Planning for Construction of the Modern Wing

Groundbreaking Ceremony
May 31, 2005

Opening on May 16, 2009
Predicting the Impact of Vibrations on Artwork

Object Characteristics
- Size
- Weight
- Shape
- Material
- Construction Method
- Condition
- Treatment History

Vibration Characteristics
- Amplitude
- Frequency
- Duration
A Need for Certainty

- Which artworks will need to be de-installed or relocated?
- How much temporary art storage will we need?
- Do any galleries need to be closed to the public?

- What would be a safe vibration limit during construction?
- How do we effectively monitor vibrations?
- How do we enforce the agreed upon limit?
Overriding Goals

- Keeping artwork safe through all phases of construction
- Avoiding costly suspensions of construction once it has begun
From Ambiguity to Certainty

- Which artworks will need to be de-installed or relocated?
- How much temporary art storage will we need?
- Do any galleries need to be closed to the public?

- What would be a safe vibration limit during construction?
- How do we effectively monitor vibrations?
- How do we enforce the agreed upon limit limit?
References


Technical Presentation *(Yes, I’m the engineer 😊)*

**References**


Goals of Vibration Control in Museum Context

- **Protection of collections** and museum buildings during all stages of construction.

- **Guidance** to the museum, before construction starts, to facilitate advanced planning (what vibration levels to expect, zones where limits could be exceeded, where/what to de-install, etc.)

- During design/construction process, **reliable enforcement of clear, conservative vibration limits** without unduly encumbering the designers and contractors.
Human Perception

![Graph showing particle velocity vs frequency]

- **Particle Velocity (in/sec)**
- **Frequency (Hz)**
- **INTOLERABLE**
- **DISTURBING**
- **PERCEPTIBLE**
- **ISO 2631-1 PERCEPTION**
Human Perception

The human body can perceive very low levels of vibrations.

Roughly, the perception threshold for steady-state vibrations is 0.03 in/sec.
Human Perception

The human body can perceive very low levels of vibrations.

Roughly, perception threshold for steady-state vibrations is 0.03 in/sec.

Vibrations become disturbing at 0.1-0.2 in/sec.
Ambient (Background) Levels in Buildings

Common Values:

- Closing doors, crowds walking: 
  \( \sim 0.02 \text{ - } 0.05 \text{ in/sec} \)
- Running, jumping: 
  \( \sim 0.05 \text{ - } 0.10 \text{ in/sec} \)
- Trains next to AIC: 
  \( \sim 0.03 \text{ - } 0.07 \text{ in/sec} \)
- Moving tables and chairs for event: 
  \( \sim 0.10 \text{ - } 0.15 \text{ in/sec} \)
Ambient (Background) Levels in Buildings

Common Values:
- Closing doors, crowds walking: ~0.02 - 0.05 in/sec
- Running, jumping: ~0.05 - 0.10 in/sec
- Trains next to AIC: ~0.03 - 0.07 in/sec
- Moving tables and chairs for event: ~0.10 - 0.15 in/sec
**Ambient (Background) Levels in Buildings**

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Damage Levels for Buildings

U.S. Bureau of Mines testing, 1970s and 1980s
**USBM RI-8507 Damage Levels for Buildings**

<table>
<thead>
<tr>
<th>Damage Observed</th>
<th>PPV (in/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Threshold damage (hairline cracking in plaster, opening of old cracks, etc.)</td>
<td>3.0</td>
</tr>
<tr>
<td>Minor damage (hairline cracking in masonry, breaking of windows)</td>
<td>&lt;0.5 (never)</td>
</tr>
<tr>
<td>Major structural damage (cracking or shifting of foundations or bearing walls)</td>
<td>8.0</td>
</tr>
</tbody>
</table>
Artwork and Vibrations
Artwork in Transit
Artwork in Transit

- Special vetting, crating, and bracing of objects is performed
Artwork in Transit

- Special vetting, crating, and bracing of objects is performed.
- Shocks (short, transient vibrations) of 10g's (31 in/sec) on objects are common (e.g., due to crate handling, abrupt starts/stops, etc.)
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- During truck transit, sustained vibrations on objects of 1.5 to 3.0 in/sec are common
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- **During truck transit, sustained vibrations on objects of 1.5 to 3.0 in/sec are common**
- Yet, adverse effects rarely occur.
Artwork in Transit

- Special vetting, crating, and bracing of objects is performed

- Shocks (short, transient vibrations) of 10g’s (31 in/sec) on objects are common (e.g., due to crate handling, abrupt starts/stops, etc.)

- During truck transit, sustained vibrations on objects of 1.5 to 3.0 in/sec are common

- Yet, adverse effects rarely occur
Artwork Near Construction

- Vibration limits from **0.1 to 1.5 in/sec** have been successfully used to protect artwork during past museum construction projects (i.e. with no damage reported)
Artwork Near Construction

- Vibration limits from **0.1 to 1.5 in/sec** have been successfully used to protect artwork during past museum construction projects (i.e. with no damage reported)

- Very little information on levels that have caused damage, as this is obviously to be avoided

- One case reported: British Museum, 2000:
  - **Damage occurred** to 12 art objects at **~0.6 to 1.8 in/sec**, all in areas of pre-existing weakness
Superimpose and Simplify...

Particle Velocity (in/sec)

10
1
0.1
0.01
Superimpose and Simplify...

Art in shipment/transit:
~1.5 to 3 in/sec common, much larger periodic shocks

USBM residential building damage research:
- Minor to major structural damage from ~2 to 8 in/sec
- Threshold cracking never observed below 0.5 in/sec

Damage at British Museum (pre-existing weaknesses)
~0.6 to 1.8 in/sec

Vibration limits in this zone should be adequate to protect artwork in reasonably sound condition

Ambient levels: ~0.02 to 0.1 in/sec

Human perception threshold: ~0.03 in/sec
Superimpose and Simplify...

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Limits for Museum Art Collections

- **Limit of 0.1 in/sec** should be conservative to protect most art objects in reasonably sound condition
- Used successfully on several U.S. museum construction projects
Limits for Museum Art Collections

- **Limit of 0.1 in/sec** should be conservative to protect most art objects in reasonably sound condition
- 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 continuous construction vibrations
  - Extremely fragile objects or those with serious pre-existing weaknesses
Vibration Control Methodology
Vibration Control Methodology

Goals:
1. Protect collection and building
2. Guidance to museum for advance planning
3. Enforce limits without undue constraints
Vibration Control Methodology

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1. Protect collection and building
2. Guidance to museum for advance planning
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Before Construction

At Start of Construction

During Construction

Preconstruction testing
Planning with museum
Specification
Vibration Control Methodology

Goals:
1. Protect collection and building
2. Guidance to museum for advance planning
3. Enforce limits without undue constraints

Before Construction:
- Preconstruction testing
- Planning with museum

At Start of Construction:
- Submittals
- Vibration trials

During Construction

Legs:
- Blue:
- Grey:
  - Planning with museum
  - Preconstruction testing
Vibration Control Methodology

Goals:
1. Protect collection and building
2. Guidance to museum for advance planning
3. Enforce limits without undue constraints

- Before Construction:
  - Preconstruction testing
  - Planning with museum

- At Start of Construction:
  - Submittals
  - Vibration trials

- During Construction:
  - Vibration monitoring
  - Alarms and protocols
Example - The Modern Wing
Before Construction

Selection of vibration limits
Preconstruction testing
Planning with museum
Vibration control specification
Preconstruction – Vibration Limits

Building limit:
- 0.5 in/sec baseline (USBM safe limit)

Artwork limit:
- 0.1 in/sec baseline
- Conservative for objects in reasonably sound condition
Preconstruction – Site Testing to Predict Levels

AIC Lower Level

AIC First Level
Preconstruction – Site Testing to Predict Levels

- To be demolished
- To remain

Demolition Line

AIC Lower Level
AIC First Level

Make impact (low-level)
Measure response
Preconstruction – Site Testing

Modal hammer impacts

Vibration sensors in galleries
Preconstruction – Vibration Prediction

“Contour lines” for large hydraulic breakers operating along demolition line
Preconstruction – Vibration Prediction

“Contour lines” for large hydraulic breakers operating along demolition line

To be demolished

AIC Lower Level

Demolition Line

AIC First Level

Demolition Line
Preconstruction – Vibration Prediction

“Contour lines” for large hydraulic breakers operating along demolition line

To be demolished

Demolition Line

AIC Lower Level

AIC First Level
Preconstruction – Define “Safe Lines”

AIC Lower Level

“Safe Line”

Protected zone (safe for sensitive art to remain)

AIC First Level

“Safe Line”

Protected zone (safe for sensitive art to remain)
Preconstruction – Define “Safe Lines”

AIC Lower Level

Protected zone (safe for sensitive art to remain)

“A Safe Line”

AIC First Level

Protected zone (safe for sensitive art to remain)

“A Safe Line”
Preconstruction – Define “Safe Lines”

Unprotected zones (de-install sensitive art)

“Safe Line”

Protected zone (safe for sensitive art to remain)

AIC Lower Level

Unprotected zones (de-install sensitive art)

“Safe Line”

Protected zone (safe for sensitive art to remain)

AIC First Level
SECTION 01576
VIBRATION PROTECTION REQUIREMENTS
FOR EXISTING BUILDINGS ALONG INTERFACES
WITH NEW CONSTRUCTION

PART 1 - GENERAL

1.1 RELATED DOCUMENTS
A. Drawings, Specifications and general provisions of the Contract, including General and
   Supplementary Conditions and other Division 1 Specification Sections, apply to this Section.

1.2 SUMMARY
A. This Section includes the following:
   1. This section defines requirements and limitations for the contractor’s operations with
      respect to causation of vibrations and vibration-induced damage within the existing
      buildings that are to remain adjacent to the south elevation line of the New North Wing.
      These areas include existing areas of the Art Institute, the McKinlock, Rubloff,
      Gusmanus, and Rice Buildings. This Section also defines requirements for monitoring
      procedures and inspections to be taken by the Contractor within the existing
      buildings during the construction activities. This Section also provides requirements for
      actions that shall be taken in the event that exceed vibration limits are exceeded and/or
      that construction activities cause damage to existing buildings or building contents.
   2. The requirements, limitations and inspections of this Section are intended to help avoid
      vibration-induced damage to the existing buildings and building contents. These
      provisions were developed to help prevent damage caused by site dewatering. Refer to
      other sections of the project specifications for special provisions regarding site
      dewatering.
   3. The provisions of this section are minimum requirements that shall be followed. They
      do not relieve the Contractor of the responsibility to prevent construction-related damage
to the existing buildings and building contents during all of the construction activities.
      This responsibility rests solely with the Contractor. Any damage to the buildings or
      building contents caused by the Contractor shall be repaired to the Owner’s satisfaction
      at no cost to the Owner.

1.3 REFERENCE DOCUMENTS
A. “Study to Estimate Vibration Caused by Demolition Activities at New North Wing Interfaces,”
   prepared for the Art Institute of Chicago by Wiss Janney Elstner Associates, Inc. A copy of this
   report is available from the Owner upon request. This study provided estimates of vibration
   levels that could be caused by standard pieces of construction equipment operating near
   the demolition line. The estimates were developed to assist the Owner in their decisions about

VIBRATION PROTECTION MEASURES
ALONG EXISTING BUILDING INTERFACES

- Vibration limits and “safe lines”
- Contractor devise work so as not to exceed limits
Vibration Control Specification

- Vibration limits and “safe lines”
- Contractor devise work so as not to exceed limits
- Minimum requirements, guidance to contractor
- Require field trials
- Define monitoring system and alarm capabilities
- Define protocols to be followed if above-limit alarm occurs
Vibration Control Specification

- Vibration limits and "safe lines"
- Contractor devise work so as not to exceed limits
- Minimum requirements, guidance to contractor
- Require field trials
- Define monitoring system and alarm capabilities
- Define protocols to be followed if above-limit alarm occurs
At Start of Construction

Contractor means and methods submittals
Vibration trials
Field Trials

1. Conduct Field Trials for every vibration-causing activity
   - Actual methods at safe distance from art
   - Monitoring during simulated activities
2. If vibration levels are within limits, proceed
3. If not, change methods and repeat trial
Vibration Trials

Caissons / drilled piers

H-piles and sheet piling
Field Trials

Large hydraulic breakers

Cooling tower selective demolition
During Construction

Vibration monitoring
Alarms and event protocols
Vibration Monitoring

Demolition line monitors (0.50 in/sec)

"Safe Line" monitors (0.10 in/sec)

Protected zone (safe for sensitive art to remain)

AIC Lower Level

AIC First Level
Alarms and Notifications

- Monitoring system capable of immediate email notifications of any above-limit measurements.
Part 1 - General

1.1 Related Documents
A. Drawings, specifications and general provisions of the contract, including general and supplementary conditions and other division, specification sections, apply to this section.

1.2 Summary
A. This Section includes the following:

1. This Section defines requirements and instructions for the contractor's operations with respect to cessation of vibration and vibration-related damage within the existing buildings that are to remain adjacent to the south demolition line of the New North Wing. These areas include existing areas of the buildings known as the McKie Building, Rasoff, Cunard, and Rice Buildings. The Section also defines requirements for monitoring procedures and inspections to be carried out by the Contractor within the existing buildings during the construction activities. This Section also provides requirements for actions that shall be taken in the event that specified vibration limits are exceeded and/or that construction activities cause damage to the existing buildings or building contents.

2. The requirements, instructions, and procedures of this Section are intended to help avoid vibration-induced damage to the existing buildings and building contents. These provisions will not be held in damages caused by site excavation, refer to other sections of the project specifications and provisions regarding site excavation.

3. The provisions of this Section are minimum requirements that shall be followed. They do not relieve the Contractor of the responsibility to prevent construction-related damage to the existing buildings and building contents during all of the construction activities. This responsibility rests solely with the Contractor. Any damage to the buildings or building contents caused by the Contractor shall be repaired to the Owner's satisfaction at no extra cost to the Owner.

1.3 Reference Documents
A. "Study to Estimate Vibrations Caused by Demolition Activities at New North Wing Interfaces," prepared for the Architect of Chicago by Wiss, Janney, Elstner Associates, Inc. A copy of this report is available on request. This study provided estimates of vibration levels that could be caused by standard pieces of construction equipment operating near the demolished line. These estimates were developed to assist the Owner in their decisions about vibration protection measures.
Alarms and Notifications

- Monitoring system capable of immediate email notifications of any above-limit measurements
- Construction must stop immediately!
- Review cause, inspect building, change methods
Alarms and Notifications

- Monitoring system capable of immediate email notifications of any above-limit measurements

- Construction must stop immediately!

- Review cause, inspect building, change methods
Weekly Data Reports

### Vibration Monitoring Summary Report

**Report Period:** 01/07/2008 - 01/13/2008

**Project:** AIC Galleries Hall Restoration

**Client:** The Rise Group

**Contractor:** Turner Special Projects

**Owner:** The Art Institute of Chicago

#### Vibration Data Summary

<table>
<thead>
<tr>
<th>Axis</th>
<th>Velocity (in/sec)</th>
<th>Frequency (Hz)</th>
<th>Time of Day (HMS)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>North-South</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>East-West</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vertical</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gallery 21A</td>
<td>0.009</td>
<td>3.1</td>
<td>1:09:15.78</td>
</tr>
<tr>
<td>Gallery 149</td>
<td>0.010</td>
<td>2.6</td>
<td>1:03:58.10</td>
</tr>
<tr>
<td>Gallery 244</td>
<td>0.011</td>
<td>4.8</td>
<td>1:11:08.51</td>
</tr>
<tr>
<td></td>
<td>North-South</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>East-West</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Vertical</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gallery 113A</td>
<td>0.010</td>
<td>3.3</td>
<td>1:00:40.15</td>
</tr>
<tr>
<td>Gallery 246</td>
<td>0.012</td>
<td>2.8</td>
<td>1:04:09.09</td>
</tr>
<tr>
<td>Gallery 247</td>
<td>0.012</td>
<td>2.8</td>
<td>1:04:09.09</td>
</tr>
<tr>
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<td>0.012</td>
<td>2.8</td>
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</tr>
<tr>
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</tr>
<tr>
<td></td>
<td>Vertical</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gallery 248</td>
<td>0.013</td>
<td>3.0</td>
<td>1:01:18.24</td>
</tr>
</tbody>
</table>

**Remarks:**
1. See Pages 7-7 for comparison of PPU against project threshold levels.
2. See Pages 8-10 for time history chart of PPU.
3. This weekly vibration summary report does not include vibration events occurring at frequencies greater than 100 Hz. High frequency vibrations should not be damaging to artwork or building components and therefore are not included in the project limit. Note that accelerations are set for trigger events occurring at any frequency, including those greater than 100 Hz to allow for engineering review and to ensure that underlying low-frequency vibrations do not exceed the project limits.

**Signed:** Nathan K. Mendel

**Submitted By:** Nathan K. Mendel

### Peak Particle Velocity vs. Frequency

**AIC Gallery 131A: Gallery Floor**

**Instantaneous Peak Velocity Limit**

**SERIAL NO.: 12564**

**REPORT PERIOD:** 01/07/2008 - 01/13/2008

**Frequency (Hz) vs. Peak Particle Velocity (in/sec)**

- **x: Longitudinal**
- **o: Transverse**
- **c: Vertical**

- **AIC Galleries Hall Restoration Project Limit**

- **Project Limit**

- **Serial Number:** 12564
Vibration Control Methodology

Goals:
1. Protect collection and building
2. Guidance to museum for advance planning
3. Enforce limits without undue constraints

- Preconstruction
  - Planning testing
  - Specification

- Before Construction

- At Start of Construction
  - Vibration trials

- During Construction
  - Alarms and protocols

- Vibration monitoring
Vibrations During Normal Operations

Possible Sources:
- Heavy traffic outside (trains, buses, trucks, etc.)
- Construction on neighboring sites
- Mechanical equipment
Vibrations During Normal Operations

Mitigation:

1. Advocate with entity causing the vibration (reduce or control their activities)
2. Move sensitive artwork away from high vibration zones
3. For non-moveable objects, design vibration isolation mounts or supports
Vibration Demonstration!

Shake it up baby!

WJE-Designed Vibration Simulator
Vibration Demonstration!

Shake it up baby!

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Vibration Demonstration!

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Vibration Demonstration!

WJE-Designed Vibration Simulator

Shake it up baby!
Vibration Demonstration!

Shake it up baby!

WJE-Designed Vibration Simulator
Typical Vibration Monitoring Equipment

Typical seismograph

Custom laptop-based system
Typical Vibration Monitoring Equipment

Typical seismograph

Custom laptop-based system
Human Perception (2 Volunteers Please! 😊)

- Intolerable:
- Disturbing:
- Perceptible:
- ISO 2631-1 Perception:

Frequency (Hz)

Particle Velocity (in/sec)
Potential for Resonance

Art Institute jade collection

Model to replicate jade collection

Constant PPV = 0.5 in/sec
Sweep through frequencies:
Potential for Resonance

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Sweep through frequencies:
Potential for Resonance

Constant PPV = 0.5 in/sec
Sweep through frequencies:
5 Hz – little response
9 Hz – RESONANCE right
10.5 Hz – little response
12 Hz – RESONANCE center
20 Hz – little response
33 Hz – RESONANCE left
Potential for Resonance

Constant PPV = 0.5 in/sec
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“Walking” (light objects, smooth surfaces)

Clark Art Institute – potential for walking

Taft Museum of Art – potential for walking

Simulation...
Watch cordial walk to RIGHT...

Steady-state
\[ f = 32 \text{ Hz} \]
"Walking" (light objects, smooth surfaces)

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Steady-state
f = 32 Hz

Simulation…
Watch goblet walk to LEFT…

Steady-state
f = 20 Hz
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Simulation... Watch cordial walk to RIGHT...
Steady-state $f = 32$ Hz

Taft Museum of Art – potential for walking

Simulation... Watch goblet walk to LEFT...
Steady-state $f = 20$ Hz
Human Perception (Tell us what you feel! 😊)

- Intolerable
- Disturbing
- Perceptible

ISO 2631-1 Perception

Particle Velocity (in/sec)

Frequency (Hz)
Human Perception (Tell us what you feel! 😊)

- Intolerable
- Disturbing
- Perceptible

ISO 2631-1 PERCEPTION

Particle Velocity (in/sec)

Frequency (Hz)

0.03

0.01

0.001

0.0001

0.00001
Questions

Vibration Control During Museum Construction Projects
Journal of the AIC 2013, Vol. 52 No. 1, 30-47