Vibrations and Museum Collections, Part 1

The Effects of Vibrations from Human Traffic and Construction on Museum Collections

By Arne Johnson and Mohamed ElBatanouny

Introduction

Vibration of museum gallery floors, and the corresponding vibration of museum objects, can be caused by normal human activities under certain circumstances. Vibrations can also be caused by nearby construction work, and these vibrations are often of greater magnitude and significance when it comes to potential damage to collections. Mitigation of problematic floor vibrations, although sometimes challenging, can be achieved using a variety of engineering evaluation and design methods.

This article provides brief background on human- and construction-induced vibrations, and illustrates these principles using a recent case study: mitigation of floor vibrations in the new SUE gallery at The Field Museum in Chicago, Illinois. Part 2 will cover current knowledge and in-progress research by the authors on vibrations caused by the transportation of objects, and by musical events in galleries.

Vibrations from Human Activities

The human body can perceive vibrations of extremely low magnitude. People can often feel floor vibrations in buildings from everyday activities such as crowds walking, people running or jumping, doors opening or closing, and buses or trains operating outside. However, when floor vibrations are high, occupants may complain or even become physically disturbed by the motion.

Various standards and references exist to design and evaluate floor structures within performance levels that are tolerable to humans. AISC's Design Guide 11[1] (DG11) is an internationally recognized guide to assist engineers in avoiding floor designs with objectionable vibrations due to common human activities. ISO 2631-1[2] provides measures to assess whole-body human perception and annoyance with regard to vibrations.

DG11 recommends limiting vibrations in an office environment to a baseline acceleration value of 0.5% of gravity (0.005g) in the frequency range of 4 to 9 Hz (Figure 1), which is equivalent to 0.03 to 0.07 inches per second (in/sec) peak particle velocity (PPV) in that frequency range. A museum gallery environment is similar to an office environment, with humans tending to be in a quiet, contemplative state when vibrations occur.

Selecting floor-vibration limits that are appropriate for the protection of museum collections is more challenging, due to the inherent variability among museum objects, both in terms of geometry and condition. However, as discussed by the authors in other publications,[3] a vibration limit of 0.1 in/sec PPV should be conservative to protect most museum objects that are already in reasonably sound condition. This limit has been used successfully to protect museum collections during several recent construction

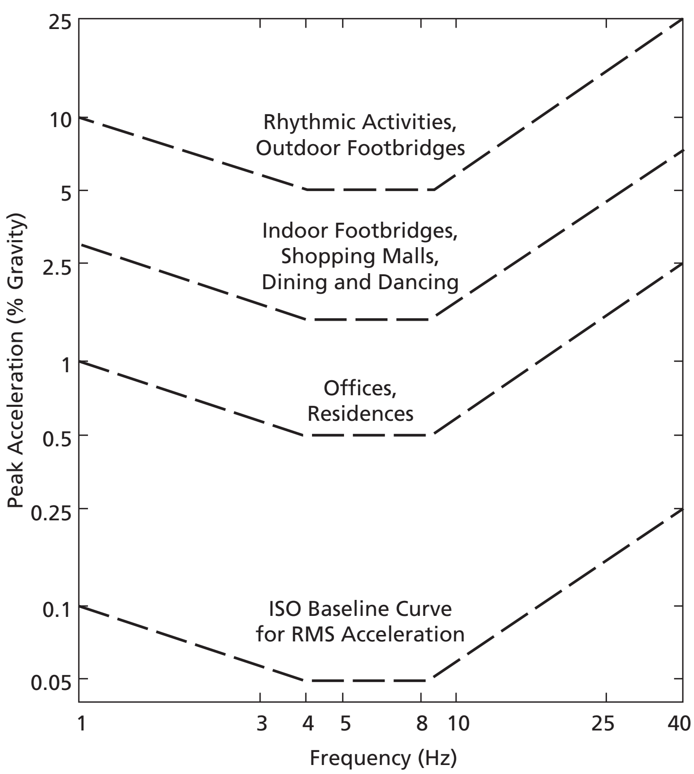


Figure 1. Design criteria recommended by AISC DG11 for various environments.

[1] Thomas M. Murray, David E. Allen, Eric E. Ungar. 1997. *Floor Vibrations Due to Human Activity*. Steel Design Guide Series 11. Chicago: American Institute of Steel Construction, Inc., 1-69.

[2] ISO (1997), ISO 2631-1: *Mechanical Vibration and Shock—Evaluation of Human Exposure to Whole Body Vibration*, 2nd edition.

[3] Arne Johnson and Robert Hannen, "Vibration Limits for Historic Buildings, Art Collections and Similar Environments," APT Bulletin, *Journal of Preservation Technology*, Vol. 46:2-3, 2015, pp. 66-74.

projects. Special vibratory effects and circumstances can, however, make objects susceptible at lower levels and should be considered.

Floor vibrations that meet these performance requirements can be easily achieved in certain types of floor construction, including the stiff and massive structures typical of most older museums. However, human-induced floor vibrations can be much greater, and sometimes problematic, in other types of floor construction, such as modern lightweight steel-framed construction with longer spans. The susceptibility of individual floors to vibration should be assessed on a case-by-case basis during the structural design phase for new buildings, or by field testing of existing facilities when necessary.

Vibrations from Nearby Construction

Ground-borne vibrations originating from construction activities, such as heavy demolition or vibratory pile-driving, can transmit to museums and affect museum objects. A methodology to control construction vibrations near museum collections was developed and has been previously reported.[4] Through preconstruction testing and analysis, vibration levels can be predicted in advance of the construction, allowing a museum to take precautions before construction begins.

In addition, minimum requirements and practical guidelines can be established for contractors so that construction costs and schedules are not inflated due to unknowns. During construction, the collection is protected using a program of continuous vibration monitoring, with appropriate alarms and work-stoppage protocols. For critical though less extensive works, a vibration-control plan can be more targeted, as was recently accomplished at the Neue Galerie New York.[5]

Case Study: The SUE Gallery

The following case study illustrates these principles, particularly as they relate to flexible floor systems. In 2018, The Field Museum moved SUE, its iconic *Tyrannosaurus rex* specimen, from Stanley Field Hall on the first floor of the museum, where SUE had been located for 18 years, to a new location on the second floor.

The first-floor structure in Stanley Field Hall consists of heavy concrete framing and terracotta arches. The new gallery is located in a portion of the building that was originally an open-air light well.

About 20 years ago, the light well was filled in with three levels of steel-framed, lightweight concrete floors spanning approximately 39 feet between original load-bearing masonry walls (Figure 2). The floor structure at the new location was assessed with the weight of SUE in mind; however, during assembly of the skeleton, Field Museum staff noted concerns with respect to floor vibrations and the accompanying dynamic response of the reassembled skeleton.

The Field Museum engaged the authors' firm to perform vibration testing at the previous and new exhibit locations. The testing confirmed the museum's concerns. Floor vibrations from human activities and scissor-lift operations at the new exhibit location were three to six times greater than in SUE's previous location, and the natural frequency of the floor at the new location was approximately 6 Hz, compared to approximately 13 Hz at the previous location. The lower natural frequency of the floor is much closer to the pace of human walking, which creates the potential for dynamic amplification (resonant-like behavior) during human activities.

Subsequently, the authors investigated the feasibility of potential vibration-mitigation measures, assisted The Field Museum in selecting a mitigation strategy to achieve a targeted reduction in vibration response, and designed and helped install the selected mitigation retrofit.

Performance Goals and Mitigation Options

The goal in relation to human annoyance was to keep floor vibrations within DG11 limits for offices (0.5% g). With respect to protecting SUE, it was recognized that a safe vibration limit for a one-of-a-kind object of this type is unknown. However, it was reported that SUE was displayed for 18 years at its previous location with no adverse effects.

Field testing at the Stanley Field Hall location showed that SUE had been subjected to frequent vibrations (e.g., from footfalls) of approximately 0.02 in/sec PPV, and infrequent vibrations (e.g., from heel drops and scissor-lift operation) of up to 0.11 in/sec PPV. The latter value is comparable to the limit of 0.1 in/sec PPV that has been used by several institutions to protect museum objects from

Figure 2. Vibration testing underway in the new SUE gallery during gallery construction.

[4]Arne Johnson, Robert Hannen and Frank Zuccari, "Vibration Control During Museum Construction Projects," *Journal of the American Institute for Conservation*, Vol. 52 No. 1, 2013, p. 30-47.

[5]Arne Johnson and Mark DeMairo, "The Neue Galerie: Targeted Vibration Control During Internal Construction," Papyrus, Fall 2017.

construction vibrations.[6] Reducing vibration levels in the new gallery floor to the levels measured in Stanley Field Hall was deemed a sensible goal.

Three general approaches were considered to reduce vibrations around SUE in the new gallery:

- stiffening the entire floor structure in the vicinity of the armature base;
- adding supplemental damping to the floor system; and
- isolating the armature base from the top of the concrete floor surface.

WJE developed a finite element structural analysis model of the floor structure and calibrated the model to match measured field vibrations. Using this model, the relative benefit of various vibration-mitigation solutions was studied analytically, as discussed below.

Supplemental columns

Stiffening the floor structure by adding columns below the mid-point of the long-span steel girders under SUE was the most direct method of increasing the floor's natural frequency, and of reducing vibrations from human traffic. The columns would need to be installed using a field jacking and preloading procedure, allowing the columns to provide immediate support for the very small displacements associated with footfall-induced vibrations.

Variations in column placement were studied, including one column below the center of SUE, three columns extending across the entire footprint of SUE, and columns landing on the first floor below or extending down an additional level to new spread footings in the basement.

The primary advantage of the supplemental column solution is that it provides a relatively reliable reduction in vibrations for a relatively low construction cost. The primary disadvantage is that the columns would be permanent obstructions within the building spaces below.

Girder stiffening

Another means of stiffening the floor structure would involve stiffening the long-span girders located below SUE. A substantial increase in stiffness, with a modest increase in mass, can be achieved using an inverted queen-post type retrofit, which would involve welding small bars and angles into an efficient pattern below the existing bottom flange.

Note that adding mass tends to decrease natural frequency, which negates the benefit of stiffening. The advantage of the girder-stiffening approach is that it would not obstruct the gallery space below, and should achieve considerable improvement in floor performance. Its primary disadvantage is its high cost, because of the custom engineering design and field-welded construction that are involved.

Tuned mass dampers

A tuned mass damper (TMD) is a device with a mass supported by a spring and damping mechanism which, when tuned to a dominant floor frequency, can significantly reduce the amplitudes of load-induced vibrations at that frequency. For the subject case, TMDs would be suspended from the floor adjacent to the existing girders below SUE (Figure 3).

By tuning the vibration characteristics of the TMD to the floor structure, the TMD counteracts the resonant or harmonic response of the floor at the targeted frequency. A TMD system typically performs best for floors with a single dominant mode of vibration and minimal participation from other nearby response modes.

The advantage of a TMD approach in this case is that it would not obstruct the gallery space below, and should result in considerable improvement to floor performance. Its primary disadvantage is that, in the authors' experience, the benefit of TMDs is difficult to predict analytically, and past results have been mixed.

In addition, TMDs do not reduce the first impulse of a transient event. For example, the first impulse from a scissor lift would not be reduced, and would transmit into SUE—although the ongoing response would be quickly dampened.

Direct-acting dampers

Another strategy would be to add damping to the system using direct-acting dampers (DADs), which are essentially very long shock absorbers that could be installed vertically between the underside of the second-floor girders and the top of the first-floor slab. In theory, the DADs could add a large amount of very effective damping to the second floor. However, DADs would also create obstructions in the first-floor gallery space, similar to the supplemental columns. Since the supplemental columns would provide even more vibration-mitigation benefit than the DADs in this case, DADs were not pursued.

DEICON, INC.

Figure 3. Example of TMD suspended below a floor structure.

[6]Arne Johnson and Robert Hannen, "Vibration Limits for Historic Buildings, Art Collections and Similar Environments," APT Bulletin, *Journal of Preservation Technology*, Vol. 46:2-3, 2015, p. 66-74.

Isolation of SUE from floor structure

In theory, inserting an isolation material between the top of the concrete floor and the bottom of the armature base would reduce vibrations transmitted from the floor into SUE. By way of analogy, a person on a waterbed does not feel rapid motions from the floor below, and passengers in a car with a sufficiently soft suspension do not feel the impact of their tires on the roadway.

To achieve significant isolation, the ratio of the driving frequency of the floor to the vibration frequency of the isolation material should be a factor of at least 1.5, and preferably 3 or more. The amount of damping in the isolation material also increases the isolation effect. For the subject floor, which has driving frequency of approximately 6 Hz, the isolation material should have a frequency of 2 to 3 Hz.

Sorbothane pads are synthetic rubber pads often used in museum environments to isolate shelving, casework and objects. Even the thickest and softest arrangement of Sorbothane pads, however, would have a natural frequency no lower than about 9 Hz.

Air isolators, spring isolators, or custom active isolators could provide frequencies in the desired range of 2 to 3 Hz. However, supporting SUE on such a soft system would introduce other risks, including the propensity of the object to be excited (i.e., caused to vibrate) in slow rocking and lateral displacement modes (essentially wobbling and/or translating back and forth). Rocking is exacerbated by the skeleton's high center of gravity. These additional risks could be solved using clamping and restraining mechanisms, but given the risks, along with a very challenging design and associated costs, base isolation was not pursued in this case.

Analysis Results and Retrofit Implemented

The analysis showed that the most effective mitigation options—in order of anticipated benefit—would be stiffening the floor structure with supplemental columns, stiffening the floor girders, and adding tuned mass dampers below SUE. It was determined that, for the supplemental column solution, a single column—or landing the columns on top of the first floor—would not fully achieve the vibration-performance goals.

After consideration, The Field Museum selected the supplemental column strategy, involving three columns extending down two floor levels and supported on new spread footings below the existing basement slab (Figure 4). The multiple walls and exhibit cases in the Ancient Americas gallery located below the SUE gallery allowed the columns to be located with diminished disruption to the gallery, and the basement was flexible back-of-house space.

During construction, WJE operated hydraulic rams and digital instrumentation to preload the columns (Figures 5 and 6), which ensured tightness of the system and pre-compression of existing soils below the new spread footings. The new columns were 8x8-inch structural steel tubes with shop-welded brackets at their heads to facilitate the hydraulic preloading.

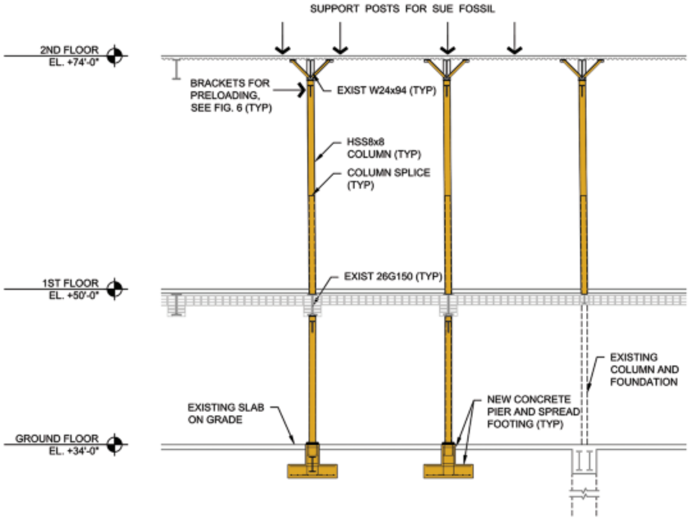


Figure 4. Cross-section through the building structure, showing supplemental columns installed (shading indicates structural elements added).

Figure 5. View from below of two of the three supplemental columns installed below the SUE gallery.

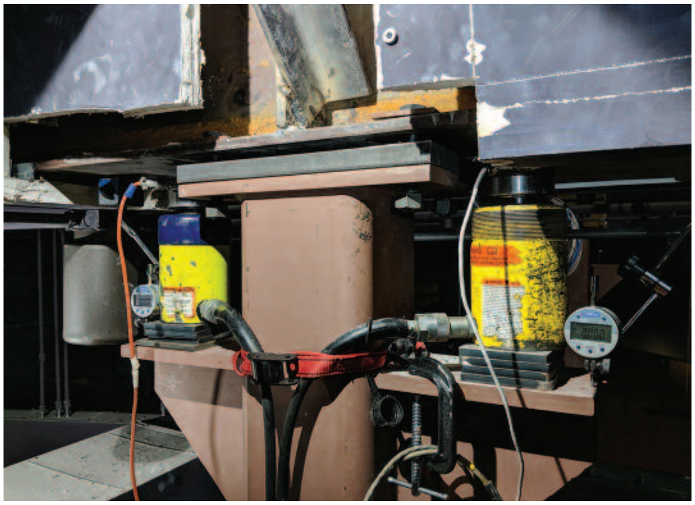


Figure 6. Close-up of top of column during hydraulic preloading.

Vibration Testing Before and After Retrofit

To give a true before-and-after comparison, field vibration testing of the retrofitted gallery floor was performed in the same manner and at the same locations as before the retrofit. Testing showed that the natural frequency of the floor system had been increased from approximately 6 Hz to approximately 12 Hz, which agreed well with the analytical predictions. Floors with frequencies in this higher range are much less likely to be excited by human walking activities, as compared to flexible floors with frequencies near and below 6 Hz.

As shown in Table 1, typical peak response to walking around SUE was only 0.01 to 0.03 in/sec—several times less than the approximately 0.14 in/sec measured in the floor before the retrofit. This response was near, although slightly above, the ideal target value of 0.02 in/sec, which was the maximum response measured due to walking at SUE's previous location in Stanley Field Hall. Figure 7 shows the dramatic change in the frequency response function (FRF) of the floor before and after the retrofit.

Damping of the floor system increased from about 4% to 6%—ostensibly due to the addition of floor finishes and

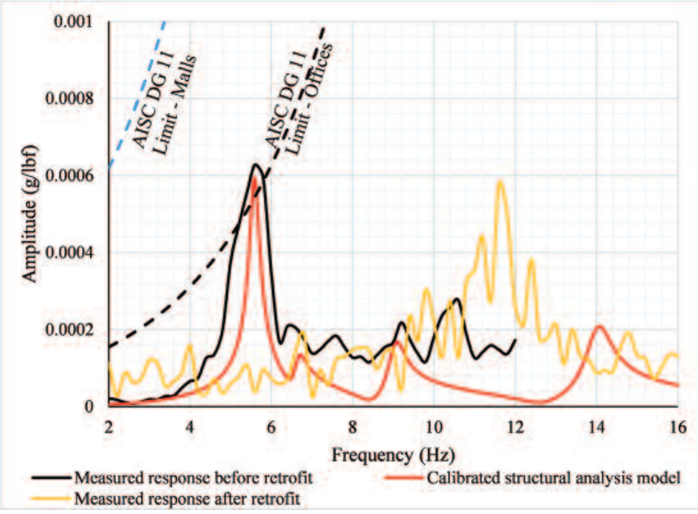
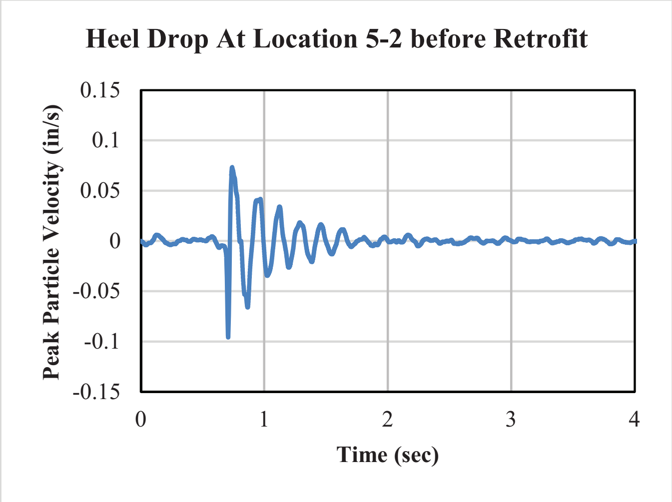


Figure 7. Frequency response function showing the field data before the retrofit (black line), the calibrated structural analysis model before the retrofit (red line), and the field data after the retrofit (yellow line). Note the increase in predominant frequency and the substantial reduction in amplitude in the lower frequency range.



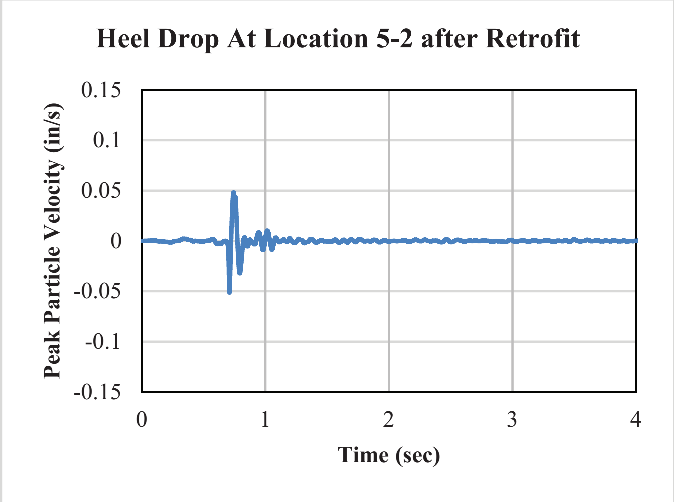


Figure 8. Typical response of floor to impact before (left) and after (right) retrofit, illustrating increased stiffness and damping.

Table 1
Summary of Vibration Testing Results Before and After Retrofit

	Natural frequency (Hz)	Damping (% critical)	Typical maximum response to walking (PPV, in/sec)	Typical maximum response to the impact of heel drops and scissor lifts (PPV, in/sec)	Typical maximum floor acceleration response due to footfalls (ESPA, % of g)
Stanley Field Hall	13	8%	0.02	0.07 to 0.11 in/sec	0.1% of g
New SUE Gallery (before retrofit)	6	4%	0.14	0.35 to 0.44 in/sec	1.0% of g
New SUE Gallery (after retrofit)	12	6%	0.01 to 0.03	0.06 to 0.19 in/sec	0.1% of g

room contents, which absorb dynamic energy—between initial and final testing. The increase in damping is evidenced by the short time it takes for vibrations to decay (i.e., decrease with time) when the floor is activated (Figure 8).

Monitoring of Retrofitted Floor

The new gallery (Figure 9) opened to the public soon after the vibration-verification testing. A vibration monitor with real-time remote access was installed on the floor inside the base of SUE to collect vibration data continuously for the first month that the new gallery was open. Analysis of the data showed that, considering active hours between 6:00 a.m. and 9:00 p.m., 83% of the measured vibration amplitudes were less than the ideal target of 0.02 in/sec, and 98% of the amplitudes were less than 0.04 in/sec, which confirmed the highly effective performance of the retrofitted floor.

COURTESY OF THE FIELD MUSEUM

Figure 9. View of stunning new SUE gallery soon after public opening.

Summary and Conclusions

In summary, floor vibrations caused by human activity in museum galleries can be quite significant, and potentially problematic for museum objects. However, there are ways of designing new floors to avoid such problems, and to retrofit existing floors manifesting such problems.

When construction must be performed near museum galleries, there are scientific means of keeping vibrations at levels that should not have an adverse impact on the museum's collection, nor undue constraints on designers or contractors. Assessment early in the design process is key to providing advance input to the museum and contractors.

The vibration testing and mitigation design for the new SUE gallery provide an excellent example of how potentially problematic floor vibrations can be responsibly addressed. Once the vibrations were identified, field testing determined the root cause and quantified the problem. Performance goals for the one-of-a-kind object were rationally established using available references and comparison of the new floor with the previous floor where SUE had existed with no adverse effects for 18 years. A feasibility and cost study for the range of possible mitigation options was conducted utilizing a computer model calibrated to the field measurements. In the end, the supplemental column retrofit strategy that was implemented dramatically improved the vibration performance of the floor in the vicinity of SUE, protecting this extremely important object for years to come.

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