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A Numerical Study on the Environmental Vibration in Surrounding Buildings Induced by Freight Train Operations

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Abstract

The proliferation of railway systems in urban areas has heightened concerns regarding ground-borne vibrations and their impact on adjacent structures. This study presents a comprehensive numerical framework for predicting building vibrations induced by freight train traffic, addressing a gap in vehicle-specific analyses. A coupled modeling approach is employed, integrating multi-body dynamics and finite element methods. The vehicle-track interaction for a 60-ton freight wagon is simulated using the multi-body dynamics software SIMPACK to obtain the dynamic axle loads. These loads are then applied to a detailed 3D finite element model, developed in ANSYS, that captures the track-soil-building interaction, including nonlinear contact at the foundation-soil interface. The model is used to evaluate the Vibration Acceleration Level (VAL) within a building and to conduct a sensitivity analysis on key parameters. The results indicate that the vibration level decreases significantly with increasing distance from the railway, with an attenuation rate consistent with empirical laws for surface waves. A parameter study revealed that a ±20% variation in soil shear wave velocity can alter predicted VAL by up to 5 dB. At a distance of 20 m, the predicted VAL was found to satisfy standard building vibration limits for the modeled scenario. Furthermore, the vibration response was non-uniform within the building and exhibited a complex, non-monotonic relationship with train speed, indicative of critical speed effects.

Keywords: Train-induced Vibration, Freight Train, Environmental Impact, Building Vibration, Finite Element Analysis, Multi-body Dynamics

Introduction

The environmental impact of ground-borne vibrations generated by railway traffic has become a critical research focus in urban engineering [1,2]. The increasing density and operational speed of train networks, driven by modern societal demands, have led to elevated vibration levels that can cause structural damage, human discomfort, and interference with sensitive equipment [3,4]. While passenger trains are often studied, freight operations present distinct challenges due to higher axle loads and different dynamic characteristics [5].

The primary source of these vibrations is the dynamic load at the wheel-rail interface, which arises from moving axle loads and track irregularities [6]. This vibration energy propagates through the track system into the underlying soil, generating waves that travel through the ground and excite nearby structures [7]. To mitigate these effects, international standards such as DIN 4150-3 [8], ISO 14837-1 [9], and GB 55016 [10] have established vibration thresholds for buildings.

Accurate prediction of these vibrations is essential during the planning stages of new railway lines, particularly in proximity to vibration-sensitive buildings. While empirical and experimental methods are valuable, numerical simulations offer a powerful tool for detailed analysis [11,12]. However, the predictive accuracy and parameter sensitivity of numerical models must be critically assessed [13,14]. Many studies lack validation against field measurements, and the influence of key parametric uncertainties, such as soil properties, on predicted vibration levels is often not quantified [15,16].

This study aims to address these gaps by proposing a coupled simulation framework specifically for freight train-induced vibrations, and (2) systematically analyzing the influence of critical operational and geometric parameters. A coupled simulation strategy is adopted, combining a multi-body dynamics model of the vehicle-track system in SIMPACK with a 3D finite element model of the soil-building system in ANSYS. While full-scale validation is a future goal, this study provides a qualitative comparison with established empirical attenuation laws to bolster the credibility of the results and includes a sensitivity analysis to assess the impact of key parameters such as soil properties and train speed [17,18].

Numerical Modeling Methodology

The analysis employs a two-step, coupled modeling approach. First, the dynamic forces generated by a moving freight train on the track are calculated. Second, these forces are used as input to a model of the surrounding environment to predict the building's response.

Vehicle-Track Interaction Modeling using SIMPACK

The vehicle-track interaction was modeled using the multi-body dynamics software SIMPACK. A 60-ton freight wagon was modeled as a multi-body system comprising rigid bodies (car body, bogies, wheelsets) interconnected by spring and damper elements representing the primary and secondary suspensions (Figure 1). This model captures the specific dynamic characteristics of a freight vehicle, which differ from passenger trains due to mass distribution and suspension stiffness.

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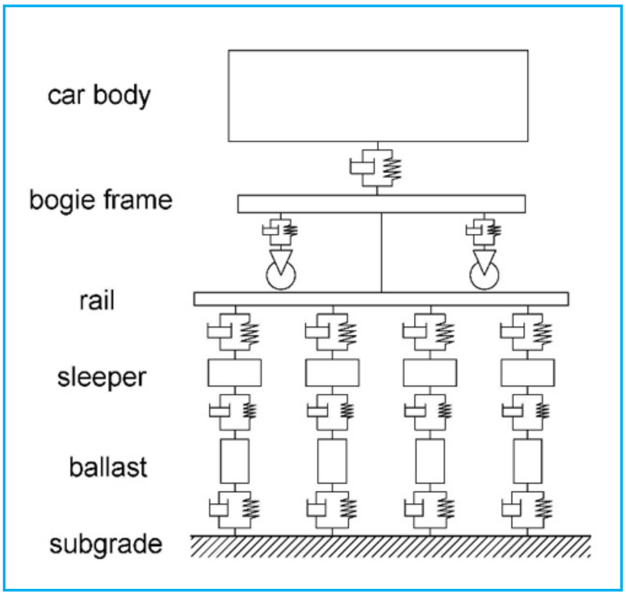
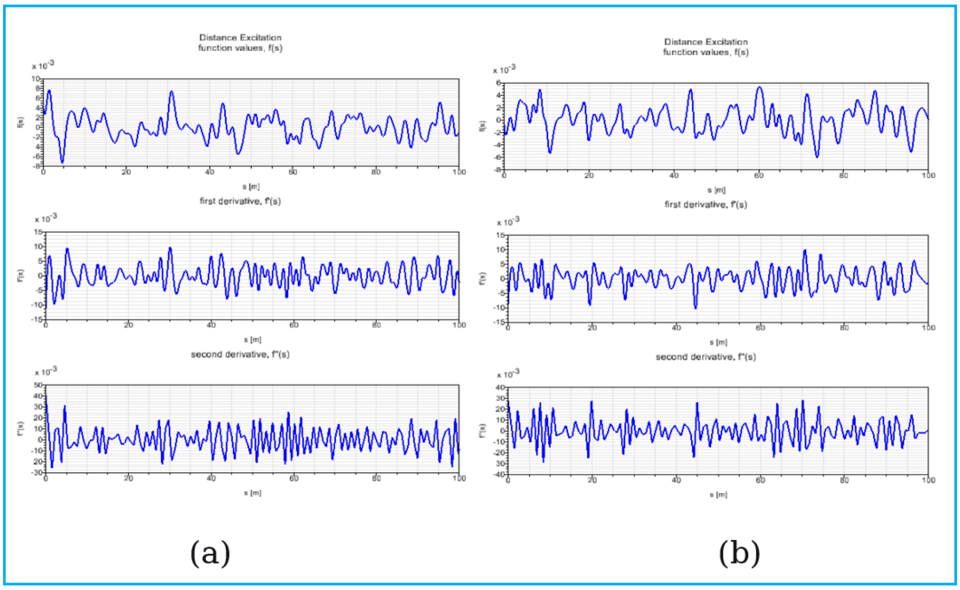


Figure 1. Multi-body dynamics model of the 60-ton freight wagon

Track irregularities, a primary source of excitation, were incorporated as random functions based on power spectral density (PSD) [6,19]. The PSD functions for alignment, vertical, and cross-level irregularities were defined, and their parameters are listed in Table 1. The simulated track irregularities generated in SIMPACK are shown in Figure 2.

Table 1. Coefficients for the power spectral density function of rail irregularities

Coefficient	A (cm^2·rad/m)	A (cm^2·rad/m)	Ωc (rad/m)	Ωr (rad/m)	Ωs (rad/m)
Low Order	2.119×10^{-7}	4.032×10^{-7}	0.0206	0.8426	0.4380
High Order	6.125×10^{-7}	10.80×10^{-7}	0.0206	0.8426	0.4380



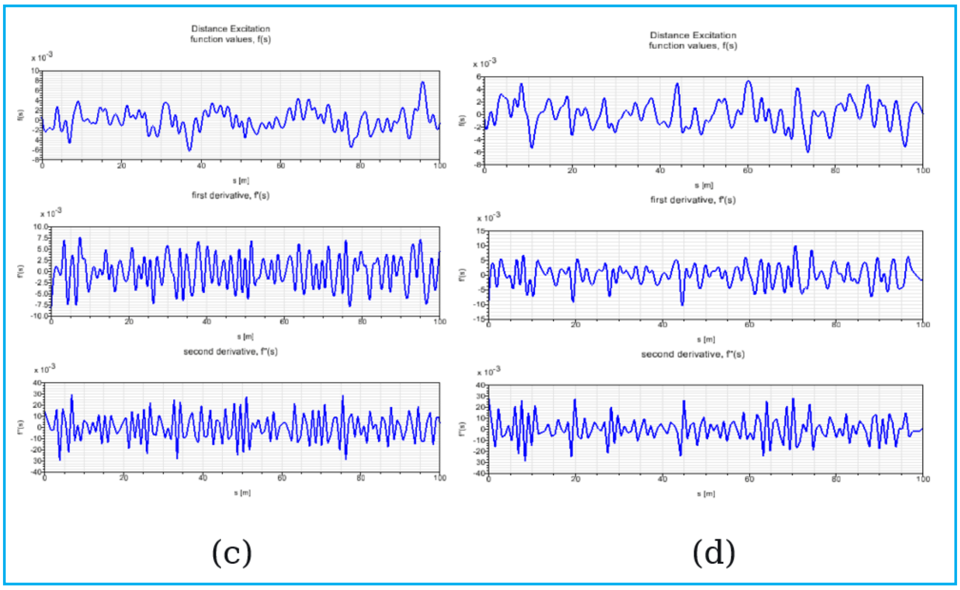


Figure 2. Simulated rail irregularities: (a) left rail alignment, (b) right rail alignment, (c) left rail vertical profile, (d) right rail vertical profile

The output from this model is the time-history of the dynamic reaction forces at the base of the track, which serve as the excitation for the soil-building system (Figure 3).

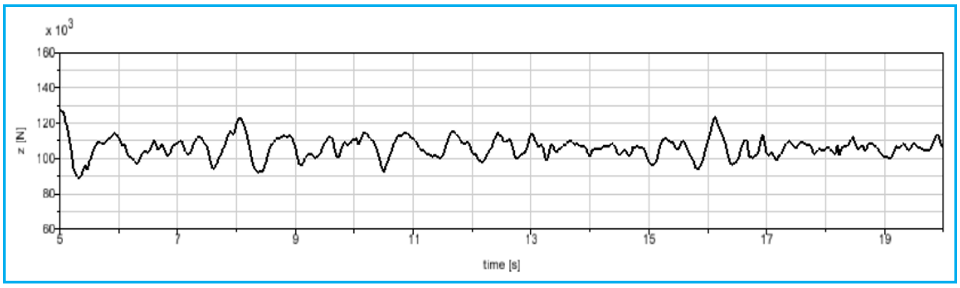


Figure 3. Dynamic reaction force on the subgrade obtained from the SIMPACK model

Soil-Building Interaction Modeling using ANSYS

A three-dimensional finite element model was developed in ANSYS to simulate vibration propagation from the track through the soil and into a nearby building.

- **Soil Domain and Mesh Design:** The soil was modeled as a continuum using SOLID185 elements. To accurately capture wave propagation, the mesh size was constrained to be smaller than one-sixth of the shear wavelength (λs/6) at the frequency of interest [20]. The model dimensions (60 m x 58 m x 17.8 m) were chosen to be sufficiently large to minimize wave reflection from boundaries. The shear wave velocity of the soil, a critical parameter, was selected based on typical values for the soil type (Table 2).
- **Building Model:** The building was modeled using BEAM188 elements for columns and beams and SHELL181 elements for slabs and walls, creating a 3D frame structure.

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Table 2. Typical shear wave velocities for different ground types [21,22]

Ground Type	Loam	Clay	Sand	Gravel	Weathered Rock	Bedrock
Shear Wave Velocity (m/s)	90-270	100-450	100-450	200-500	350-500	>500

- **Soil-Building Interface:** The interaction between the building's foundation and the soil was modeled using surface-to-surface contact elements (TARGE170 and CONTA174). This allows for the simulation of potential separation and sliding, capturing the nonlinear contact behavior that significantly influences vibration transmission [23].
- **Boundary Conditions:** To simulate wave radiation into the infinite domain, viscoelastic artificial boundaries were applied [24,25]. These boundaries use combinations of springs and dampers (COMBIN14 elements) to absorb outgoing wave energy, simulating a semi-infinite soil domain.

The final integrated finite element model is shown in Figure 4. The material properties used for the soil and building are summarized in Table 3.

Table 3. Material properties of the soil-building system (Baseline Case)

No.	Parameter	Value	Unit
1	Soil Elastic Modulus	2.86×10^{8}	Pa
2	Soil Poisson's Ratio	0.4	-
3	Soil Density	2000	kg/m^3
4	Building Elastic Modulus	3×10^{10}	Pa
5	Building Poisson's Ratio	0.3	-
6	Building Density	2400	kg/m^3

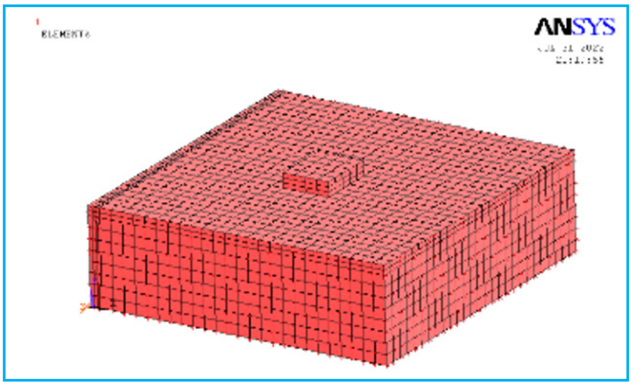

Figure 4. The 3D finite element model of the ground-building system in ANSYS

Model Considerations and Parameter Sensitivity: The selected soil parameters (Table 3) represent a typical soft to medium-stiff soil condition. It is acknowledged that shear wave velocity (V_s) is a highly influential and variable parameter in ground vibration prediction [26]. The complex vehicle-track interaction is the primary source of excitation, the modelling of which has been extensively reviewed [27]. To address this from a technical rigor perspective, a supplementary parameter study was conducted where V_s was varied ±20% from its baseline value while maintaining a constant Poisson's ratio (affecting the compression wave velocity proportionally). This analysis, detailed in next section, quantifies the model's sensitivity to this key geotechnical input. The results are specific to the modeled freight vehicle; passenger vehicles with different axle loads and suspension characteristics would yield a different dynamic forcing function.

Simulation Results and Discussion

The dynamic reaction forces from the SIMPACK analysis (Figure 3) were applied as input loads to the track in the ANSYS model. The dynamic response of the building was then computed in terms of displacement, velocity, and acceleration.

Spatial Variation of Vibration within the Building

The vibration response was analyzed at two locations: the center and the edge of the building's ground floor, with the building located 12 m from the track and a train speed of 40 km/h. The time-history responses are shown in Figure 5, and the peak values are summarized in Table 4.

Table 4. Dynamic response at different locations within the building

Location	Max. Displacement (10^{-3} m)	Max. Velocity (10^{-3} m/s)	Max. Acceleration (10^{-2} m/s²)
Center	0.38	0.159	0.332
Edge	0.36	0.108	0.124

The Vibration Acceleration Level (VAL) was calculated from the root-mean-square (RMS) of the acceleration time-history using Equation (1), where a_{rms} is the RMS acceleration and a_{ref} is the reference acceleration (10^{-6} m/s²) [28].

$$VAL = 20\lg\left(\frac{a_{rms}}{a_{ref}}\right) \tag{1}$$

The VAL at the center of the floor was 70.5 dB, compared to 62.0 dB at the edge. This significant difference (8.5 dB) underscores that vibration levels are not uniform within a structure and are typically highest at the center of large floor slabs due to the fundamental mode of vibration. Therefore, for assessment against standards, the most critical location should be considered.

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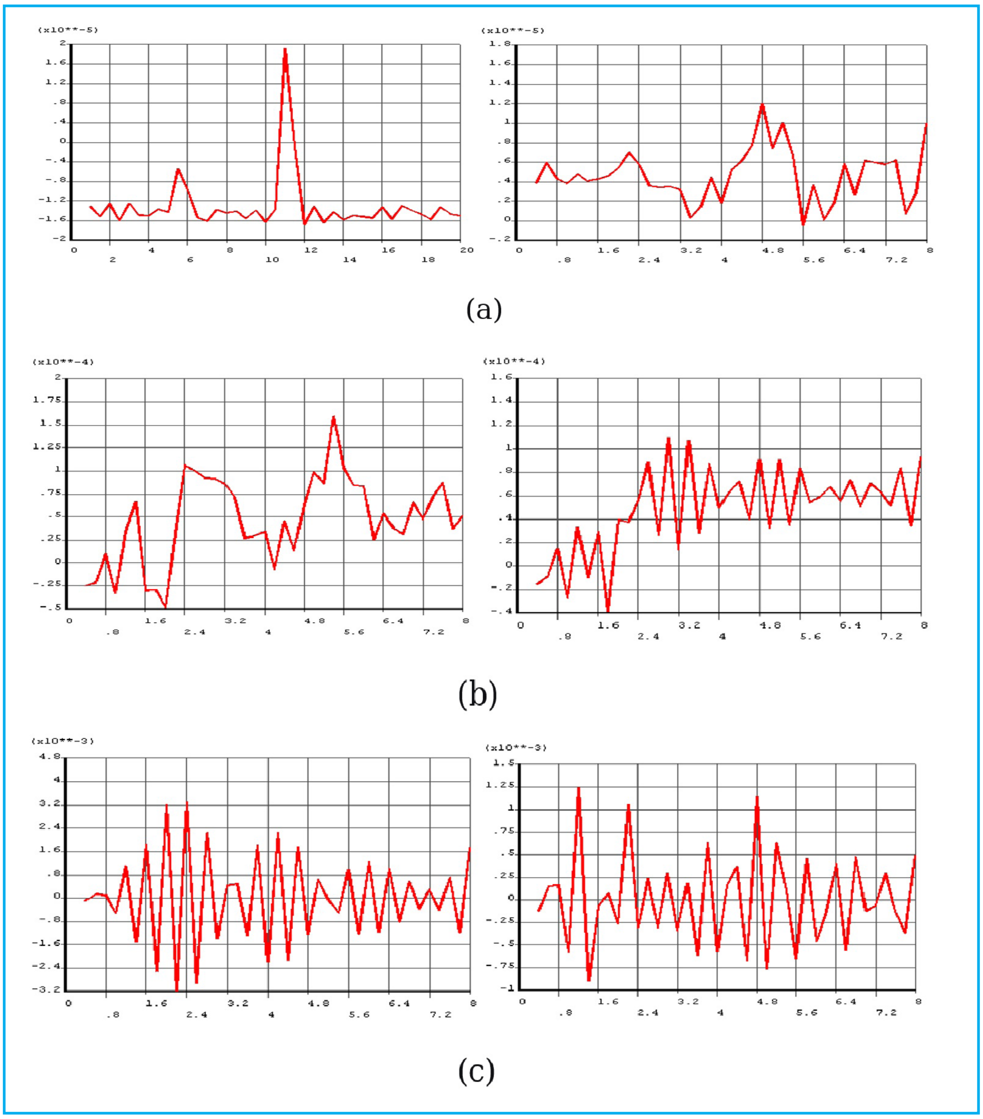

Figure 5. Dynamic response at different locations within the building: (a) displacement, (b) velocity, (c) acceleration

Influence of Train Speed

The effect of train speed on building VAL was investigated for different building distances (6 m, 16 m, 20 m). The results, shown in Figure 6, indicate a complex, non-monotonic relationship. VAL generally increased with speed up to 60 km/h, followed by a decrease at 80 km/h and a subsequent gradual increase. This behavior suggests the possible influence of critical speeds related to the vehicle-track system or wave propagation in the soil [29,30]. At certain speeds, the dominant excitation frequency may approach the natural frequencies of the vehicle suspension or layered soil system, leading to resonant amplification or, conversely, cancellation effects. This complex interaction underscores the necessity of a coupled modeling approach that captures these dynamics. The general increasing trend over a wider speed range remains consistent with the literature [3, 31]. As expected, the VAL was consistently higher for the building closer to the track (6 m), with an average value of 76.9 dB, compared to 66.6 dB at 16 m—a difference of about 10 dB.

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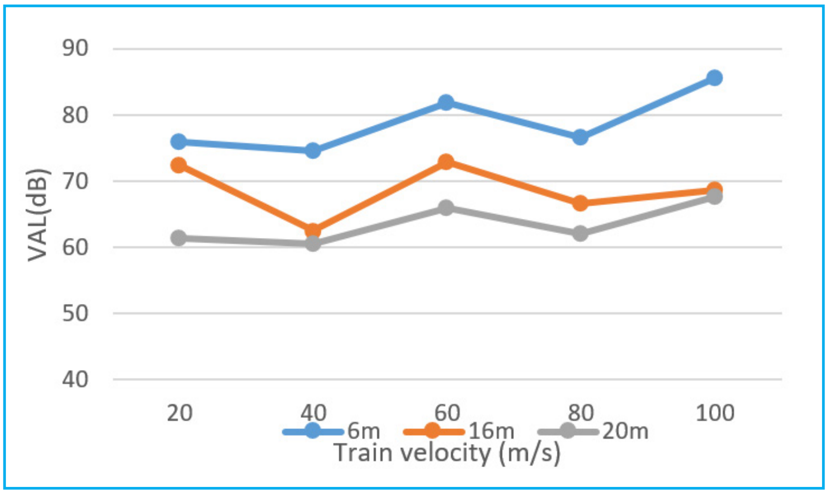

Figure 6. Variation of building VAL with train speed for different building distances

Influence of Soil Shear Wave Velocity (Sensitivity Analysis)

Recognizing the uncertainty in geotechnical parameters, a sensitivity analysis was performed on the soil's shear wave velocity (V_s). The baseline V_s (derived from the elastic modulus and density in Table 3) was increased and decreased by 20%, and the simulation for a train speed of 40 km/h and a building distance of 12 m was repeated. The change in the predicted VAL at the building's center is summarized in Table 5.

Table 5. Sensitivity of predicted VAL to changes in shear wave velocity

Case	Shear Wave Velocity Change	VAL at Building Center (dB)	Change from Baseline (dB)
1	-20%	73.8	+3.3
2	Baseline	70.5	0
3	+20%	68.0	-2.5

The results demonstrate that the model is sensitive to this parameter. A 20% decrease in V_s (softer soil) increased VAL by 3.3 dB, while a 20% increase (stiffer soil) decreased it by 2.5 dB. This highlights the importance of accurate site characterization for quantitative predictions and indicates that the absolute VAL values presented have an uncertainty band associated with soil property variability.

Influence of Distance from the Railway and Qualitative Validation

The attenuation of vibration with distance is a key factor in environmental impact assessment. Figure 7 shows the VAL of the building for various train speeds as a function of the distance from the track. The results clearly demonstrate a consistent decrease in VAL with increasing distance due to geometric damping and material damping in the soil [1,7].

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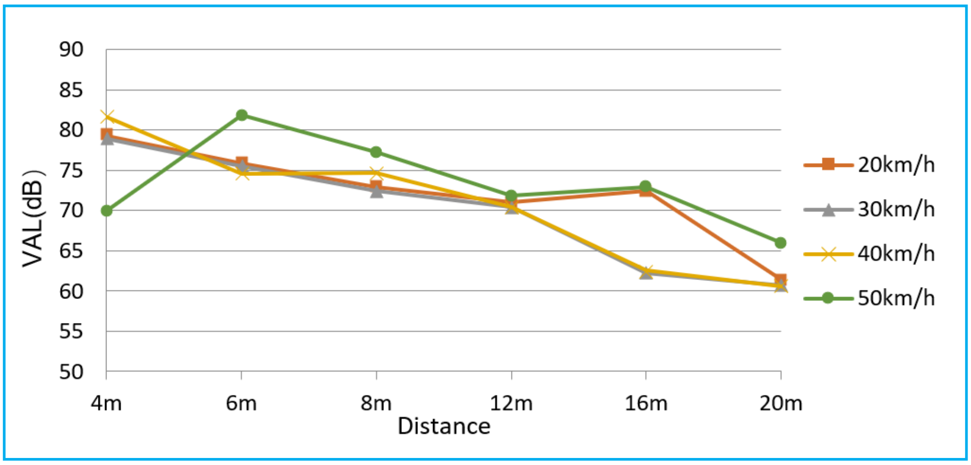

Figure 7. Attenuation of building VAL with increasing distance from the railway

To contextualize the predicted attenuation trend, the results are compared with empirical decay laws. The predicted reduction of approximately 15 dB between 4 m and 20 m corresponds to a distance decay rate roughly proportional to $R^{-1.0}$ to $R^{-1.2}$ (where R is distance). This falls within the range of decay rates ($R^{-0.5}$ to $R^{-1.5}$) reported for surface waves (Rayleigh waves) in homogeneous soils [7,32]. This qualitative agreement supports the plausibility of the numerical model's prediction of ground wave propagation, despite the absence of direct field validation in this study.

The average VAL across all speeds was 77.45 dB at a 4 m distance, reducing to 62.2 dB at a 20 m distance—a reduction of approximately 15 dB. Crucially, the VAL at the 20 m distance was found to be below the common vibration limit of 70 dB for buildings [8,10], suggesting that a 20-meter buffer may be sufficient to mitigate adverse effects for this specific freight train and soil scenario.

Conclusions

This study successfully established a coupled numerical methodology to analyze freight train-induced environmental vibrations. The integration of multi-body dynamics (SIMPACK) and finite element analysis (ANSYS) provided a robust tool for assessing the impact on nearby buildings. The following key conclusions were drawn:

1. Spatial Variation: Vibration levels within a building are not uniform. The Vibration Acceleration Level (VAL) at the center of a floor slab can be significantly higher (over 8 dB in this case) than at the edge, highlighting the importance of sensor placement for monitoring and assessment.

2. Speed Dependency: The relationship between train speed and building vibration is complex and non-linear, likely influenced by system resonances and critical speed effects. While a general increasing trend was observed over a larger speed range, local variations exist.

3. Parameter Sensitivity: The model is sensitive to geotechnical input, particularly shear wave velocity. A ±20% variation in V_s can lead to a

change in predicted VAL of 2.5-3.5 dB, underscoring the need for accurate soil characterization in practical applications.

4. Distance Attenuation: The distance between the railway and the building is a dominant factor. A rapid attenuation of about 15 dB was observed between 4 m and 20 m, with a decay rate consistent with empirical surface wave theory. For the specific conditions modeled, a distance of 20 m was sufficient to reduce vibrations below a standard threshold of 70 dB.

Limitations and Future Work: This study employed specific, deterministic parameters for a freight vehicle and soil. The sensitivity analysis confirms that geotechnical uncertainty can significantly affect the absolute predicted vibration levels. Future work should focus on: (1) Validation against field measurements from a freight railway corridor to calibrate and confirm the model's accuracy. (2) Advanced parametric studies considering soil non-linearity [33] and stochastic analysis [34] to quantify the probability of exceeding vibration thresholds given natural variations in soil properties and track conditions. (3) Extending the analysis to different vehicle types (high-speed passenger trains, heavier freight locomotives) and mitigation measures (trenches, barriers) to provide a more comprehensive engineering tool.

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Conflicts of Interest

The authors declare no conflicts of interest.

Author Contributions

Changhyon Choe: conceptualization, methodology, writing - original draft. **Kwanghyok Jong:** formal analysis, data curation, visualization. **Chungil Choe:** supervision, validation, writing - review & editing. **Cholhyok Kang:** investigation, resources. **Daehyok Ko:** software.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

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