

Vibration Mitigation and Sound Testing in SUE Hall at the Field Museum in Chicago

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How to settle down your *Tyrannosaurus rex* before you take it out in public: vibration-mitigation design for a 67-million-year-old museum specimen.



Fig. 1. Completed SUE Hall, Field Museum, Chicago, Illinois, soon after public opening, with sound show and digital animations on glass screens in background. Photograph by John Weinstein, 2018. © Field Museum of Natural History GN92620_092B.



Fig. 2. SUE showing nearly complete reassembly at its new second-floor location when vibration concerns were first identified. Photograph by WJE, 2018.

“SUE” is the most complete *Tyrannosaurus rex* specimen in the world, with approximately 90 percent (by volume) of its actual bones mounted for exhibit. The specimen was discovered in 1990 in western South Dakota from the Hell Creek Formation dated approximately 67 million years old. The Field Museum in Chicago, Illinois, acquired the specimen, catalog no. PR 2081, now one of the most valuable objects in the museum’s collection, in 1997 for \$8.3 million. From the outset, the museum intended to mount the real bones, not facsimiles, and hired a specialist to produce an intricate steel armature constructed in such a way that the bones could be removed for study. All mounts of real dinosaur bones are fragile, and this one particularly so because of its complexity.

The museum building had been constructed in 1915 with six light wells to allow natural light and air into the building. Over the years, five of the six light wells were roofed over, and the floors filled in to add space for the museum’s ever-growing research collections.

The museum intended to put SUE into its own gallery in the middle of the fossil halls on the second floor, at the location of the one light well that had

not yet been filled in. However, infill of that light well was not expected to occur until the mid-2000s. Therefore, SUE was temporarily installed at the north end of Stanley Field Hall, the large main exhibit hall on the first floor of the museum, and unveiled to the public in 2000. Though the remaining light well was filled in by 2005, it was not until 2018 that funding became available to finally move SUE into the gallery always meant to be its final home (Fig. 1).

In February 2018, SUE was dismantled and moved into Hall 25A (SUE Hall). The steel post at the center of the armature was carefully positioned over an existing steel girder. During the remounting, it was noticed that the floor transmitted vibrations much more readily than the floor in Stanley Field Hall. The remounting was on display through a window in the adjacent fossil hall, which attracted crowds of visitors during spring break. On March 30, bone fragments were found on the floor below SUE. The area was carefully examined, and all fragments were collected. The distal section of one of the neck ribs had detached from the armature. It was suspected that vibrations originating from visitors at the viewing window caused the rib to fail. Though the rib was reassembled without any loss of bone, the museum concluded that the floor was too “lively” and needed remediation.

Defining the Problem

The authors’ firm was engaged by the museum to define and solve the vibration problem. The first step was to review the structure and perform in situ testing.

At SUE’s previous location in Stanley Field Hall, the first-floor structure is original to the building; it consists of heavy concrete framing and terra-cotta arches. In contrast, the second-floor structure in SUE Hall (the infill constructed in 2005) consists of a lightweight concrete slab on a metal deck supported by 24-inch-deep steel girders, which span the entire width of the gallery, approximately 39 feet, in between the original load-bearing masonry walls (Figs. 2 and 3).

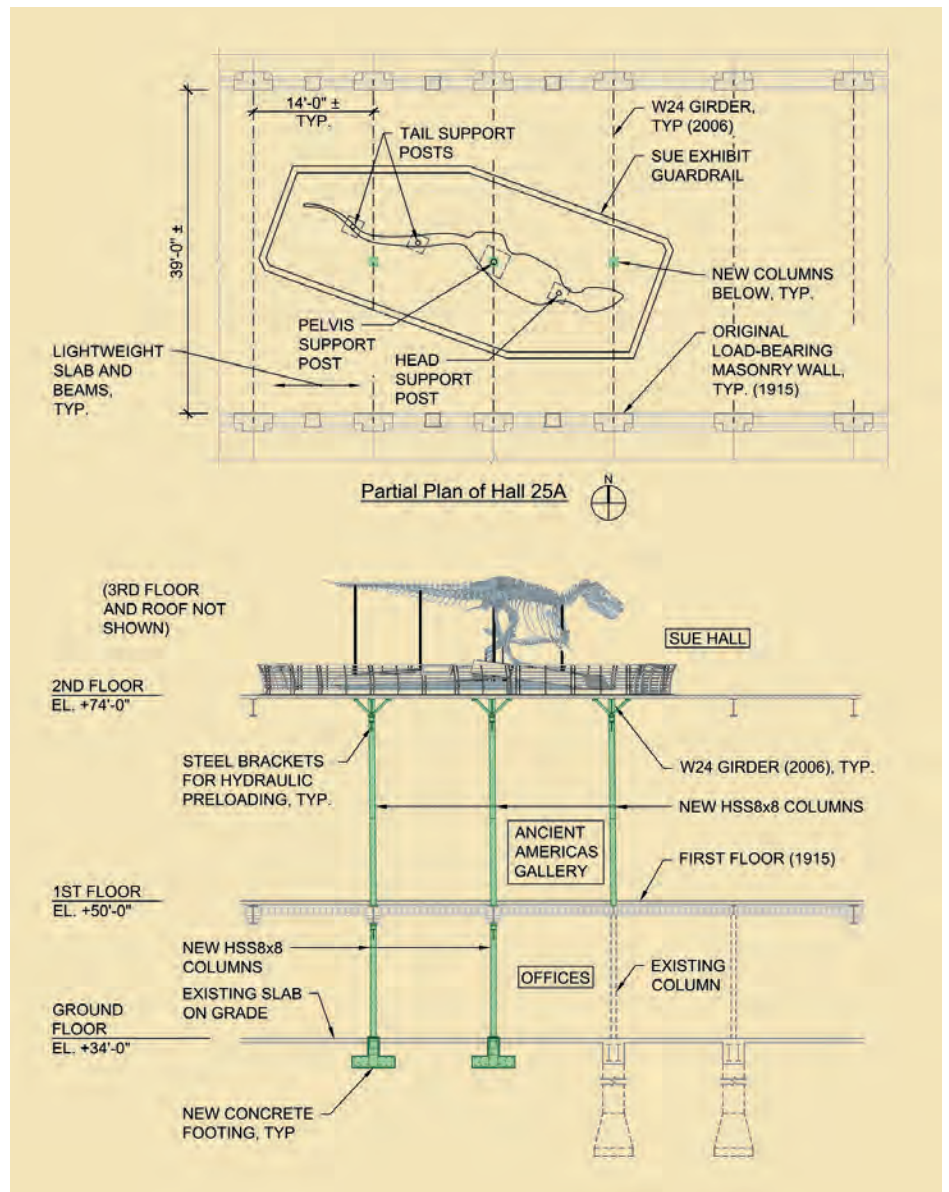


Fig. 3. Partial plan and section through the new SUE Hall, with new columns and footings shown in green. Drawing by WJE.

Vibration testing quickly confirmed the museum’s concerns. Floor vibrations from human activities and hydraulic scissor-lift operations in SUE Hall were three to six times greater than at SUE’s previous location. Furthermore, the natural frequency of the second floor was only approximately 6 Hertz (Hz), compared to approximately 13 Hz in Stanley Field Hall. Brisk walking and sharp movements with a scissor-lift in the vicinity of SUE produced distinctly perceptible floor vibrations and noticeable dynamic response (resonant shaking) of individual bones in the mounted skeleton.

Structural review determined that the structure, though sufficient to support the weight of SUE, was susceptible to vibrations because of its long flexible span, relatively lightweight framing, lack of structural continuity, and lack of energy-absorbing (damping) components like partition walls. With the floor's natural frequency of approximately 6 Hz closer to the input frequencies commonly associated with human foot traffic, typically 1.5 to 2.2 Hz, the new location experienced greater dynamic amplification from human activities than the stiffer floor at the previous location. Moreover, the floor vibrations at the new location transmitted readily into the armature base and support posts of SUE since the armature is stiff relative to the floor. Resonant shaking of individual bones occurred where the localized vibration characteristics happened to match or be multiples of the frequency of the floor vibrations.

The Museum's Goals

The museum's goals were clear: to protect SUE by reducing the movement of the bones during normal gallery use and to install the vibration-mitigation solution before the new gallery opened in six months. With the tight time frame and the gallery debut already announced to the public, the solution had to work. At the time the vibration concern was identified, mounting of the specimen was nearing completion; disassembling or lifting the skeleton to install a vibration-mitigation scheme was not feasible. Any vibration-mitigation solution needed to be hidden within the base of SUE or in the ceiling of the first-floor gallery below.

Toward a Solution

The target with respect to human annoyance (i.e., visitors being concerned by noticeable floor vibrations) was to reduce floor vibrations to within the recommendations of the American Institute of Steel Construction's Steel Design Guide Series 11 for an office environment: that is, no more than a baseline acceleration of 0.5 percent of gravity (0.005 g) in the frequency range of 4 to

Table 1. Vibration-Testing Results before and after Retrofit.

	Stanley Field Hall	New SUE Hall before retrofit	New SUE Hall after retrofit
Structure	Heavy concrete framing with terracotta arches	39-ft span, lightweight steel framing	Columns added to reduce span by half
Natural frequency	13 Hz	6 Hz	12 Hz
Damping (% critical)	8%	4%	6%
Walking, typical maximum response	0.02 in/sec	0.14 in/sec	0.01 to 0.03 in/sec
Impacts (heel drops and scissor-lifts), typical maximum response	0.07 to 0.11 in/sec	0.35 to 0.44 in/sec	0.06 to 0.19 in/sec
Typical maximum floor acceleration response due to footfalls	0.1% of g	1.0% of g	0.1% of g

9 Hz.¹ An office environment represents humans in a quiet, contemplative position, which was judged to be consistent with the gallery environment.

With respect to protecting SUE, it was recognized that a safe vibration limit for such a one-of-a-kind object was unknown. Generalized vibration limits have been used to protect "most museum objects in reasonably sound condition" during numerous construction projects.² More specific to this case, it was recognized that SUE had subsisted without adverse effects for almost 18 years at its previous location in Stanley Field Hall.

Testing in Stanley Field Hall demonstrated that SUE had been subjected to frequent floor vibrations (e.g., from footfalls) of approximately 0.02 in/sec peak particle velocity (PPV) and infrequent floor vibrations (e.g., from 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 construction vibrations.³ It was agreed that reducing vibrations in SUE Hall to those measured in Stanley Field Hall was a sensible target for protection of SUE.

For assessment relative to these targets, a finite-element structural-analysis model of the second-floor structure was developed and calibrated to match the field

measurements. Using the "tuned" model, the relative benefit of various vibration-mitigation solutions was studied.

Vibration-Mitigation Options

The vibration-mitigation options that were studied, and the calculated benefits and disadvantages of each, are detailed in a previous article by the authors.⁴ In summary, the following approaches were considered:

- stiffening the floor structure by retrofitting (stiffening) the existing long-span girders
- stiffening the floor structure by adding columns below the girders
- adding damping to the floor using tuned mass dampers or direct-acting dampers
- isolating the base of SUE by inserting isolation pads or springs between the concrete floor and the armature.

Investigation showed that even the thickest and softest arrangement of isolation pads (such as Sorbothane) would have a natural frequency no lower than about 9 Hz, well above the 2 to 4 Hz needed to effectively isolate SUE. Other systems, such as air isolators, spring isolators, or custom active isolators, could provide frequencies in the desired range; however, such an extremely soft support could introduce other risks, including the propensity of the specimen to slowly rock back and forth, since it has a high

center of gravity. Given the challenges and associated costs, base isolation was not pursued.

Vibration-Mitigation Retrofit

Analytical modeling showed that the most effective vibration-mitigation options—in order of anticipated benefit—would be stiffening the floor structure by adding columns, stiffening the girders, and adding tuned mass dampers.

After weighing all the factors, the Field Museum elected to install three columns below the footprint of SUE, with the columns extending two floors to the ground (see Fig. 3). The multiple walls and exhibit cases in the Ancient Americas gallery on the first floor allowed the columns to be positioned with limited disruption to gallery use.

In the late 1800s, the Chicago lakefront had been reclaimed using urban fill, so the soils below the new spread footings in the basement of the museum could prove to be soft and variable. During construction, the exposed soils were tested, and the new columns and spread footings were preloaded using hydraulic rams and digital instrumentation (Fig. 4). This ensured initial tightness of the system and pre-compression of the soils as necessary for effective long-term performance of the retrofit.

Verification Testing

The retrofitted gallery floor was tested in the same manner and at the same locations as before the retrofit. As shown in Table 1, consistent with the analytical predictions, the natural frequency of the floor system increased from approximately 6 to 12 Hz.

Typical peak response to walking around SUE ranged from 0.01 to 0.03 in/sec PPV—roughly 5 to 10 times less than the approximately 0.14 in/sec measured before the retrofit. The typical response was near, although slightly above, the target value of 0.02 in/sec, which was the maximum response measured due to walking at SUE's previous location.

Higher peak response was measured near the head post (up to 0.04 in/sec) and near the mid-tail post (up to 0.05 in/sec) because these posts are located between the supported girders. Reducing

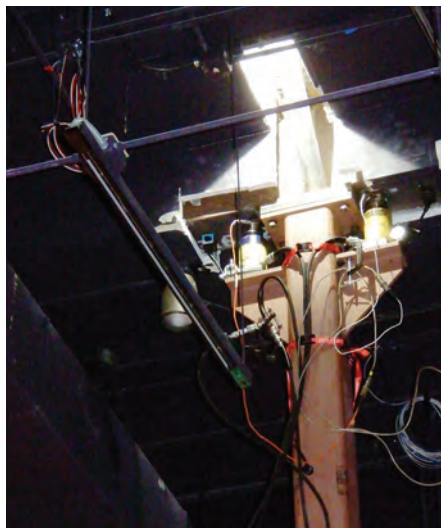


Fig. 4. One of three supplemental columns installed below the existing steel girders of SUE Hall, with hydraulic preloading underway to ensure initial tightness of the system and preloading of the soil below the new spread footings. Photograph by WJE, 2018.

the response, if found to be necessary in the future, could be accomplished by locally stiffening the slab or adding isolation pads below the posts.

SUE Hall opened to the public with great acclaim on December 21, 2018. To verify performance during public occupancy, a vibration-monitoring system was installed inside the base of SUE. During the first month the gallery was open, 83 percent of the measured vibration amplitudes were less than the target of 0.02 in/sec, and 98 percent of the amplitudes were less than 0.04 in/sec, confirming the successful performance of the retrofit.

Vibrations Induced by the Sound System

SUE Hall includes digital animations with soundtracks that illustrate SUE hunting for food and fighting other dinosaurs, complete with loud growling and roaring noises. Six 9-foot-tall, ultra-high-definition screens are situated behind SUE, forming a panorama, that project a series of rotating five-minute videos. The show employs six projectors, audio amplifiers, 17 ceiling speakers, four wall-mounted cabinet speakers, and six ceiling-mounted subwoofers. A narrated light show also points out key details on SUE's bones.

As part of the vibration assessment, questions were raised about whether

the exhibit show, and especially the low-frequency growling and roaring noises, would cause detrimental vibration of the fossils, even after the retrofit. Similar questions are being raised by museums worldwide regarding the vibratory effects of sound and music on museum collections. Research into this topic by the present authors and others is ongoing. A survey sponsored by several museum organizations was recently circulated in order to gather data on museums' current practices and experiences with respect to musical events.⁵

The retrofitted SUE gallery presented an ideal opportunity to compare human traffic-induced vibrations, to which museum objects are routinely exposed, with vibrations of objects induced by sound systems. To this end, non-contact laser vibrometer measurements were taken directly on selected bones in the mount of the skeleton during human activities in the gallery (previous measurements were taken only on the floor and armature base). The laser vibrometer measurements were repeated during the exhibit sound show, without human traffic. Under the museum's supervision, the soundtrack volume was increased, especially the growling and roaring segments, while the response of the fossils was monitored. A digital synthesizer and music clips were also played through the sound system in the gallery.

Six setups were completed, with three setups on each side of the specimen. In each setup, the floor vibrations, as well as the vibrations of selected presacral ribs and gastralia (rib-like bones below the rib cage), were measured during the following activities:

- ambient conditions, no sound or human traffic (ambient vibrations were essentially zero)
- floor impact using a calibrated heel-drop plate
- random walking (three to four people) around the specimen
- roar segments excerpted from the soundtrack
- single low-frequency synthesizer notes
- four genres of music (classical, jazz, rock, and R&B).

Maximum vibration of the fossils due to random walking was measured to be approximately 0.2 to 0.5 in/sec, indicating an amplification of three to eight times the maximum vibrations of the floor from walking (this is a common amplification range due to resonant-like behavior of geometric objects supported on a floor). By comparison, the maximum vibration of the same fossils due to the roaring segments of the soundtrack was lower, from approximately 0.03 to 0.2 in/sec. Similar results were obtained for the synthesizer and music clips.

In short, vibrations of the fossils induced by the sound system, though noteworthy, were considerably less than the vibrations of the fossils caused by normal walking in the gallery after installation of the vibration-mitigation retrofit. As such, vibrations from the exhibit show should not have any significant detrimental effects on SUE. It should be noted that the sound system in the SUE gallery is not designed to have a large bass response like that in a live band or DJ setup; strong bass inputs may cause more significant vibration of objects.

Summary and Conclusion

The move and reassembly of SUE onto the flexible floor of an infilled light well presented the museum with unforeseen problems that had to be solved in short order. Vibration testing and analysis assisted museum staff in understanding the problem and selecting a solution (from a variety of options) that best fit the museum's needs. Now that the museum staff knows this may be a problem, testing and study will precede exhibit construction for future projects involving fragile, vibration-sensitive objects.

SUE is one of the crown jewels of the Field Museum's collections, and SUE Hall is a driver of attendance for the institution, which stands at over 1.3 million visitors annually. Supporting the weight of the dinosaur and its mount was straightforward but getting the gallery floor "tuned" properly to avoid vibratory response of this fragile object was challenging and had to succeed. With the vibration-mitigation retrofit installed, the gallery is now a safe

place for SUE to "live" and a pleasant space for visitors to gather without bothersome vibrations.

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