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# Controlling construction-induced vibrations in healthcare facilities

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**Abstract.** Controlling excessive floor vibrations is critical in modern healthcare facilities where high-resolution imaging and diagnostic equipment are often used. These types of equipment have stringent floor vibration criteria to ensure the accuracy of their results. Controlling floor vibrations is further complicated as existing healthcare facilities are being renovated and upgraded to meet current healthcare demands, while remaining in operation. This paper presents a case study of an existing hospital which is undergoing extensive renovations. This hospital houses a variety of diagnostic imaging equipment including Magnetic Resonance Imaging (MRI) and Computed Tomography (CT) equipment, as well as mass spectrometers. To determine the extent of the vibration mitigation required such that the equipment can remain operational during construction, vibration tests simulating the future construction activities were conducted. The vibration tests consisted of striking the ground with an excavator, while accelerometers were placed at strategic locations throughout the hospital to capture the excitation.

## 1 Introduction

Many healthcare facilities are undergoing renovations and upgrades to meet the growing healthcare demands. Simultaneously, medical equipment and technology are also constantly improving and producing more accurate results. With the advancement of medical equipment, the acceptable vibrations that the equipment can accurately operate under, are also becoming more stringent. As such, being able to predict and control construction-induced vibrations within healthcare facilities is steadily becoming an integral part of the planning, design and construction of these renovation projects.

This paper presents an ongoing renovation project for an existing hospital complete with diagnostic imaging equipment and clinical laboratory spaces that must remain operational throughout the construction period. Construction vibration simulations and prediction methods are described, along with a variety of considered vibration mitigation options.

## 2 Vibration criteria

Prior to the construction vibration simulation testing, an extensive study of the potentially vibration-sensitive equipment within the facility was conducted. Where available, the manufacturer-specified vibration requirements were used. However, the majority of the equipment did not have manufacturer-specified vibration requirements. As such, the generic vibration criteria (VC) curves were used to provide guidelines on the various equipment vibration requirements.

These VC curves are based on the ISO 2631-2 (1989) [1] base curve for human response to whole body vibration, also known as the threshold for human perception. Since then, the VC curves have evolved to provide frequency-dependent sensitivities for different classes of equipment and are internationally accepted as a basis for designing and evaluating the vibration performance of structures. The VC curves range from Workshop (least stringent) to VC-G (most stringent) and are expressed in one-third octave band root mean square velocity between the frequencies of 1 to 80 Hz.

Of the equipment studied, it was found that the most sensitive equipment within the hospital was required to meet the VC-D (6.25 μm/s) vibration criterion. The highly sensitive equipment included high magnification fluorescent microscopes, quadropole mass spectrometers and a magnetic resonance imaging (MRI) machine.

## 3 Vibration investigation

Based on the proposed renovations, it was determined that a variety of vibration-inducing construction activities would occur throughout the duration of construction. These activities included concrete saw-cutting, concrete coring, structural and interior finish demolition, as well as the operation of a construction hoist. Given the variety of construction activities and activity locations, multiple types of construction vibration simulation testing were conducted to predict the vibration levels at the sensitive equipment locations.

To simulate the different activities, the following simulation activities were conducted: excavator bucket striking the ground at three different locations outside the hospital, heavy weight drop within the basement, and concrete coring at two different locations within the hospital. The outdoor excitations were conducted to simulate the pavement grading and entranceway demolition activities, while the heavy weight drop within the basement was to simulate the future saw-cutting and demolition activities in the basement for a new elevator installation. The impulse vibration excitations caused by the excavator bucket and heavy weight created a broadband excitation that would allow for the frequency-dependent attenuation to be determined. Finally, the concrete coring was conducted at the areas where the future concrete saw-cutting and coring activities were expected to occur. The concrete coring excitation allowed for direct vibration levels to be determined at the sensitive locations, while also providing spectral source levels. In addition to these construction simulations at the facility, vibration levels were measured at a nearby construction site with an active construction hoist to determine the source vibration levels due to construction hoist operation.

During the construction simulations within the hospital, vibration levels were measured with accelerometers placed on both the basement and first floor of the hospital, as all of the sensitive equipment were located on these two floors. These accelerometers were placed at varying distances from the sensitive equipment, mounted triaxially, so that the vibration attenuation with distance in three axes could be determined. An accelerometer was also placed adjacent to the construction simulation activity to measure the source levels.

## 4 Analysis

To determine the site-specific ground vibration attenuation characteristics, the measured velocity at each of the measurement locations was fitted against a curve of best fit. Typical earth vibration due to construction curves [2] were used to quantify the expected vibration levels at the source for a variety of different construction equipment. The site-specific vibration attenuation characteristics were then applied to each of the construction equipment source levels, allowing for the prediction of a variety of equipment vibration levels. An example of one of these predictive curves is shown in Figure 1. This is the predictive curve generated based on the excavator ground strikes at the 25 Hz vibration frequency. Similar predictive curves were created for each one-third octave frequency band between 1 to 80 Hz for each type of simulated excitation.

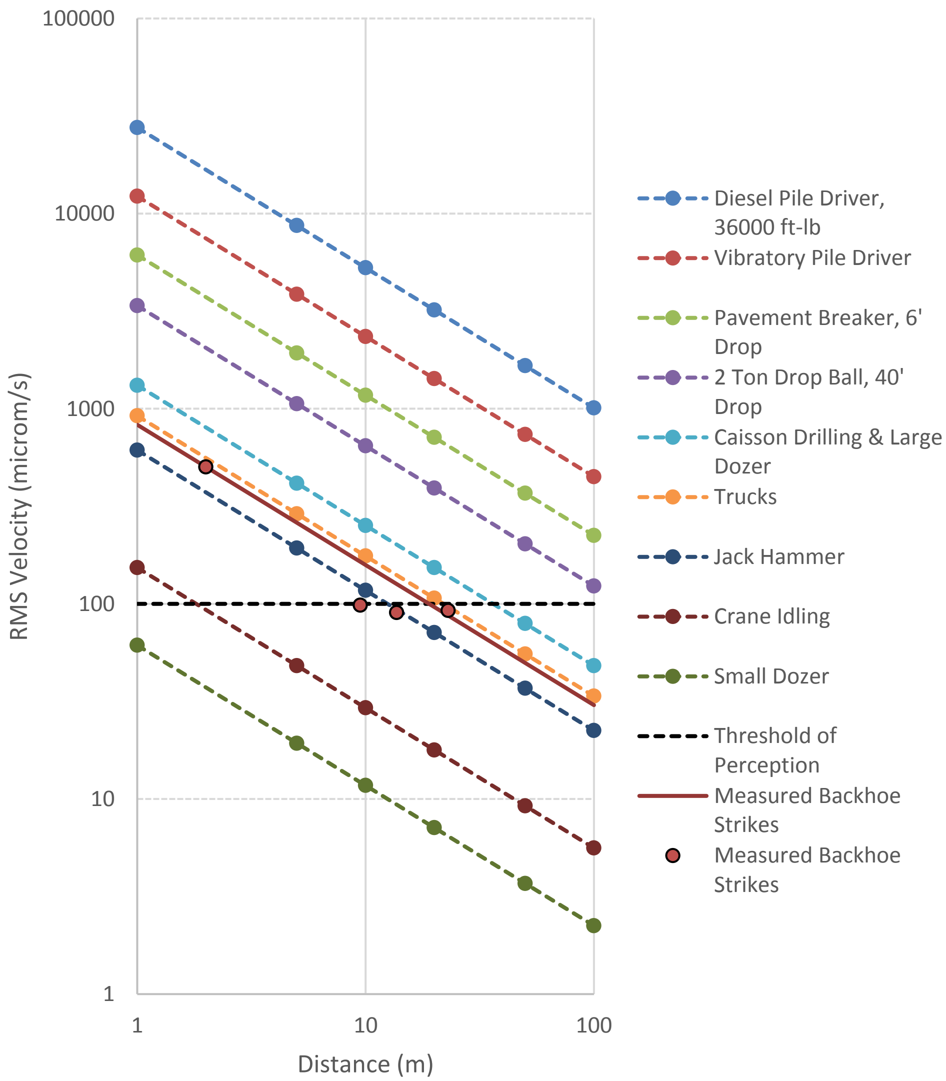


**Figure 1.** Measured Data vs. Site-Specific Earth Vibrations Due to Construction at 25 Hz Frequency

From these predictive curves, contour maps showing the expected VC criteria from the different construction activities were created. The different vibration-sensitive equipment were also included, colour-coded based on their required vibration criterion, to easily determine whether a particular unit is expected to meet or exceed its criterion during the construction activity under consideration. An example of one of these contour maps is shown in Figure 2. This contour map shows the predicted VC criterion met in the basement due to a slab removal. Contour maps were created for each construction activity and location, to determine which stage of construction would affect the different pieces of vibration-sensitive equipment.


**Figure 2.** Construction Vibration Zone of Influence Contour Map

## 5 Vibration mitigation

Based on the contour maps, it was found that certain activities would result in nearly all of the clinical laboratory and diagnostic imaging equipment exceeding their vibration criteria. Given this, the following vibration mitigation options were proposed to the hospital:

1. Equipment relocation;
2. Isolation tables / mounts;
3. Scheduling certain construction activities during equipment down-time; and
4. Adopting a less disruptive construction / demolition technique

By using the contour maps, the first option of equipment relocation could be used for certain pieces of equipment. However, given the large amount of logistics planning required should certain equipment need to be relocated (such as the MRI), this option may not be feasible for some instruments. Instead, using isolation tables or mounts were considered as a possible feasible solution for many of the equipment located in the basement. The stiffness of the basement slab-on-grade allows for the efficient isolation of equipment using vibration isolation pads. For smaller scale construction activities, such as a slab removal, it was recommended that these take place during equipment down-time, as they impact a large number of equipment but can be completed relatively quickly. Finally, adopting less disruptive construction methods was also proposed. One example was the construction hoist, as it was predicted to have significant effects on the vibration-sensitive equipment. As such, it was recommended that the existing interior elevators be used in lieu of an exterior construction hoist. A combination of all of these vibration mitigation options will likely need to be employed throughout the construction process to ensure the hospital's facilities can operate as usual, while taking into consideration operational, cost and scheduling implications.

## 6 Conclusions

A case study has been presented in which an existing healthcare facility with diagnostic imaging and clinical laboratory equipment will undergo extensive renovations. Based on construction vibration simulation testing, it was predicted that a large number of the vibration-sensitive equipment will exceed their vibration requirements as a result of the construction activities. The following conclusions have been made:

1. Exterior construction hoist-induced vibrations can exceed those of saw-cutting, coring and demolition activities.
2. Exterior ground level vibration excitations attenuate slower on basement slab-on-grades as compared to suspended ground level slabs.
3. Administrative mitigation methods such as scheduling construction activity during off-hours can be a viable and efficient method to controlling construction-induced vibrations.
4. Dividing the construction activities into stages and offering vibration predictions stage-by-stage, can be an important tool when deciding equipment relocations.

## 7 References

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