Building Tomorrow's Society
Bâtir la Société de Demain

Fredericton, Canada
June 13 – June 16, 2018/ *Juin 13 – Juin 16, 2018*

MONITORING AND EVALUATION OF PEDESTRIAN-INDUCED VIBRATIONS

Van Engelen, Niel[1,3], and Graham, Julia[2]
[1] Department of Civil and Environmental Engineering, University of Windsor, Canada
[2] RWDI Inc., Canada
[3] Corresponding Author: niel.vanengelen@uwindsor.ca

Abstract: Vibrations due to pedestrian footfalls are often the governing source of vibration on the upper floors of structures. These vibrations may cause discomfort for occupants, or interfere with the operation of sensitive equipment in structures such as research and healthcare facilities. A conflicting trend in structural engineering has emerged. Structural designs have progressed towards longer spans with efficient designs that are increasingly flexible, rendering them more susceptible to pedestrian-induced vibrations. Meanwhile, the vibration targets of high precision equipment, such as CT scanners and MRIs, have become increasingly stringent. Mitigating pedestrian-induced vibrations often results in considerable re-design of the structure to obtain a sufficiently stiff and massive floor, particularly in applications with sensitive equipment. Design guidelines assist structural engineers in achieving vibration performance objectives based on discrete walking speeds or a range of walking speeds. Long-term vibration measurements were undertaken in an office setting. Statistical analysis is applied to compare the long-term vibration performance of the floor against existing methods of predicting floor response due to pedestrian-induced vibrations and field measurements taken by an engineer used to evaluate the performance. The analysis is used to evaluate the accuracy of the predicted vibration performance and the field measurements in comparison to regular vibration performance.

1 INTRODUCTION

Continued research and development in structural engineering has increased the efficiency of structures resulting in lightweight floors that can span large distances. Such structures are more susceptible to pedestrian-induced vibrations owing to the increased flexibility and reduced mass of the structural system. Pedestrian-induced vibrations (PIVs) are often the governing source of vibration in healthcare and research facilities.

In general, structural design codes are primarily concerned with avoiding structural failure. Consideration of PIVs is an important serviceability limit state that can significantly impact the performance and utility of a structure. For healthcare and research facilities especially, there exists a conflict between efficient structural design and the extreme vibration sensitivity of specialty equipment such as electron microscopes, CT scanners and MRIs. Excessive vibrations can adversely affect the performance of sensitive equipment or cause discomfort for occupants. The issue is compounded by the fact that the permissible vibration levels for sensitive equipment are often considerably below the threshold of human perception. Therefore, it may not be intuitive to the users what the cause of poor performance is, or that a vibration issue is affecting performance.

Design guidelines (e.g. Murray et al. 2016, NRCC 2015, Smith et al. 2007, Willford and Young 2006, ATC 1999) have been developed to provide direction on predicting and evaluating expected vibration levels within a structure. Consideration of PIVs is an important step in the design process that should be considered early to accommodate changes to the structural and architectural design. Vibration considerations typically govern over strength considerations and the required changes to the structural system can be substantial, consequently adding additional cost to the structure and potentially impacting other areas of design (e.g. foundation, electrical and mechanical systems).

It is often of value to conduct measurements in a building to assess the vibration performance. The measurements may be conducted to confirm the appropriateness of the space for vibration-sensitive equipment or to identify the source causing a known vibration issue. Due to budgetary and time constraints, the measurements are usually taken over a short period of time, often based on a controlled walking test. In this paper, a renovated steel structure is investigated for vibration performance. Vibration predictions based on relevant guidelines are compared against short-term vibration measurements due to controlled walking tests and long-term vibration measurements conducted over a seven-day period. The three methods are compared and discussed.

Note that the discussion in the paper specifically relates to occupant comfort due to vibrations produced by a single walker. Scenarios based on group loading, such as stadium grandstands or pedestrian bridges, are beyond the scope of this paper.

2 BACKGROUND

2.1 Vibration Criteria

There are many different vibration criteria that can be applied depending on the type of structural system, use of the area, and receptor type (e.g. occupant comfort or sensitive equipment). For floor systems, Vibration Criteria (VC) curves are commonly applied. VC curves provide vibration limits in terms of the root-mean-squared (RMS) spectral velocities in 1/3 octave bands of frequency. Commonly applied vibration criteria include human comfort levels, based on the International Organization for Standardization (ISO 1989, 1997, 2007), and levels for sensitive equipment based on VC curves (Amick et al. 2005, Ungar et al. 2006); the collective is commonly referred to simply as VC curves. VC curves are defined over a frequency range of 1 to 80 Hz and are based on continuous vibrations. In general, each VC level is a multiple of 2 from the previous level (with some exceptions). Table 1 shows selected VC levels and their applicability (Murray et al. 2016, Willford and Young 2006, Smith et al. 2007).

Table 1: VC curves description

VC Curve	Maximum RMS Velocity (μm/s)	Description
Office (ISO)	400	Offices
Residential Day (ISO)	200	Residences, computer equipment
Operating Theatre (ISO)	100	Surgery facilities, operating theatres, bench microscopes up to 100x
VC-A	50	Microbalances, spectrophotometers, bench microscope up to 400x magnification
VC-B	25	Microsurgery, bench microscopes at greater than 400x magnification

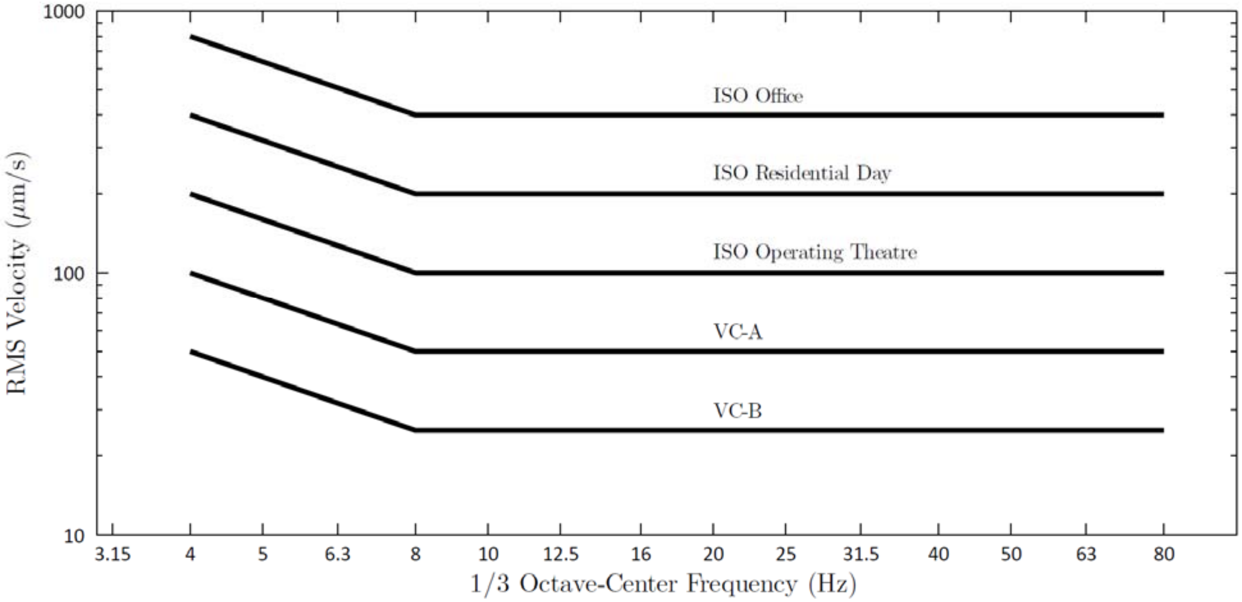


Figure 1: Selected VC Curves

2.2 Vibration Prediction for New Construction

2.2.1 Guidelines

There are several different guidelines available (e.g. American Institute of Steel Construction (AISC) Design Guide 11 (Murray et al. 2016), Applied Technology Council (ATC) Design Guide 1 (ATC 1999), the Concrete Center CCIP-016 (Willford and Young 2006) and the Steel Construction Institute SCI P354 (Smith et al. 2007)) to predict the vibration performance of a structure. The commentary of the current edition of the National Building Code of Canada (NRCC 2015) references an earlier edition of AISC Design Guide 11 (Murray et al. 2016) and ATC Design Guide 1 (ATC 1999) for evaluation of PIV in structures. Although vibration performance predictions can be made using simplified assumptions, as described in the guidelines, advanced techniques based on finite element analysis can also be pursued. A three-dimensional finite element model of the structure can be developed to estimate the dynamic properties (i.e. mode shapes and natural frequencies). These techniques provide a better representation of the frequency content of the expected floor response and can be used to generate time histories for subsequent post-processing. Furthermore, manufacturers of vibration-sensitive equipment often recommend frequency-dependent vibration criteria that benefit from advanced finite element techniques to accurately represent a range of frequencies. As the predictions are being compared directly to measurements, only advanced techniques based on finite element analysis are considered herein. For additional information on finite element analysis techniques for PIV see the respective guidelines.

2.2.2 Loading

The application of the dynamic load is treated differently for low-frequency and high-frequency modes of vibration. A high-frequency mode is generally considered to have a natural frequency greater than approximately 10 Hz. For modes close to 10 Hz, both the low-frequency and high-frequency dynamic loads can be applied to obtain the governing case. In both cases, the application of the loads is done by selecting specific nodes of the finite element model to represent a single walker at different locations within the structure. Note that the walker is stationary. For low-frequencies, the dynamic load is applied as a sinusoidal excitation for each harmonic with a correction applied to account for resonance buildup. The magnitude of the loading varies somewhat between different guidelines. In general, the harmonic loads were determined from numerous walking studies and the magnitude of the impulse loading used in high-frequency modes are variations of the method proposed by Willford et al. (2006).

In the analysis, the weight of the walker is assumed to be 746 N (168 lb) which is to represent an *average* person (Murray et al. 2016, Smith et al. 2007).

2.2.3 Walking Speed and Walker Location

The speed of the walker used is dictated by the architecture and the natural frequency of the structural bay of interest. For low-frequency modes, a walker with a speed that generates a resonant response will govern. In the case of a high-frequency mode, a faster walker is expected to produce a larger vibration response and the fastest walking speed should be applied.

The range of walking speeds recommended varies between guidelines. In general, the architecture determines the maximum considered walking speed for an area (i.e. people are expected to walk slower in areas with obstructions, such as classrooms and laboratories, in comparison to open hallways with no obstructions). Guidelines for PIVs recommend a minimum walking speed of 75 steps/minute (spm) (Murray et al. 2016), and a maximum walking speed of 150 spm (Willford and Young 2006); although an upper-bound of 132 spm is often considered based on the probability of occurrence (Smith et al. 2007).

Often, there are numerous areas of concern within a structure, or a minimum vibration performance level may be required and the entire structure must be analyzed. Such instances result in many walkers applied to different areas of the structure with a range of walking speeds considered for each walker. Software can be used to determine the maximum response due to all walkers and walking speeds for each node of the finite element model. This can subsequently be used to generate a contour map based on the selected vibration criteria. The generation of a map is convenient to identify areas of the structure that are performing well and areas of the structure that require attention or mitigation measures.

2.3 Existing Structures

2.3.1 Short-term Monitoring

Existing structures allow for the vibration-performance of a floor to be determined directly without the need for complex modelling or other vibration-prediction methodology. Measurements of vibrations in existing structures is conducted to confirm that the measured area of the structure is achieving the desired vibration performance. This can be completed to validate the modelling results, to evaluate an existing space for the relocation of equipment, or to identify a potential vibration issue. Although it may be more ideal to monitor the floor for a long period of time while the structure is in use, this is often not practical either due to the construction phase (i.e. the space is evaluated prior to occupancy of the new structure) or due to budget considerations, as discussed in the subsequent section. Consequently, the primary intent of the short-term monitoring is to generate a response that represents a *near* worst-case response from a single walker that is expected to realistically occur in day-to-day operations.

The typical procedure to conduct short-term measurements is to first identify the appropriate location to position the accelerometer. The selected position depends on the objective, but is usually at the base of the vibration-sensitive equipment of interest, or at the center of the structural bay where the maximum response is expected. Heel drop tests can then be conducted to determine the natural frequency of the floor. Based on the natural frequency, walking scenarios can be developed to produce a maximum vibration response at the measurement location. Usually, a minimum of two scenarios are considered based on a single walker located within the room and a single walker travelling through the nearest open corridor. The walking speed for each scenario is determined as a multiple of the natural frequency to ensure that the higher harmonics produce a resonant response of the floor. For stiff floors with high natural frequencies, which are common in hospital and research structures, the walking speed may be determined as the maximum considered speed for confined or open spaces. During each walking test, a single person walks along a designated path following a metronome to maintain the correct walking speed.

An inherent disadvantage with the short-term monitoring is that the measured response will vary from walker to walker. If possible, numerous walkers can be considered to remove some of the uncertainty.

Although, due to the cost considerations of engaging numerous people to conduct walking tests, this may not be feasible.

2.3.2 Long-term Monitoring

Long-term monitoring is comparatively rare due to the costs and difficulties associated with on-site measurements. These difficulties include the cost of installation and removal of equipment, which requires a technician or engineer to visit the site multiple times, the cost associated with leaving equipment on-site, concerns over the safety of the equipment to avoid vandalism or accidental damage, and concerns over proper equipment placement (i.e. that the monitoring equipment does not interfere with day-to-day activities within the building). Furthermore, the timeline of a project often determines that long-term monitoring is prohibitive. The primary advantage of long-term monitoring is that it provides a better insight to the vibration levels regularly experienced by the structure in day-to-day use.

To conduct long-term measurements, an accelerometer and data logger must be installed at the location or locations of interest. It is often beneficial that the users of the space are not aware that measurements are being conducted, or that limited knowledge of the measurements is permitted. This is to avoid issues with vandals purposely attempting to excite the floor which produces biased results. Depending on the type of building, data collected during unoccupied hours (e.g. overnight) may be discarded. The remaining data can be evaluated based on the maximum response or statistical analysis, as required for the use of the space being evaluated.

3 EXPERIMENTAL PROGRAM AND RESULTS

3.1 Structure

The structure investigated was a renovated two-storey commercial building located in Ontario, Canada. The occupants of the building had recently relocated from a slab-on-grade location and there had been complaints from the occupants of perceptible vibrations on the elevated floor at the new location. As part of an extensive measurement program, short-term and long-term measurements were conducted at multiple locations. Knowledge of the measurements was limited, and most occupants were unaware that measurements were being conducted.

For the results presented herein, a single SENSR CX1 tri-axial accelerometer (resolution 0.00005g) was placed beneath the desk of one of the occupants as shown in Figure 2. The measurement location was determined by the occupants and the need to remain discrete. The cubicles continue in the plan north, south and east direction of the figure; the plan west direction is the exterior façade. Discussion with the occupants identified that the corridor along the façade is rarely used. All measurements were sampled at 125 Hz.

The building is steel construction with a 254 mm (10 in) hollow core precast concrete slab with a 51 mm (2 in) normal weight concrete overlay supported on steel beams (W16x100). The measured area is a cubical environment with no partitions. The structural bay that the measurements were conducted in was approximately 7.8 m x 12.2 m (25.5 ft x 40.0 ft). The vibration analysis in the subsequent sections is based on a 1-second running average RMS velocity response with 1/3 octave bandwidths. The plots show the maximum observed value for each 1/3 octave independently (max-hold).

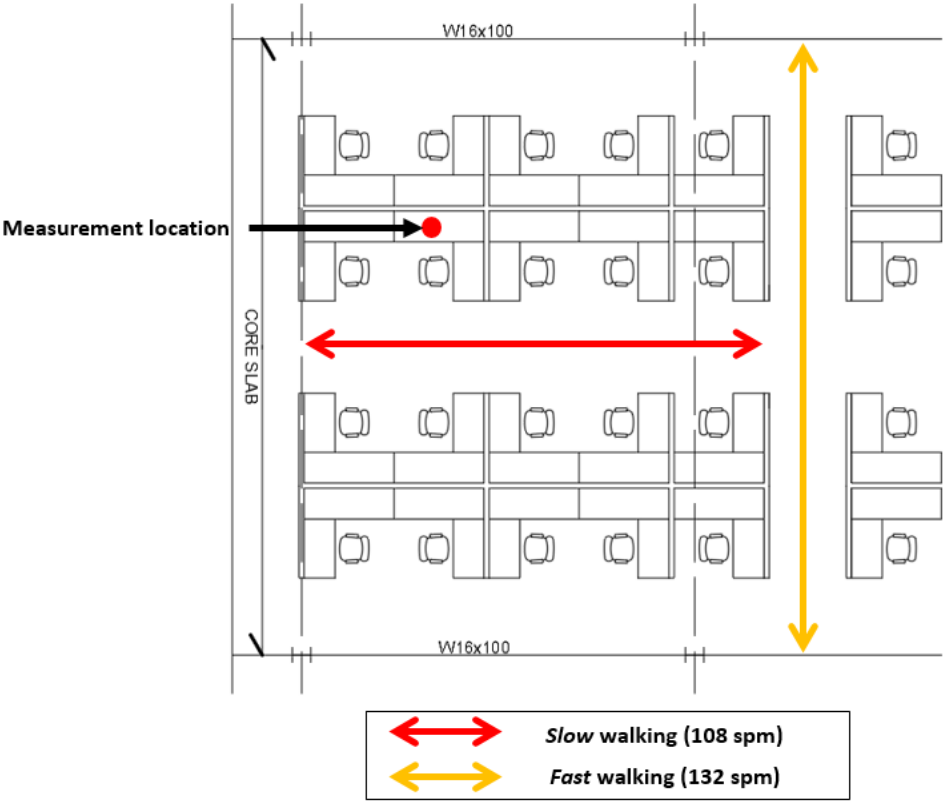


Figure 2: Architectural layout, measurement location and selected walking paths

3.2 Vibration Prediction

A finite element model of the structure was developed and analyzed according to the recommendations of SCI P354 and CCIP-016 (Smith et al. 2007, Willford and Young 2006). It was assumed that the damping of the structure was 2.0 % in the analysis as recommended for a post-tensioned concrete floor with low outfit (Willford and Young 2006). A *fast* (132 spm) and *slow* (108 spm) walking scenario were considered as shown in Figure 2. These walking speeds correspond to the maximum recommended walking speed in enclosed spaces and open spaces, respectively (Smith et al. 2007).

Figure 3 shows the expected vibration response of the floor when subjected to the discrete *slow* and *fast* walking speeds. Based on the analysis, the measurement location is expected to achieve ISO Residential Day and ISO Operating Theatre (marginally exceeding VC-A) for the slow and fast walking scenarios, respectively.

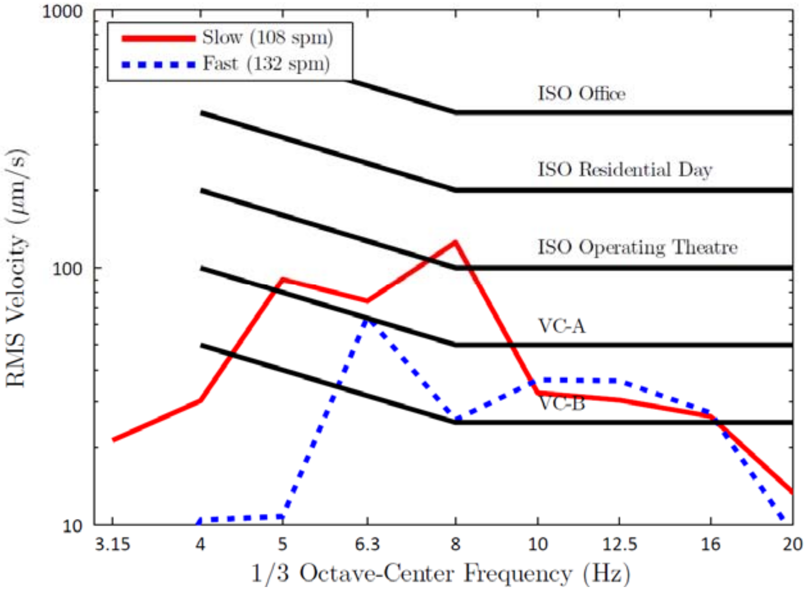
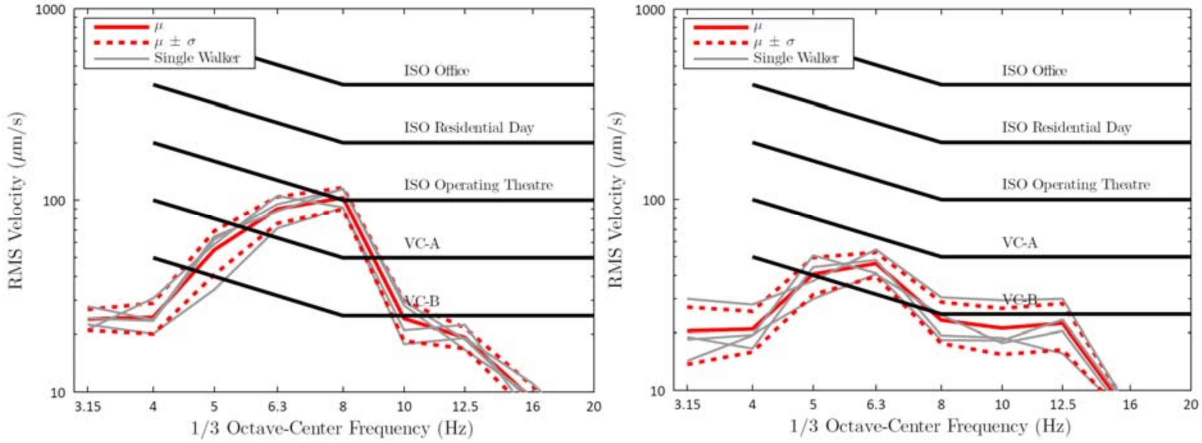


Figure 3: Predicted vibration performance at the measurement location for the slow and fast walking scenarios

3.3 Short-term Monitoring

Short-term monitoring was conducted with four people of varying age, gender, and weight. The mass of the walkers has been scaled to 746 N (168 lb) (Murray et al. 2016, Smith et al. 2007). Although heavier individuals are expected to generate larger vibrations, scaling the weight allows for a more direct comparison between walkers and theoretical predictions. This is particularly advantageous when comparing numerous measurements from different locations and different walkers.

Each walker conducted two scenarios: a *slow* walking scenario was conducted within the cubical area at 108 spm, and a *fast* walking scenario was conducted at 132 spm in the corridor between cubicles (as shown in Figure 2). Figure 4 shows the maximum response observed in each 1/3 octave bandwidth for both walking scenarios. The figure shows the mean, μ, plus or minus a standard deviation, σ, as well as the results from each individual walker. Based on the mean response of the walking scenarios conducted, the measurement location is achieving ISO Residential Day and VC-A for the slow and fast scenarios, respectively. The coefficient of variation (COV) between the individual walkers at the maximum 1/3 octave RMS velocity response was 16% and 14% for the slow and fast scenarios, respectively.



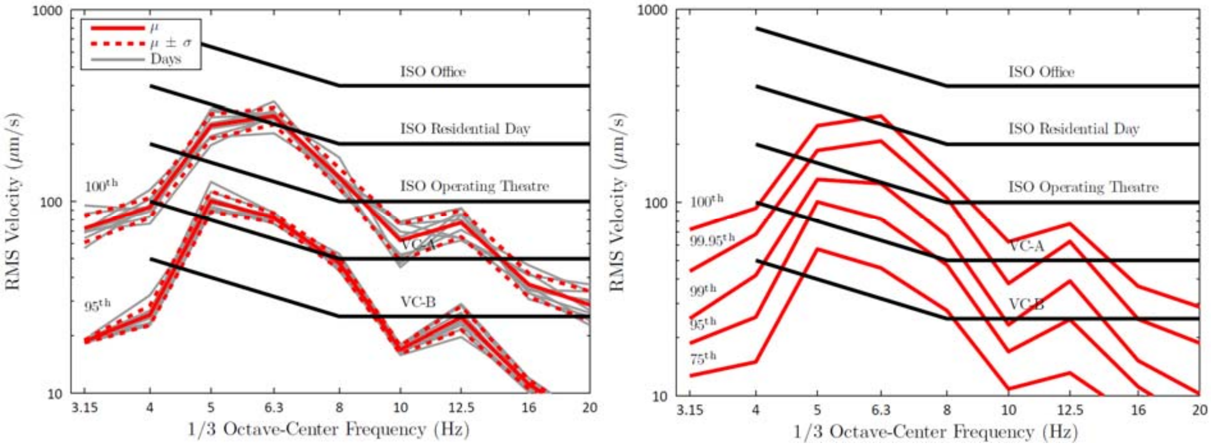
(a)

(b)

Figure 4: Maximum measured response based on short-term measurements for the (a) 108 spm and (b) 132 spm short-term measurements

3.4 Long-term Monitoring

The long-term measurements were conducted for seven days; only measurements conducted during the regular office hours on weekdays (i.e. 8:00 am to 5:00 pm) were considered. Each day was initially analyzed independently. Figure 5a shows a comparison of the mean and measured values for the 100th and 95th percentile of the seven days recorded. In general, it was found that there was good agreement between the day-to-day vibration response of the floor. Based on the mean 100th percentile, the floor experienced a maximum vibration response of ISO Office in day-to-day use. The COV at the maximum RMS velocity, which occurred at 5 Hz for the 95th percentile, and 6.3 Hz for the 100th percentile was 13 % and 10 %, respectively. Figure 5b shows the mean value of the daily measurements for selected percentiles. The level of vibrations experienced by the floor diminished steeply with respect to probability of occurrence; at the 99th percentile, the floor is achieving ISO Operating Theatre. The 99th percentile represents approximately 324 seconds (5.4 minutes) of exceedance in a 9-hour period.



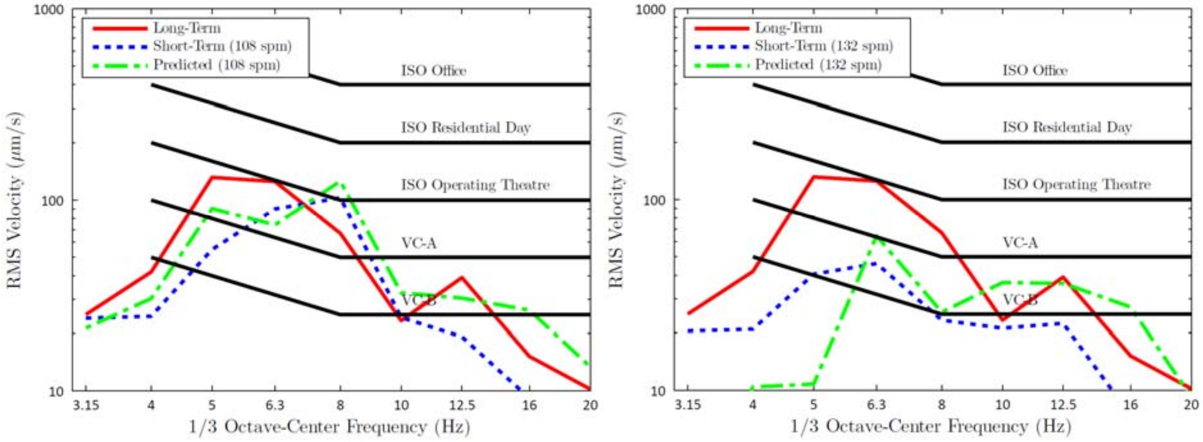
(a)

(b)

Figure 5: A (a) comparison of the daily measurements showing the mean and standard deviations and (b) the distribution of the mean daily measurements for selected percentiles

4 DISCUSSION

The vibration prediction and short-term monitoring both indicate that walking within the structural bay is the governing case, as expected, and will be the primary focus of the following discussion. Figure 6 compares the predicted response, the short-term measurements based on the mean of the maximum observed response of the four walkers, and the long-term measurements based on mean 99th percentile of the seven days measured. In general, good agreement has been found between the three methods of evaluation, particularly for the governing slow walking scenario (Figure 6a). The VC classification between the three methods varies somewhat owing to the response occurring approximately at the transition between ISO Operating Theatre and ISO Residential Day. Note that the predicted response and the short-term measurements are based on a discrete excitation frequency. A walking speed of 108 spm has a fourth harmonic within the 8 Hz 1/3 octave bandwidth. This corresponds well with maximum 1/3 octave band response observed within the two methods. It is postulated that if more discrete walking speeds were considered that the envelope of the predicted and short-term response would more closely resemble the day-to-day distribution.



(a) (b)

Figure 6: Comparison of the predicted vibrations and the 99th percentile of the long-term measurements to the (a) 108 spm and (b) 132 spm short-term measurements

For the floor considered, the short-term and long-term measurements were both found to exhibit good repeatability and consistency between the individual walkers (when normalized by mass) and day-to-day measurements, respectively. For the cases considered, the COV ranged between 10-16 %. As each VC class is separated by either a 100 % increase or 50% decrease in vibrations, the results suggest that short-term controlled walking tests and long-term monitoring based on a single day is expected to be accurate within a VC class.

In the design guides (Willford and Young 2006, Smith et al. 2007) it is noted that the dynamic load factor recommended for design of low-frequency floors is based on the 75th or 85th percentile of experimental results. However, no additional uncertainty is directly accounted for in other parameters (e.g. the mass of the walker) and it is not clear what probability of exceedance is the intended target for human comfort. VC curves are based on continuous vibrations, which ISO (2007) defines as vibrations that have a duration of more than 30 minutes in a 24-hour period, which is approximately equivalent to the 98th percentile. It is believed that the vibration prediction and short-term measurements close agreement with the 99th percentile of the day-to-day measurements is acceptable. However, depending on the use and occupants of the structure, it is possible that the approximately 5.4 minutes of exceedance over a 9-hour period may be unacceptable and result in complaints. An improved representation of the probability of exceedance in the design process and response of floors is an area requiring more attention. The employee at the measurement location "*rarely*" perceived vibrations, which appears to be in good agreement with the measured and predicted response at that location within the structure.

5 SUMMARY AND CONCLUSIONS

Pedestrian-induced vibrations remain a challenging serviceability design consideration. The desire to have lightweight floors over long spans often conflicts with the stiffness and mass requirements for acceptable vibration performance. In this paper, a renovated commercial building was investigated for complaints related to pedestrian-induced vibrations. Vibration predictions, short-term controlled walking tests, and long-term measurements of day-to-day activity were considered and compared. It was found that the vibration predictions and maximum observed response of the short-term measurements based on controlled walking tests were in good agreement with the 99th percentile of long-term measurements. Good consistency between mass-normalized individual walkers for controlled walking tests, and day-to-day vibration measurements were also observed. For the structure considered, it is believed that the vibration predictions and short-term measurements are both good representations of the maximum floor response experienced in day-to-day use of the structure. These results serve to validate the vibration prediction methodology based on advanced finite element techniques, as well as to validate the use of controlled walking tests for the evaluation of floor vibrations. Additional research is required in this area to examine other factors such as the impact of floor frequency.

References

Amick, H., Gendreau, M., Busch, T. and Gordon, C. 2005. Evolving Criteria for Research Facilities: I-Vibration. SPIE Conference 5933, International Society for Optics and Photonics, San Diego, CA, USA, **1**:1-13.

Applied Technology Council (ATC). 1999. ATC Design Guide 1: Minimizing Floor Vibration. ATC, Redwood City, USA.

International Organization for Standardization (ISO). 1997. ISO 2631-1 Evaluation of Human Exposure to Whole-body Vibration – Part 1: General Requirements (1 Hz to 80 Hz).

International Organization for Standardization (ISO). 1989. ISO 2631-2 Evaluation of Human Exposure to Whole-body Vibration – Part 2: Vibration in Buildings (1 Hz to 80 Hz).

International Organization for Standardization (ISO). 2007. ISO 10137 Bases for Design of Structures – Serviceability of Buildings and Walkways against Vibrations.

Murray, T.M., Allen, D.E., Ungar, E.E., and Davis D.B. 2016. *Vibration of Steel-Framed Structural Systems Due to Human Activity.* 2nd Edition. American Institute of Steel Construction, USA.

National Research Council Canada (NRCC). 2015. *User's Guide-NBC 2015 Structural Commentary (Part 4 of Division B)*, *National Building Code of Canada*, Canada.

Smith, A.L., Hicks, S.J., and Devine, P.J. 2009. *SCI P354: Design of Floors for Vibration: A New Approach*. The Steel Construction Institute, Ascot, UK.

Willford, M.R., and Young, P. 2006. *A Design Guide for Footfall Induced Vibrations of Structures.* Concrete Society, London, UK.

Willford, M.R., Young, P, and Field, C. 2006. Improved Methodologies for the Prediction of Footfall-induced Vibration. Building Integration Solutions, Architectural Engineering Institute, Omaha, NE, USA.

Ungar, E., Zapfe, J., and Kemp J. 2006. Predicting Footfall-induced Vibration Relative to Criteria for Sensitive Apparatus. *ASCE Structures Congress,* ASCE*,* Reston, VA, USA*,* **1**:1-13.