Master WAVES

(Waves, Acoustics, Vibrations, Engineering and Sound)

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Prediction of railway-induced vibrations in buildings

Overview and comparison of methodologies

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Abstract

When constructing buildings near railways infrastructures, assessing the vibration levels within these structures is crucial to ensure both safety and comfort. As the number of such buildings continues to grow, it becomes increasingly important to have a method for evaluating ground-borne vibrations that minimizes computational time. This study begins with a review of the fundamental principles of vibration transmission and the impact of these vibrations on buildings. Various predictive engineering approaches, including the FTA, SBB, BAM, CSTB, and DB models are analyzed highlighting their strengths and limitations in different contexts. The primary objective of this study is to implement a simplified method for calculating ground-borne vibrations in building structures efficiently. It focuses on the development and application of a 2D Finite Element Method (FEM) model that incorporates soil-structure interaction (SSI) as a spring-damped system to simulate the dynamic response of buildings to railway-induced vibrations. A key aspect of this research is the use of real-world vibration data, used as the excitation input in the model, specifically measured vibration data from a site in Saint-Cloud, France, where a building will be constructed 20 meters away from a tram line. To enhance the accuracy of the model, two different approaches, based on the works of Lopez et al. and Auersch for calculating stiffness and damping, are employed allowing for a more nuanced representation of soil-structure interaction. The FEM model is applied to various structural scenarios, ranging from simple two-story buildings to complex multi-story frames. The results of these simulations are compared with those from FTA empirical method.

CHAPTER 1

Introduction

1.1 Master WAVES overview

This internship master thesis represents the final phase of the Erasmus Mundus Joint Master Degree WAVES program. The WAVES program is organized across four semesters, each hosted by renowned European institutions. The academic journey begins at the University of Coimbra in Portugal, progresses to the Polytechnic University of Valencia in Spain, and continues at École Centrale de Marseille and Aix-Marseille Université in France for the third semester. This international program provides comprehensive training in acoustics, blending traditional lectures with practical sessions and innovative teaching methods.

The final semester, dedicated to the Master Thesis, includes a four to six-month internship, which can be undertaken in either an industrial setting or a research laboratory specializing in acoustics and vibrations. This structure ensures a balance between theoretical knowledge and practical experience, preparing students for careers in both industrial and academic environments.

1.2 Company Presentation

For this thesis, the internship was conducted at SLAM Acoustique, a growing firm based in Marseille specializing in acoustics and vibration. Founded in 2016 by two acoustics engineers - Phileppe Schmid and Thibaud Leportois - SLAM Acoustique has offices in Marseille and Ivri-sur-Seine, near Paris. With a team of around 15 employees, the company works in projects in France and internationally, in a wide range of applications, reflecting the diverse challenges in the field of acoustics, with expertise in noise and vibration control, environmental acoustics and building acoustics.

1.3 Context and objectives

During the internship at SLAM Acoustique in Marseille, a range of activities were undertaken, providing a comprehensive understanding of acoustics and vibration engineering. Responsibilities included research and development as well as technical consultancy tasks.

In the technical consultancy aspect, acoustic measurements were conducted for a variety of projects, including commercial, environmental, and residential developments. This practical experience involved utilizing advanced measurement equipment and software to analyze and interpret data, ensuring compliance with regulatory standards. Furthermore, close collaboration with clients was essential to address their specific needs and provide tailored solutions to mitigate noise and vibration issues.

Context

In the research and development segment, efforts were focused on creating a predictive tool for estimating ground-borne vibration noise exposure in buildings located near railways.

The necessity of developing this predictive tool emerged when the company undertook a project in 2023 to conduct vibro-acoustic studies for a project involving the construction of three new houses near the tramway T2 in Saint-Cloud, near Paris, as shown in Figure 1.1. The aim of that project was to assess the noise and vibrations generated by nearby tram way and to deduce recommendations for appropriate mitigation in order to limit the inconvenience for future occupants.

Figure 1.1: Satellite view of the three plots which are bordered to the west by rue de Béarn and to the east by the RATP T2 tramway .

Thus, for the airborne noise study, the local regulation was applied and recommendations to improve the façades performance were made. However, when it came to the railway vibration impact on the future three houses, it was necessary to know what would be the buildings response for the tramway induced vibrations. Thus, measurements in situ at the location where the houses would be situated were done Figure 1.2. Nevertheless, the company lacked of a tool that could estimate how this measured vibration would be transmitted to the constructions and its impact on the residents. Therefore, given this scenario, it became necessary to implement a tool that could assist in estimating the response of the buildings to the existing railway traffic in the area.

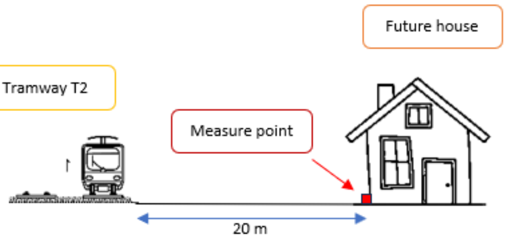

Figure 1.2: Illustration of measurement point and location of the future houses

Objectives

Given this scenario, this master's thesis research was undertaken with the aim of developing a tool to be utilized by the company's team, capable of using measured railway-induced ground vibration data to estimate the response of future constructions to these vibrations. Nevertheless, due to the limited duration of the internship, the focus was on initiating the development of this tool, with the intention that the company's team would continue its refinement and further development afterward.

This project addressed a critical issue in urban planning and environmental engineering, as vibration-induced noise can significantly impact the quality of life for residents in proximity to railway lines. The development process began with a comprehensive review of existing literature and benchmarking of current market solutions. This was followed by the application of hybrid methods that consider in-situ measured data with prediction models. Thus, the primary goal was to investigate the annoyance caused by railways to nearby residents. The tool aims to enhance understanding of how ground-borne vibrations from railways translate into noise within buildings and, more importantly, how this noise contributes to annoyance levels experienced by residents.

Thus, this research has potential implications for urban noise policies, railway operation guidelines, and the development of mitigation strategies to improve living conditions in areas affected by railway vibrations. Therefore, this internship at SLAM Acoustique provided an opportunity to link theoretical knowledge with practical application in the field of acoustics and vibration engineering, contributing significantly to the preparation for future projects in this field.

1.4 Organization of the thesis

The thesis is organized into five additional chapters that follow a straightforward and clear progression.

In the next chapter, the topic of railway-induced vibrations is reviewed, explaining how these vibrations occur, how they travel through the ground, and how they affect buildings. This chapter provides the basic information needed to understand the rest of the study.

Chapter 3 discusses the most commonly used methods for assessing railway-induced vibrations, analysing different approaches, such as empirical numerical and hybrid.

On chapter 4, it is introduced a simplified model using the Finite Element Method (FEM) that includes soil-structure interaction (SSI). This chapter explains how the model is built and used to simulate how buildings respond to vibrations from the ground.

Therefore, chapter 5 compares different structural models by analyzing various scenarios. It includes the results of simulations that examine how five different frame structures react to vibrations, ranging from simple to more complex designs. This chapter looks at how vibrations move through these structures.

Finally, Chapter 6 summarizes the main findings of the thesis. It provides conclusions based on the research and discusses the implications of these findings. Also, it is suggested areas for future work, focusing on how this research can be applied or further developed in practical settings.

CHAPTER 2

Overview of Railway-Induced Vibrations

In everyday life, people experience various types of vibrations, which are often perceived as normal and not concerning, such as those felt while driving a car or riding in an elevator. However, vibrations originating from external sources like heavy road traffic, trams, and railway lines— either on the ground or underground — may sometimes be felt inside homes. These vibrations typically manifest as a subtle trembling of the house, particularly noticeable on the floors. Also, the vibrations can create a rumbling sound as the building radiates these vibrations into the rooms, a phenomenon known as structure-borne sound. Additionally, secondary noises, like rattling doors or pottery, can amplify or make the sound more noticeable.

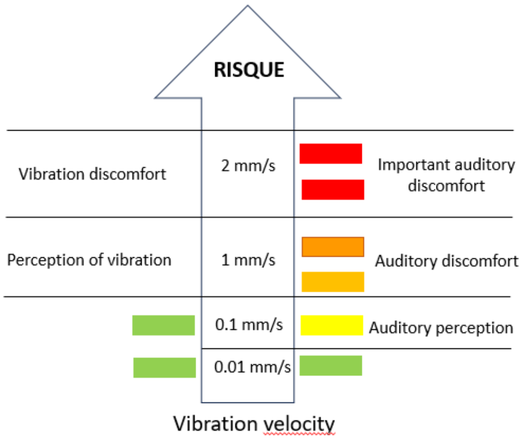

Figure 2.1: Different perception/discomfort/risk thresholds scale [SLAM Acoustique, 2023]

Perception of vibrations depends on several factors, such as the distance from the source, the speed and type of traffic, the condition of the road or track, the type and composition of the ground and the construction of the building itself. Therefore, modification in the soil, such as alterations in the sewer network or even in nearby buildings, can interfere in vibrations or ground-borne noise [1]. Vibration caused by railway traffic may be too weak damage the building structure. However, people who are residents of railway areas may experience irritation and affect quality of life. Furthermore, the perception of vibration can be masked by the airborne sound coming from the train passing. Even though the personal sensitivity plays an important role at the vibration perception, reference [2] states that human sensitivity to vibration usually begins at around 65 VdB, with significant annoyance typically occurring above 70 VdB, as shown in table 2.1.

Vibration Velocity Level	Noise Level Low Freq	Noise Level Mid Freq	Human Response
65 VdB	**25 dBA**	**40 dBA**	Approximate threshold of perception for many humans. Low-frequency sound: usually inaudible. Mid-frequency sound: excessive for quiet sleeping areas.
75 VdB	**35 dBA**	**50 dBA**	Approximate dividing line between barely perceptible and distinctly perceptible. Many people find transit vibration at this level annoying. Low-frequency noise: tolerable for sleeping areas. Mid-frequency noise: excessive in most quiet occupied areas.
85 VdB	**45 dBA**	**60 dBA**	Vibration tolerable only if there are an infrequent number of events per day. Low-frequency noise: excessive for sleeping areas. Mid-frequency noise: excessive even for infrequent events for some activities.

Table 2.1: Vibration velocity levels, associated noise levels, and human response [2].

At first, railway induced vibration was noticed and labelled as in issue related to underground train lines [1]. However, vibrations from surface train or tram tracks recently has been receiving more attention. For the surface lines scenario, the vibration is usually followed by ground-borne noise, having the relative contribution of each depending on the soil properties. In areas with stiff soils, such as solid rock, ground-borne noise tends to be more significant than vibrations, and the dominant vibration frequencies are higher (around 50 Hz). In contrast, in regions with softer soils like clay or peat, vibrations may be more prominent than ground-borne noise, with dominant frequencies being lower (around 5 Hz)[1]. Thus, one can say that the soil type is a key factor in determining the effectiveness and selection of mitigation strategies.

In railways, vibrations are primarily caused by the contact between the train wheels and the tracks. These vibrations travel from the tracks through the ground and into the building foundation. Typically, the intensity of ground vibrations decreases with distance from the track. However, according to FTA [2] the vibration levels may increase on higher floors within the building due to structural resonances.

Recently, the global expansion of rail infrastructure has been notable and is expected to continue. According to the Ministery of Ecologique Transition and Territories Cohesion of France, in 2022 France is served by 26.946 Kilometers of railway network, including high-speed trains (TGV), multi-tracks and single tracks. Furthermore, the urban rail infrastructure has seen significant growth, with metros and RER lines extending to 483 kilometers, and tramways reaching 900 kilometers in length. This represents a notable expansion in urban rail systems, particularly in tramways, which have increased by nearly 30% since 2013 [3]. This growth has been accompanied by increased public awareness of ground vibration and more stringent international standards on allowable limits. Recent studies have highlighted the importance of accurately estimating ground-borne vibrations from railways, as they can have significant health impacts on nearby residents beyond mere annoyance. For instance, Croy et al. (2013) [4] demonstrated that train passages can cause heart rate increases of up to 3 bpm during sleep for people living close to railways, potentially affecting long-term cardiovascular health. Additionally, Maclachlan et al. (2017) [5] found that railway-induced vibrations can disrupt restoration throughout the day for nearby residents, potentially leading to long-term health effects due to interference with the body's normal stress response mechanisms.

These findings highlights the critical need for accurate tools to estimate ground-borne vibrations in buildings near railways. Such tools can assist urban planners, engineers, and policymakers in assessing potential health risks for residents in proposed developments near railway lines, developing appropriate mitigation strategies to reduce vibration impacts, and informing evidence-based policies for railway operations and urban development. By developing an estimation tool, this research aims to contribute to a better understanding and management of railway-induced ground-borne vibrations, ultimately helping to protect public health in urban areas with rail infrastructure.

2.1 Characterization of railway-induced vibrations

In order to investigate the railways impact in its surrounding, first it is necessary to differentiate the terms that can be confusing. Reference [1] explains that Ground-borne vibration (which is the most commonly perceived kind of "vibration") is generated by the interaction between train and track (and subsoil). The vibration is transmitted through the ground and may reach the foundation of a building. The building responds to the vibration; vibration is transmitted through the building structure, and may be observed as perceivable vibration of the floor. Ground-borne vibration is associated with a frequency range of roughly between 1 and 100 Hz. Furthermore, according to [7], ground-borne railway noise is defined as the "noise generated inside a building by ground-borne vibration generated from the pass-by of a vehicle on rail", which applies for both light and heavy rail and excludes air-borne noise. Figure 2.1 illustrates the different types of mechanisms that generate and transmit air-borne noise, ground-borne vibrations, and ground-borne noise.

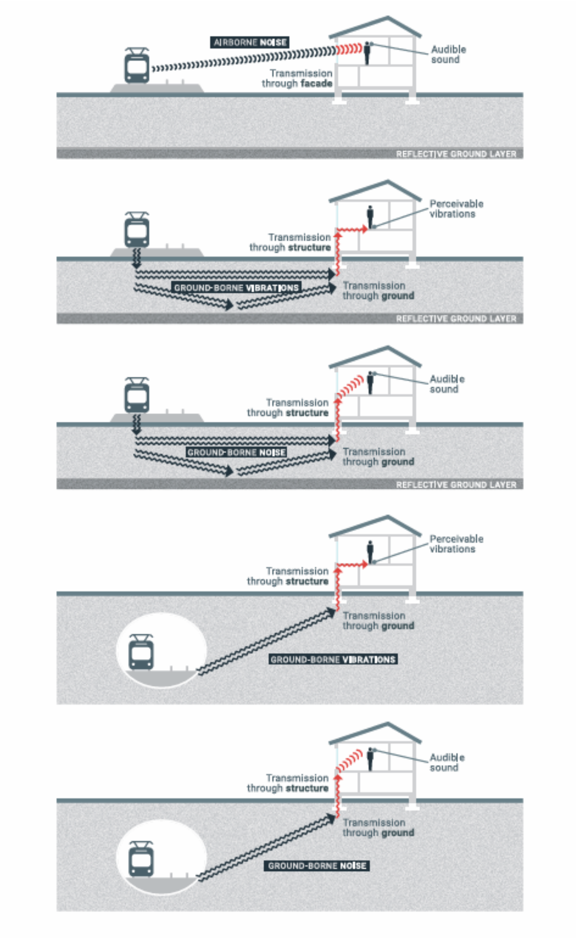

Figure 2.2: Sources and transmission paths of air-borne noise (not for underground lines), ground-borne vibrations, and ground-borne noise [1].

2.2 Ground-borne vibration and noise metrics

Vibration, as it is an oscillatory motion, can be expressed in terms of displacement, velocity or acceleration. Thus, due to the oscillatory motion, there is no net movement of the vibration element, consequently the average of any of the motion measure is zero. Thus, most transducers used for measuring ground-borne vibration use either velocity or acceleration. Furthermore, the response of humans, buildings, and equipment to vibration is more accurately described using velocity or acceleration [2]. Thus, the amplitude of the vibration may be described by either its peak or maximum value or by the average (rms) value of either the velocity or acceleration [1].

Parameters	Abbreviation	Definition
Vibration Decibels	**VdB**	The vibration velocity level in decibel scale.
Root Mean Square	**rms**	The square root of the arithmetic average of the squared amplitude of the signal.
A-weighted	**dBA**	Adjusted sound level in frequency to approximate typical human hearing.

Table 2.2: Description of vibration and sound parameters [1]

2.3 Railways vibration generating systems

A running train applies a quasi-static and dynamic loads on the track [8] The quasi-static part in frequency domain is described in equation 2.1.

$$\hat{u}_{sj}(\omega) = \hat{u}_{s0j}(\omega) \left[\sum_{k=1}^{n_a} w_k \exp\left(+i\omega \frac{y_{k0}}{v} \right) \right] \tag{2.1}$$

Where n_a is the number of axles of the train, w_k is the weight carried by axle k, $u_{s0j}(t)$ is the response due to a moving load with a unit magnitude, y_{k0} is the position of the axle on the track at a reference time $t = 0$ and v is the train velocity.

Vibration generation is the consequence of the vehicle forces passing from the wheel into the track. These forces arise from the weight of the vehicle, which is the quasi-static excitation, and irregularities/discontinuities at the wheel/rail interface and then propagate outwards from the track, which are the dynamic component of the excitation. The vibration level experienced at all other locations within the track, soil or nearby structures is a function of this force, depending on the natural frequency of each component Koroussis et al [9]. Thus, resultant frequencies of the vibration generated by the mechanism mentioned above.

Thus, if an oscillating point load is applied to an unloaded elastic-half space, three types of waves will be generated from the loading point. The Rayleigh surfaces (or R-waves) that propagates on the surface and decrease in the far field at a rate inversely proportional to the square root of the surface's distance. The other two waves are related to body waves, which are the compression waves, called 'P-waves', and the shear waves, called 'S-waves' [4].

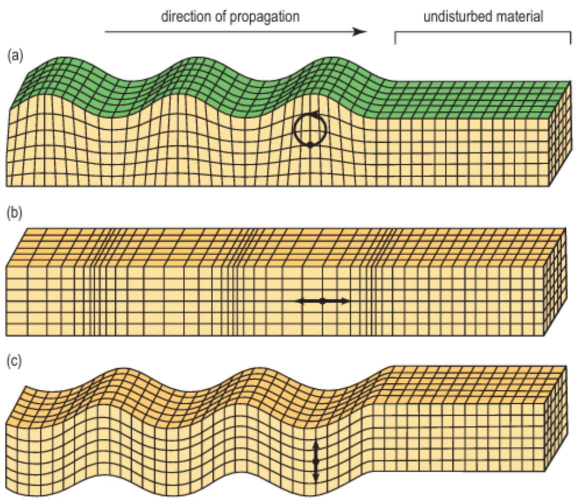

Figure 2.3: (a) Raylegh waves. Propagates on the surface of the soil (b) P-waves. Longitudinal waves, propagating manly downward into the medium. (c) S-waves: transversal waves, normally directed obliquely into the medium [1]

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Furthermore, the soil serves to dampen vibrations, particularly at high frequencies so the majority of the vibration spectrum arriving at these structures is below 100 Hz [29].

2.4 Vibration transmission in buildings

Part of the vibration produced by a running train can travel through the ground and reach the foundations of nearby buildings. Depending on the foundation type, the building may respond to these vibrations, transmitting them through its structure. Therefore, the amount of vibration transmitted into a building is influenced by the coupling between the ground and the foundation. Typically, a reduction in vibration levels occurs due to impedance mismatch when waves from the soil encounter the foundation. This mismatch causes a portion of the energy to be reflected at the interface, leading to a decrease in vibration levels. The coupling between the soil and foundation is quantified by the ratio of the vibration levels of the foundation to the soil, expressed in decibels (dB) [27]. Remington et al. [28] investigated building foundation slabs that are in direct contact with the underlying soil and discovered that they experience similar vibrations to those of the ground. Consequently, the coupling loss was found to be 0 dB for frequencies below the slab's resonance frequency. For other type of vibrations, the coupling loss varies, usually from 2 to 15 dB, depending on the frequency and on the foundation type. This explains the reason for lower vibration levels inside some buildings when compared to measurements inside open fields [27].

While the foundation or base plate of a building typically shows minimal response, the ground floor and upper floors may experience slight trembling. Furthermore, wooden floors are particularly sensitive to low-frequency vibrations. In multi-storey buildings, vibrations can become more pronounced as they travel from the ground floor to higher levels. Thus, to assess the strength of these vibrations, measurements are usually taken at the foundation or the center of higher floors, where the highest vibration levels are typically observed [1]. Figure 2.4 illustrates five translational mode shapes of five storey frame.

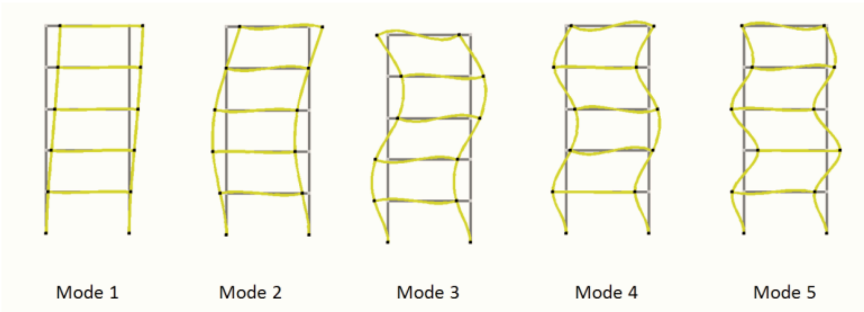


Figure 2.4: Five translational mode shapes of a five storey frame

2.5 Ground-borne noise in buildings

Vibrations in the foundation can be transferred to the building structure. Thus, depending on the mass, stiffness and damping of the walls and floors, these vibrations can achieve the audible frequency range. Therefore, the vibrating walls and floors can produce noise that may be perceptible in the building's dwellings. Furthermore, at some certain frequencies, the wavelengths can lead to amplification inside the rooms, by creating standing waves. The consequence is the ground-borne noise, which may be more noticeable to the residents than the vibrations themselves.

Thus, The occurrence of ground-borne noise thus depends both on the frequency content of the ground vibration that reaches the foundation, on the transmission in the building structure, and on the acoustic properties of the receiver room [1].

2.6 Simplified prediction methods

Despite significant advancements in numerical models for predicting railway-induced vibrations, these models are predominantly used for research purposes. In contrast, engineering practice continues to rely largely on empirical methods. The ISO 14837-1:2005 standard [88] provides general guidelines for ground-borne noise and vibration from rail systems. It outlines that the requirements for accurate predictions vary at different stages of a project's development, categorizing models into scoping models (for the earliest stage), environmental assessment models (for the planning process),

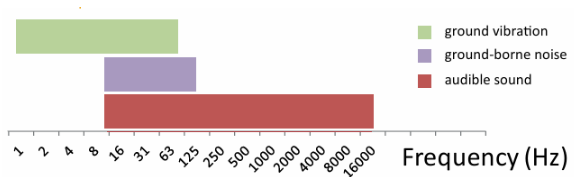


Figure 2.5: Frequency range of audible sound, noticeable ground-borne vibration and ground-borne-noise Frequency ranges for audible sound, feelable ground-borne vibration and ground-borne noise [1].

and detailed design models (for the construction and design phases). This classification is common in many empirical models currently in use and also applies to numerical models.

Empirical methods include procedures developed by various organizations, such as the Federal Railroad Administration (FRA) and the Federal Transit Administration (FTA) of the U.S. Department of Transportation [2], the Swiss Federal Railways (SBB) [10]. The FTA method align with the ISO 14837-1 standards three assessment levels, with the Detailed Vibration Assessment employing a prediction technique from Bovey [11] and Nelson and Saurenman [12] for more precise prediction of ground-borne vibrations and re-radiated noise. The SBB method includes two models, VIBRA-1 and VIBRA-2, with VIBRA-2 offering a more detailed approach, including frequency-dependent attenuation models. Similarly, the methods by Madshus et al. [13] and Hood et al. [14] follow a comparable structure to the SBB approach while also addressing prediction uncertainties [8].

The ISO 14837-1 standard approach aims to predict the magnitude of a quasi-stationary vibration level $A(f)$ at a given frequency f in a building for a passing train which can be get from the product of the $S(f)$ which represents the source strength, $P(f)$ that is for the propagation path and $R(f)$ which accounts for the receiver.

$$A(f) = S(f)P(f)R(f) \tag{2.2}$$

$A(f)$ is usually the root mean square value of velocity or acceleration in one-third octave bands. In order to obtain it, each of the three terms in equation 2.2 is calculated at the same frequency f. However, it is not valid for moving sources because of the Doppler effect. Thus, $S(f)$ will also depend on the distance. Hence, it works better when the train speed is relatively low compared to the wave velocities in the soil, as this condition helps minimize the impact of the Doppler effect on the results. The source term $S(f)$ forms the basis of the prediction[8].

Reference [80] also emphasizes that prediction through empirical methods are reliable by providing vibration velocity levels, when there is a suitable source characterization, either in terms of force density at the wheel/rail interface or a reference vibration level at a defined location (e.g. tunnel wall, or to the side of the track on the ground, etc). Therefore, empirical methods based on in situ vibration measurements may only be applied for prediction on scenarios where there are very similar conditions to those where the data were collected (e.g rolling stock, track, soil).

2.7 Detailed numerical approaches

In the past few decades, significant studies were done with the objective to develop predictive numerical models for building vibrations caused by trains, as well as to investigate the vibration mitigation measures at the railways, in the propagation path and at the buildings[8]. It involves various complex physical phenomena, e.g the generation of dynamic axle loads, 3D wave propagation in the soil and dynamic soil-structure interaction (SSI). Thus, different approaches have been made, such as semi-analytical, finite-infinite element method and coupled finite element-boundary element method models. However, computational costs and lack of knowledge on appropriate parameters for each models, leads to the insertion of simplifying assumptions. For example, the soil is usually assumed to be horizontally layered and to behave as a linear elastic isotropic medium, with a perfect contact with the structure, and without considering the presence of nearby structures[15].

A very usual approach on numerical models for the dynamic soil-structure interaction (SSI) is to assume that both source and receiver (building) are uncoupled [16].

Kouroussis et al. [17] introduced a decoupled finite element (FE) model to estimate building vibrations caused by tramway traffic with local irregularities. Also, reference [18] proposes soil-structure transfer functions considering SSI. Therefore, these soil-structure transfer functions are combined with free-field vibrations to calculate building vibrations with low computational cost. It follows the procedure of ISO 14837-1, shown on equation 2.2. The model is validated through numerical comparison with Boundary Element Method (BEM) and Finite Element Method (FEM) model. Fiala et al [19] assumes that there is a weak coupling between the incident wave field and the structure, implying that the building does not influence the vibration generation mechanism. Then, free field displacements are used as the excitation for the coupled soil–structure model. Aubry et al. [20] considers the ground displacement $\hat{u}^g$ is written as a combination of two displacements fields, $\hat{u}_0$ and $\hat{u}_{sc}$, where $\hat{u}_0$ represents the displacement caused by the incident wave field, satisfying a zero displacement boundary condition on the soil-structure interface Σ, and $\hat{u}_{sc}$ the displacement field radiated by the motion of the structure $\hat{u}_b$ on the interface.

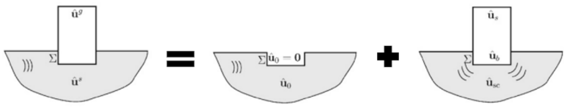


Figure 2.6: Soil displacement field $\hat{u}^{\mathrm{g}}$ is decomposed into the displacement field $\hat{u}_0$ and radiated field $\hat{u}_{\mathrm{sc}}$

To investigate the building response to railway induced vibrations, [18] follows the recommendations from the National Institute of Standards and Technology [21], which proposes to integrate the SSI by adding spring-damper elements on the foundation of the building. [22] also represents the soil on his model by a spring and a damper element.

2.8 Recent European projects

To better understand and mitigate railway-induced vibrations, several European projects have emerged, providing valuable insights into the interaction between railway operations and their environmental impact. Among these, the RIVAS (Railway Induced Vibration and Stability) and SILVASTAR (Sustainable Infrastructure for Low-Vibration and Acoustic Solutions for Railway Systems) projects are notable for their approaches and comprehensive methodologies. Thus, these projects aim to develop and implement innovative solutions to mitigate the environmental impact of vibrations caused by railways, which are often a major concern for communities near railway lines. As the objective of this research is in the building response for ground-borne vibrations, a particular attention will be given for the project reports that address this topic, namelly D1.6 of RIVAS [23]and D1.1 of SILVASTAR[8].

The RIVAS project is a collaborative research initiative that aims in the development of mitigation measures at source, track, propagation path and vehicle [24]. Thus, in order to analyse the effect of the mitigation measures on people in nearby buildings, the performance of these mitigation techniques are translated in term of vibration attenuation and ground-borne noise exposure in buildings and corresponding decrease in annoyance. [23]. For this, firstly, all models of ground-borne vibration transmission from the source to a building are divided into three stages: emission, propagation, and immission. Emission involves the vibrations generated by the source and the surrounding ground conditions, resulting in vibration levels (L_{v1}) measured at a specified distance from the tracks (e.g., 8 meters as used in RIVAS). Propagation refers to how these vibrations travel through the ground to the building location (without the building), producing free-field vibration levels (L(L_{v2})) at the same distance from the building, with the transfer function between (L_{v2}) and (L_{v1}) denoted as TF1. Immission covers the interaction between the ground vibrations and the building, comprising three steps: (i) transmission from the ground to the building foundation (transfer function TF2), leading to foundation vibration levels ((L_{v3})); (ii) transmission from the foundation to the floor (transfer function TF3), affecting floor vibration levels ((L_4)); and (iii) transmission from the floor to ground-borne noise (transfer function TF4), resulting in sound pressure levels in the room ((L_{p})). Figure 2.7 below illustrates the vibration transmission path according to RIVAS [23].

It is recommended to use consistent metrics, preferably on a logarithmic scale, for both vibration and ground-borne noise measurements and estimates. This consistency is crucial unless the metrics poorly correlate with subjective annoyance. Therefore, two types of indicators for evaluating impacts are meaningful: maximum values of running root mean square (r.m.s.) quantities, which

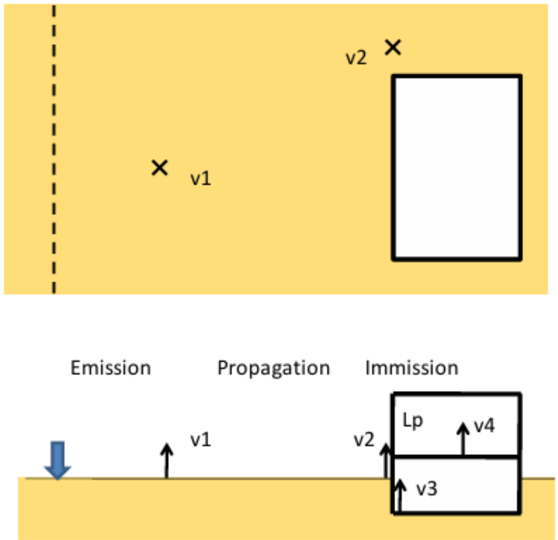


Figure 2.7: Ground-borne vibration transmission from source to imission [23]

are associated with sleep disturbance, and traffic-oriented equivalent values (either r.m.s. or VDV), which are linked to general annoyance. VDV (vibration dose value) is a measure used to assess the exposure of humans to vibration, particularly in the context of health and comfort. It is especially important in environments where vibration may be prolonged, such as in vehicles, machinery, or workplaces. A VDV over train passage T is calculated as shown in equation 2.3. Consequently, this approach leads to the use of four distinct descriptors: two for vibration and two for ground-borne noise.

$$\mathrm{VDV} = \left(\int_0^T s_w(t)^4 \, dt \right)^{\frac{1}{4}} \tag{2.3}$$

where:

$s_w(t)$ = weighted acceleration as a function of time

W = frequency weighting W of each 1/3 octave.

The calculation procedure starts at ground level and uses as input data the transfer functions TF1 to TF4. The transfer functions are represented as 1/3 octave band amplification or attenuation spectra in decibels (dB). These functions are applied to the ground vibration signal measured at 8 meters, with frequency weightings consistent with those used for calculating the descriptors. Additionally, the performance of mitigation measures, expressed as insertion loss in 1/3 octave bands, can be applied to the input signal to determine the descriptor values after applying the mitigation. For the noise, the same calculations are performed, but whitout VDV, replacing W weighting by A or C weighting.

On the other hand, the SILVARSTAR project aims to deliver a commonly accepted, practical and validated method for assessing ground vibration impacts from railways, along with a user-friendly prediction tool for environmental impact studies. This tool is developed in order to facilitate the evaluation of new or upgraded railways on a system-wide scale and make ground vibration predictions. The SILVARSTAR prediction tool employs a hybrid approach that integrates both numerical and experimental methods. It follows an internationally recognized framework, expressing vibration levels in buildings as a product of source, propagation, and receiver terms, each of which is frequency-dependent and can be determined through either numerical models or experimental data [25].

The calculation vibration response in a building is decomposed as the combination of the source, propagation and receiver. Figure 2.8 demonstrates the concept of this decomposition. Therefore, each term is computed from either numerical or empirical results, following the procedure of the Detail Vibration Assessment proposed by the FTA/FRA of U.S Department of Transportation, but allowing for a numerical or experimental representation for each of the terms involved in the prediction, wich conforms with the general framework recommended in ISO 14837-1:2005 [8].

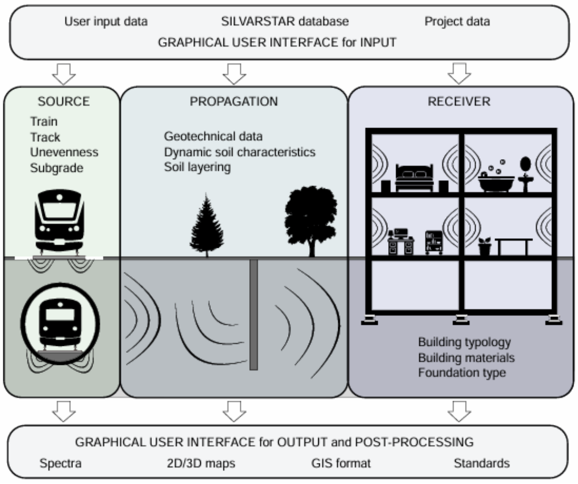


Figure 2.8: Ground vibraton prediction scheme and integration of graphical user interface

Thus, the SILVASTAR tool works with four computation methods for combination of source and propagation: fully empirical, fully numerical, hybrid model 1 (numerical source model combined with an empirical propagation term) and hybrid model 2 (empirical source term combined with a numerical soil model).

On the fully numerical computation, the train-track-soil interaction problem is analyzed in the frequency-wavenumber domain using models of the train and track along with pre-computed soil data. The train and track are modeled based on parameters like axle and bogie distances, mass, spring, and damping characteristics, as well as rail and wheel unevenness spectra. Soil propagation is described using pre-computed transfer functions and impedances, with the database covering 5 homogeneous and 7 layered soil types found in Europe. To reduce computation costs while maintaining accuracy, several assumptions are made: track compliance is calculated for a stationary load, axle loads are treated as fixed rather than moving with the train, and axle loads are considered incoherent.

In the hybrid 1 computation scheme, the same equations used in the empirical approach are applied, with the source term (force density L_F or vibration level L_v) computed as the fully numerical scheme. This source term is then combined with a measured propagation term (line source transfer mobility T_{ML} or ΔT_{ML}). To integrate an empirical propagation term with a numerical model, users must provide specific metadata to ensure proper combination for hybrid calculations.

In the hybrid 2 computation scheme, the same equations as the empirical approach are used (see section 2.2). However, the propagation term (line source transfer mobility T_{ML} or ΔT_{ML}) is computed numerically, following the method outlined in the fully numerical computation scheme (see section 2.3). This numerical propagation term is then combined with the measured source term (force density L_F or vibration level L_v). When importing an empirical source term, users must specify several pieces of information, referred to as metadata, to enable its proper combination with a numerical model for hybrid computations.

CHAPTER 3

Overview of the most used engineering approaches

3.1 FTA method

The model developed by Federal Transit Administration (FTA) of the U.S. Department of Transportation is a notable empirical method which aligns with the ISO standard's levels of assessment.

On the section 6 of the manual, it is outlined the process for determining the appropriate level of vibration analysis required for assessing potential ground-borne vibration and noise impacts from public transportation projects. Given the varied nature of transit projects and their potential to generate different levels of vibration, the FTA has developed a structured, tiered approach to vibration analysis. This approach ensures that each project is assessed according to its specific characteristics, with the level of analysis scaled to the project's potential impact.

The process begins with the Vibration Screening Procedure, a preliminary step designed to quickly determine whether a project poses any significant vibration risks that warrant further investigation. This procedure is especially useful in the early stages of project development when detailed data may not yet be available. If the screening suggests that there could be significant impacts, the analysis proceeds to the General Vibration Assessment.

This intermediate level, which is called General Vibration Assessment, provides a standardized a prediction model for evaluating the potential impacts of ground-borne vibration on different types of land uses. These criteria consider factors such as the frequency and magnitude of vibration events, the sensitivity of the affected environment, and the proximity to vibration-sensitive structures (table 3.1).

Land Use Category	Frequent Events	Occasional Events	Infrequent Events
Category 1: Buildings where vibration would interfere with interior operations.	65 VdB	65 VdB	65 VdB
Category 2: Residences and buildings where people normally sleep.	72 VdB	75 VdB	80 VdB
Category 3: Institutional land uses with primarily daytime use.	75 VdB	78 VdB	83 VdB

Table 3.1: Ground-borne vibration impact Levels (VdB re 1 micro-inch/sec) [2]

By applying these criteria, the assessment can determine whether the predicted vibration levels exceed acceptable thresholds, guiding the need for further analysis or mitigation measures.

For projects where significant impacts are identified or where the environmental context is particularly sensitive, a Detailed Vibration Analysis is required

This Detailed Vibration Analysis criteria separates the prediction into source, propagation, and receiver components. The propagation term is derived from field measurements by combining contributions from uncorrelated point sources along the track, resulting in a line source transfer mobility. The source strength , referred to as force density, is indirectly calculated using the measured response and the experimental line source transfer mobility. Vibration levels at new sites can then be predicted using a database of source strengths from various locations, combined with site-specific line source transfer mobility measurements. Thus, when compared to numerical models, the FTA method offers an advantage over by directly incorporating measured transfer functions, thus accounting for site-specific vibration transmission characteristics. This approach eliminates the need for simplifying assumptions about soil stratification and avoids the complexity of determining dynamic soil properties through in situ geophysical testing [8]

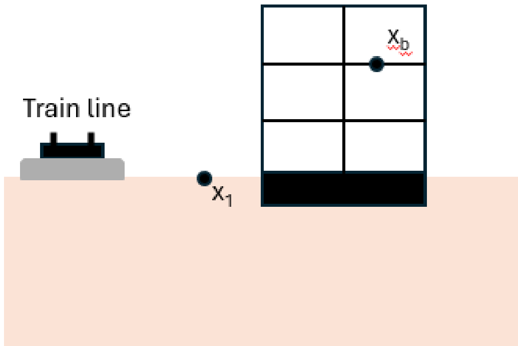


Figure 3.1: Source and receiver points according to FTA manual

.

The FTA manual estimates the vibration velocity level L_v at the receiver (x_b) inside the building as the root mean square of the velocity during the stationary part of a train part. This is measured in decibels (dB ref 10^{-8} m/s) in one-third octave bands, leading to the summation of the terms, instead of a product, as equation (3.1) [8].

$$L_v = FDL + LSTM + C_{\text{build}} \tag{3.1}$$

The FDL term is the force density level, which is a measure for the power per unit length radiated by the source, $LSTM$ is the line source transfer-mobility level in dB transmitted through the soil relative to the power per unit of length. The C_{build} term accounts for the receiver, which is the adjustment to account for ground-building foundation interaction and attenuation of vibration amplitudes as vibration propagates through buildings.

This method described by the formula (3.1) applies for scenarios where there are already an existing railway and a receiver building. For new-build situations, such as new railways infrastructure, new rolling stock or a new buildings constructed nearby a track infrastructure, different approaches shall be taken, as described on FTA manual. For the purpose of this study, it is investigated the new building on a railway area scenario. For this case, according to the reference [2], the vibration level L_v is measured on free field, considering the type of train and its speed. Thus, the measure levels might be corrected with the receiver term C_{build} as described on the FTA method. Figure 3.2, then, show the coupling loss values to be applied in frequency domain according to the type of building. The FTA values for attenuation from floor to floor and also for the amplification due to resonances are expressed on Table 3.2 and will be used on the empirical method analysis.

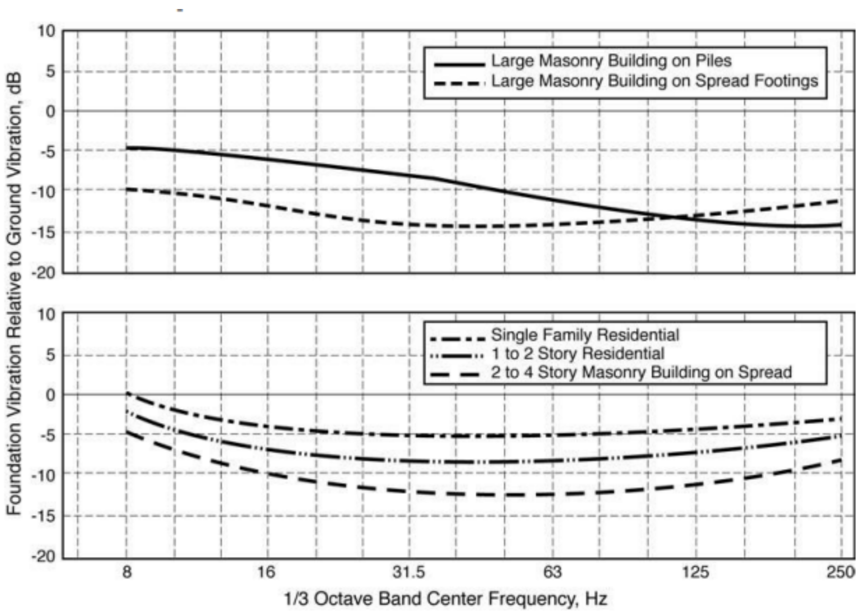


Figure 3.2: Foundation response for different types of building [2]

Receiver Factor	Adjustment to Propagation Curve	
Floor-to-floor attenuation	1 to 5 floors above grade	-2 dB/floor
	Floors 5 to 10 above grade	-1 dB/floor
Amplification due to resonances of floors, walls, and ceilings	+6 dB	

Table 3.2: Receiver Factors and Adjustments to Propagation Curve

3.2 SBB model

This model developed by Swiss Federal Railways (SBB), the VIBRA-2, model consists in a frequency-dependant empirical method based on measured data. It is a full EPI model, which means it deals with emission, propagation and emission. Thus, it is described by the classical equation (3), with all the parameters frequency dependent (1/3 octave) [23]:

$$v_j = v_{0,j} \left(\frac{G}{G_0}\right)^h \cdot F_t \cdot F_s \cdot F_b \cdot \left(\frac{r_0}{r}\right)^m \cdot F_a \cdot F_d \tag{3.2}$$

In which:

- $v_{0,j}$ is the ground velocity at 8 meters from the tracks for train type j.
- G is the train speed, G_0 is a reference speed, and h is a frequency-dependent exponent.
- F_t is a factor that accounts for the track situation (e.g., ground surface, embankment).
- F_s is a factor for particular track situations (e.g., switches).
- F_b is a factor that considers the track sub-ground.
- r is the distance from the track to the building, r_0 is the 8-meter reference distance, and m is a frequency-dependent exponent that accounts for both geometrical spreading and ground material damping.
- F_a is the transfer factor from free field ground velocity at distance r to building foundation velocity.
- F_d is the transfer factor from building foundation velocity to building floor velocity at mid-span.

When it comes to the transfer function TF2, from ground to building foundations, the SBB model communicates the transfer spectra measured in different places. Hence, an average spectrum and respective standard deviation have been calculated. Therefore, two categories of buildings are considered separately, which are houses and multifamily buildings. In the other hand, details about the foundation types and ground conditions are not available, since no information could be obtained.

Then, for the transfer factor from building foundations to floors at mid span (TF3), data is categorized by floor type (concrete or wood) and their frequency ranges. Finally, regarding the transfer factor from building floors at mid span to ground-borne noise (TF4), the analysis includes two types of floors—concrete and wood. For each type, SBB has provided measured transfer spectra, from which average spectra and standard deviations are also determined.

Thus this procedure of successive multiplication of the source spectrum with various transfer spectra brings us finally to the vibration in the room and to the ground borne noise [26].

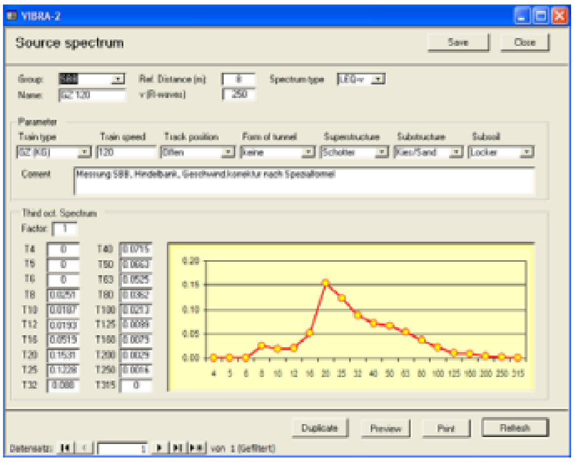


Figure 3.3: Sample of source spectrum [26]

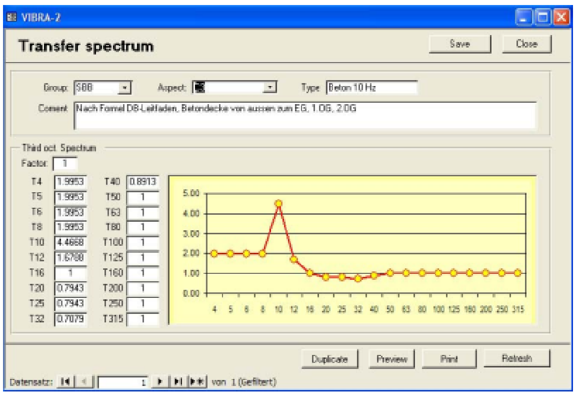


Figure 3.4: Sample of transfer spectrum [26]

Therefore, the SBB model provides a good basis for statistical predictions of immission vibration transfer functions, assuming that data from other countries measured in similar conditions are compatible with this model.

3.3 BAM model

The model developed by the German Federal Institute for Materials Research and Testing (BAM), is tool a that, as detailed by Rücker and Auersch [27], provides a comprehensive framework for predicting railway-induced ground vibrations and their subsequent impact on nearby buildings. It is a full model, approaching emission, transmission, and immission.

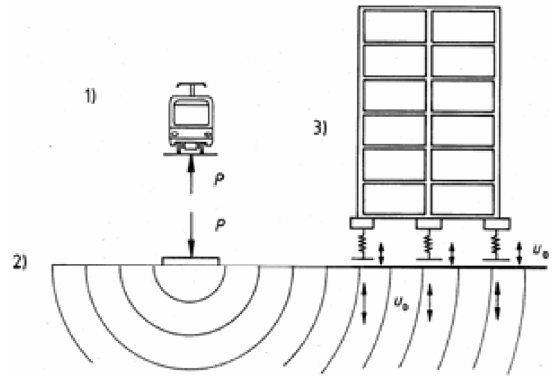


Figure 3.5: Railway induced vibration, excitation by dynamic loads (1), wave propagation through the soil (2), transfer from soil to building (3) [27]

In the emission phase, the model focuses on the excitation of ground vibrations caused by dynamic interactions between railway vehicles and tracks. Various sources of these dynamic loads are identified, such as track alignment irregularities, rail roughness, and the out-of-roundness of wheels. Yet, BAM model uses simplified effective representations, including multi-body models for vehicles and beam-on-support models for tracks, to simulate these interactions and predict the forces that cause vibrations to propagate into the ground.

Then, the model addresses the transmission of these vibrations through the soil. The soil's properties, such as shear wave velocity and material damping, play a critical role in determining how vibrations propagate. Softer soils, for instance, tend to amplify low-frequency vibrations while attenuating higher frequencies more significantly compared to stiffer soils. The BAM model approximates this complex wave propagation process by treating the soil as a homogeneous half-space, with adjustments made to reflect the layered nature of realistic soils.

In the final step of the BAM model, the effects of vibration transfer from soil to building structures are analyzed using a combination of numerical and experimental methods. Finite element methods (FEM), including those combined with the thin-layer method, are applied to study various building types and foundation depths, while the combined finite and boundary element method is used to assess wave-field excitation. Measurements have been conducted on both small residential buildings and more complex structures across Europe, with detailed analysis on selected buildings using 60 measuring points to understand their vibration modes.

Therefore, to model the immission of vibrations within the building, a wall-floor approach is used, integrating multiple wall and floor components along with a soil element represented by a spring-damper system. These elements are analyzed using transfer matrices, and the model's parameters are fine-tuned through averaging and smoothing techniques to align with both experimental data and theoretical principles. This comprehensive approach ensures that the model accurately predicts how vibrations are amplified or attenuated as they propagate through the building

3.4 CSTB model (MEFISSTO)

MEFISSTO is a tool developed by the French Center for Building Science and Technology (CSTB). It consists in a ground-structure vibration interaction model that integrates both the Finite Element Method and the Boundary Element Method. In this approach, FEM is applied to the building structure, where the entire domain of the structure is discretized, allowing for detailed analysis of stresses and displacements. In the other hand, BEM is used for the ground, where only the boundaries of the domain are meshed, simplifying the computational complexity, especially in 2D where it results in meshing simple contours [26].

The basic configuration modeled in MEFISSTO involves a half-space ground domain, represented through the BEM approach, in contact with a building structure modeled using FEM. The ground surface, which theoretically extends infinitely, is practically limited in the meshing process due to the high absorption characteristics of the ground, allowing only a portion of the ground beyond the area of interest to be meshed. At the common boundaries between the ground and the building, the model assumes continuity of displacement and stress, ensuring accurate interaction between the two domains. Figure 3.5 illustrates a half space ground in contact with a structure. [23]

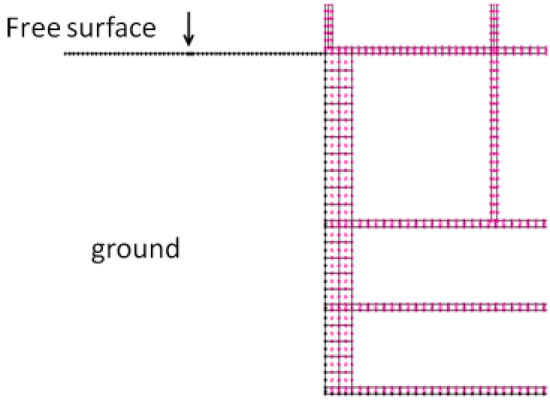


Figure 3.6: Half space ground in contact with a building. Ground surface and interfaces between ground and structures in black and the structure FEM meshing in red (only part of the ground and the building are illustrated) [26]

.

Continuity of displacement and stress is maintained at the interfaces between the FEM and BEM domains. Calculations using FEM and BEM are carried out across narrow frequency bands; however, the resulting frequency spectra are ultimately presented in a more robust format, using 1/3 octave bands[23].

For modeling train excitation, MEFISSTO utilizes a 2.5D approach, where a 2D geometry is extended to be infinite in the third dimension (parallel to the train tracks). This configuration enables the simulation of point excitations at any location within the 3D space while maintaining computational efficiency compared to full 3D modeling. In this setup, the train excitation is effectively represented by an uncorrelated line force along the tracks, allowing for accurate analysis with reduced computational demands [26].

Both the excitation forces and ground parameters require calibration: the source is calibrated using ground vibrations measured at a specific distance from the tracks, while the ground is calibrated using vibrations measured at varying distances, with trains serving as the source. The measured vibration spectra at these different distances are then compared to the spectra calculated by MEFISSTO for three types of half-space ground conditions: a "normal" ground with a shear velocity of 200 m/s, and two variants that are either stiffer or softer, with shear velocities either twice as high or half as low, respectively. The ground type that best matches the measured data is selected for further analysis. These ground types align with the French classification system for seismic events [23].

Building foundations are modeled using MEFISSTO 2.5D to accurately capture ground vibration attenuation over distance and the vibration transfer functions from ground to foundation. Then, the transfer functions from foundation to floor are then estimated using either 2D or 3D models, usually employing purely structural FEM models.

Ground-borne noise is calculated in a separate module, derived from the average velocity level of the floor using building acoustics theory. Then, a frequency-dependent transfer function based on an energy approach is applied:

$$\mathrm{Lp}_{\mathrm{av}} - \mathrm{Lv}_{\mathrm{av}} = 10 \log \sigma + 10 \log \left(\frac{4S}{A} \right) \tag{3.3}$$

Where:

- σ is the radiation efficiency of the floor.
- S is the surface area of the floor.
- A is the absorption area of the room.

Also, the reference for sound level is 2×10^{-5} Pa and for velocity level 5×10^{-8} m/s and a 3 dB constant is often added, assuming both the floor and ceiling are the main ground-borne sources in the room.

3.5 DB model

The DB model was developed by Deutsche Bahn (DB), which is the German national railway company. This model consists in a statistical approach to the analysis of vibration transfer from building foundations to floors, based on an extensive empirical data. Differently from VIBRA-2 model that is purely empirical, the DB model contains data collected from approximately 800 standard buildings. This large dataset allows the model to generate statistically significant transfer functions that describe how vibrations propagate from foundations through various building floors [23].

Similar to the SBB model, the DB model considers two main categories of floors: concrete and wood. However, the subcategories in the DB model, which correspond to the floors' first resonant vibration modes, differ slightly from those in the SBB model. These subcategories are defined across 1/3 octave bands ranging from 8 Hz to 80 Hz, resulting in 11 distinct subcategories. Each subcategory's outcome is represented as an idealized average floor frequency response.

Regarding the transfer function TF4, which describes the relationship between building floor vibrations at mid-span and ground-borne noise generated by at-grade railway traffic, DB employs statistical transfer functions that are represented as frequency-dependent regression curves for each 1/3 octave band from 25 to 80 Hz. These curves are derived from field measurements of both the floor velocity at mid-span and the noise levels within the room. The results focus on sound levels measured within a limited frequency range (up to 100 Hz) to minimize the impact of unwanted airborne noise and to improve the correlation coefficient. The analysis considers two types of floors: concrete and wood.Table 3.2 gives as an example the regression curves obtained for concrete floors; the unusual relationships used are supposed to correctly relate the total ground borne noise radiated by all the building elements (floor, ceiling and walls) in the room, to the floor velocity only.][23].

Frequency (Hz)	**Regression curves (Lp in dB, ref.2×10^{-5} Pa; Lv in dB ref. 5×10^{-8} m/s)**
25	Lp = 32.4 + 0.418 · Lv
31,5	Lp = 28.0 + 0.501 · Lv
40	Lp = 28.8 + 0.506 · Lv
50	Lp = 25.3 + 0.557 · Lv
63	Lp = 22.6 + 0.595 · Lv
80	Lp = 23.7 + 0.597 · Lv

Table 3.3: Floor velocity to ground borne noise regression curves; DB data for concrete floors [23]

CHAPTER 4

A simplified FEM model accounting for a SSI

4.1 Global model overview

The model presented in this study simulates the dynamic response of a building to ground-induced vibrations generated by railway traffic. The building is modeled as a 2D frame consisting of beam elements, with each element's stiffness and mass properties derived from the geometry and material characteristics of the building.

Thus, the interaction between the soil and the building is represented using a spring-damper system, based on recommendations from the National Institute of Standards and Technology [21]. The model investigate, then, two different approaches for the stiffness and damping calculation: one based on the López-Mendoza et al. model [18] and the other on Auersch model [22]. Both models consider a structure with a rigid foundation, as illustrated in figure 4.1 where u_g is the free field vibration, u_0^s is the building foundation response and u^s is the building response.

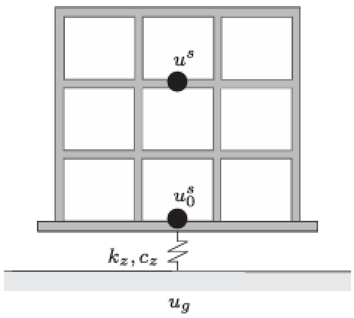


Figure 4.1: Simplified building-soil coupling model with a rigid foundation [18]

These models are incorporated into the simulation through dynamic stiffness matrices that adjust the system's response based on the soil-structure interaction's properties.

Therefore, the excitation input, corresponding to ground vibrations, is initially applied as a unitary velocity at the building's base. This is achieved by constructing the force vector `F` such that the resulting displacement at the foundation node, when multiplied by the angular frequency, produces a unitary velocity across the entire frequency range. This approach allows the model to accurately calculate the building's response to this standardized input across a range of frequencies.

Hence, the primary goal of this model is to investigate how ground vibrations propagate through the structure and to quantify the resulting vibration levels at different locations within the building. To ensure the results reflect realistic conditions, the calculated response is adjusted using a reference spectrum of measured ground vibrations, then providing a realistic prediction of the vibration behavior within the building.

4.2 FEM formulation for elastodynamics

Elastodynamics is the study of how elastic materials behave under dynamic loading conditions, where both stress and strain vary with time. Thus, to model and analyze the response of structures, such as buildings subjected to vibrations from sources like railways, the Finite Element Method (FEM) is employed as a powerful computational tool. The FEM discretizes the structure into a finite number of elements, allowing for the approximation of the governing elastodynamic equations over each element. Therefore, this approach enables the investigation of how vibrations propagate through a structure and interact with its components. Therefore, the dynamic equilibrium equation of a structure can be written as equation (5).

$$\mathbf{M}\ddot{\mathbf{u}}(t) + \mathbf{C}\dot{\mathbf{u}}(t) + \mathbf{K}\mathbf{u}(t) = \mathbf{F}(t) \tag{4.1}$$

Where $\mathbf{M}$ is the mass matrix, $\mathbf{C}$ is the damping matrix, $\mathbf{K}$ is the stiffness matrix, $\mathbf{u}(t)$ is the displacement vector, $\dot{\mathbf{u}}(t)$ and $\ddot{\mathbf{u}}(t)$ are the velocity and acceleration vectors, respectively, and $\mathbf{F}(t)$ is the external force vector [18] In the context of FEM, these matrices are constructed by summing contributions from individual elements.

For a specific beam element e, the local stiffness matrix $\mathbf{K}_e$ and mass matrix $\mathbf{M}_e$ are derived from the geometry and material properties of the element, which are then assembled into the global matrices used to solve the system:

$$\mathbf{K}_e = E\mathbf{K}_e^0, \quad \mathbf{M}_e = \rho AL\mathbf{M}_e^0$$

Here, E is the Young's modulus, ρ is the material density, A is the cross-sectional area, L is the element length, and $\mathbf{K}_e^0$ and $\mathbf{M}_e^0$ are the normalized stiffness and mass matrices based on the element's geometry.

Then, FEM is implemented to simulate the elastodynamic behavior of a building structure subjected to ground vibrations. The structure is modeled as a two-dimensional frame with beam elements, where the global stiffness and mass matrices are assembled from the contributions of individual elements. The dynamic response of the building is then computed across a range of frequencies, incorporating the effects of soil-structure interaction through spring-damper elements.

Then, in order to analyse the system in the frequency domain, the time-dependent displacement, velocity and acceleration are represented as function of angular frequency $\omega = 2\pi f$.

Therefore: $\dot{u}(t) = i\omega\ u(\omega)$, $\ddot{u}(t) = -\omega^2 u(\omega)$

Furthermore, the material damping is included in the stiffness matrix through the use of a complex young modulus E, which is defined as $E = E_0(1 + \eta i)$, where E_0 is the real part of the Young's modulus and η is the damping ration, which represents the material damping.

These equations are fundamental to the dynamic analysis performed in Matlab, providing the necessary framework to simulate how the building structure responds to vibration forces over a range of frequencies.

4.3 Building model

The building model implemented in the MatLab code is designed as a two-dimensional (2D) frame structure, which is a simplified but effective representation of a building's structural behavior under dynamic loading conditions, such as ground-induced vibrations. The structure is discretized into beam elements that represent the columns and floors of the building. Thus, this model captures the essential structural components and their interactions. Figure 4.2 illustrates an example of a 2D frame building model.

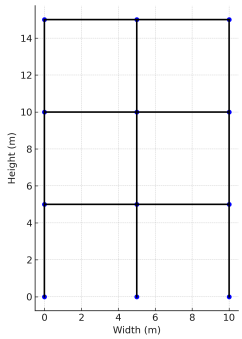


Figure 4.2: 2D frame building model with 3 floors and 2 spans

Therefore, the frame model is defined by several parameters, including the number of spans and floors, the floor height, and the span length. These parameters allow for a flexible configuration of the building, enabling the analysis of various structural layouts.

Furthermore, the elements are defined by their material properties, such as Young's modulus E and density ρ. Geometrically, each beam element is defined by its cross-sectional area A and its moment of inertia I, which is calculated as written in equation (6), moment of inertia for rectangular cross-sections.

$$I = \frac{bh^3}{12} \tag{4.2}$$

The frame is assembled using a specified number of nodes per beam, ensuring that the displacement and rotation at each node are accurately captured during the dynamic analysis.

4.4 Soil-structure interaction

The model also incorporates the interaction between the building and the underlying soil, which is critical for understanding how vibrations propagate from the ground into the structure.

For that, it is considered a rigid foundation. The rigid foundation model assumes that the building foundation behaves as a single, monolithic unit, without deformation during vibration transmission. This assumption simplifies the computation by allowing the foundation's vertical stiffness and damping properties to be represented by single values, calculated from soil parameters, such as the shear modulus and Poisson's ratio.

$$G = \frac{E}{2(1+\nu)} \tag{4.3}$$

Where:

- G is the shear modulus,
- E is the Young's modulus,
- ν is Poisson's ratio.

Thus, this soil-structure interaction is modeled using spring-damper elements, which are based on established methods from the literature, specifically the approaches proposed by López-Mendoza et al. [18]and Auersch [22]. These spring-damper elements simulate the effects of the soil's stiffness and damping characteristics on the building's foundation.

Method I

The first method is based on the model proposed by López-Mendoza et al [18]. According to it, when the foundation is considered rigid, it can be modeled using a single spring-damper element characterized by stiffness (k_z) and damping (c_z). The vertical stiffness of the entire system, k_z, is computed using the following formula:

$$k_z = K_{z,\text{surf}} \cdot a_z \tag{4.4}$$

Here, $K_{z,\text{surf}}$ represents the vertical static stiffness of a surface foundation, and a_z is the dynamic stiffness modifier. The static stiffness $K_{z,\text{surf}}$ is derived from the soil's shear modulus G and Poisson's ratio ν, along with the foundation's dimensions L (length) and B (width):

$$K_{z,\text{surf}} = \frac{GB}{1-\nu}\left[3.1\left(\frac{L}{B}\right)^{0.75} + 1.6\right] \tag{4.5}$$

The dynamic stiffness modifier a_z accounts for the structural properties and is calculated as:

$$\alpha_z = 1 - \frac{\left(0.4 + \frac{0.2}{L/B}\right)a_0^2}{\frac{10}{1+3\left(\frac{L}{B}-1\right)} + a_0^2} \tag{4.6}$$

Here, a_0 is the dimensionless frequency, which is computed from the S-wave velocity c_s and the angular frequency of the structure's first bending mode ω_1 (without considering soil-structure interaction):

$$a_0 = \frac{\omega_1 B}{c_s} \tag{4.7}$$

Where:

$$c_s = \sqrt{\frac{G}{\rho_{\text{soil}}}} \tag{4.8}$$

After determining the vertical stiffness k_z, the damping coefficient c_z for the entire foundation is calculated using the formula:

$$c_z = 2k_z\frac{\beta_z + \beta_s}{\omega_1} \tag{4.9}$$

Where β_s represents the damping ratio of the soil, and β_z is the radiation damping ratio, which is obtained as follows:

$$\beta_z = \frac{4\psi\frac{L}{B}a_0}{\frac{K_{z,\text{surf}}}{GB}\cdot 2\alpha_z} \tag{4.10}$$

Here:

$$\psi = \sqrt{2(1-\nu)(1-2\nu)}, \quad \text{limited to } \psi \leq 2.5. \tag{4.11}$$

Method II

The second method of calculation is based on the model proposed by Auersch [22]. In this approach, the soil beneath the foundation is also modeled as a spring-damper system, with the foundation's stiffness k and damping c as the key parameters.

The vertical stiffness k of the rigid circular foundation is calculated using:

$$k = 3.4G\sqrt{A_s} \tag{4.12}$$

Where G is the shear modulus of the soil, calculated as (4.3), and A_s is the foundation area. The damping coefficient c is determined by:

$$c = 1.6\sqrt{G\rho A_s} = 1.6\rho c_s A_s \tag{4.13}$$

Where ρ is the mass density of the soil, and c_s is the shear wave velocity and is calculated as shown in equation (4.8). This simplified approach provides an efficient way to predict how vibrations from sources such as railway traffic will affect building foundations, making it useful for practical engineering applications where detailed models may be impractical.

CHAPTER 5

Model comparison

5.1 Analysed scenarios

Input ground vibration vibration data

The excitation input of the system is applied with the measured data collected in situ, in August 2023, by the team of SLAM Acoustique in the location mentioned on Chapter 1. This data represents the measurement of a single tram passage, taken approximately 20 meters from the tramway. The measurements were recorded in 1/3 octave bands, covering a frequency spectrum ranging from 10 to 160 Hz.

Hz	**10**	**12.5**	**16**	**20**	**25**	**31.5**	**40**	**50**	**63**	**80**	**100**	**125**	**160**
dB	34.0	36.0	42.7	41.3	39.3	34.5	27.3	21.5	16.4	14.4	13.2	12.1	11.0

Table 5.1: Measured tram-induced ground-vibration data in Saint-Cloud, France, 20 meters from the tram line T2 [SLAM Acoustique, 2023]

Building models

In this study, we simulate and analyze five distinct frame structures to evaluate their vibration responses under external excitation. Each scenario considers a standard a span length s equal to 4 meters and floor height h equal to 3 meters. The receivers are placed in the sensitive points of the structure, in order to capture the response at the worst case scenario.

The first scenario involves a simple frame structure with one span ($s = 4$) and two floors ($h = 6$), where the receiver is positioned at mid-span on the first floor ($h = 3$), as shown in figure 5.1 (a). Following this, we analyze a slightly more complex structure with two spans and two floors, maintaining the receiver at the first floor ($s = 2$) , while keeping the floor height consistent, Figure 5.1 (b).

Figure 5.1 (c) shows the third scenario, which involves a frame with two spans and four floors ($h = 12$), with receiver positioned at both the third ($h = 9$) floor.

The fourth scenario, Figure 5.1 (d), examines a frame with four spans ($s = 16$) and four floors, with one receiver placed at the third floor at $s = 2$.

Finally, the fifth scenario, includes a frame with six spans ($s = 24$) and six floors ($h = 18$), with receiver at the mid-span of the fifth floor ($h = 15$ e $s = 6$) floors, as illustrated in Figure 5.1 (e).

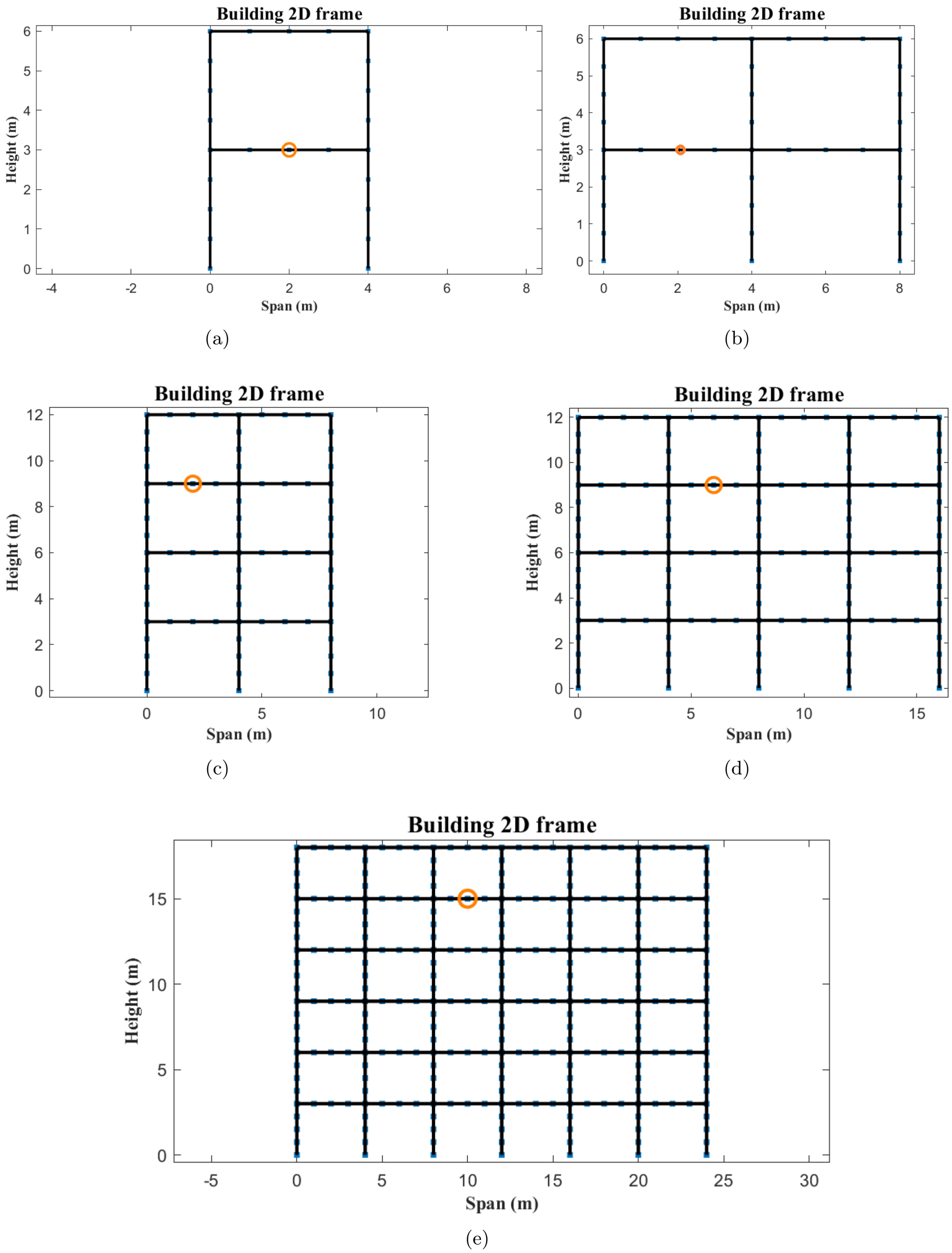


Figure 5.1: Analysed 2D frame structures with the receiver positions are marked with orange circles.

Thus, these configurations provide a comprehensive understanding of how both horizontal and vertical expansions of the building influence its vibrational characteristics. After simulating these scenarios, the results will be compared against the empirical method provided in the Federal Transit Administration (FTA) manual.

5.2 Obtained results

In this section, it is presented and discussed the results obtained from the vibration analysis of the five distinct frame structures introduced earlier. For each scenario, methods I and II are investigated, then compared with the FTA method.

5.2.1 Scenario I - Single span, two floors

In this scenario, we examine a simple frame structure, with $s = 4$ and $h = 6$, as shown in Figure 5.1 (a). Thus, the structural response of a building is investigated under a unitary velocity vibration input, which serves as a reference vibration to evaluate how different parts of the structure react to external excitation across a frequency range of 10 Hz to 100 Hz, as shown in Figure 5.2.

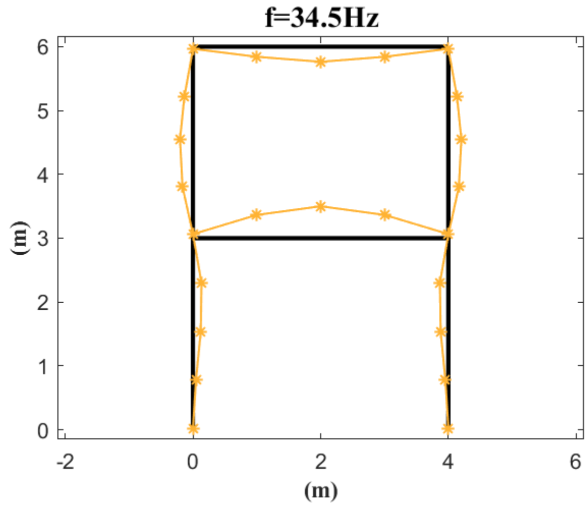
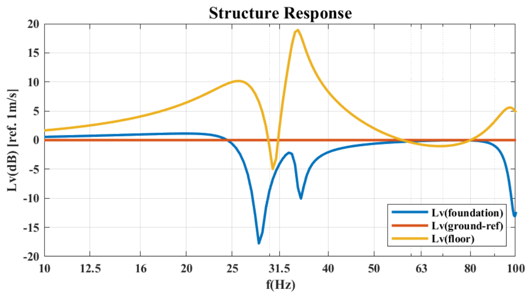
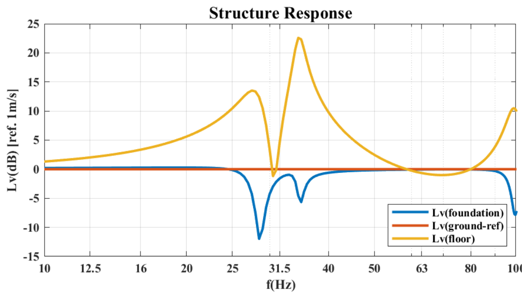


Figure 5.2: Structure mode of vibration at 34.5 Hz

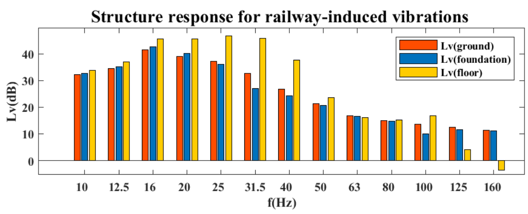


(a) Method I

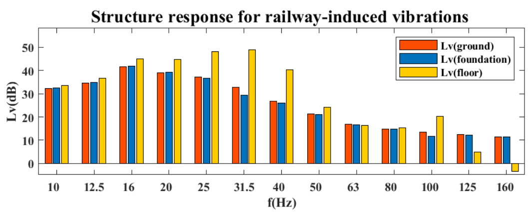


(b) Method II

Figure 5.3: Structure response on scenario I for a unitary velocity vibration input.

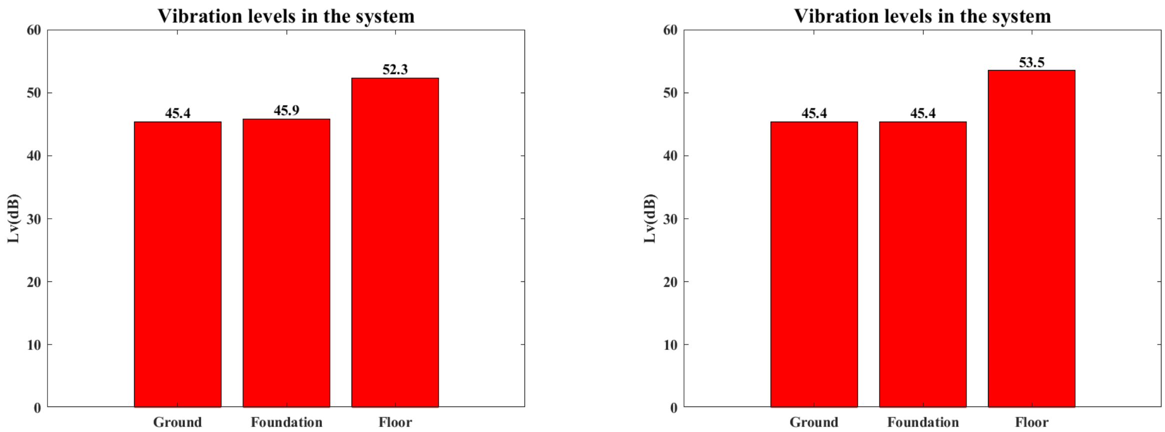


(a) Method I



(b) Method II

Figure 5.4: 1/3 octave band structure response on scenario I for the tram-induced vibration per 1/3 octave band.



(a) Method I (b) Method II

Figure 5.5: Global response of the system on scenario I for tram induced vibration.

In the analysis of the vibration response, the receiver is positioned in the mid-span of the first floor. When comparing result, both methods present result curves with similar behaviours, Figure 5.3 .The mid-span responses in the first floor, represented by the yellow curves, exhibit an amplification at 34.5 Hz, indicating a resonance at this frequency. However, their amplitudes differ, with method II exhibiting an amplification 5 dB higher than the method I. When it comes to the foundation response, both methods shows a sharp attenuation at 28.5 Hz, with the method I predicting around - 18 dB attenuation, while method II estimates a - 12 dB attenuation. A similar behaviour occur at 35 Hz, with the method I showing a 5 dB higher attenuation than method II. These dips suggest that the foundation is effectively damping vibrations at these frequencies, possibly due to the soil-structure interaction. Then, at 100 Hz, method II presents + 5 dB in both foundation and floors curve, when compared to method I.

Figure 5.4 shows the 1/3 octave band response of the system when submitted to the tram excitation. One can observe that the maximum amplitudes of vibration occurs at 25 Hz and 31.5 Hz octave bands, and in both methods the amplitudes are lower than the human threshold (65 dB), as shown in Table 2.1. Figure 5.5 shows the global response of the system. Thus, even with the floor amplifications due to resonances, the vibrations are still below the human limit of perception.

5.2.2 Scenario II - Two span, two floors

For this case, it will be analysed a frame structure with $s = 8$ and $h = 6$, as illustrated in Figure 5.1 (b). The structural response of a building is investigated with the same approach as section 5.2.1, with the receiver located in the third floor.

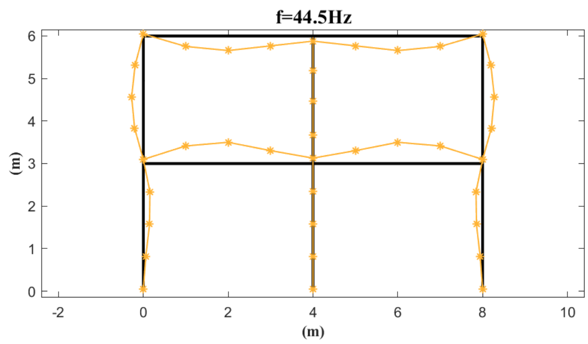
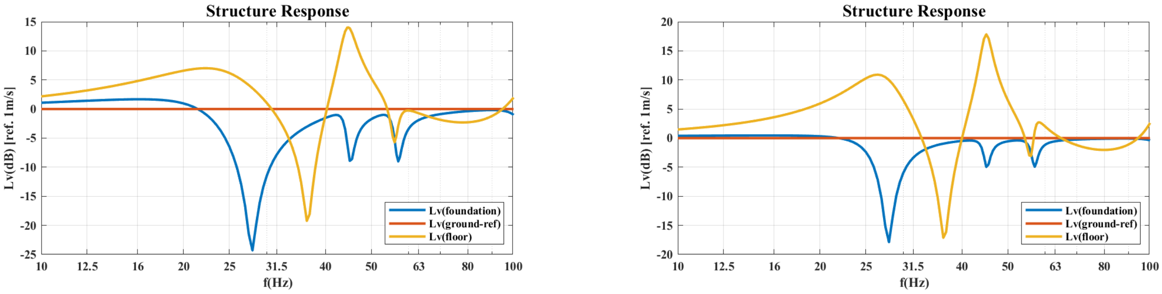
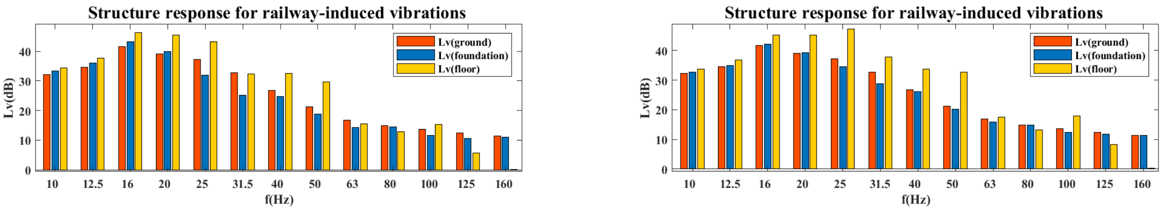


Figure 5.6: Structure vibration mode at 44.5 Hz



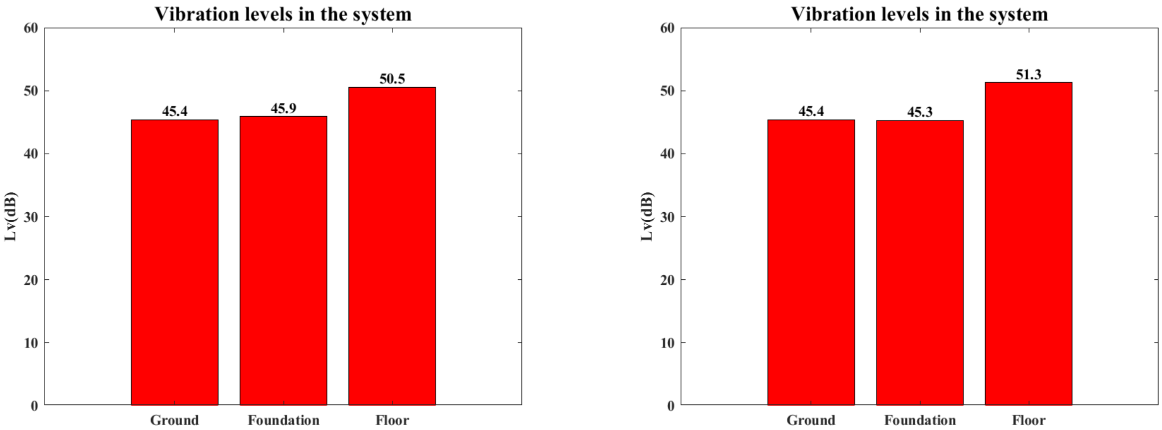
(a) Method I (b) Method II

Figure 5.7: Response of foundation and third floor on scenario II for a unitary velocity vibration input.



(a) Method I (b) Method II

Figure 5.8: 1/3 octave band structure response on scenario II for the tram-induced vibration per 1/3 octave band.



(a) Method I (b) Method II

Figure 5.9: Global response of the system on scenario II for tram induced vibration.

In this type of structure, the mid-span responses on the first floor (Figure 5.7) presents a similar behaviour as the first scenario, however the peak amplification occurs around 44.5 Hz with lower amplitudes. Method II again predicting a slightly greater amplification (approximately 3 dB higher) compared to Method I. This trend is consistent with the first scenario, where Method II generally predicts higher amplification.

For the foundation response, both methods continue to show sharp attenuation at certain frequencies, notably around 28 Hz, as the structure with one span and two floors, with the wider structure presenting a higher amplitude. As in the first scenario, method I predicts a more significant attenuation (-15 dB) compared to Method II (-10 dB), indicating that Method I is more conservative in estimating the damping effect at these frequencies. Finally, the difference on the global response of the system between both methods are negligible.

5.2.3 Scenario III - Two span, four floors

In this section it will be analysed a frame structure with $s = 8$ and $h = 12$, as illustrated in Figure 5.1 (c). Then, the vibration building response is investigated.

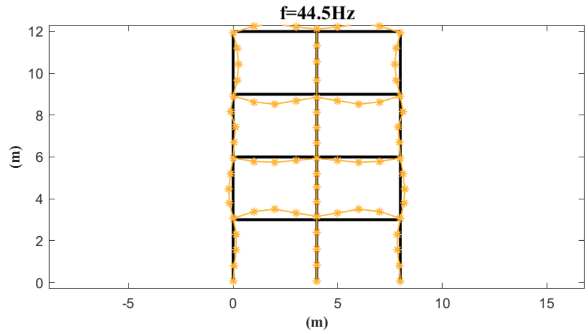
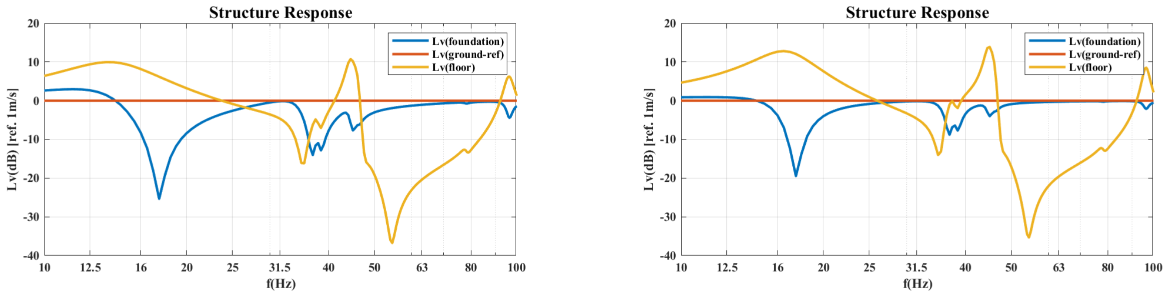


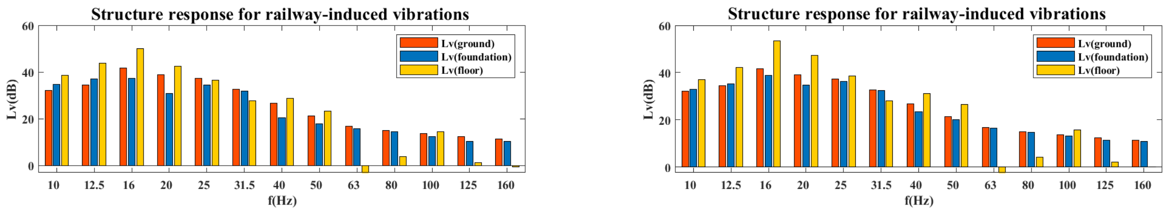
Figure 5.10: Vibration mode of the two spans and four floors structure at 44.5 Hz



(a) Method I

(b) Method II

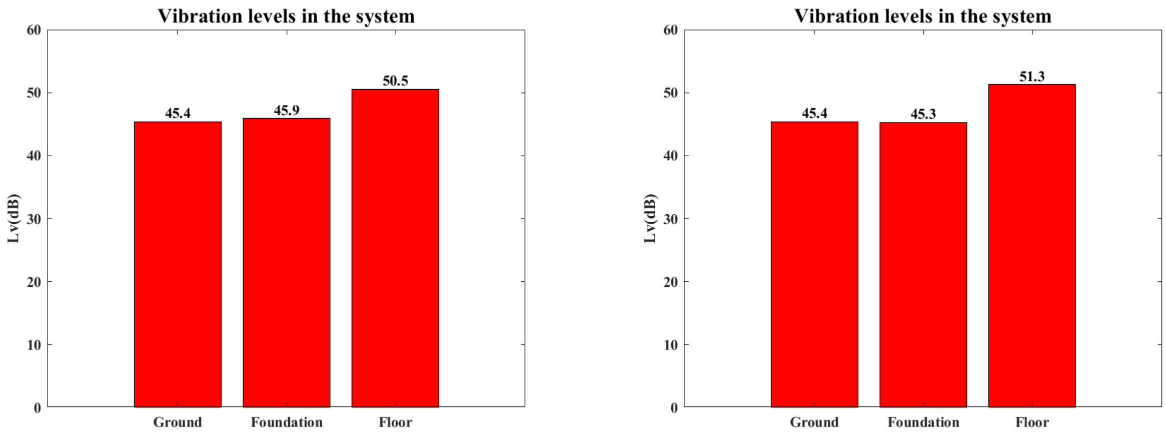
Figure 5.11: Structure response on scenario III for a unitary velocity vibration input.



(a) Method I

(b) Method II

Figure 5.12: 1/3 octave band structure response on scenario III for the tram-induced vibration per 1/3 octave band.



(a) Method I

(b) Method II

Figure 5.13: Global response of the system on scenario III for tram induced vibration.

In the analysis of the vibration response for the third scenario, the receiver is positioned at the mid-span ($s = 2$) of the third floor. When comparing the results, both methods exhibit similar behaviors in the response curves, as shown in Figure 5.11. The floor shows significant amplification at 44.5 Hz, as scenario II. Method II predicts a slightly higher amplification by about 3 dB compared to Method I. Regarding the foundation response, both methods display sharp attenuation at 17.5 Hz, with, again, Method I showing a more pronounced dip of approximately -25 dB, while Method II estimates a -15 dB attenuation. These differences suggest that the foundation is effectively damping vibrations at this frequency, with Method I indicating a stronger damping effect. Thus, one can say that with an increase in the building's mass, the foundation demonstrates enhanced attenuation of vibrations. This is likely attributable to the increased structural mass, which enhances the damping effect and more effectively dissipates the energy transmitted from ground-borne vibrations. The vibration levels in the system on both methods are similar, with unimportant differences.

5.2.4 Scenario IV - Four spans, four floors

For the fourth scenario, it will be analysed a structure with $s = 16$ and $h = 12$. As shown in Figure 5.1 (d), the receiver is placed in $h = 9$. Then, the system response is analysed for two floors.

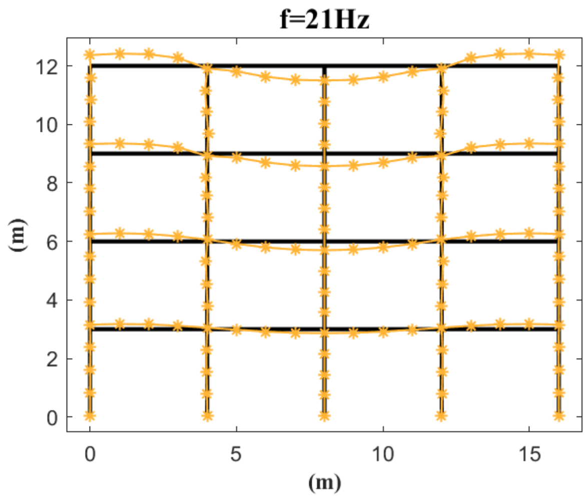
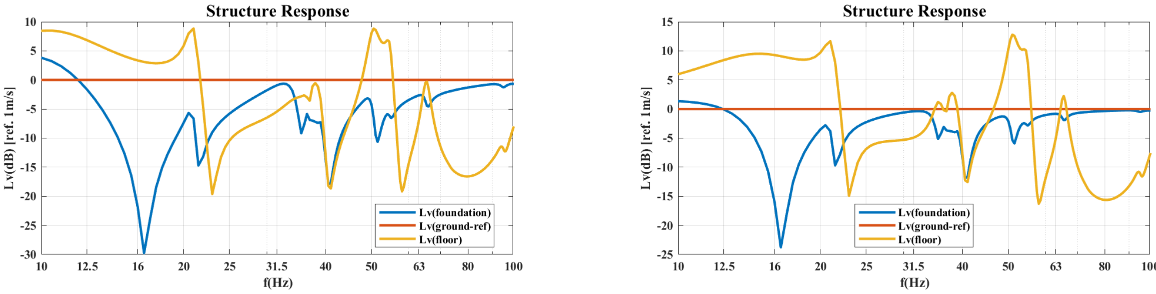
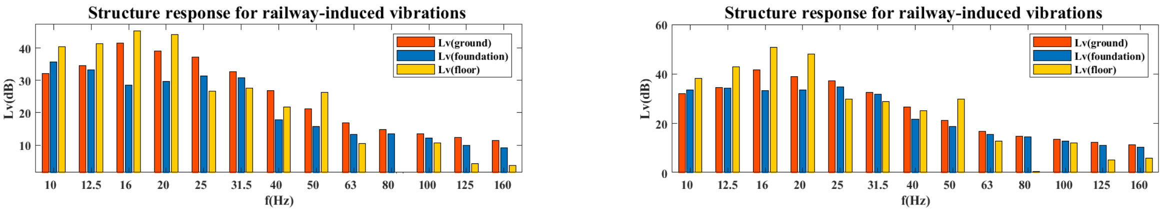


Figure 5.14: Vibration mode of the four spans and four floors structure at 21 Hz



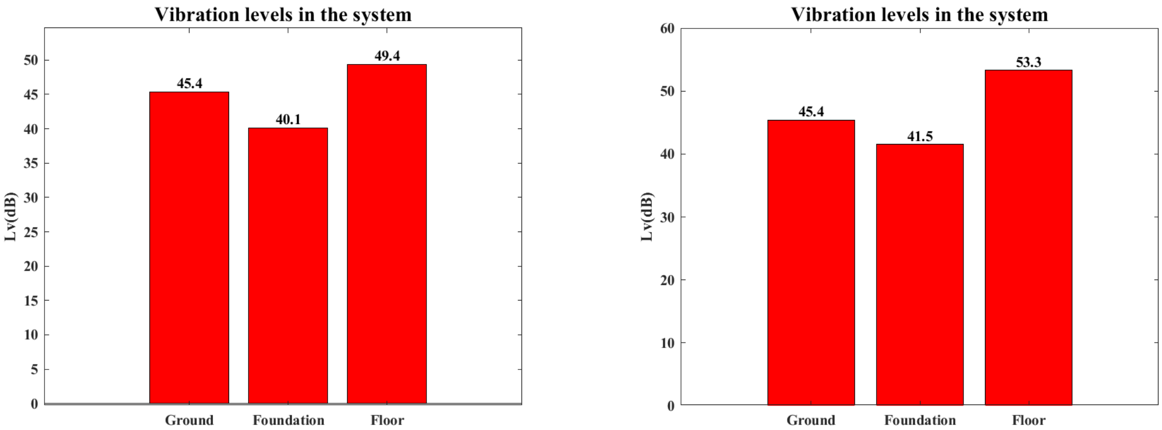
(a) Method I (b) Method II

Figure 5.15: Structure response on scenario IV for a unitary velocity vibration input.



(a) Method I (b) Method II

Figure 5.16: 1/3 octave band structure response on scenario IV for the tram-induced vibration per 1/3 octave band.



(a) Method I (b) Method II

Figure 5.17: Global response of the system on scenario IV for tram induced vibration.

At approximately 21 Hz, both methods show significant amplification in the floor response. Beyond the primary resonance, both methods show additional peaks and troughs, particularly around 50 Hz. These likely correspond to higher-order vibration modes of the structure. This may occur due to the different natural frequencies of each component of the structure, creating a series of peaks in the vibration response. Furthermore, a cancellation occurs at 80 Hz, with no floor response at this frequency.

In both methods, the simulated SSI present a sharp attenuation around 16 Hz, similarly to scenario III, suggesting that, despite the number of spans, the height of structure plays an important role in determining the natural frequencies related to the foundation response.

Finally, the global floor vibration level on method II has an considerable difference of 4 dB compared to method I.

5.2.5 Scenario V - Six spans, six floors

In this scenario, the building with 18 meters height and 24 meters width is analysed. the receiver is placed in $h = 15$ and $s = 10$, where it presents the highest deformation.

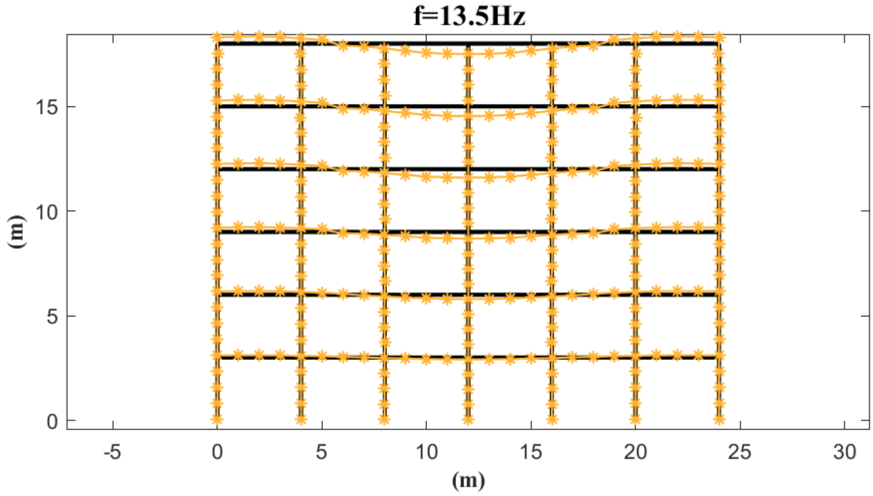
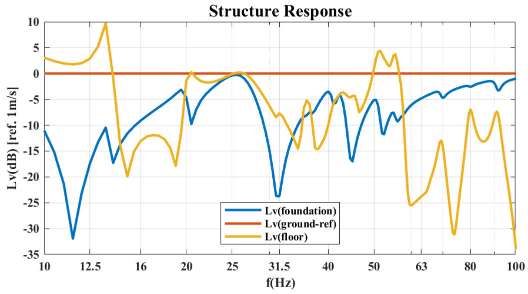
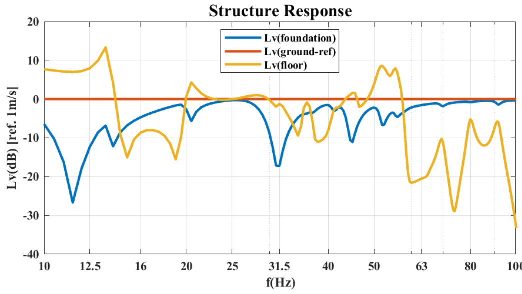


Figure 5.18: Vibration mode of the six floors and six spans structure at 13.5 Hz

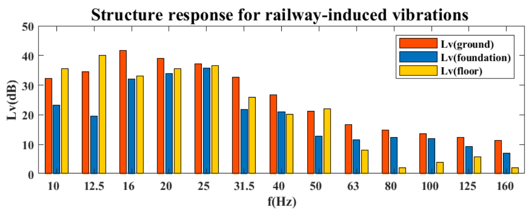


(a) Method I

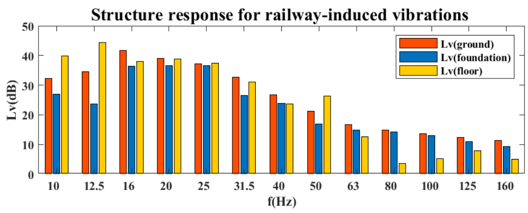


(b) Method II

Figure 5.19: Structure response on scenario V for a unitary velocity vibration input.

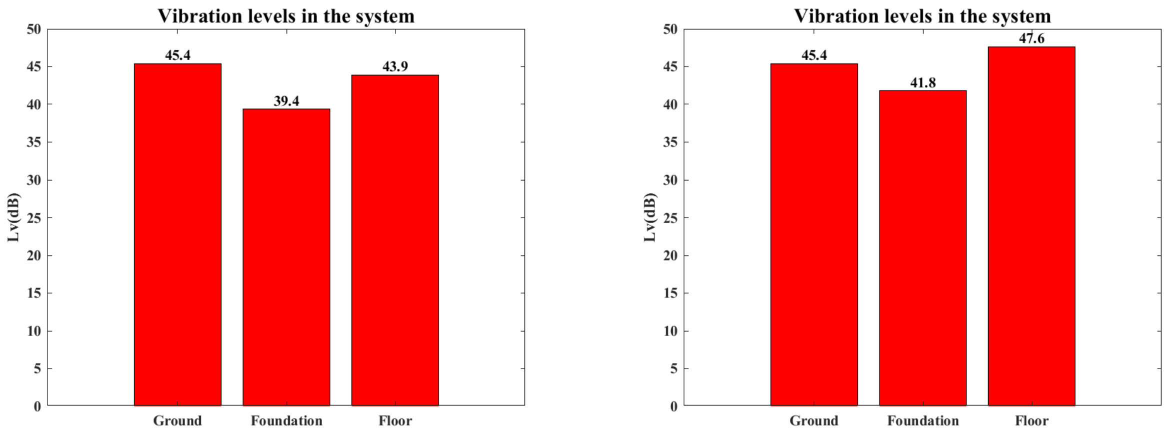


(a) Method I



(b) Method II

Figure 5.20: 1/3 octave band structure response on scenario V for the tram-induced vibration per 1/3 octave band.



(a) Method I (b) Method II

Figure 5.21: Global response of the system on scenario V for tram induced vibration.

Analysing the behaviour of the fifth floor, at the span $s = 10$, one can say that both methods display multiple peaks and troughs in the floor and foundation responses across the entire frequency range. These fluctuations indicate the presence of higher-order vibration modes and complex interactions between the building's multiple spans and floors.

Notable dips are observed around 12 Hz and 31.5 Hz in both methods, with the floor response in Method I showing a more pronounced dip compared to Method II. This suggests that the building's floors are effectively dampening vibrations at these frequencies, possibly due to the internal damping mechanisms or energy dissipation across the multiple spans and floors.

Scenario V shows that the building's increased span and floor count lead to more complex vibration behaviors, with significant resonance effects at low frequencies and multiple higher-order modes across a broader frequency range. Both methods identify similar key frequencies where significant amplification or attenuation occurs, although the magnitudes differ, with Method I generally predicting stronger damping and Method II showing more pronounced resonances.

Finally, the global response of the system, depicted in Figure 5.21, shows that Method I predicts lower overall vibration levels compared to Method II. Besides the 2 dB difference on the vibration level at the foundation, indicating that Method I assumes more effective damping at the foundation level, the floor response in Method II is notably higher (47.6 dB) than in Method I (43.9 dB), suggesting that Method II predicts stronger amplification of vibrations as they propagate through the structure .

The responses of the system components are provided in Appendix A.

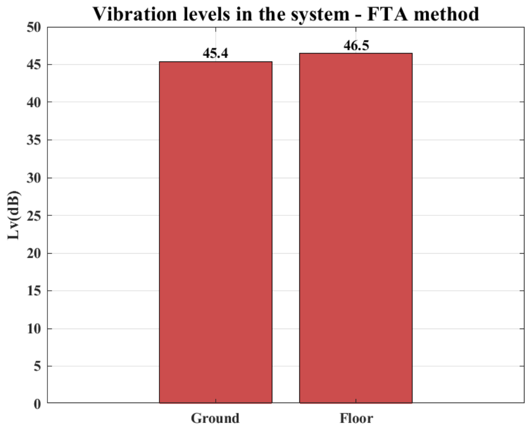
5.3 Comparative analysis with empirical method

The results from the FEM methods are compared with the structures response estimated by the FTA method. The Detailed Vibration Analysis model, the number of spans are not taken into account, which means only the number of floors are relevant to predict the building response to a railway-induced vibrations. Also, note that the correction is zero when estimating basement floor vibration or vibration of at-grade slabs.

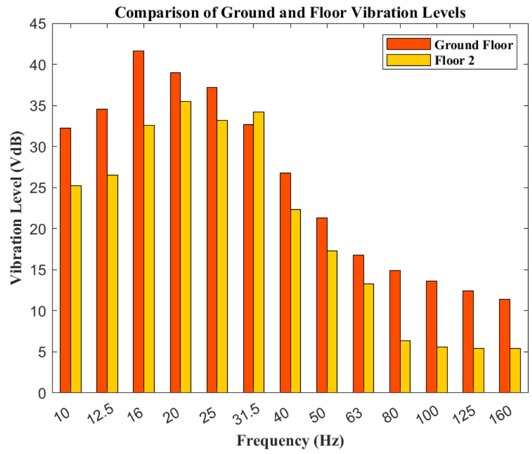
Therefore, scenarios I and II are shown as one building response. The same is for scenarios III and IV.

The coupling-loss values shown in Figure 3.2 and also the floor-to-floor attenuation, as the amplification due to resonances presented in Table 3.2, will be applied to the tram-way-induced vibration data. Then each scenario results is exposed and then discussed.

Scenarios I and II



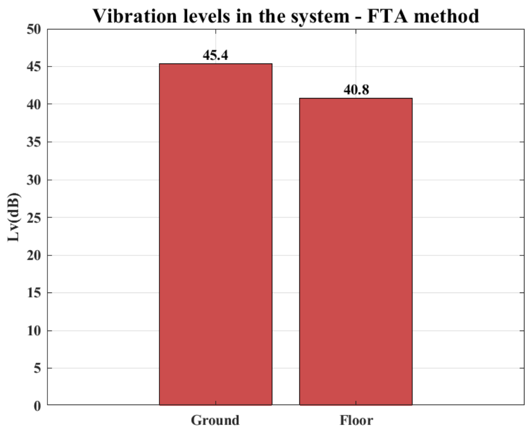
(a) Method I



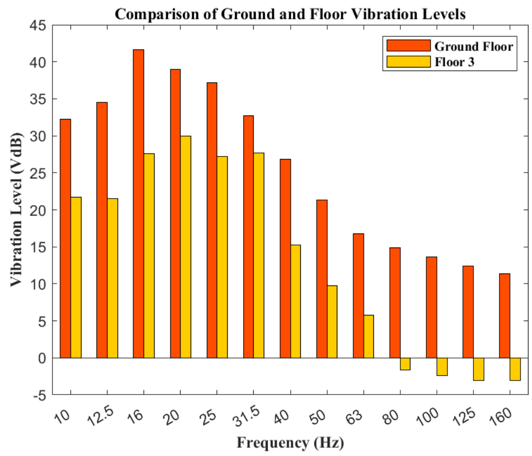
(b) Method II

Figure 5.22: System response for scenarios with two floors.

Scenarios III and IV



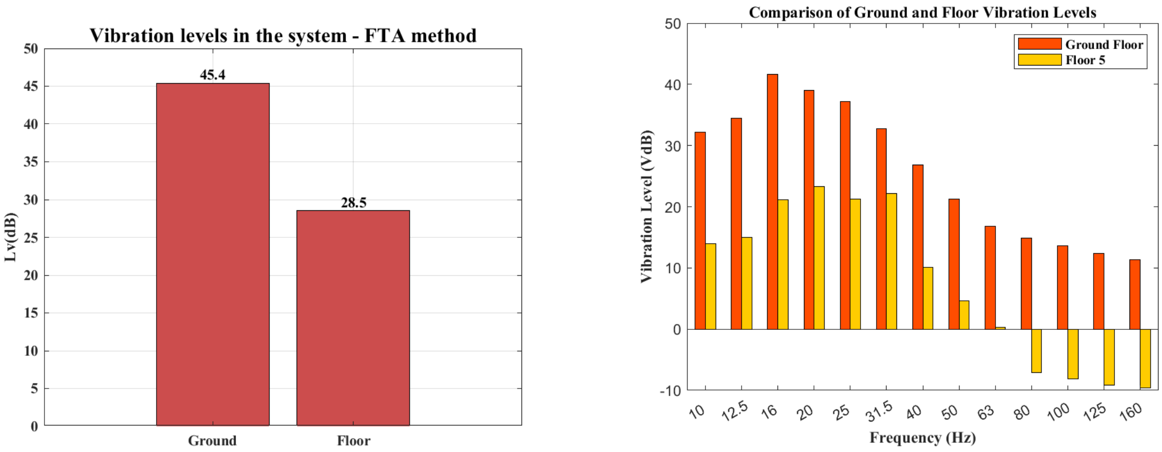
(a) Method I



(b) Method II

Figure 5.23: System response for scenarios with 4 floors.

Scenario V



(a) Method I

(b) Method II

Figure 5.24: System response for scenarios with 6 floors.

When comparing the FEM 2D approaches with the FTA model, significant differences in the building's response are observed. In the scenarios with two floors, the FTA method predicts a response of 46.5 dB at the receiver floor, whereas the FEM models produce responses around 50 dB across both scenarios and methods, indicating a discrepancy between 4 dB, when compared to method I of scenario II, and 7 dB, comparing to method II of scenario I. This difference becomes more pronounced in the scenarios with four floors, where the FTA method estimates a response of 40.8 dB, resulting in +10 dB divergences when compared to the numerical models. A similar trend is observed in the 6-floor scenario, further highlighting the consistent sub estimation of vibration levels by the FTA model relative to the numerical predictions.

Nevertheless, the FTA manual suggests, for light-weight buildings, an adjustment of +3 to +6 dB when predicting indoor vibration levels from outdoor data. Thus, considering scenarios I, II and III as light-weight buildings, this adjustment is not implemented in Scenario V, resulting in a more pronounced difference.

Nonetheless, both approaches indicate that buildings located 20 meters from the tramway would not experience significant impacts from railway-induced vibrations. According to Table 2.1, the predicted vibration levels remains well below the human perception threshold of 65 dB. Although there are discrepancies between the models analyzed, both approaches consistently indicate that the building's response to these vibrations would be imperceptible to the occupants.

5.3.1 Ground-borne noise response

For the calculation of the ground-borne noise response, it was implemented the FTA method for both numerical and empirical approaches. The projected floor vibration is used to estimate the levels of ground-borne noise. The primary factors affecting noise level are the average vibration level of the room surfaces and the amount of acoustical absorption within the room. The radiation adjustment is -5 dB for typical rooms, which gives the equation 5.1.

$$L_A \approx L_v + K_{A-\text{wt}} - 5 \tag{5.1}$$

where:

- L_A = A-weighted sound level in a 1/3-octave band
- L_v = rms vibration velocity level in that band
- $K_{A-\text{wt}}$ = A-weighting adjustment at the 1/3-octave band center frequency

Configuration		FEM		FTA
		Method I	**Method II**	
2 floors	**Scenario I**	4.8 dB	7.4 dB	-7.7 dB
	Scenario II	0.5 dB	3.2 dB	
4 floors	**Scenario III**	-3.2 dB	-0.6 dB	-13 dB
	Scenario IV	-4.2 dB	-1 dB	-15 dB
6 floors	**Scenario V**	-6.8 dB	-3.8 dB	

Table 5.2: Ground-borne vibration noise prediction.

Given that the predicted vibration levels are below 65 dB, both approaches indicate that, for a building located 20 meters from the tramway, the ground-borne noise levels would be below the threshold of perception for most occupants. The noise responses of each building structure are given in Table 5.2. Thus, the most sensitive scenario is the building configuration with two floors and one span. However, even in this case, the noise levels remain below the threshold for human perception, as outlined in the FTA manual.

We observed that tram-induced ground vibrations, despite occurring within 20 meters of the track—well within the screening distance defined by FTA manual - specified in the Appendix C —, remain below the threshold of human perception. This phenomenon is particularly noteworthy given the proximity to the track, typically considered a sensitive distance. The likely explanation for this low vibration output lies in the flat topography of the site and the straight alignment of the tram line, both of which are known to reduce vibration levels. To explore more critical scenarios, we analyzed data from the RIVAS project in Germany, which involved measurements of ground vibrations generated by a passenger train, recorded at a distance of 8 meters from the track. This data is applied as input in a 6 story structure. The results are in the Appendix B.

In this context, it is crucial to assess the accuracy of the models used to predict the responses of the scenarios under consideration, specifically the 2D Finite Element Method (FEM) and empirical methods. While a 3D model would generally offer more realistic estimations, a 2D approach was adopted to reduce computational costs. However, this simplification may omit certain 3D physical effects that are important for accurate predictions. Nevertheless, the 2D approach can still produce reasonably accurate results within certain limits. The results indicate that the 2D FEM model is more reliable than the empirical method because it is based on a generalized model that, although restrictive to certain factors, accounts for more specific physical phenomena. For example, the empirical method's assumption regarding the attenuation per floor is based on generalizations that may vary depending on the materials used in the structure, and it does not account for the variable span of the building.

On the other hand, the 2D FEM model also has limitations and cannot be fully relied upon for several reasons. For instance, the model assumes a rigid foundation, which does not accurately reflect a realistic scenario. A rigid foundation provides lower damping, resulting in higher transmission of vibrations to the structure. This creates a trade-off between the empirical and numerical 2D FEM approaches.

CHAPTER 6

Final remarks

6.1 Conclusions

The issue of building vibrations induced by railway traffic necessitates careful study during the project planning and development phases. In this context, fast-running methods are valuable tools for quickly assessing building vibrations across multiple scenarios. In this work, a simplified FEM method is presented to achieve this objective and then it is compared to the empirical model developed by the Federal Transit Administration of U.S. (FTA).

The FEM model incorporates a soil-structure interaction (SSI) to simulate the dynamic response of buildings subjected to ground-induced vibrations from railway traffic. By employing a 2D frame structure and incorporating a spring-damper system to simulate the SSI, the model captures the essential dynamics of building vibrations. Thus, based on the work of López-Mendoza et al [18]. and Auersch [22], the comparative analysis of stiffness and damping calculations has provided insights into the influence of these factors on each scenario to predict vibration levels in the receiver floors.

In Scenario I, Method I predicts a higher level of foundation attenuation, especially at lower frequencies. In both methods, an important dip in the foundation response appears at 160 Hz. Method I leads to a lower floor resonance peak at 34.5 Hz when compared to Method II. Then, the global vibration level in the receiver floor when applying method II, is around 1 dB higher than the method proposed by López-Mendoza et al.

This trend continues in Scenario II, where Method II shows higher floor amplification and lower foundation attenuation in the analysed frequency domain. In Scenario III, Method I again estimates greater foundation attenuation, with the Auersch approach yielding a similar floor response.

In more complex structural scenarios, such as Scenario IV, a distinct behavior in the floor response is observed, particularly at lower frequencies, with the global system output showing a discrepancy of approximately 4 dB in floor vibration response. In the scenario involving six spans and six floors, the method proposed by López-Mendoza et al. predicts a lower floor response while indicating higher foundation attenuation. The overall system response in this scenario is approximately 4 dB lower compared to that estimated by Method II.

It can be observed that the choice of method can influence, with relevant difference in the results depending on the scenario. For example, when comparing the global floor responses of scenario III structure, the discrepancy between the methods is the order of 1 dB. In scenario V the difference in global floor response is approximately 4 dB.

However, when comparing the results from the simplified 2D FEM with those from the FTA empirical model, significant discrepancies are evident. These differences can be attributed to several factors. The FTA model is based on statistical analysis and data-driven insights derived from real-world measurements, which may not account for the specific characteristics of each scenario. In contrast, the simplified 2D FEM method has limitations that must be considered. Due to its two-dimensional nature, it does not incorporate physical parameters critical in the third dimension, such as additional damping and stiffness, which play a crucial role in accurately predicting a building's response to vibration. Additionally, the assumption of a rigid foundation, where the building and foundation move as a single unit during vibrations, results in lower damping and more pronounced vibrations.

Nevertheless, the proposed methodology offers significant computational savings compared to numerical approaches that require solving the entire modeling domain for each individual train passage. An advantage of this method is that it utilizes real-world measured data as input excitation, making it particularly useful for predicting the response of a structure that will be located at the site where the measurements were taken. By accurately incorporating soil properties and structural parameters, the output can serve as a valuable complementary tool for prediction.

6.2 Future work

To address the accuracy issues encountered in this study, we propose the implementation of alternative approaches. As previously discussed, the current method's advantage lies in its computational efficiency, particularly because it operates within a 2D framework. However, to improve prediction accuracy, especially in real-world applications, future work should consider incorporating flexible foundation models, which can introduce additional damping through soil-structure interaction, better replicating real-world conditions. While the existing method is computationally efficient, it does not fully account for the complexities of three-dimensional interactions and the intricate behaviors of real-world structures. Therefore, developing and implementing 3D FEM models should be a priority for future research, as these models would enhance the accuracy of predictions, particularly for complex building geometries and soil-structure interactions. Additionally, the current use of a standard spring-damper system for representing soil-structure interaction (SSI) could be expanded by exploring alternative damping mechanisms, such as viscoelastic or nonlinear damping models, to capture the complex behaviors observed in structures under dynamic loading more effectively.

Moreover, advanced techniques could further enhance prediction accuracy. One promising approach is the implementation of the Spectrum Element Method (SEM) in analyzing building responses to ground vibrations. SEM's ability to model complex wave propagation through heterogeneous materials, including layered soils and structural components, would provide a more detailed understanding of how vibrations are transmitted and amplified within buildings, potentially leading to more accurate and reliable predictions.

As a final recommendation, it is crucial to validate the predictive models used in this study by conducting in-situ measurements once the building is constructed. Given that this research was specifically aimed at estimating the vibration response of a building situated 20 meters from a tramway, obtaining real-world data after the building's completion will be essential. These measurements should be directly compared with the predicted results to assess the accuracy and reliability of the model. Such a comparative analysis will not only validate the current approach but also provide valuable insights for refining future predictive models and enhancing their applicability in similar contexts.

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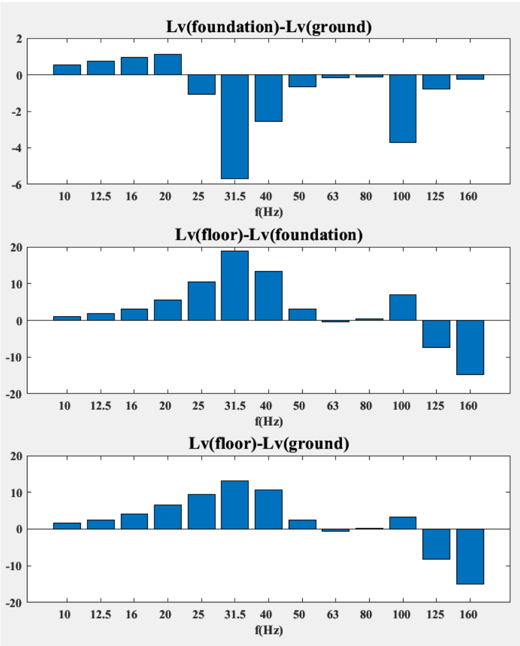
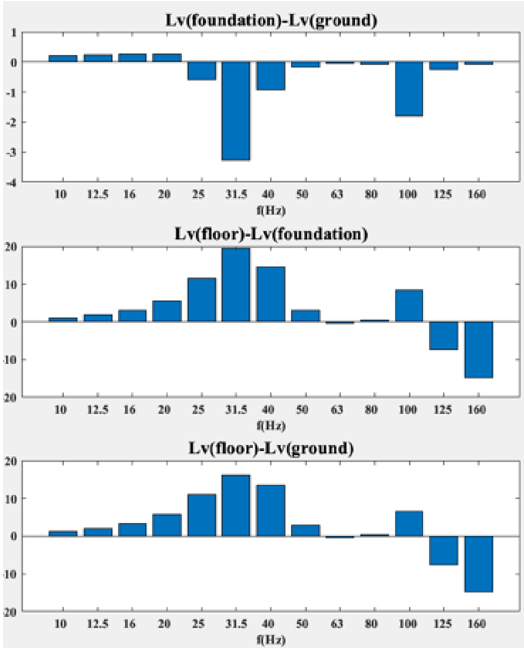
Appendix

A

Scenario I



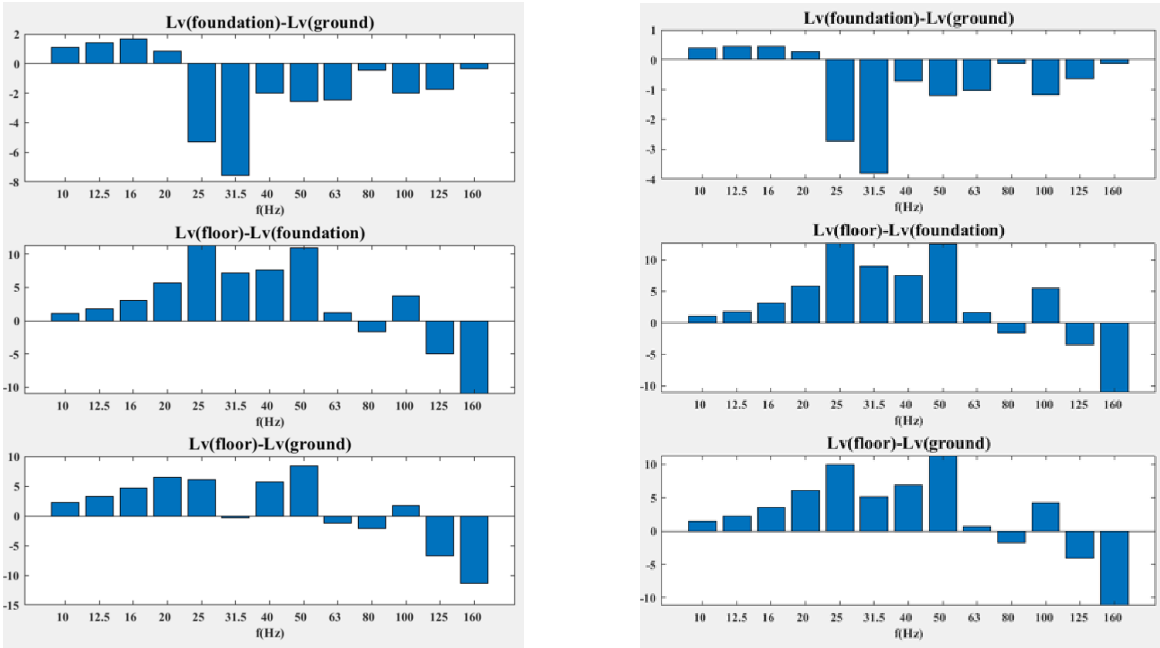
(a) Method I



(b) Method II

Figure 1: Structure components response on scenario I.

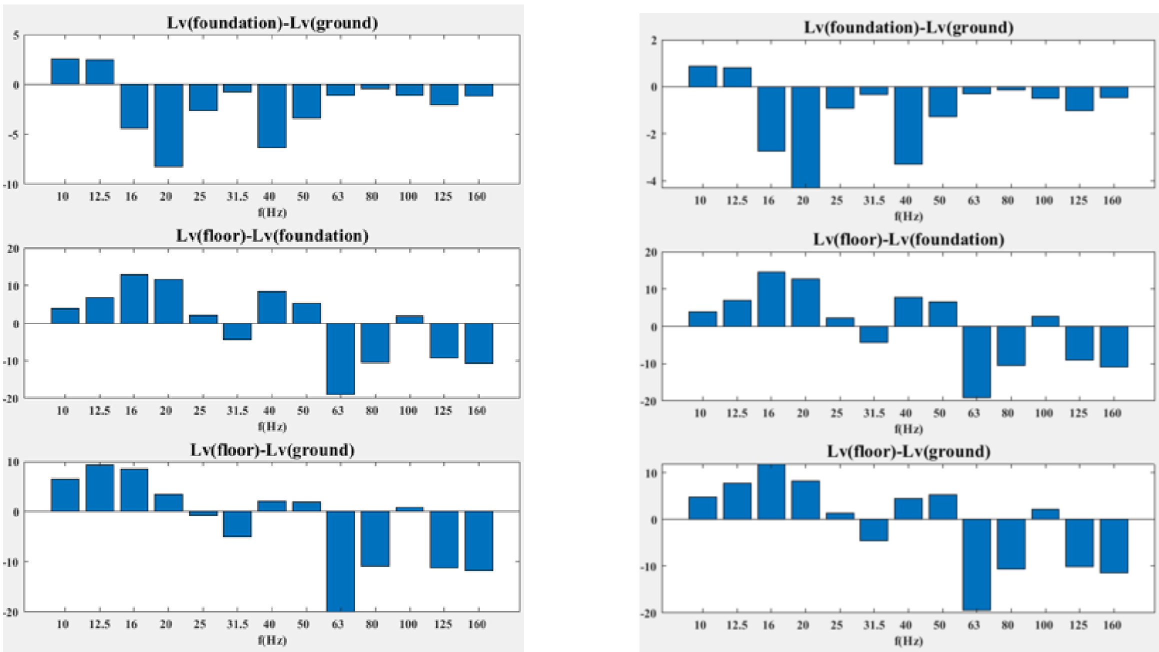
Scenario II



(a) Method I (b) Method II

Figure 2: Structure components response on scenario II.

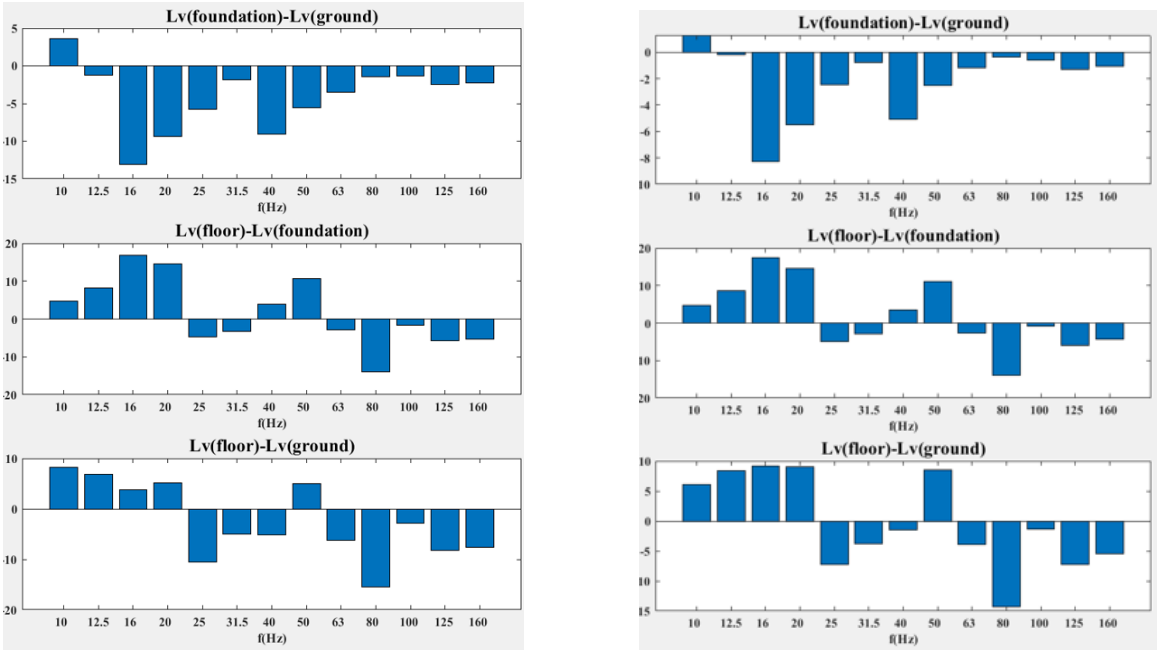
Scenario III



(a) Method I (b) Method II

Figure 3: Structure components response on scenario III.

Scenario IV

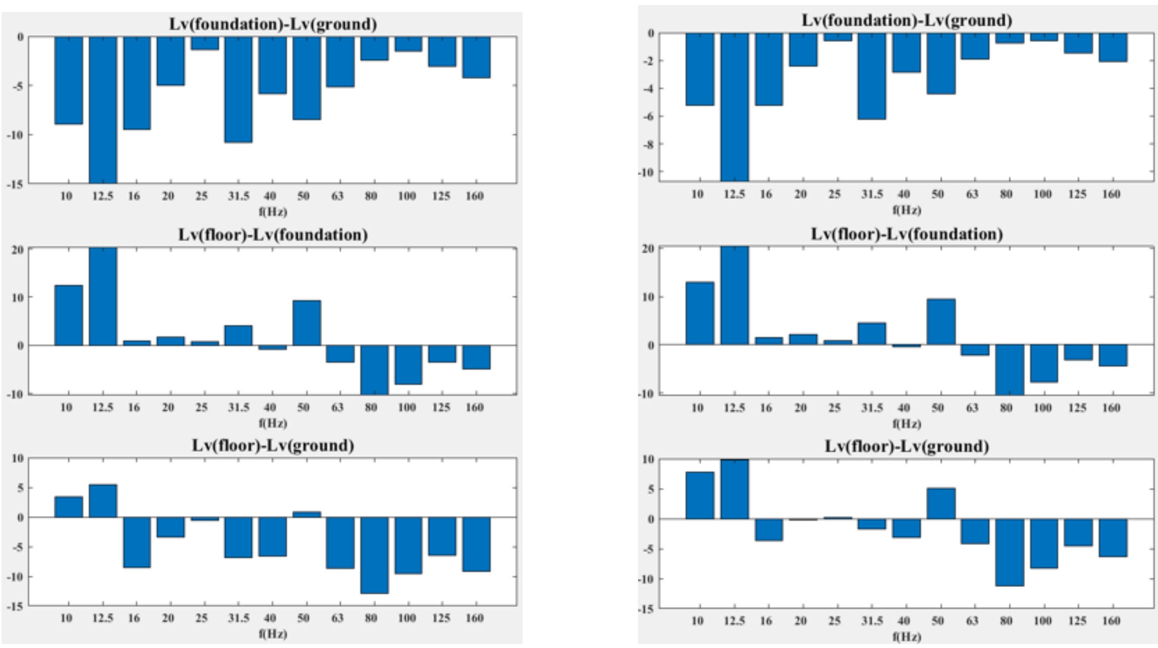


(a) Method I

(b) Method II

Figure 4: Structure components response on scenario IV.

Scenario V



(a) Method I

(b) Method II

Figure 5: Structure components response on scenario V.

B

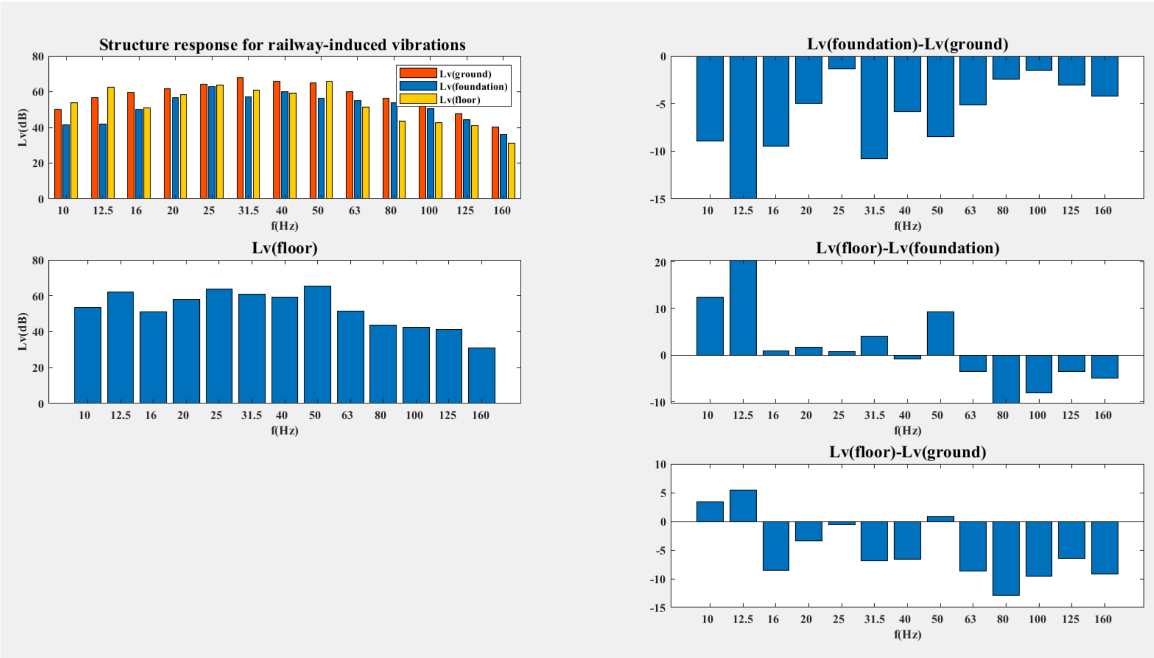


Figure 6: Structure response on frequency domain of a 6 floors and 6 spans building located 8 meters from a train track.

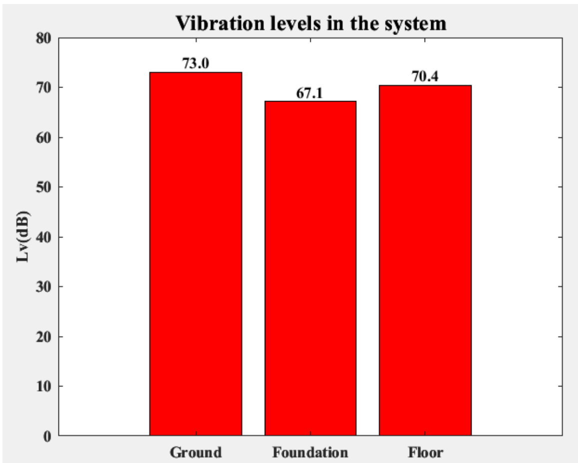


Figure 7: Global response of the structure when submitted a train-induced vibration

C

Table 6-3 Indoor Ground-Borne Vibration (GBV) and Ground-Borne Noise (GBN) Impact Criteria for General Vibration Assessment

Land Use Category	GBV Impact Levels (VdB re 1 micro-inch /sec)			GBN Impact Levels (dBA re 20 micro Pascals)		
	Frequent Events	Occasional Events	Infrequent Events	Frequent Events	Occasional Events	Infrequent Events
Category 1: Buildings where vibration would interfere with interior operations.	65 VdB*	65 VdB*	65 VdB*	N/A**	N/A**	N/A**
Category 2: Residences and buildings where people normally sleep.	72 VdB	75 VdB	80 VdB	35 dBA	38 dBA	43 dBA
Category 3: Institutional land uses with primarily daytime use.	75 VdB	78 VdB	83 VdB	40 dBA	43 dBA	48 dBA

* This criterion limit is based on levels that are acceptable for most moderately sensitive equipment such as optical microscopes. For equipment that is more sensitive, a Detailed Vibration Analysis must be performed.
** Vibration-sensitive equipment is generally not sensitive to ground-borne noise; however, the manufacturer's specifications should be reviewed for acoustic and vibration sensitivity.

Figure 8: Criteria for ground-borne vibration and noise for special land uses

Table 6-7 Project Types for Vibration Screening Procedure

Project Type Number	Project Type	Description
1	Conventional Commuter Railroad	Both locomotives and passenger vehicles create vibration. For commuter trains, the highest vibration levels are typically created by the locomotives. Electric commuter rail vehicles create levels of ground-borne vibration that are comparable to electric rapid transit vehicles.
2	RRT	Ground-borne vibration impact from rapid transit trains is one of the major environmental issues for new systems. Ground-borne vibration is usually a major concern for subway operations. It is less common for at-grade and elevated rapid transit lines to create intrusive ground-borne vibration and noise since air-borne noise typically dominates.
3	LRT and Streetcars	The ground-borne vibration characteristics of light rail systems are very similar to those of rapid transit systems. Because the speeds of light rail systems are usually lower, typical vibration levels are usually lower. Steel-wheel/steel-rail AGT is included in either this category or the ICT category depending on the level of service and train speeds.
4	Intermediate Capacity Transit	Because of the low operating speeds of most ICT systems, vibration problems are not common. However, steel-wheel ICT systems that operate close to* vibration-sensitive buildings have the potential of causing intrusive vibration. With a stiff suspension system, an ICT system could create intrusive vibration.
5	Bus and Rubber-Tire Transit Projects	This category encompasses most projects that do not include steel-wheel trains of some type. Examples include diesel buses, electric trolley buses, and rubber-tired people movers. Most projects that do not include steel-wheel trains do not cause vibration impacts.**

Figure 9: Definition of the types of transport vehicles

Table 6-8 Screening Distances for Vibration Assessments

Type of Project	Critical Distance for Land Use Categories*		
	Distance from ROW or Property Line, ft		
	Land Use Cat. 1	Land Use Cat. 2	Land Use Cat. 3
Conventional Commuter Railroad	600	200	120
RRT	600	200	120
LRT and Streetcars	450	150	100
ICT	200	100	50
Bus Projects (if not previously screened out)	100	50	--

Figure 10: Critical distances in ft according to the type of project