# U.S. Practice in Vibration Control During Museum Construction Projects

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## Introduction

Protecting museum collections against potentially damaging construction vibration is of paramount importance. Significant advances have been made recently in the practice of vibration control during museum construction projects in the United States. A significant step forward occurred as part of the Modern Wing addition to the Art Institute of Chicago, designed by renowned architect Renzo Piano. In the early 2000s, faced with an addition to the Art Institute that included very heavy construction work nearby many interfaces with existing occupied galleries, the authors partnered with Frank Zuccari, longtime Head of Conservation at the Art Institute, to find a solution that would protect the artwork while still allowing practical design and construction methods so that Renzo's vision for the museum could become a reality.

A comprehensive literature search of conservation and engineering journals was conducted to learn about measuring and mitigating vibrations on artwork during its transit and during the execution of nearby construction. Mervin Richard, Head of Conservation at the National Gallery of Art and noted expert in art transit and crating, was a valuable consultant. Information from these sources was coupled with the authors' experience in the field of testing and instrumentation to establish a scientific, step-by-step methodology to protect the Art Institute of Chicago's collection throughout the multi-year construction of the Modern Wing, which opened in 2009.

Given the success of the Modern Wing project, the authors were retained to provide similar assistance at other museums. In 2013, the authors teamed with Frank Zuccari to produce a technical paper summarizing their approach.[1] Since publication of the paper, the authors have continued to apply and refine their methods as part of numerous other museum construction projects.

This paper summarizes the current state of practice for construction-related vibration control at museums in the United States and identifies areas where further development would be useful.

## General Methodology

As detailed in the referenced article, the five steps listed below comprise the foundation of a practical method for protecting vibration sensitive museum contents during a construction project. Each step includes common tasks. The extent to which any particular task is implemented, or whether additional efforts are warranted, should be based on project-specific considerations, including the needs and goals of each institution.

### Step 1 - Preconstruction testing

- Ambient (background) vibration measurements within the museum
- In situ vibration measurements at the museum using low-level calibrated impacts or simulated activities using actual construction equipment
- Estimation, based on the test data, of the actual levels of vibration that the museum is likely to experience due to planned construction activities

### Step 2 - Preconstruction planning

- Selection of vibration criteria (limits) for the project considering the following: potential damage thresholds and typical artwork and building protection limits; results of ambient vibration monitoring; recommendations of a collections specialist or conservator regarding the specific art objects to be protected
- Development of artwork stabilization and relocation plans, if any, considering results of preconstruction testing, selected vibration criteria, and input from collections specialist or conservator

### Step 3 - Development of a vibration control specification

See referenced article for details to be included in a project-specific vibration control specification that should be included in the contract documents for the construction project. General provisions are usually as follows:

- Require careful pre- and post-construction surveys of building and artwork

[1] Johnson, A. P., W. Robert Hannen, and F. Zuccari, "Vibration Control during Museum Construction Projects", Journal of the American Institute for Conservation, Vol. 52 No. 1 (2013), p. 30-47.

- Define the vibration limits and the lines in the museum along with those limits apply, termed “safe lines,” and require contractor to devise their work so as not to exceed the limits (vibration-sensitive artwork is moved behind the “safe lines” before construction begins)

- Provide minimum requirements and guidance for the contractor’s means and methods

- Require field trials at the start of construction

- Define the vibration monitoring system, including immediate alarm and notification capabilities

- Mandate that construction stop immediately if an alarm is triggered

- Define exact procedures to be followed after all alarm events, including engineering evaluation, repeat surveys, and possible modifications to construction methods

### Step 4 - Field vibration trials using proposed construction methods

- At the start of construction, execution of field trials consisting of vibration measurements in the museum during trial activities using equipment and methods proposed for use by the contractor

- Verification that measured vibrations are within adopted protection limits

### Step 5 - Vibration monitoring during actual construction

- Review of contractor’s vibration control plan and means and methods submittals

- Continuous vibration monitoring throughout construction at locations consistent with specifications

- Monitoring system to provide immediate notifications of above-limit measurements, halt all work when such notifications occur, and evaluate artwork in area(s) affected by above-limit vibrations before construction is allowed to resume

- Regular inspection of art objects by museum staff

*Figure 1: Demolition of existing buildings and buried seawall adjacent to active art galleries at The Art Institute of Chicago*

## Project Experience

Listed below are institutions and projects where the authors have implemented vibration control plans as outlined above. The vibration limit used for protection of artwork has typically been 0.10 or 0.12 in/sec, although a few special cases required lower limits. Each project was completed with no observable damage to the artwork.

- Art Institute of Chicago: Modern Wing Addition (2001-2009); Gunsaulus (Alsdorf) Hall Renovation (2008-2009); Jackson Drive Bridge Reconstruction (2006-2008); Various gallery renovations (2006, 2007, 2010, 2016)

- Saint Louis Art Museum Expansion, St. Louis, MO (2007-2011)

- Clark Art Institute Expansion, Williamstown, MA (2010-2012)

- Oriental Institute Museum at University of Chicago (adjacent construction 2011-2014, 2016)

- Taft Museum of Art, Cincinnati, OH (adjacent construction 2013-2016)

- Pulitzer Arts Foundation, St. Louis, MO (interior gallery expansion, 2014-2015)

- Smart Museum at the University of Chicago (adjacent demolition 2013-2016)

- Neue Galerie, New York, NY (interior construction 2016)

- Albright-Knox Art Gallery, Buffalo, NY (art storage facility expansion 2016-2017)

- Carnegie Museum of Art, Pittsburg, PA (adjacent building construction, 2016 study)

- Kemper Art Museum at Washington University in St. Louis, MO (adjacent construction 2016-2019)

In each case, the museum staff and contractors found the process to be reasonable. From the contractor's perspective, the construction was achievable within the specified vibration limits. Having clearly defined limits and alert response protocols meant the ability to plan their work in advance, estimate costs accurately, and execute with a minimum of disruption. Synchronized monitoring provided rapid feedback, enabling construction methods to be modified as needed to minimize impact. From the museum's perspective, the ongoing monitoring and rapid warning mechanism offered assurance that any construction activities exceeding the limits would be detected and corrected quickly. Advance prediction of vibration levels made it possible to make informed decisions about which galleries to keep open, which to close, and which pieces to deinstall or relocate.

In cases where vibration transmission into the existing building was complicated and uncertain, and levels of vibration near adjacent artwork could be high, extensive preconstruction testing and vibration trials were conducted. Where vibration transmission was easier to predict and levels were not expected to be near a conservative artwork protection limit, preconstruction testing was omitted and vibration trials simplified to the first day of work with the most critical vibration-causing equipment.

In most cases, the artwork remained and was protected with a carefully-designed monitoring system. In a few cases, artwork was deinstalled from the galleries closest to the construction, and so-called "safe lines" were established in front of the remaining artwork, along which vibration monitors were installed as a "line of defense" to protect the remaining artwork. Where trials or alarms indicated excessive vibrations, the contractor's equipment and methods were restricted in the problem areas. Where such limitations were not practical, protection or relocation of sensitive artwork was necessary.

## References

Several recently-published technical articles provide information on this topic, each with its own focus and usefulness, as highlighted below. Presentations have been made by the authors at the following conferences: American Institute for Conservation (2013), Association for Preservation Technology International (2014), Association of Registrars and Collections Specialists (2015), International Association of Museum Facility Administrators (2015), and the Smithsonian Institution in Washington D.C. (2015).

### Johnson et al., JAIC 2013[1]

This paper provides a comprehensive summary of vibrations in terms of human perception, damage to buildings, and artwork exposed to vibrations in transit from nearby construction. It also presents a generalized methodology for vibration control during museum construction projects, along with case studies examples. The methodology utilizes a structure-level protection approach, as further described below.

### Wei et al., 2014[2]

This publication provides an overview of the effects of vibrations on artwork, particularly objects exposed to vibrations for long periods of time. Based on their research, the authors are evaluating fatigue of art objects and attempting to develop methods to predict the time to damage for a given vibration level. Pending further research, a protection limit of 0.08 in/sec (2 mm/sec) is recommended for vibration exposure of up to six months.

### Johnson and Hannen, APT 2015[3]

This document reviews international standards for vibration limits for buildings, and by synthesis of those standards puts forward a rational method for developing vibration limits at particular historic buildings adjacent to particular construction sites. Comments on vibration limits for historic museum buildings and art collections are included.

### Smyth et al., JAIC 2017[4]

This paper describes an object-level approach used for vibration control during a recent construction project at the Metropolitan Museum of Art (the Met) in New York City. It discusses innovative vibration mitigation strategies for individual objects, including use of Sorbothane pads below individual objects and casework (along with a custom software tool for optimal design of isolation pads), and a tuned mass damper to reduce floor vibrations in a gallery.

The object-level approach used by Smyth et al. is fundamentally different from the structure-level approach used by Johnson et al. Both approaches are valid and, if correctly understood, complementary. They can be used separately as situations dictate, or in combination in some situations for more effective/efficient results. The

[1] Ibid.

[2] Wei, W., L. Sauvage, and J. Wölk. 2014. "Baseline Limits for Allowable Vibrations for Objects." In ICOM-CC 17th Triennial Conference Preprints, Melbourne, 15-19 September 2014, ed. J. Bridgland, art. 1516, 7 pp. Paris: International Council of Museums. (ISBN 978-92-9012-410-8).

[3] Johnson, A.P. and W. R. Hannen, "Vibration Limits for Historic Buildings and Art Collections," APT Bulletin - Journal of Preservation Technology, 46:2-3, 2015, p. 66-74.

[4] Smyth, A. W., P. Brewick, R. Greenbaum, M. Chatzis, A. Serotta and I. Stunkel, "Vibration Mitigation and Monitoring: A Case Study of Construction in a Museum," Journal of the American Institute for Conservation, Vol. 55 No. 1 (2016), p. 32-55.

differences between the two methods are presented in Table 1 and noted as follows:

- The structural-level approach follows the format of international standards for vibration limits for buildings, in which vibrations are assumed to originate outside the structure and to be measured at the base of the building. The vibration limits increase at higher frequencies because higher frequency vibrations typically attenuate (reduce with distance) relatively rapidly in the transmission process. Also, most building structures do not significantly amplify higher frequencies. (Note that these factors do not necessarily apply for vibration sources internal to a structure and in close proximity to the artwork.)

- The structural-level approach uses a "line of defense" concept where vibrations are measured at the base of the structure or at "hard points" within the structure nearer to the vibration source(s) than the protected artwork, not on a wall or floor or on an object within the building. As such, the "line of defense" acts to measure the effectiveness of the soil and structure as attenuators of the vibrations before they reach the objects. Such a method is typically more practical and cost effective than in the object-level approach. For example, a few vibration monitors positioned along a monitoring line could protect hundreds of art objects located behind the line, whereas individual monitors would be required at each object under the object-level approach.

- In the structure-level approach, vibrations at locations of artwork support are not monitored. This means that amplification between a monitoring point and a piece of artwork can go undetected. (Amplification occurs when the natural frequency of the structure, or a sub-assembly within the structure, is close to the frequency of the vibration input.) As such, Johnson et al. are careful to caution that special risks exist in the structure-level approach, such as "walking" of light objects on smooth surfaces and greater than normal amplification (approaching resonance) of objects that happen to have natural frequencies similar to continuous vibration inputs. Special measures need to be taken to protect against these unique risks where they exist.

- The artwork limit recommended by Johnson et al. for the structure-level approach (0.1 in/sec PPV, increasing at higher frequencies) is based on many factors and assumptions, recognizing that there is no standardized limit to protect artwork and that the response of artwork is too complicated to generalize. The recommended limit follows the format of many international standards for vibration limits for buildings, but includes an arbitrary reduction factor ("importance factor") as is appropriate for the museum environment. The limit is characterized as a conservative limit for artwork in reasonably sound condition, to be adjusted for individual projects and special cases.

- The object-level approach measures vibration directly on objects or on the floors or casework adjacent to objects. Although this can be a more accurate means of protecting individual objects, it must be understood that the response of different art objects is extremely complicated and variable. As such, this approach would require monitoring of every object being protected and a corresponding array of item-specific vibration limits, which might not be practical.

*Figure 2: Earth retention system and deep excavation for expansion to The Saint Louis Art Museum, with active art galleries inside museum walls*

## Further Development

From the authors' perspective, the current state of practice could benefit from further development in the following areas:

- Education on the differences between a structure-level and object-level protection approach, along with the limitations of each and how the methods can be used separately or in combination to achieve improved results.

- For the structure-level approach, further understanding on when limits should be allowed to increase at higher frequencies. At present, the authors do not allow an increase when the vibration source is interior to the building and in close proximity to installed artwork. An increase is allowed when vibrations originate outside or at the perimeter of the structure and not in close proximity to installed artwork.

- For the object-level approach, further understanding of the vibration limits that should be used for individual objects or types of objects.
- Further understanding and usage of object-level mitigation techniques (isolation pads, dampers, etc.), along with strategies for practical implementation.
- More accurate prediction of vibration transmission for specific buildings and construction activities, using a combination of in situ preconstruction testing and structural analysis techniques.
- Further understanding of the potential for dynamic amplification (resonance) of building components and sub-assemblies within buildings subjected to continuous vibrations, along with possible mitigation techniques.
- Further research into the effects of long-term exposure of art objects to vibrations.

| **Structure-based approach used by Johnson et al.** | **Object-level approach used by Smyth et al.** |
|---|---|
| a. The method was developed over the course of a few projects and generalized in order to be applicable to many museum environments with similar conditions. Its recommendations need to be verified and adjusted for each individual case, as described in the paper. | a. Method is specific to one very specialized case, not generalized. The project involved an extremely large collection of extremely fragile and valuable objects, many of which could not be moved, and all of which were located immediately adjacent to construction that occurred within the building. |
| b. Construction is assumed to occur outside or at the perimeter of the building, and not in close proximity to artwork. As such, the soil and structure act as a “filter” before vibrations reach the interior of the structure or objects within the building. | b. The construction occurred inside the building, not outside. Some construction occurred directly on the structure very close to supported objects. This created a much different object-level response than if the vibrations originated outside the building |
| c. The method appeals to vibration limits developed for monitoring vibrations at the base of a building, not directly on objects or building components (walls, floors, ceilings, etc.) where amplification effects are occurring. The limits are factored down due to uncertainties and the cultural value inherent in a museum environment and account for the fact that some moderate level of amplification will occur in building components and objects. For example, a U.S. Bureau of Mines study measured amplification of 4 to 8 times on walls and ceilings. In other words, the limits take this typical level of amplification into account. Therefore, in the implementation of this method, vibrations are measured at the base of the building or at “hard spots” inside the building such as next to building columns or load bearing walls where amplification is not occurring. | c. Vibrations were measured directly on objects, as well as on casework and floors. This means that the measured vibrations included a myriad of complex structural component and object-level effects, including amplification at a wide range of natural frequencies. Therefore, Smyth et al. opted to use very low vibration thresholds from 0.04 and 0.12 in/sec, independent of frequency. This was a very conservative approach that was appropriate for this individual case. Note, however, that there is little basis for the vibration thresholds used. A possible basis could be gained by citing ambient levels of vibration measured directly on the objects, or vibration that occur directly on art objects during art shipment/transit. |
| d. Structure-based, generalized, “line of defense” approach intended to protect most art objects in reasonably sound condition. | d. Object-level approach for one particular project. Objects were extremely fragile, numbered in the thousands, were generally not moveable, and construction occurred inside the building. |
| e. The method provides cautions and caveats for special cases that can occur within certain museum environments, including walking of light objects on smooth surfaces at lower vibration levels, potentially problematic resonance effects (i.e., higher than normal amplification at certain objects or building components), and potential vulnerability of extremely fragile objects at lower vibration levels. The paper cautions that special measures should be taken to protect against these risks on a case-by-case basis. | e. Accounts for the caveats and special cases mentioned in the Johnson et al. paper by using a very conservative, frequency-independent limit (alert threshold) and taking special measures to protect individual objects. |

*Table 1: Comparison of structure-level protection approach (after Johnson et al.) and object-level protection approach (after Smyth et al.)*