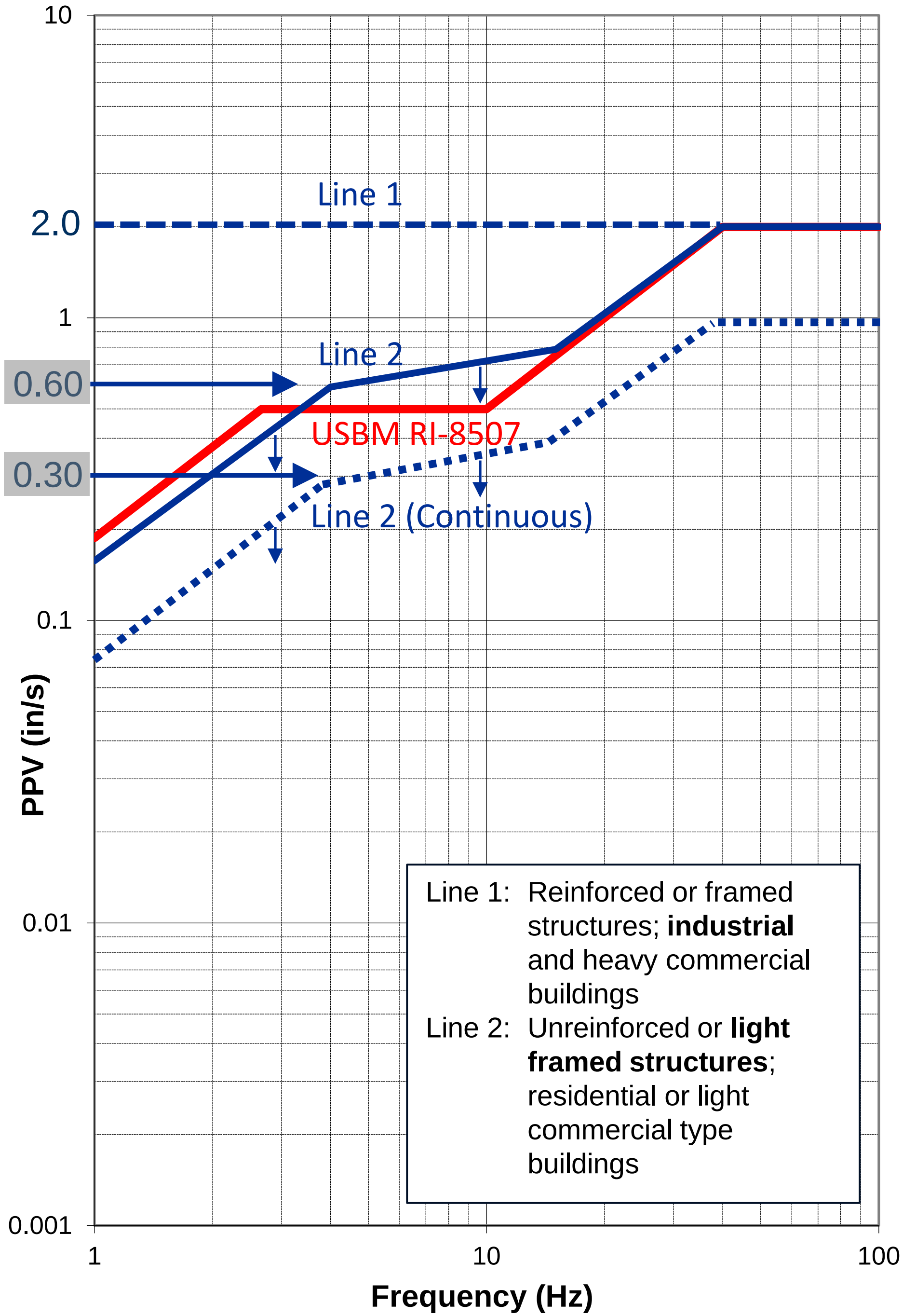
- Safe limit to prevent threshold cracking in plaster
- Vibrations measured in ground at base of building

1. Building Type / Condition:
   - Residential buildings (natural *f* ~5 to 10 Hz)
   - Condition varied
2. Vibration Type:
   - Blast
   - Limited steady-state testing
3. Importance Factor



2. British BS 7385

1. Building Type / Condition:
   - See legend
   - Part 1, Annex A – Classification of Buildings
2. Vibration Type:
   - Transient
   - Continuous: Reduce by up to 50%
3. Importance Factor
   - "Important buildings which are difficult to repair may require special consideration on a case-by-case basis…."



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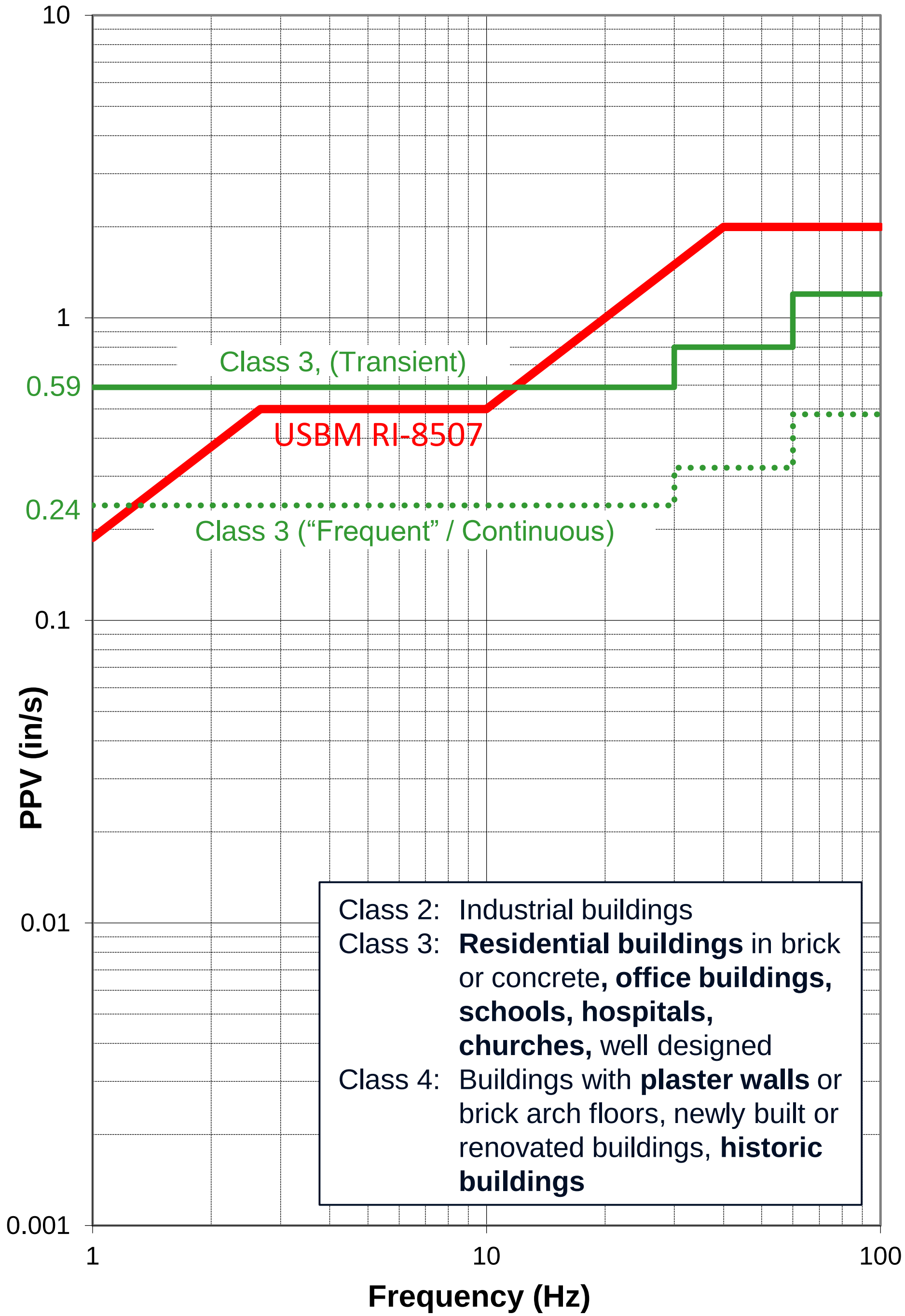
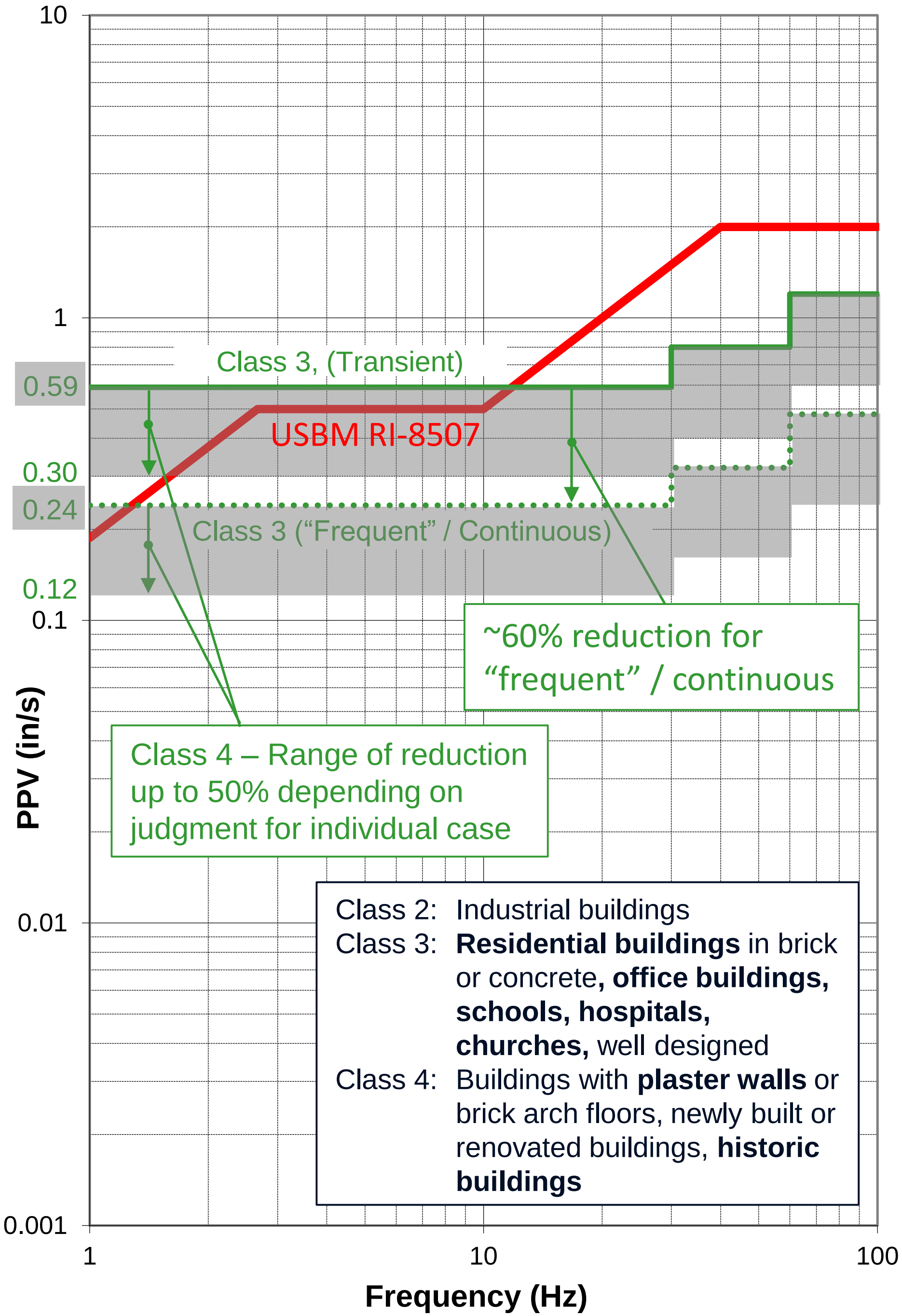


3. Swiss SN 640 312

(Only available in German or French)

1. Building Type / Condition
   - See legend
2. Vibration Type:
   - Transient: < 1,000 cycles
   - Continuous: < 100,000 cycles
3. Fragility and Importance Factor
   - Built into Class 4
   - Guide value for Class 4 is a range "between the values for Class 3 and half thereof"
   - i.e., professional judgment



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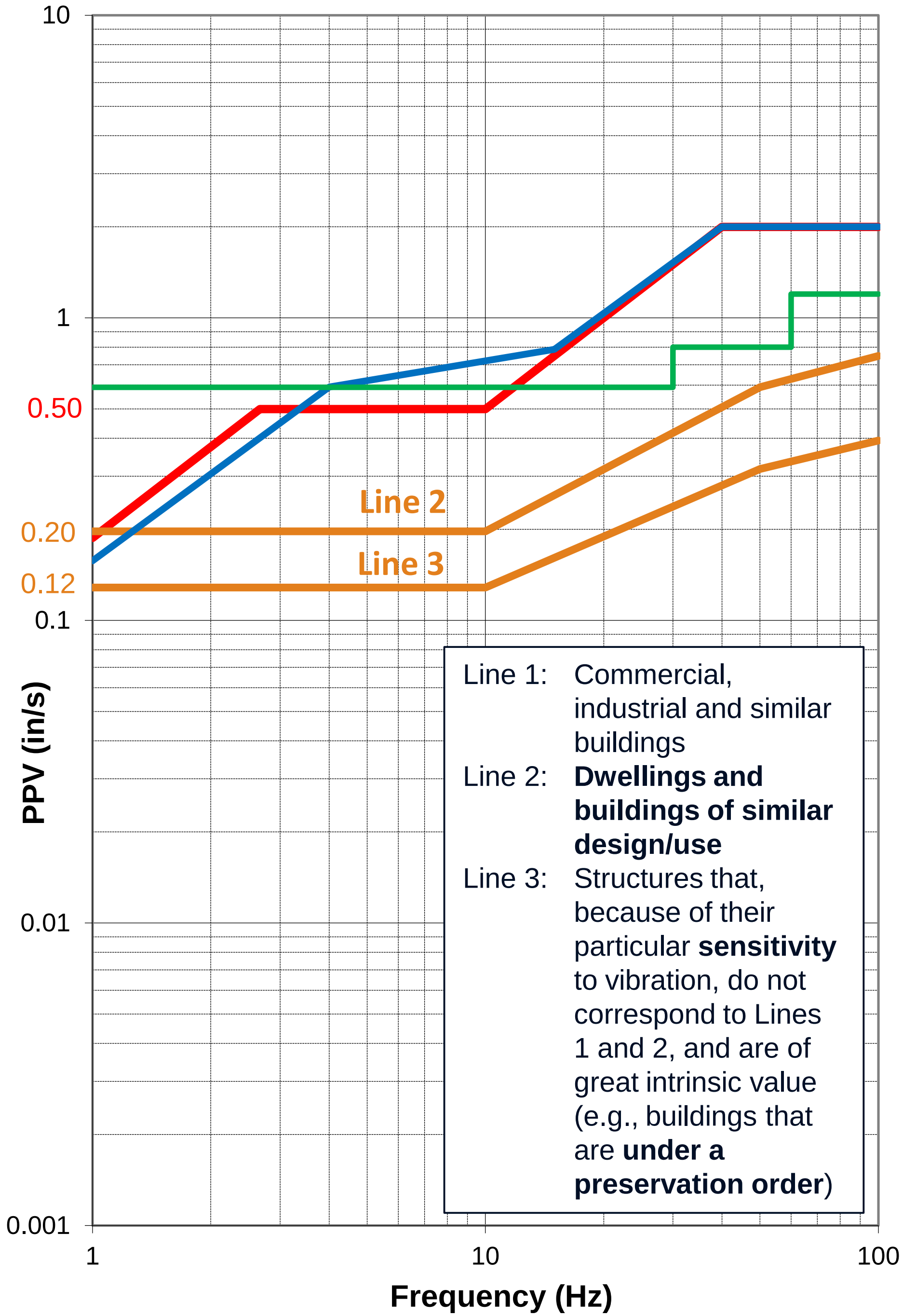
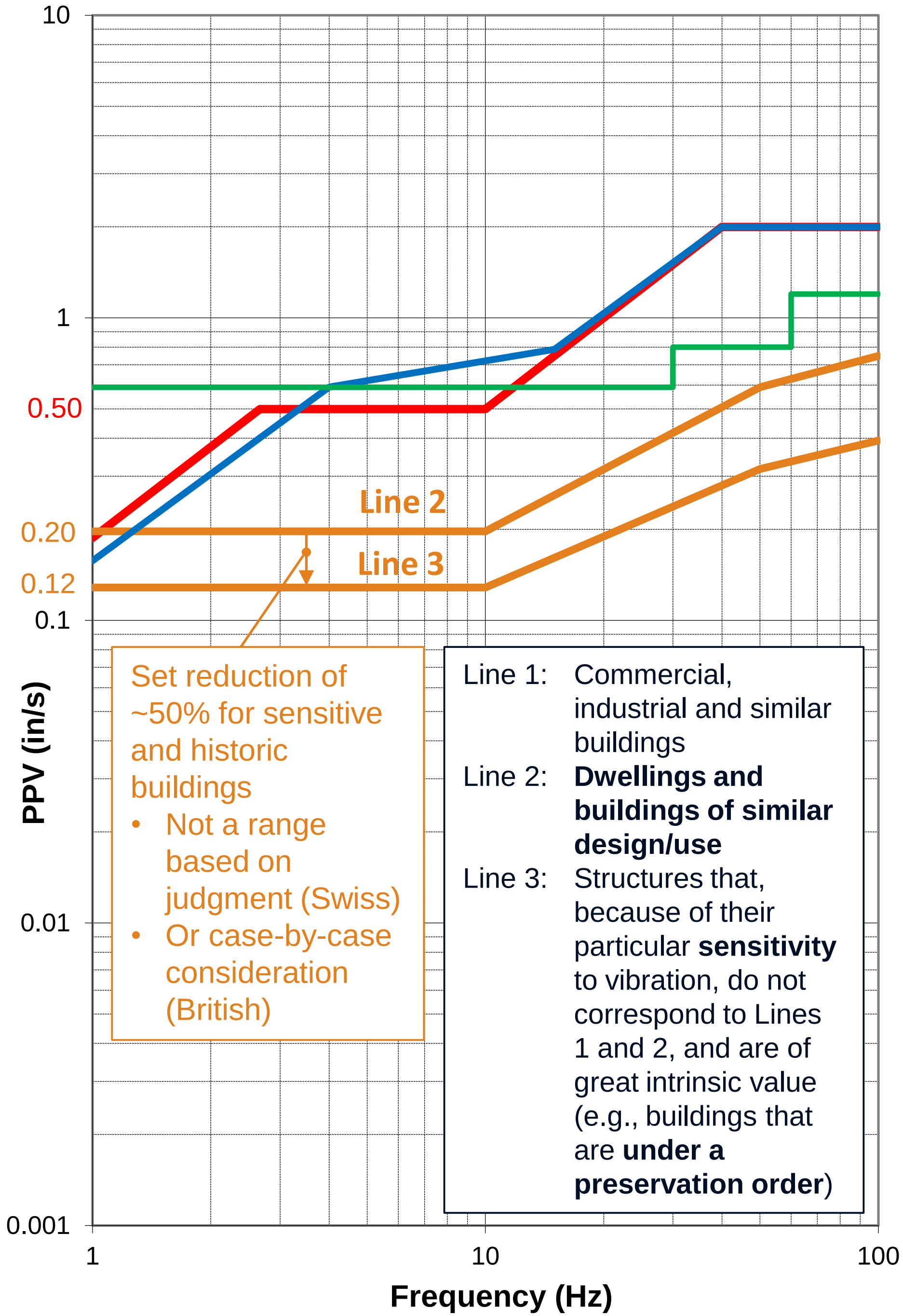


4. German DIN 4150

1. Building Type / Condition:
   - See legend
2. Vibration Type:
   - Transient ("short term") only

→ *Markedly lower than other 3 standards; no known basis; possibly more of "an annoyance standard not based on observed cracking" (Dowding 2000)*

3. Importance Factor
   - Extra degree of conservative apparently already included
   - Set reduction for historic buildings



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Limits for Historic Buildings

1. Initial screening procedure assuming conservative thresholds (0.2 in/sec transient; 0.1 in/sec continuous) and simple vibration prediction methods

2. If exceedance of conservative thresholds is anticipated at a particular building, then perform higher level of analysis

   - Detailed vibration prediction (field testing, structural analysis)
   - Detailed evaluation of building for sensitivity and fragility
   - Develop a project- and building-specific protection limit

Limits for Historic Buildings

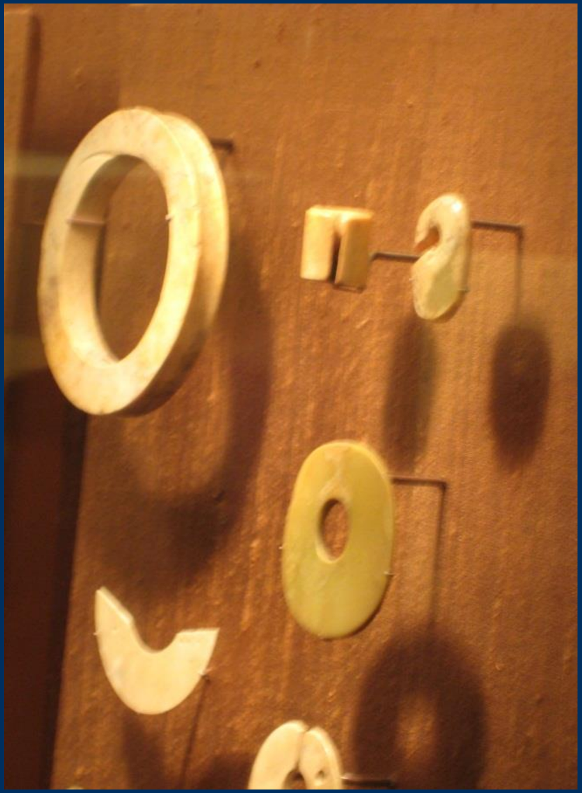
3. Develop a project-specific and building-specific protection limit based on 3 key factors:
   - Building type/condition
   - Vibration type
   - Importance factor
   - Human disturbance
4. Final limit likely in the <u>range of 0.12 to 0.5 in/sec</u> depending on the individual case
5. Swiss standard most comprehensive reference (if properly understood)

Artwork (and Other Fragile Building Contents)

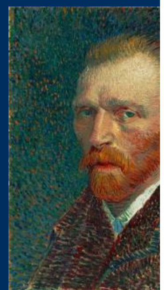






Artwork (a Contents)



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KEYWORDS: *vibration, shock, construction, museums, artwork, monitoring, vibration limits*

1. INTRODUCTION

With virtually any kind of construction project, especially with the heavy construction such as selective demolition and foundation installation commonly associated with museum expansions, significant levels of vibrations will be transmitted into the existing buildings. Such vibrations can be damaging to irreplaceable collections as well as to adjacent galleries, which might themselves be aging structures, susceptible to transmitted vibrations.

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Limits for Museum Art Collections

- Given extreme variability, value and non-repairable nature of most art objects, a very high degree of conservatism (i.e., Importance Factor) is usually desired by museums
- Limit of 0.1 in/sec judged very conservative and used successfully on several U.S. museum construction projects
- Possible exceptions / caveats:
  - "Walking" of light objects on smooth surfaces
  - Resonance of objects with natural frequencies similar to construction vibrations
  - Extremely fragile objects or those with serious pre-existing weaknesses

Project Examples

- Historic Buildings (many)
- Museum Art Collections
  - Art Institute of Chicago (several phases) - HISTORIC
  - Saint Louis Art Museum Expansion - HISTORIC
  - Clark Art Institute, Williamstown, MA - HISTORIC
  - University of Chicago
    - Oriental Institute Museum - HISTORIC
    - Smart Museum
  - Taft Museum of Art, Cincinnati, OH - HISTORIC
  - Pulitzer Foundation for the Arts, St. Louis, MO

The Art Institute of Chicago Campus

The Art Institute of Chicago Campus

Vibration Limits:
Buildings: 0.5 in/sec*
Artwork: 0.1 in/sec*
* frequency dependent

Chicago Stock Exchange Arch

Chicago Stock Exchange Arch


Chicago Stock Exchange (1893)


Vibratory pile driving (30 ft)


Site demolition and grading (5 ft)

<u>Vibration Limits:</u>

Continuous:	0.2 in/sec*
Transient:	0.5 in/sec*

The Saint Louis Art Museum

The Saint Louis Art Museum

Hydraulic breakers (10 ft)

Hydraulic processor (10 ft)

Tangent pile wall with tiebacks (5 ft)

<u>Vibration Limits:</u>

Buildings: 0.50 in/sec*

Artwork: 0.12 in/sec*

* frequency dependent

The Taft Museum of Art (Cincinnati, OH)

The Taft Museum of Art (Cincinnati, OH)

Vibration Limits:

Building:	0.12 in/sec*
Artwork:	0.12 in/sec*

Various art objects

Duncanson murals on plaster walls (c. 1850)

The Robie House (Frank Lloyd Wright)

The Robie House (Frank Lloyd Wright)

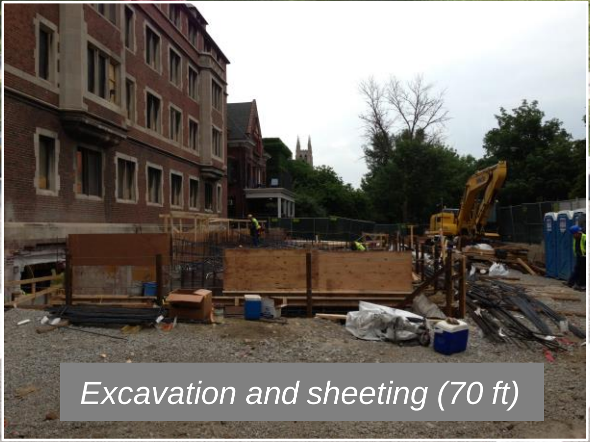
Vibration Limits:

Building: 0.20 in/sec*

Building roof: 0.50 in/sec*

* frequency dependent

Heavy truck traffic (40 ft)



Excavation and sheeting (70 ft)

Demolition on building wall (110 ft)

The Oriental Institute Museum (Chicago)

The Oriental Institute Museum (Chicago)

Assyrian reliefs, gypsum (8th century BC)

References

- *Vibration Control During Museum Construction Projects*, Arne Johnson, Bob Hannen and Frank Zuccari, Journal of the American Institute for Conservation, 2013

- *Vibration Limits for Historic Buildings and Art Collections*, Arne Johnson and Bob Hannen, APT Bulletin - Journal of Preservation Technology, 2015

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Vibration Limits for Historic Buildings and Art Collections

Arne P. Johnson and W. Robert Hannen

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

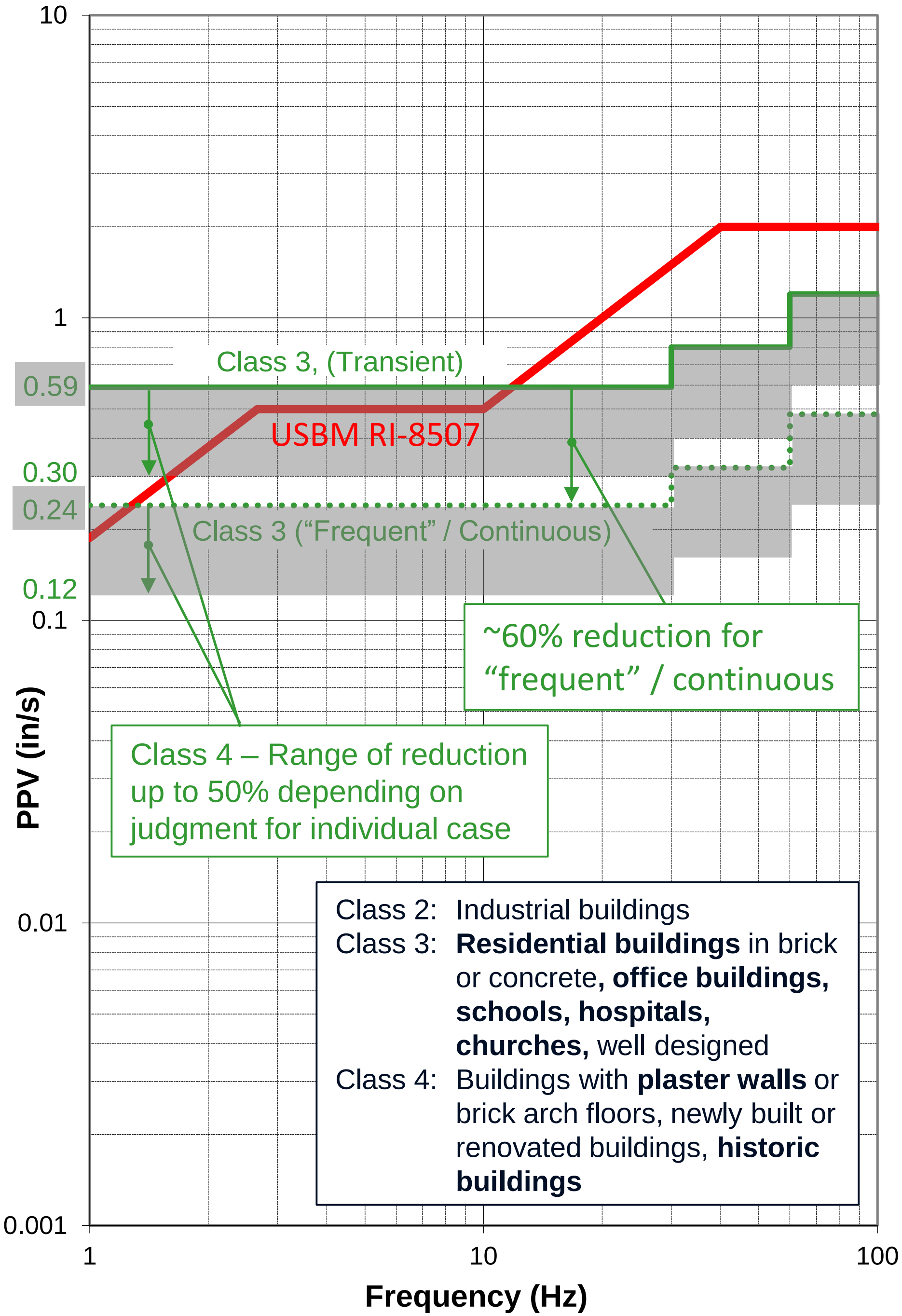
Fig. 1. The Saint Louis Art Museum, Saint Louis, Missouri, construction underway for expansion, 2010.

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.

Conclusions / Main Take Aways

- Understand the principles behind the limits and each standard's limitations
- <u>Just because a building is historic does not necessarily mean it has higher vulnerability to vibrations</u>
- <u>Evaluate each building/project on its own merits</u>
- For historic buildings, limits should be determined on a case-by-case basis:
  - Considering 1) Building type and condition, 2) vibration type, 3) importance, 4) human disturbance
  - Likely 0.12 to 0.5 in/sec depending on the individual case
  - Swiss standard most comprehensive (if properly understood)



3. Swiss SN 640 312

(Only available in German or French)

1. Building Type / Condition
   - See legend
2. Vibration Type:
   - Transient: < 1,000 cycles
   - Continuous: < 100,000 cycles
3. Fragility and Importance Factor
   - Built into Class 4
   - Guide value for Class 4 is a range “between the values for Class 3 and half thereof”
   - i.e., professional judgment

Typical Effects of Construction Equipment

For example, pile driving, sheet piling, vibratory roller compaction, grading/bulldozers, demolition, heavy truck traffic…

Important to know the TYPE of the vibration to properly compare with vibration criteria

- Transient
- Steady-state, continuous
- In between

Typical Effects of Construction Equipment

Preliminary Estimation Methods (Screening)

- Wiss 1981
- FTA 2006
- CALTRANS 2004
- NCHRP 2012
- Others

More accurate prediction methods

- Analytical
- Site-specific testing (before construction)
- Field trials with actual equipment (at start of construction)

TYPE of Vibration*

Transient — **Steady-state / continuous**

Transient:

- Blasting
- Impact pile driving
- Pavement breaker

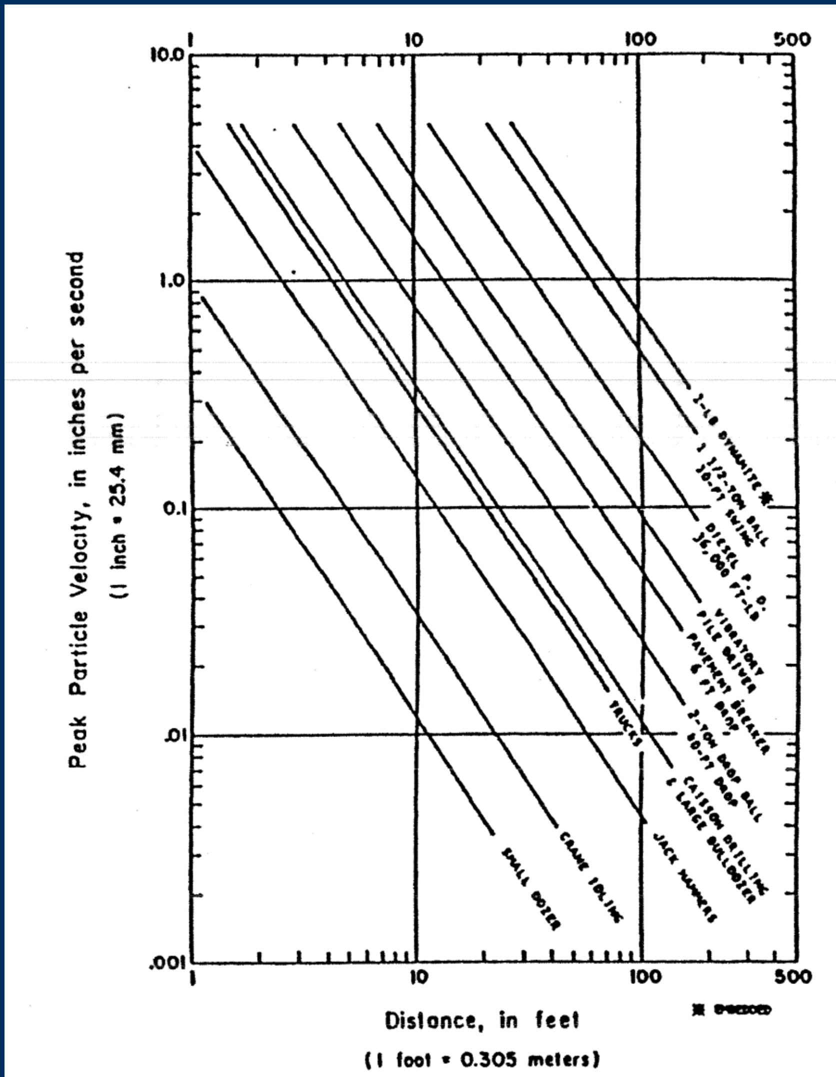
Steady-state / continuous:

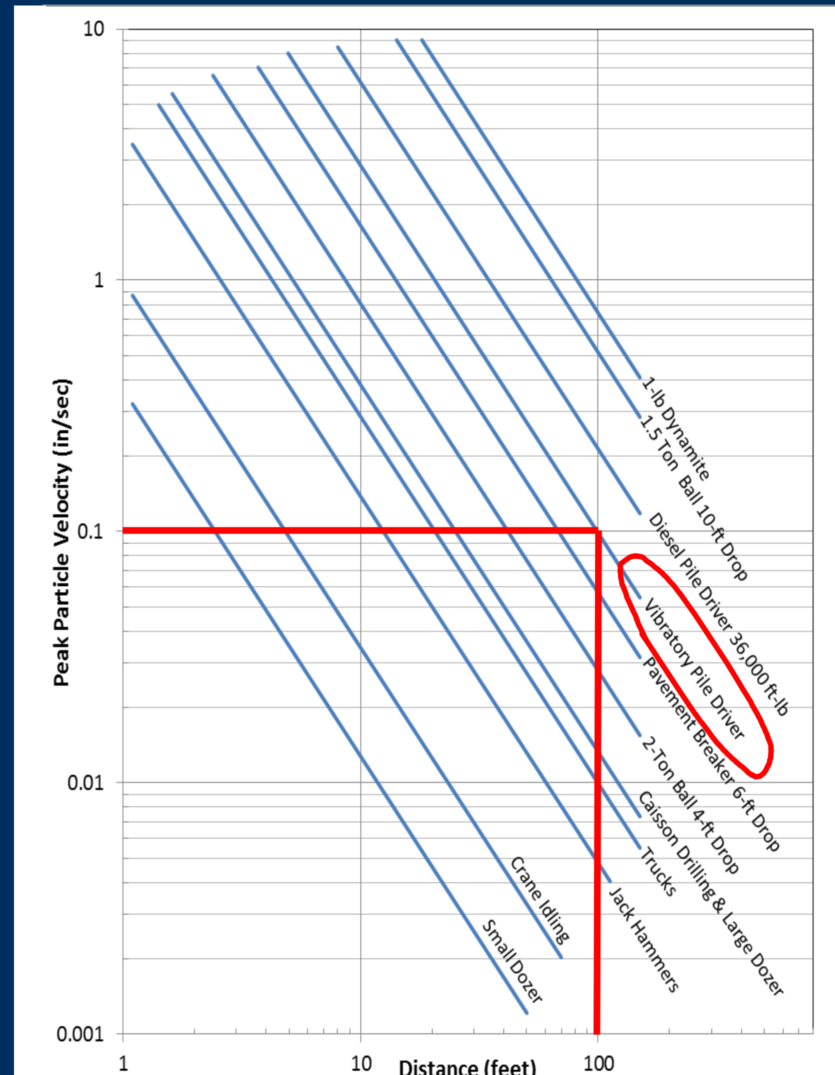
- Vibratory pile driving
- Vibratory sheet piling
- Dynamic soil composition
- Vibratory roller compaction

- Demolition
- Hydraulic breakers and similar
- Heavy construction equipment (bulldozers, etc.)
- Mass excavation, grading

* Important to know the type of the vibration to properly compare with vibration criteria

Preliminary Estimation - Wiss 1981





Wiss, John F. 1981. Construction vibrations: State-of-the-art. Journal of the Geotechnical Engineering Division, American Society of Civil Engineers..

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$PPV_{equip} = PPV_{ref} x (25/D)^n$

where: PPV (equip) is the peak particle velocity in in/sec of the equipment adjusted for distance

PPV (ref) is the reference vibration level in in/sec at 25 feet

D is the distance in feet from the equipment to the receiver

n is the attenuation exponent

n = 1.5 for *competent soils:* most sands, sandy clays, silty clays, gravel, silts, weathered rock (can dig with a shovel)

n = 1.1 for *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)

$PPV_{equip} = PPV_{ref} x (25/D)^n$

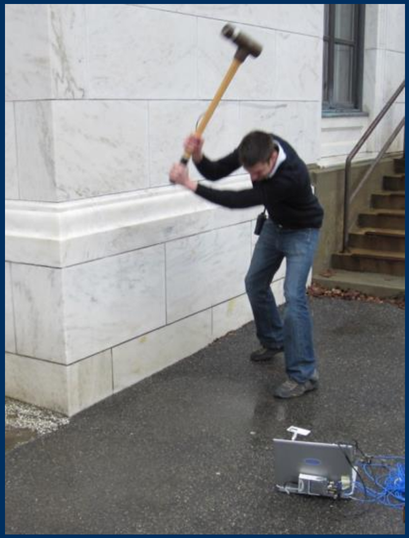
Table 2. Vibration Source Levels for Construction Equipment

Equipment	PPV at 25 feet
Pile driver (impact)	0.644 to 1.518
Pile drive (sonic/vibratory)	0.170 to 0.734
Vibratory roller	0.210
Hoe ram	0.089
Large bulldozer	0.089
Caisson drilling	0.089
Loaded trucks	0.076
Jackhammer	0.035
Small bulldozer	0.003

1. Transit Noise and Vibration Impact Assessment, Federal Transit Authority, U.S. Department of Transportation, (Washington, DC., 2006) Hanson, Towers, and Meister.
2. Transportation- and Construction-Induced Vibration Guidance Manual, prepared for Noise, Vibration and Hazardous Waste Office, California Department of Transportation, 2004, Jones, Stokes.
3. 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).

More Accurate Prediction Methods

- Analytical
- Site-specific testing (before construction)
  - Calibrated modal hammer impacts
  - Drop weight impacts
  - Soil characteristics / effects of soil-to-building interface




Most Accurate Prediction Method

- Field trials with actual equipment on location (at start of construction)

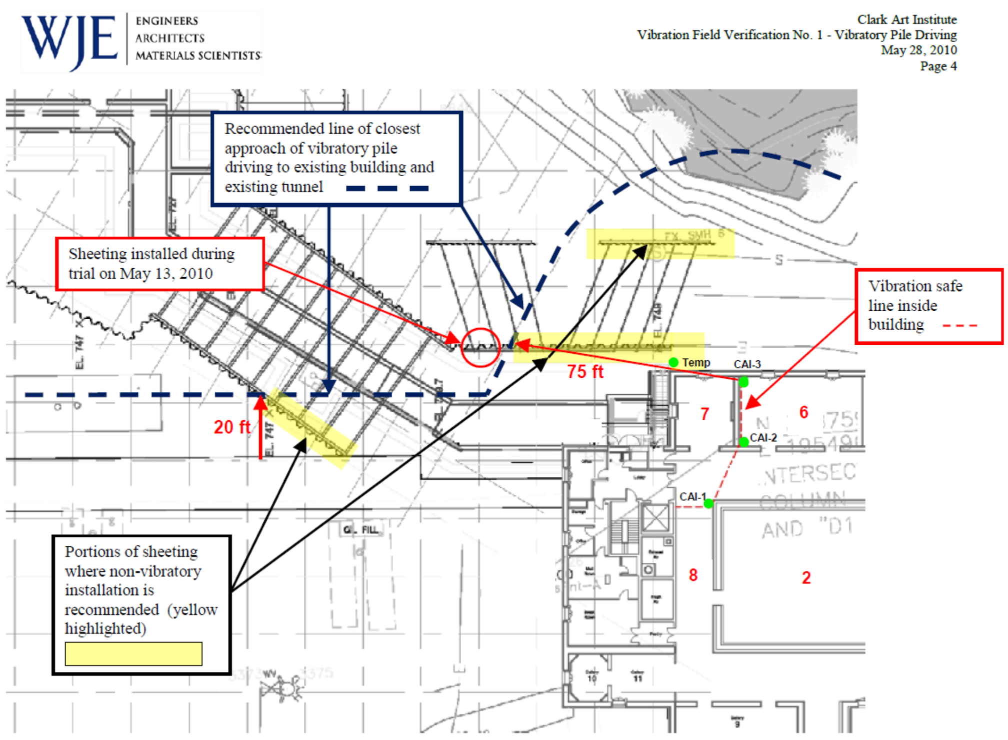


Figure 1. Plan showing sheet pile walls relative to vibration safe line, with results of trial and recommendations summarized

Typical Effects of Construction Equipment

Consider the TYPE of the vibration to properly compare with vibration criteria (transient vs. steady-state)

Preliminary estimation methods (screening)

More accurate prediction methods

- Analytical
- Site-specific testing (before construction)
- Field trials with actual equipment (at start of construction)

Questions / Discussion