Chapter 11

It's All About That Bass! Isolating For Low-Frequency Ground-Borne Vibrations

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Abstract Floor motions can disturb occupants, leading to frequent complaints and loss of functionality. In especially vibration-sensitive facilities, this issue can be more critical, as high-resolution imaging equipment with stringent vibration criteria are often employed. As urban intensification increases, new buildings are being constructed in close proximity to existing vibration sources, such as rail lines and busy roads. In many cases due to a number of site-specific factors, the low-frequency content of the ground-borne signal can be significant, which can only be properly mitigated with very low-frequency isolation systems. These systems can be extremely challenging to design, with limited options available on the commercial market for components.

In this paper, two case studies are presented of buildings that required significant effort to isolate for low-frequency rail-induced vibrations. The first project involved a low-rise residential building directly adjacent to a heavily used freight and passenger rail line. At this specific location, a bolted track joint was present with a significant misalignment which caused intense low-frequency impulsive vibrations to be felt on the project site. Base isolation was not reasonably feasible due to the foundation type required for the local soil conditions, so a complex isolation system was devised that would be installed below the second floor of the structure. The second project involved several townhouse blocks that were constructed immediately adjacent to a freight rail line, where site-specific soil conditions led to very low-frequency ground vibrations. Based on measurements taken on site it was determined that the foundation for the crash wall had significantly reduced the vibrations, but that whole building isolation was still required. The main challenge overcome in this case was designing a system that would have a low-frequency isolation system while being constrained by the relatively light-weight wood-framed constructions above.

Keywords Vibration Serviceability · Ground-borne Vibration · Vibration Isolation · Vibration Measurements · Model Validation · Sensitive Floors · Dynamic Loading

Introduction

As urban intensification increases, new buildings are being constructed in close proximity to existing vibration sources, such as rail lines and busy roads. In many cases due to a number of site-specific factors, the low-frequency content of the ground-borne signal can be significant, which can only be properly mitigated with very low-frequency isolation systems. These systems can be extremely challenging to design, with limited options available on the commercial market for components.

Vibration is generated by the contact between train wheels and the steel rails. The resulting vibration is caused by the inherent roughness and irregularities in the rail, which forces the wheels to move up and down, thus imparting a force in the rail. The vibration generated by the resulting forces propagates through the underlying structure of the transit system that supports the track and subsequently into the surrounding soil until it encounters nearby buildings, at which point the vibration is transmitted into a building through its foundation.

Ground vibration produced by rail transit systems can be annoying to human occupants in residential, office, and commercial buildings when they perceive some combination of feelable vibration, re-radiated sound, and vibration-induced rattling of building interior items. Passing railway traffic also can be disruptive to operation of sensitive equipment in manufacturing, medical facilities, and recording studios.

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Vehicles running on tracks give rise to vibration with predominant components in the frequency range of 4 Hz to 250 Hz. Vibration propagates parallel to the surface as wave modes of the layered soil and has a low rate of attenuation with distance. In the frequency range of 4 Hz to 80 Hz, the vibration may be perceived as whole-body vibration in buildings near to the line. At higher frequencies, in the range from about 20 Hz to about 250 Hz, ground vibration may excite bending resonances in the floors and walls of buildings, which then radiate a rumbling noise directly into the rooms. A third source of disturbance is due to movement of building objects, shaking of items on shelves or hanging on walls or by the rattling of windowpanes, glassware, and computer screens. In all these cases the problem of ground-borne vibration is important at frequencies typically up to about 250 Hz.

Two case studies are presented in this paper of structures that have vibration-sensitive occupancies that are directly adjacent to rail lines where measurement indicated that without significant modification to the structure, significant low-frequency ground-borne vibrations would render the spaces inadequate for their intended uses.

Vibration Criteria

For human comfort, vibration criteria are normally expressed as the root mean square (RMS) response of each one-third octave band from 1 Hz to 80 Hz [1]. For sensitive equipment, the criteria may be expressed in one-third octave bands, or other formats, including power spectral densities, peak-to-peak levels, etc. Over the past 35 years, generic vibration limits have been developed which provide frequency-dependent sensitivities for wide classes of equipment and are used extensively in design of healthcare and research facilities [2]. These vibration criterion (VC) curves are internationally accepted as a basis for designing and evaluating the performance of vibration sensitive equipment and the structures that support them. The VC curves range between Workshop (least stringent) through VC-G (most stringent). Most laboratories target at least VC-A as a maximum baseline for the majority of the facility, with certain areas requiring more stringent criteria, depending on the expected use of the space.

These curves were originally based on the ISO 2631-2 (1989) [3] base curve for human response to whole body vibration, which is considered the threshold of human perception, but have since evolved. The ISO base curve is often referred to as the ISO-Operating Room criteria. The above noted criteria are also specified as RMS velocities in one-third octave bands. The VC curves should not be used to replace manufacturers' specifications for vibration requirements, but are beneficial where manufacturers' specifications are non-existent, incomplete, or where specific equipment has not yet been selected.

The VC and ISO curves will be primarily used as a basis of evaluating the performance of the structures in this paper.

Case Study #1 – Low-Rise Residential Building

The first case study is a project that was to be constructed in the greater Chicago area, directly adjacent to a major commuter and freight rail corridor, located to the west of the site. The existing site contained an abandoned commercial strip mall. Initial screening-level measurements had indicated an exceedance of the ISO Residential Night criteria near the western property boundaries, so a more comprehensive measurement scheme was devised to determine the attenuation of vibrations into the site (Figure 1).

A total of three freight trains and four commuter trains pass-bys were measured. Sample one-third octave band spectral plots at the measurement locations due to freight train pass-by are shown in Figure 2.

The measurement results show that:

- Freight Train Pass by – the measured vibration levels exceeded the recommended "Residential Day" and "Residential Night" limit at Location #1 and Location #2. At Location #3, the measured vibration exceeded the "Residential Night" limit. The frequency of peak ground-borne vibration was measured to be at 6.3 Hz as seen in Figure 2. It should be noted that this is a considerably lower frequency than what is typically seen for rail vibration, and was attributed to a misaligned bolted joint in the rails adjacent to the site, which caused a large impulsive vibration to be generated.
- Commuter Train Pass by – the measured vibration levels at Location#1 exceeded the "Residential Day" and "Residential Night" guideline limit. At Location#2 and Location#3, the measured vibration levels exceeded the "Residential Night" limit. The frequency of peak ground-borne vibration was 20 Hz, which was less of a concern that the peak frequencies observed for the freight trains.

Additionally, the maximum structure-borne noise due to freight train pass-by was predicted to be 39 dBA which exceeded the maximum allowable sound level of 35 dBA recommended by the industry-standard guidelines for residential building.

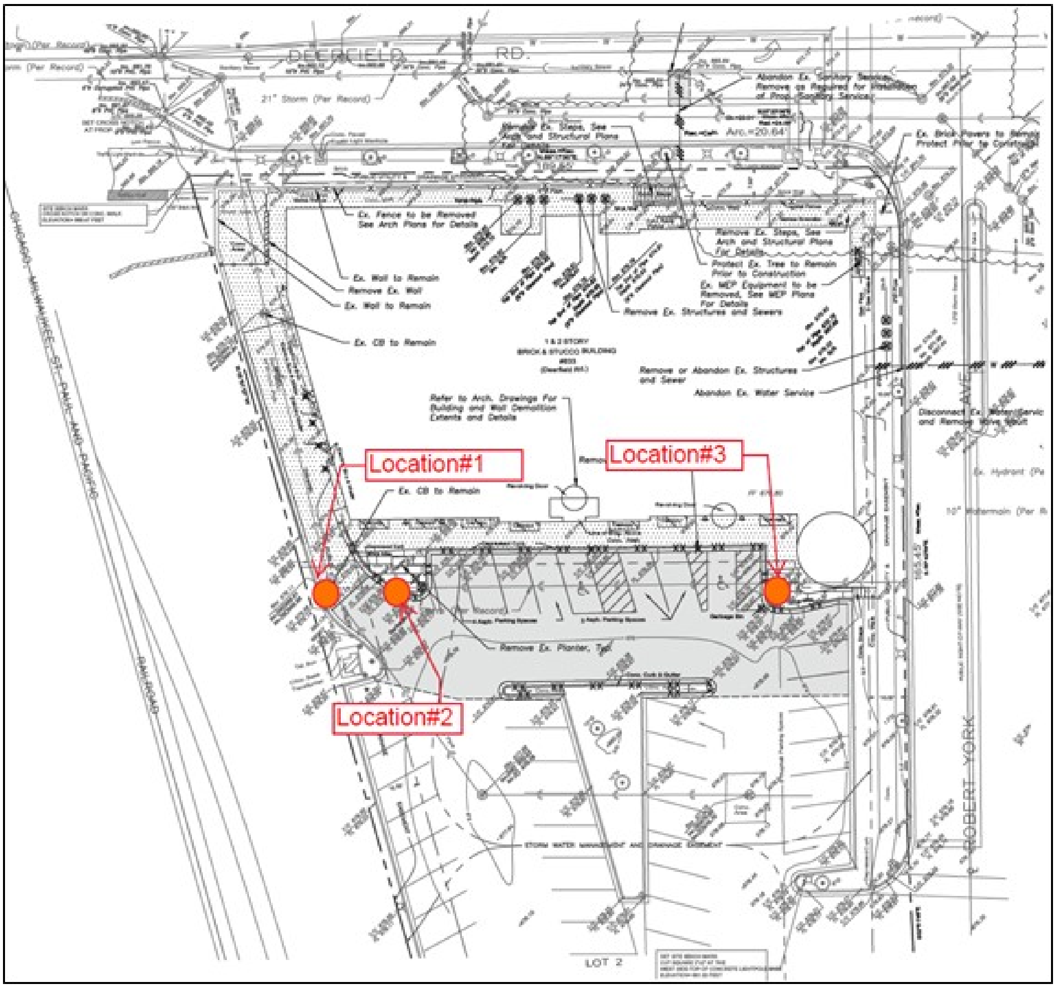

Fig. 1 Vibration Measurement Locations.

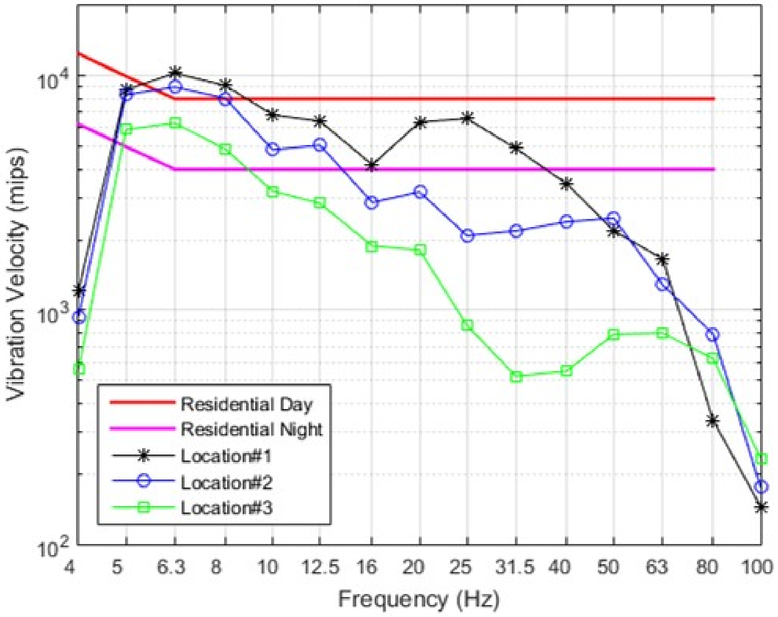

Fig. 2 One-Third Octave Band Spectral Level – Freight Train Pass-by.

Due to commuter train pass-by, the maximum sound level was predicted to be 34 dBA which is marginally lower than the recommended guideline limit.

Since the measured vibration levels (and predicted structure-borne noise inside the residential spaces) exceeded the recommended guideline limits, vibration mitigation would be required. A Finite Element (FE) model was then created in order to determine the level of attenuation in the building through the foundation, and to determine the optimal location for isolation devices. The soil conditions on the site were poor, requiring the use of aggregate piles. This complicated the ability to use more traditional base isolation due to the interface of these piles, the ground floor slab and the bearing soil around them. Since the ground floor of the structure was going to have a commercial occupancy, and was thus exempt from the Residential criteria, it was decided to install the isolation systems on the top of the first-floor columns, directly below the second floor structure (Figure 3). Owing to the low frequency of the ground-borne excitation, extremely low-frequency pre-compressed mechanical spring isolators were required, having a natural frequency of 3.5 Hz.

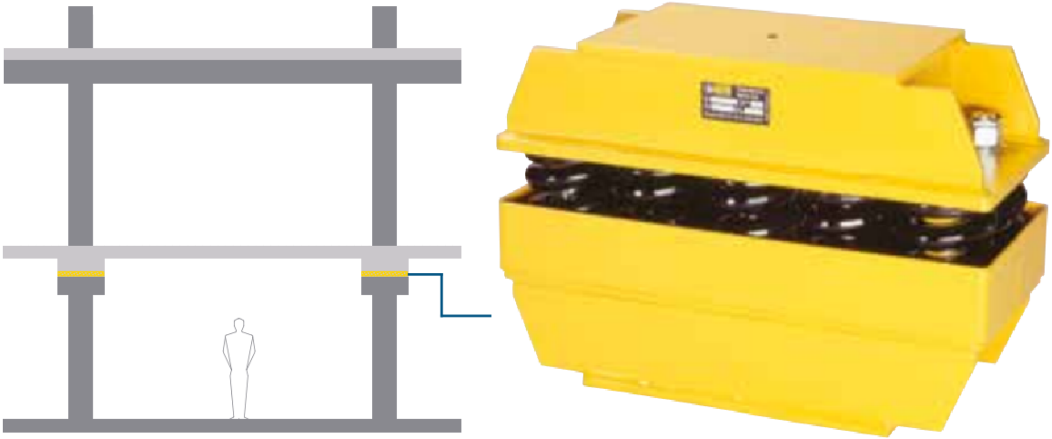

Fig. 3 Schematic Location and Configuration of Isolators.

It should be noted that once this phase of the design was completed, the project was suddenly cancelled to financial reasons stemming from the increased cost of construction materials due to the Covid pandemic.

Case Study #2 – Townhouse Residential Complex

The project used for Case Study #2 is a proposed residential development, consisting of eleven townhouse blocks. A Canadian National Railway (CNR) track is located immediately adjacent to the north side of the site. In order to establish the vibration levels and spectrum caused by train passes, continuous vibration measurements were recorded at two setback distances from the tracks, corresponding to the two closest rows of townhouses (Figure 4).

Currently, there are no guidelines for the impact of railway vibration in the land use approval process in Ontario. However, in May 2013, the Federation of Canadian Municipalities (FCM) and the Railway Association of Canada (RAC) issued ”Guidelines for New Development in Proximity to Railway Operations” [4] to address developments in close proximity to railway operations. The FCM/RAC guidelines identify dwellings within 75 meters from railways alignments as susceptible to vibration impact and recommend an overall maximum vibration limit of 0.14 mm/sec root-mean-square (RMS). The limit should be based on a one-second averaging time between 4 Hz and 200 Hz. Mitigation is prescribed when limit is exceeded.

It is our understanding that CNR has adopted the use of this guideline and the criterion for train vibration on this proposed new residential development is an overall vertical vibration level of 0.14 mm/sec (RMS) between 4 Hz and 200 Hz. This is comparable to the ISO Residential Night criteria described in Section 2.

Eight train passes were identified during the measurement period. Time histories of the vibration velocity produced by each train pass-by were band-pass filtered between 4 Hz and 200 Hz, and then processed using an RMS (root-mean-square) averaging routine with a time constant of one second. The maximum overall vertical vibration level from each train pass at each measurement location are shown in Table 1. The CNR criteria was exceeded by the average all train measurements at Location #1 (block A, B, and C). The criteria was met by the average of all trains at Location #2 (block J, K, L, and D). Spectral analysis of the results indicated that the peak frequencies of measured responses were in the 8-10 Hz range, which is considered to be lower than typical rail-induced vibration excitation.

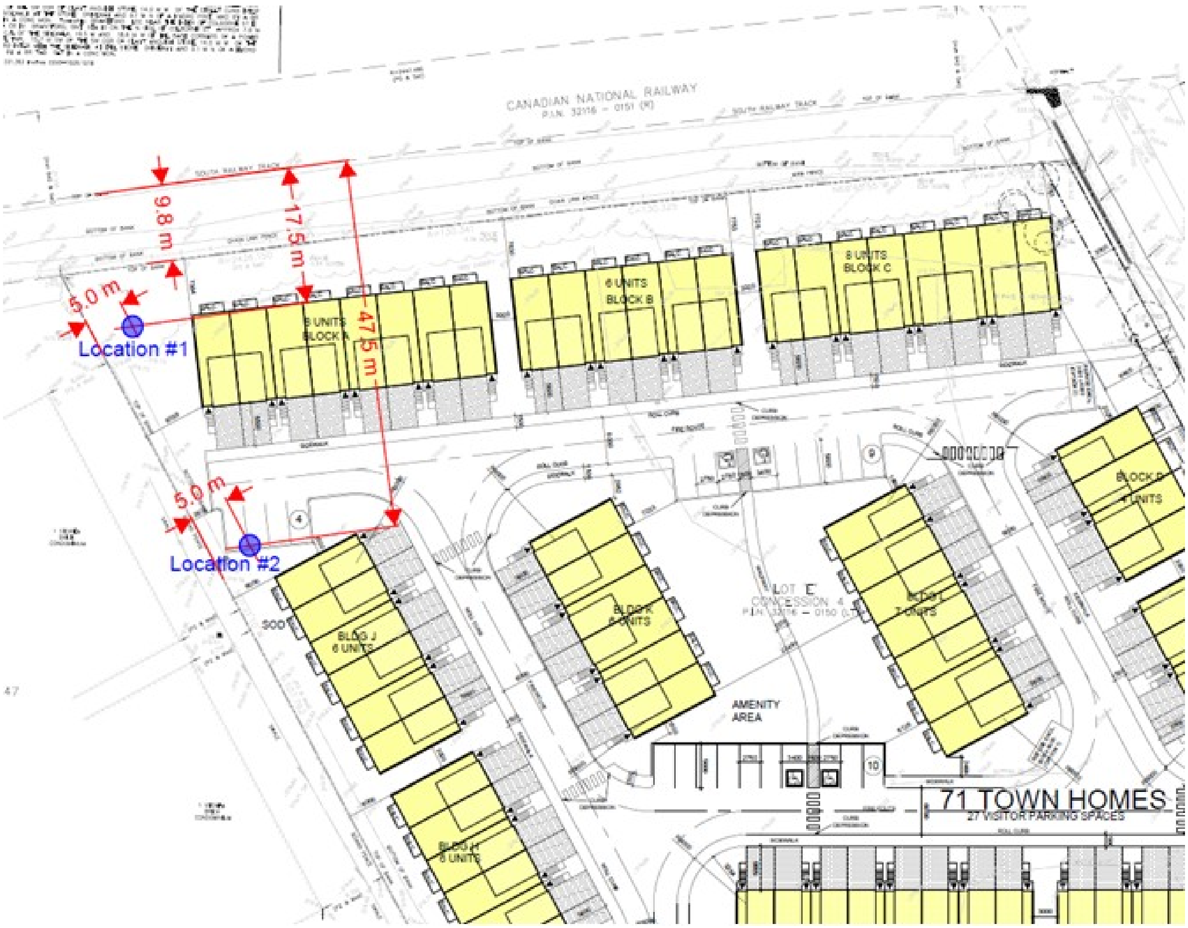

Fig. 4 Vibration Measurement Locations.

Table 1 Measured Vibration Levels for Train Passes.

Date	Time	Maximum Overall Vertical Vibration Level (mm/s RMS)	
		Location #1 (17.5m from tracks)	Location #2 (47.5m from tracks)
Feb. 15, 2021	13:18	0.21	0.13
Feb. 15, 2021	14:23	0.20	0.13
Feb. 17, 2021	10:34	0.22	0.15
Feb. 17, 2021	11:55	0.18	0.12
Feb. 19, 2021	11:54	0.23	0.12
Feb. 19, 2021	12:42	0.23	0.15
Feb. 22, 2021	11:03	0.20	0.13
Feb. 22, 2021	11:48	0.19	0.11
Feb. 24, 2021	14:19	0.19	0.13
Feb. 24, 2021	15:12	-	0.11
Feb. 26, 2021	10:34	0.18	0.12
Feb. 26, 2021	11:35	0.22	0.15
Average		**0.20**	**0.13**

When a projected vibration level exceeds the applicable criterion, it is necessary to consider vibration mitigation. Potential mitigation measures are evaluated to determine their effectiveness in reducing the projected vibration and reradiated noise. A mitigation measure's performance is referred to as its Insertion Loss (IL) in dB, which represents the difference in vibration with mitigation relative to the vibration without mitigation.

There are a number of differences in the dynamic behavior of elastomeric pads and steel springs. The most important difference is the natural frequency at which can be achieved under structural loading conditions. Elastomeric pads have typically been used in building isolation systems with natural frequencies in 5 to 15Hz. Steel spring systems for building isolation are most cost efficient in the range of 3Hz to 5Hz natural frequency. Figure 4 illustrate the achievable insertion loss (vibration attenuation) of various isolation frequencies.

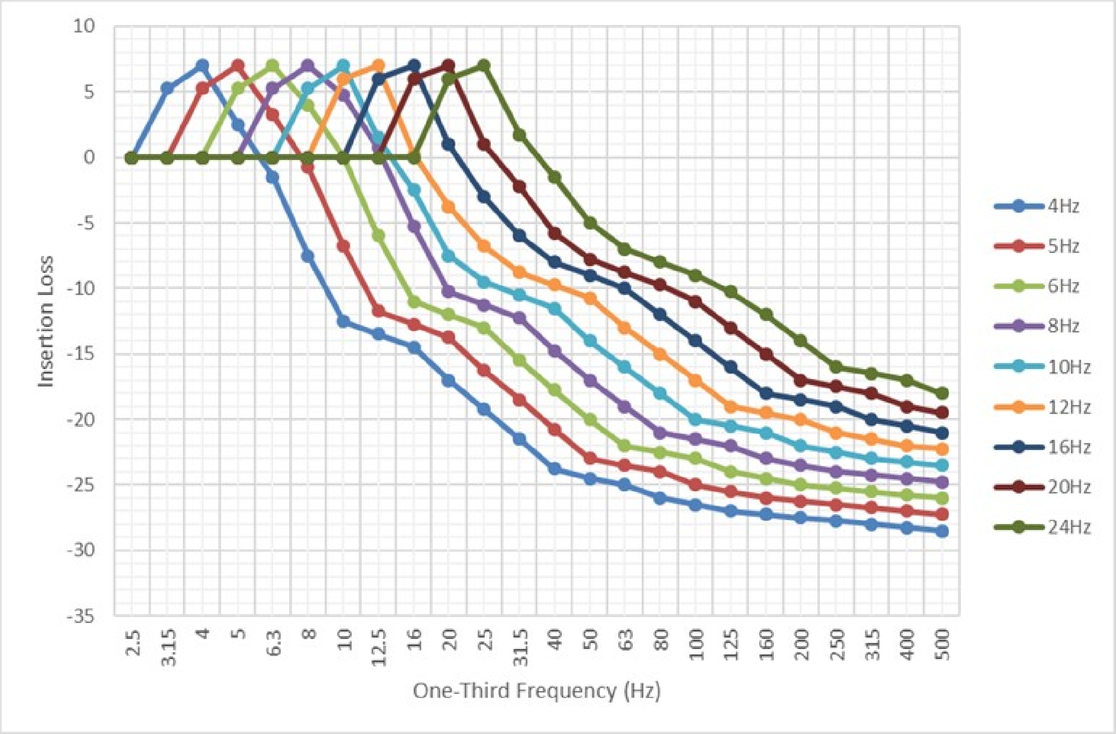

Fig. 5 Insertion Loss for Various Isolation Frequencies.

The expected performance of the base isolation was analyzed using the one-third octave vibration spectra of the measurements and adjusted by foundation coupling loss and floor amplification factors. Table 2 provides a summary of vibration predictions of the 5 Hz system. The base isolation mitigates the vibration levels to an average of 0.09 mm/sec (RMS) which is below the vibration limit.

Table 2 Measured Vibration Levels for Train Passes and Predictions of Isolation System.

Date	Time	Maximum Overall Vertical Vibration Level (mm/s RMS)	
		As Measured on Soil	With 5 Hz Base Isolation
Feb. 15, 2021	13:18	0.21	0.11
Feb. 15, 2021	14:23	0.20	0.12
Feb. 17, 2021	10:34	0.22	0.11
Feb. 17, 2021	11:55	0.18	0.05
Feb. 19, 2021	11:54	0.23	0.05
Feb. 19, 2021	12:42	0.23	0.05
Feb. 22, 2021	11:03	0.2	0.05
Feb. 22, 2021	11:48	0.19	0.14
Feb. 24, 2021	14:19	0.19	0.13
Feb. 24, 2021	15:12	-	-
Feb. 26, 2021	10:34	0.18	0.10
Feb. 26, 2021	11:35	0.22	0.12
Average		**0.20**	**0.09**

Difficulty was experienced in locating a commercially available neoprene-based isolation material that would meet the 5 Hz requirements for an isolation frequency. After an exhaustive search, one supplier was located that was able to provide the required material. Additional complications arose in the proper implementation of the selected pads to ensure no flanking pathways were created, given the complexity of physically placing the isolators in a townhouse structure. Figure 6 shows a typical detail for one isolator location. Ultimately, the isolators were successfully implemented.

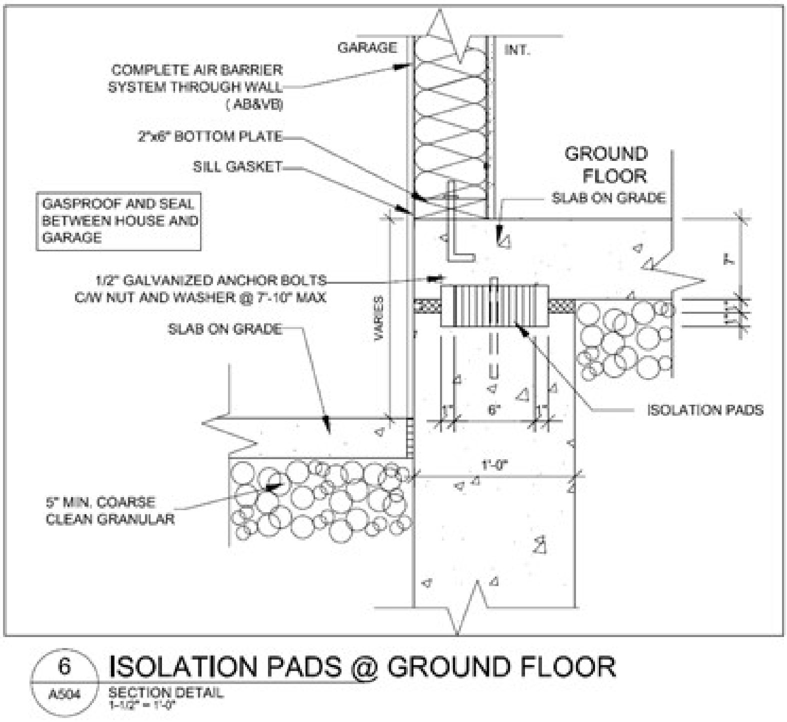

Fig. 6 Typical Detail for Isolators at the Ground Floor Level.

Conclusions

Two case studies have been presented that illustrate the significant complications arising when rail-induced vibrations have significant low-frequency components.

The following conclusions have been made:

1. In both cases the ground-borne vibrations had significant energy in the low-frequency bands.
2. This low-frequency energy requires extremely low isolation frequency materials and systems that can be challenging to procure
3. Unusual foundation configurations further complicates the appropriate integration into the structural system.
4. With careful design and detailing, it is possible to accommodate these unusual systems to successfully isolate the structures.

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