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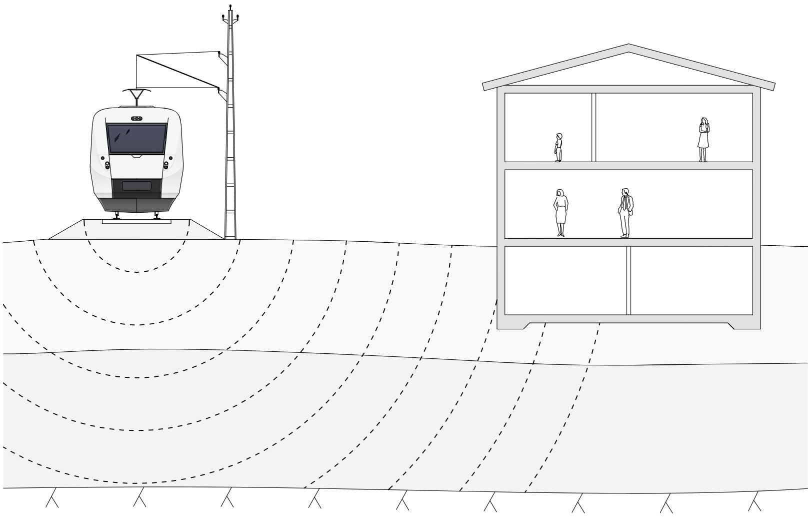

PREDICTING RAILWAY-INDUCED GROUND VIBRATIONS

NILS PERSSON

Structural Mechanics

Master's Dissertation

DEPARTMENT OF CONSTRUCTION SCIENCES

DIVISION OF STRUCTURAL MECHANICS

ISRN LUTVDG/TVSM--16/5212--SE (1-67) | ISSN 0281-6679

MASTER'S DISSERTATION

PREDICTING RAILWAY-INDUCED GROUND VIBRATIONS

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Printed by Media-Tryck LU, Lund, Sweden, June 2016 *(Pl).*

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Abstract

Population growth and densification lead to growing urban environments. Unbuilt land within cities can be used to construct residences and other facilities. Population growth can further lead to a greater demand of transportation, which can require expansion of transportation systems such as railways or road traffic. Vibrations are one of the environmental problems associated with traffic in an urban environment. The vibrations can be considered a disturbance by humans and affect structures and the performance of sensitive equipment inside facilities. In this master's thesis, vibrations induced by railway traffic were studied. Railway-induced ground vibrations can be difficult to predict, since a considerable amount of mechanisms and phenomena are involved in the transmission process.

Measurements of vibrations from railway traffic were performed in the city of Lund, southern Sweden, using seismometers. The seismometers were placed at different distances from the track and the passages of different trains were recorded. Analysis of the measurements were done in both time domain and frequency domain which resulted in information about vibration levels and frequency content of the vibrations for different trains and different distances from the track.

Numerical simulations were carried out using the finite element method. Two-dimensional models were used to study the influence of different soil parameters and some effects of building design. Simulations that incorporated results from the measurements, by scaling the load applied in the model to the measured frequency response, were performed. The conclusions from the literature, measurements and numerical simulations were used to present some important aspects to predicting railway-induced ground vibrations.

Keywords: ground vibrations, railway, train, wave propagation, vibration measurements, finite element method, dynamics.

Sammanfattning

Städer växer och förtätas vilket gör att obebyggd mark kommer att användas i allt högre grad. En ökad befolkning kan leda till ett ökat transportbehov, vilket gör att transportsystem, såsom spår- och vägtrafik, kan behöva expanderas. Trafik genererar vibrationer som fortplantas i marken och sprids till närliggande byggnader. Vibrationer kan anses störande av människor som befinner sig i byggnaderna, men även störa driften av känslig utrustning. I det här examensarbetet studerades vibrationer från spårtrafik. Att förutsäga spårvibrationers påverkan kan vara svårt, då flertalet mekanismer och fenomen är inblandade i transmissionsprocessen.

Fältmätningar av vibrationer från tågtrafik utfördes i södra Lund, Skåne, med hjälp av seismometrar. Seismometrarna placerades på olika avstånd från järnvägsspåret och vibrationerna från passerande tåg registrerades. Analys av mätresultatet gjordes i både tids- och frekvensdomänen, vilket gav information om vibrationsnivåer och frekvensinnhåll för vibrationer från olika tåg och olika avstånd från spåret.

Numeriska simuleringar utfördes med hjälp av finita elementmetoden. Tvådimensionella modeller användes för att studera hur olika jordparametrar påverkar vibrationerna, samt för att undersöka inverkan av byggnadens utformning. Simuleringar kopplade till mätningarna gjordes genom att skala den pålagda lasten i modellen till den uppmätta frekvensresponsen. Slutsatser från litteratur, mätningar och numeriska simuleringar användes för att presentera några viktiga aspekter vid analys av vibrationer från spårtrafik.

Nyckelord: markvibrationer, järnväg, tåg, vågutbredning, vibrationsmätningar, finita elementmetoden, dynamik.

Preface

This master's thesis concludes my five years of studies at Lund University, Faculty of Engineering (LTH). The work was performed at the Division of Structural Mechanics in cooperation with Sweco.

I would like to express my gratitude to Prof. Kent Persson and my supervisor Ph.D. Peter Persson for coming up with the initial idea for this thesis and for always being available for discussions and assistance throughout the work. I would also like to thank the employees at Sweco, especially my supervisor Per Jørstad, for the opportunity of presenting my work and for help and valuable discussions during several meetings.

Finally, parts of this thesis would not have been possible without the help of Brian Norsk Jensen at the Max IV Laboratory, who generously allowed me to use the measurement equipment. I am also grateful to Peter Jonsson at Engineering Geology, LTH, for providing assistance with the instrumentation.

Lund, June 2016

Nils Persson

Contents

1. Introduction

1.1 Background

Population growth and urbanisation are factors contributing to growing urban environments. To accommodate an increasing population, unbuilt land within cities can be used to construct residences and other facilities, thus resulting in densification. An increasing population can also lead to a greater demand of transportation. New methods of transportation such as tramway systems can be constructed, and expansion of existing systems such as railways or road traffic can be necessary.

Vibrations are one of the environmental problems associated with traffic in an urban environment. In this master's thesis, vibrations induced by railway traffic and their effects on buildings are studied. The vibrations can be considered a disturbance by occupants of buildings, but can also affect structures and the performance of sensitive equipment inside facilities.

When planning new buildings near railway traffic or making changes to existing railways, the vibrations need to be analysed. It is beneficial if the vibration levels can be assessed even at an early stage of planning, to state requirements for the building in order to avoid having to make costly changes at latter stages. Currently, there are no building codes, such as a Eurocode, that must be followed when analysing vibrations induced by railway traffic. Some prediction models have been developed by groups or individuals, and advances in computing power have led to the ability of using more advanced computer simulations. There is however still an interest of obtaining more knowledge in the area and to develop new prediction models or strategies for analysing vibrations induced by railway traffic.

1.2 Objective and method

Vibrations induced by railway traffic are studied in this master's thesis. The aim is partly to obtain more knowledge of the vibrations induced by railway traffic and their characteristics. In the long term, it is of interest to develop a strategy that can be used when analysing vibrations in nearby buildings.

Railway-induced ground vibrations will be studied using primarily three main approaches. Firstly, available literature and previous work in the area will be reviewed. Secondly, field measurements of vibrations in the ground near a railway will be performed. Finally, numerical calculations in the context of ground vibrations will be carried out using the finite element method. Conclusions from literature, measurements and numerical simulations will be used to present some important aspects when predicting railway-induced vibrations. These aspects can be part of a broader strategy or prediction model for railway-induced vibrations in buildings.

1.3 Outline

The thesis comprises six chapters, each containing the following:

- Chapter 1 contains the background information, the objective of the thesis and the methods used, and outlines the content of the thesis.
- Chapter 2 gives an overview of railway-induced ground vibrations. Some fundamental theory regarding ground vibrations is described, necessary to then detail the transmission process for railway-induced ground vibrations. Effects of vibrations and vibration-reduction methods are discussed, and some prediction models are reviewed.
- Chapter 3 contains theory of structural dynamics.
- Chapter 4 presents the field measurements in the form of the method and equipment used and the results acquired.
- Chapter 5 contains the numerical simulations performed.
- Chapter 6 presents conclusions from measurements and numerical simulations and suggests ideas for further work.

2. Railway-induced ground vibrations

The term ground vibration usually refers to vibration, caused by man-made activities, that uses the ground as transmission medium. This is in contrast to natural vibrations, such as earthquakes and other seismic events. Ground-borne vibration does not necessarily have to pose any problems to the ground itself. The ground can simply be a path, leading the vibration to nearby buildings.

Examples of ground vibration sources are explosions, construction activities and traffic. In this thesis, the focus lies on vibrations induced by railway traffic, illustrated in Figure 2.1. The study of railway-induced vibration has become more important in recent years due to a greater awareness of the environmental problems associated with vibrations combined with the introduction of high-speed trains. This chapter details some fundamental theory regarding ground vibrations and further describes the transmission process for railway-induced ground vibrations. Effects of vibrations are discussed, different vibration-reduction measures are presented and some prediction models for railway-induced ground vibration are reviewed.

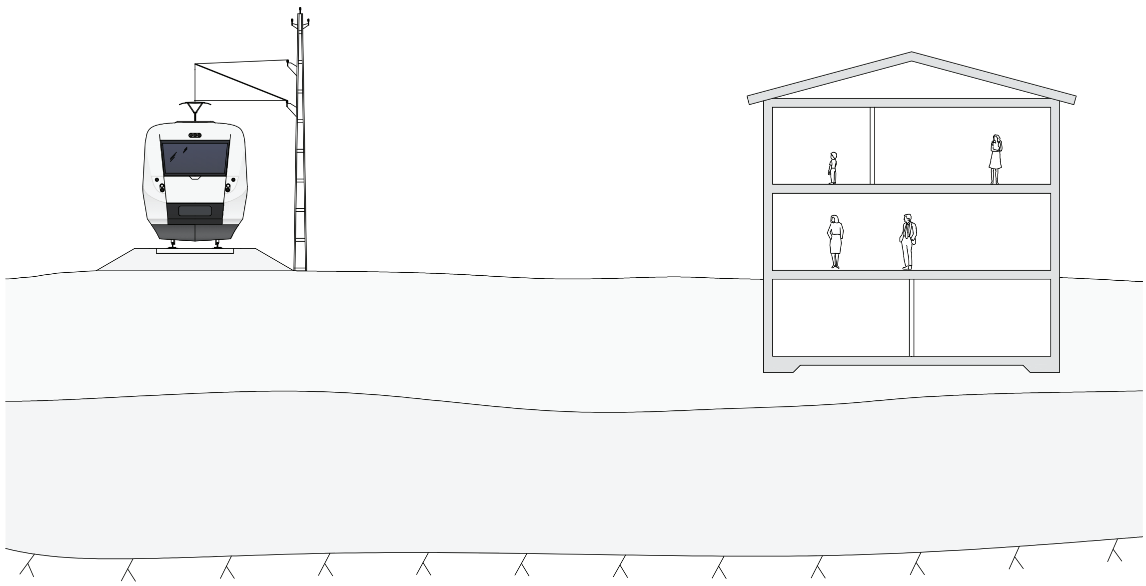


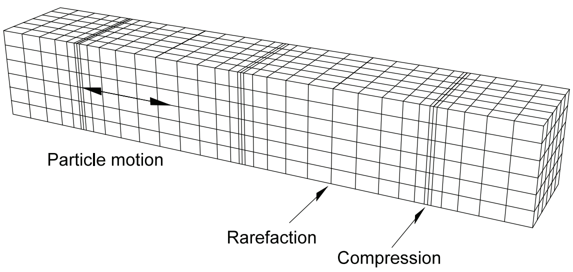
Figure 2.1: An overview of railway-induced ground vibrations.

2.1 Fundamentals of ground vibrations

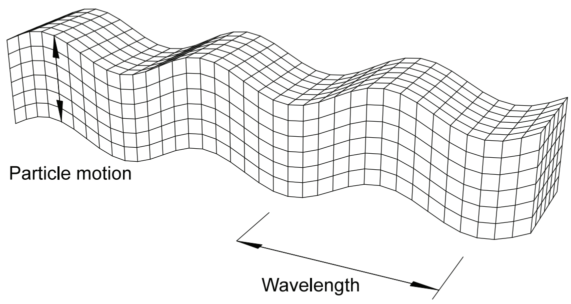
Vibrations in the ground travel using different types of mechanical waves. In soil dynamics, the study of wave propagation is therefore important. In this section, the different wave types relevant to ground vibrations will be described along with phenomena that affect the propagation of waves. Since the characteristics of the propagating waves are highly material dependent, dynamic soil properties will be discussed.

2.1.1 Wave types

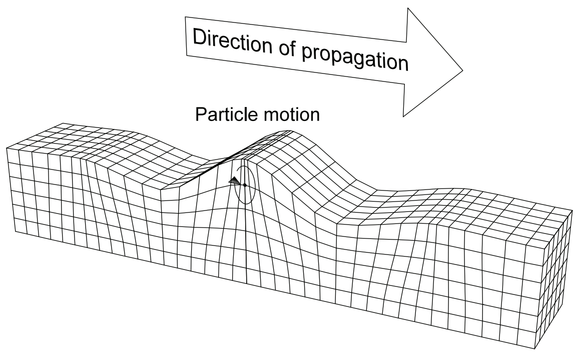
The two most basic types of wave motion in a solid medium are the body waves; pressure waves (P-waves) and shear waves (S-waves). P-waves give rise to compressions and rarefactions that spread through the medium. The particles displace parallell to the direction of the wave propagation as shown in Figure 2.2a. With S-waves, the particles instead displace perpendicular to the direction of travel, as illustrated in Figure 2.2b. S-waves can have two components, one vertical and one horizontal in the direction perpendicular to the wave propagation.



(a) P-wave.



(b) S-wave.



(c) R-wave.

Figure 2.2: The three main wave types relevant to ground vibrations.

To calculate the speed in which the body waves propagate through a solid medium, the material quantities known as the Lamé parameters λ and μ can be utilised. The first and second Lamé parameter, respectively, are given by

$$\lambda = \frac{\nu E}{(1+\nu)(1-2\nu)} \qquad \mu = \frac{E}{2(1+\nu)} \tag{2.1}$$

where E is the Young's modulus and ν is the Poisson's ratio. In the context of elasticity, the second parameter μ is known as the shear modulus, often denoted as G. The wave speeds for P- and S-waves, c_P and c_S respectively, are calculated using

$$c_P = \sqrt{\frac{\lambda + 2\mu}{\rho}} \qquad c_S = \sqrt{\frac{\mu}{\rho}} \tag{2.2}$$

where ρ is the density of the material.

At the surface of a medium, interaction between the two body waves and the surface itself can result in other types of wave motion. Especially important is the Rayleigh wave (R-wave), described by Lord Rayleigh in 1885 [41]. In isotropic solids, the individual particles move in ellipses parallell to the direction of propagation, as illustrated in Figure 2.2c. Rayleigh waves behave similar to (but are not the same as) the ripples produced from impact on a water surface.

The R-wave speed can be approximated using the following analytical expression, as proposed by Bergmann [5]

$$c_R = \frac{0.87 + 1.12\nu}{1+\nu} c_S \tag{2.3}$$

where ν is the Poisson's ratio and c_S is the S-wave speed. According to [40], the above equation is accurate for values of $0<\nu<0.5$, a range that is valid for soils. The equation further shows that the R-wave speed is very close to, but slightly lower than, the S-wave velocity in the same material. In the range $0<\nu<0.5$, the R-wave speed varies between $0.87c_S$ and $0.95c_S$.

Although more important in the field of seismology, the Love wave is another type of surface wave, named after Augustus Edward Hough Love [30]. It is characterised by horizontal motion at the surface, but since it is of minor importance in terms of man-made vibrations it will not be discussed further.

2.1.2 Wave propagation phenomena

After a generation of vibration at the source, the propagation of waves begins. Wave propagation is usually a three-dimensional problem, since waves can propagate in many directions, but it is limited by the fact that the ground has a surface. In mathematical models, this type of geometry is commonly referred to as a half-space. There are several phenomena that affect the general characteristics of the propagating waves in a half-space, some of them will be discussed in this section.

Geometrical attenuation

When waves are radiated from a source, the vibrations tend to decay as the distance from the source increases. The decay is partly due to geometrical attenuation, i.e. the wavefront spreads over a larger area as the distance from the source increases, resulting in a decrease in intensity. Body waves and surface waves behave differently in regards to the geometrical attenuation, as illustrated for a point source in Figure 2.3. Body waves spread in all directions in the ground and therefore experience greater geometrical attenuation compared to surface waves.

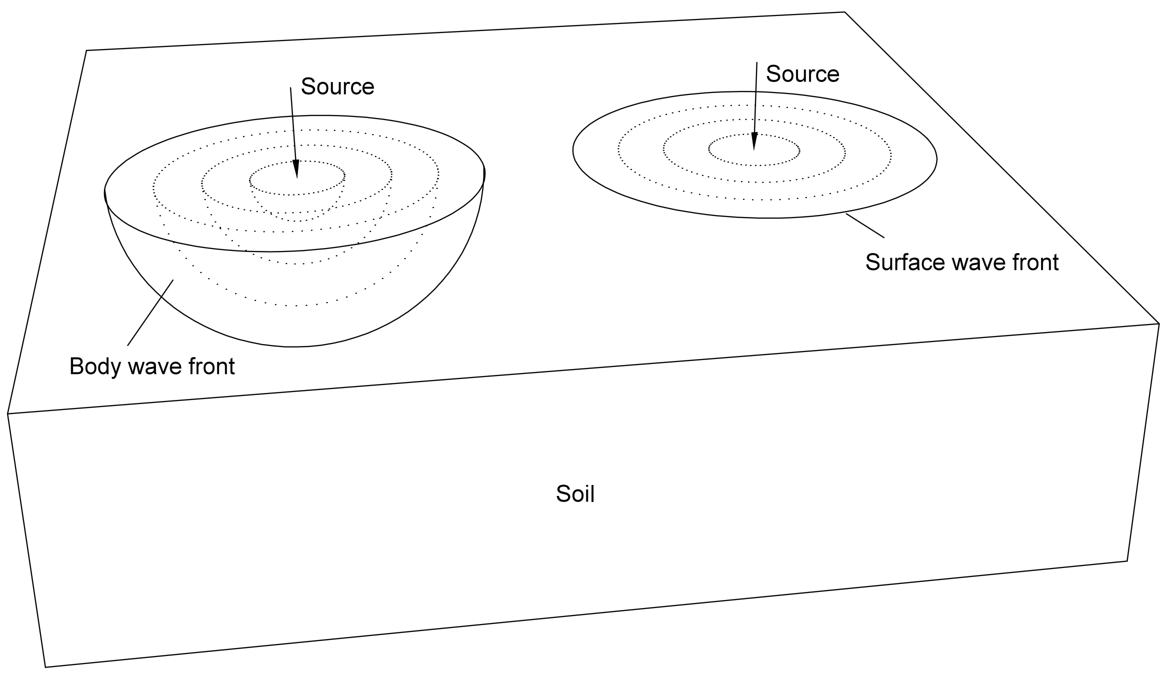


Figure 2.3: Geometrical attenuation for body waves (left) and surface waves (right).

Reflection and refraction

The ground in which the waves propagate is often composed of one or more layers of soil on top of bedrock. When a wavefront encounters an interface between two materials, it experiences reflection and refraction, as illustrated in Figure 2.4. Some waves are propagated back (reflected) and some continue in the new material (refracted). The amplitudes and angles of the reflected and refracted waves are dependent on the angle of incidence as well as the impedances of the two materials, with impedance, Z, being defined as the density multiplied by the wave speed, $Z = \rho c$.

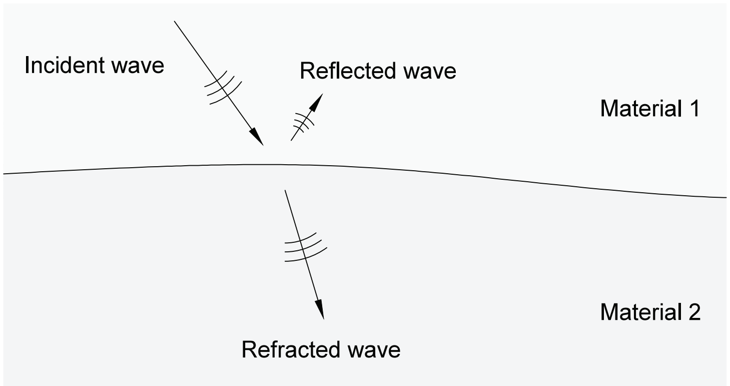


Figure 2.4: Reflection and refraction of a wave.

2.1.3 Dynamic properties of soil

The propagation of waves in the ground is highly dependent on the soil conditions. In this section, some soil properties relevant to dynamic problems will be discussed.

Constitutive relations

To describe the soil material in mathematical models, the stress-strain relation is an important measure. The elastic modulus, E, is the gradient of the stress strain curve and for a linear elastic material this takes a constant value. Soil is in reality not a linear elastic material. If strains are large, for example during earthquakes, plasticity can not be neglected. However, when dealing with small strains, a linear elastic material model can be sufficient, which is typically the case for man-made vibrations. For railway-induced ground vibrations, deformations can be non-linear at certain points, for instance just below or very close to the track, but it does not have a marked effect at distances further away from the source [28].

Homogeneity

Soil is a granular material, composed of individual particles, and in reality not a solid. With increasing depths, soils generally become gradually more compressed and stiffer. The ground can further consist of several layers of soil with different properties. Moreover, some soils can contain a great variety of particle sizes. Till is a common soil type in Sweden, as a result of deposits and erosion from moving glacial ice. It can contain a mixture of clays, sand, gravels and boulders.

Numerical models and calculations are simplified greatly if a solid homogeneous material can be assumed. In soil dynamics, this assumption can be used if the heterogeneities are small compared to the wavelengths of the waves. For railway-induced ground vibrations, mainly low frequencies are of interest. As an example, the shear wave speeds of many soils are often above 100 m/s. For a frequency of 50 Hz, this results in a wavelength of 2 m, which generally is much larger than the individual particles and their variation, thus a homogeneous material can be assumed.

Damping

Apart from geometrical attenuation, another factor contributing to decay of vibrations is energy loss in the soil. When soil vibrates, energy is dissipated for instance due to friction between the individual soil particles. The loss factor, η, can be used to described damping in soil, where an energy loss is assumed during a cycle of oscillation. The loss factor can be calculated according to

$$\eta = \frac{1}{2\pi}\frac{E_D}{E_S} \tag{2.4}$$

where E_D is the energy dissipated due to viscous damping in one cycle of motion, and E_S the strain energy. For a single degree of freedom system, oscillating at the angular frequency ω, the energy dissipated is defined as

$$E_D = \pi c \omega u^2 \tag{2.5}$$

where c is the viscous damping constant. Furthermore, the strain energy is given by

$$E_S = ku^2/2 \tag{2.6}$$

where k is the stiffness, resulting in

$$\eta = \frac{1}{2\pi}\frac{\pi c \omega u^2}{ku^2/2} = \frac{c\omega}{k} \tag{2.7}$$

2.2 Transmission process

The analysis of railway-induced ground vibration is complicated by the vast amount of factors involved, all the way from the initial generation to the receiver. To grasp the complexity of the problem, the complete transmission process needs to be understood. A graphical illustration of this process is shown in Figure 2.5.

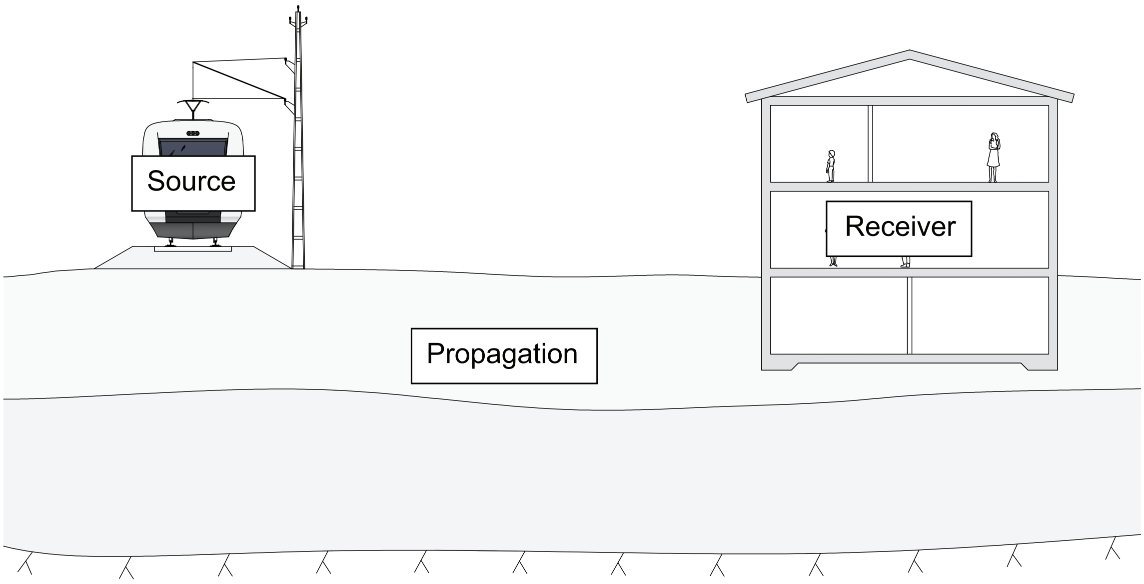


Figure 2.5: Transmission process for railway-induced ground vibrations.

Due to the rather extensive nature of the problem, it can be helpful to divide the process into different stages or regions. The first stage is the *source* where the vibrations are generated, followed by the region of *propagation* where vibrations are transferred and finally the *receiver*, usually a building. Each stage has its own properties and parameters that affect the overall vibration levels. Although the three stages function as a sequence, it can sometimes be helpful to study each stage separately, for instance when designing vibration-reduction measures.

2.2.1 Source

The first stage of the transmission process is the source where the vibrations are generated. The source region can include train, track structure, supporting structure and immediate surrounding soil, all of which play a part in the initial generation of vibration. After the source generation, vibrations are transferred through the track structure, shown in Figure 2.6, and into the ground. The source can be very complicated to describe and measure, since it involves many phenomena and interactions. According to Madshus et al. [31], measurements have shown that railway-induced vibrations are stochastic in nature.

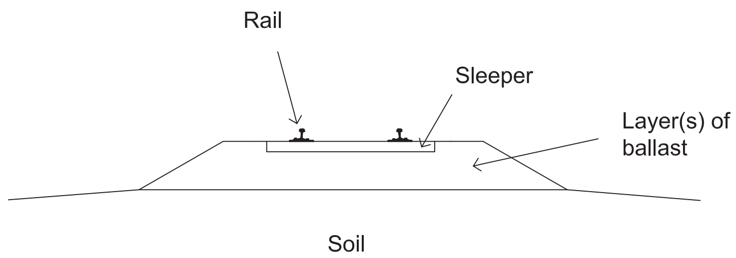


Figure 2.6: A schematic illustration of a typical railway track structure.

There are several mechanisms related to the generation of vibration. The underlying cause is the train in motion, with each wheel-axle acting as a moving load on the track. Contact between the train wheels and the rail combined with various types of irregularities in the wheels and track structure further result in dynamic excitations. Additionally, if the train speed exceeds certain critical velocities, an even further increase in vibrations can be observed.

Moving load response

When a train travels along a railway it will, due to its weight, exert a pressure on the track. The load from each wheel axle causes a downward deflection of the track that moves along the railway as the train passes. As such, the displacement at a fixed point will be time-varying. Apart from axle-weight and spacing between axles, the response in the surrounding soil for a moving load highly depends on the speed of which the load, in this case a train, travels relative to the wave speeds of the soil. Measurements have shown that vibrations generally increase with train speed [10]. There are, however, phenomena related specifically to high-speed trains that can have a big influence on the overall vibration levels. According to Krylov et al. [26], there are two critical velocities related to the track and soil system. The first critical velocity is train speeds exceeding the Rayleigh wave speed in the soil. The phenomenon is comparable to aircrafts breaking the sound barrier, resulting in a sonic boom, and a large increase in vibrations can be expected. Figure 2.7 shows the response in a soil subjected to a moving load with a speed below and above than the Rayleigh wave speed, respectively. For speeds lower than the Rayleigh wave speed, the response is quasi-static. In the case of exceeding the Rayleigh wave speed, a Mach cone is formed around the load, producing propagating waves.

The phenomenon of exceeding the Rayleigh wave speed has for example been observed in measurements at Ledsgård, Sweden [32], where the ground consisted of very soft clays. Train speeds exceeding R-wave speeds generally require high-speed trains in combination with poor soil conditions. In extreme cases, according to Madshus, et al. [32], some very soft clays may have a Rayleigh wave velocity as low as 40–50 m/s (144–180 km/h). The R-wave speed can be estimated using Equation 2.3.

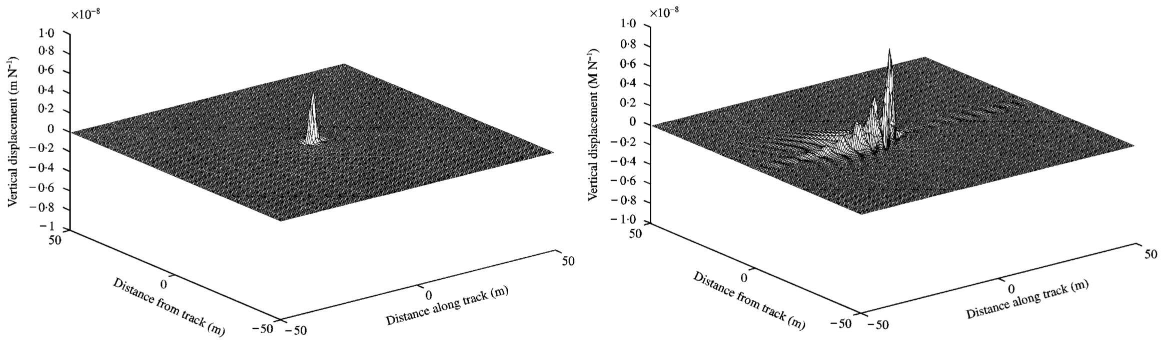


Figure 2.7: Vertical displacements in the soil for a concentrated force moving at a speed below the R-wave speed (left) and above the R-wave speed (right). From [42].

The second high-speed phenomenon is the minimum propagation speed of bending waves in the rail. Train speeds exceeding this velocity, referred to by Krylov et al. [26] as the track critical velocity, can result in further increased vibrations and even risk derailment. Krylov et al. further describe the track critical velocity as being normally 10–30% higher than the Rayleigh wave speed in the same ground, thus not a problem to the same extent as exceeding the Rayleigh wave speed. The track critical velocity can be derived from the equation of an infinite beam supported by an elastic foundation [26] and calculated as

$$c_{min} = \left(\frac{4kEI}{m^2}\right)^{1/4} \tag{2.8}$$

where k is the stiffness of the foundation, E the elastic modulus of the rail, I the moment of inertia of the rail and m the mass per unit length of the rail.

Dynamic excitations

If no imperfections within the source are assumed, the moving load effect described previously would be the sole contributor of vibrations. In reality, however, there are many irregularities in the train-track interaction that result dynamic excitations. ISO 14847 [19] and Hall [14] summarise several mechanisms. Hall further notes that many of these dynamic effects are of higher frequency and that these vibrations are not as common far away from the track.

Random irregularities, unevenness or roughness in the contact surfaces between wheel and rail cause forced excitations. Irregularities can occur already in manufacturing, but also develop during service life, for example due to corrugation. Wheel flats, which is a fault on the surface of the train wheel, is another excitation mechanism. Wheel flats are produced when a wheel is dragged along the rail while it has stopped rotating. It can be a result of slippery driving conditions, faulty brakes or emergency braking. Discontinuities along the rail, such as gaps at switches or rail joints (especially unwelded) can further lead to impact forces, which according to Heckl et al. [16] can generate a strong vibration excitation.

Parametric excitation is another important dynamic excitation mechanism causing vibrations. As the train wheel rolls over the rail, the load experiences small variations in support stiffness at the passage of each sleeper, resulting in periodical excitations at the sleeper passing frequency [46]. For high-speed trains this frequency is in the range relevant to ground-borne noise, and for lower speeds in the range relevant to vibrations [28]. As an example, a typical sleeper distance $d = 0.6$ m and a train speed $v = 300$ km/h results in a sleeper passage frequency $v/d = 139$ Hz. For a speed of 100 km/h, it is instead 46 Hz.

Train driving conditions in general can have an impact on the generation of vibrations, for example through braking and acceleration of the train, or the curvature of track. Furthermore, there are parameters within the train itself, for instance the suspension system, that affect the vibrations. Ultimately, there are many effects and parameters that affect the initial generation. The dynamic excitations are especially complicated to predict as they are random in nature.

2.2.2 Propagation

The second part of the transmission process for railway-induced vibrations is the region of propagation. The propagation region constitutes the ground profile, i.e. the layers of soil and bedrock, beneath and between the railway and receiving object. After the generation of vibration, the ground is set in motion. The vibrational energy is transferred through the soil using mainly three types of waves, namely the P-waves, S-waves and R-waves described in Section 2.1.1. The body waves (P- and S-waves) travel in all directions in the ground, and at the surface, R-waves occur. R-waves are important in the analysis of railway-induced vibrations, since when the area of the source is small compared to the propagation region, most energy will be transferred by them [16].

The magnitude of vibrations generally decay as the distance from the source increases. This is both a result of geometrical attenuation, as described in Section 2.1.2, and energy loss (damping) in the soil. R-waves suffer less geometric attenuation compared to P- and S-waves. As shown in Figure 2.8, vibrations do not necessarily have to travel using the shortest distance. Reflections and refractions at the interface between soil layers or between soil and bedrock are phenomena that can effect the propagation path. The reflections and refractions mean that there is a possibility of body waves taking different and perhaps improbable paths toward the receiver.

The propagation velocity of each wave type is governed by the soil conditions, in accordance with Equations 2.2 and 2.3 in Section 2.1.1. From these equations it can also be shown that P-waves travel faster than S-waves in the same material, since soils are stiffer in compression than in shear. R-wave speeds are slightly lower than S-wave speeds, by a factor of around 0.9 depending on the soil.

Compared to describing the source, it is simpler to describe the mechanisms regarding the propagation path. More research has been undertaken in the area of soil dynamics and it is generally a more straight-forward process. What complicates things however, since the wave propagation largely depends on the soil properties, is that the soil properties can vary greatly between, and even within, areas. Thus, predicting absolute vibration levels at a specific location can be difficult.

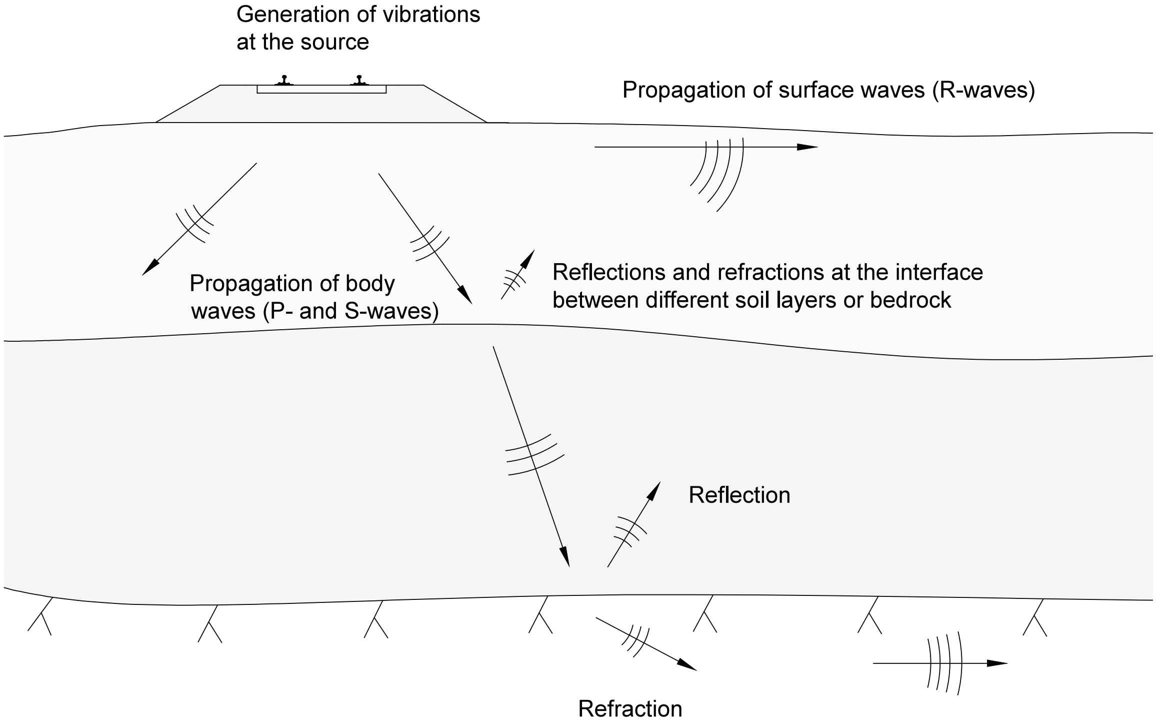


Figure 2.8: Illustration of the propagation process for ground vibrations.

2.2.3 Receiver

The third and final part of the transmission process for railway-induced vibrations is the receiver. The receiving region includes the building, its foundation and immediate surrounding soil. The vibrations are transferred from the soil at the foundation and are subsequently transmitted further in the building where they may be amplified and cause floors and walls to vibrate. The response in the building will vary depending on a number factors, such as the properties of the ground, foundation type, general geometry of the building, and the material in the structural system. Even the placement of furniture within the building can have an effect [10].

Important for the soil–structure interaction is the wavelength of the vibration in relation to the size of the footprint of the building. If the wavelength is long compared with the width of the building then the vibrations will cause only translational motion to the building [10]. Conversely, vibrations of shorter wavelengths will also introduce bending. Another important aspect is the natural frequencies of the building and of the individual elements in the framework such as the floor slabs. To excite a building at a resonance frequency it is however required that this specific frequency is present in the vibrations.

2.3 Effects of vibrations

After transmission through the receiving structure, vibrations will ultimately be perceived by the occupants inside the building. For humans, vibrations induced by railway traffic is mainly a comfort related problem. Vibrations can be considered disturbing and affect sleep patterns [35]. Since individuals perceive vibrations differently, the human response can be complex to describe. The human exposure to vibrations is detailed in ISO 2631-1 [17]. ISO 2631-1 suggests an evaluation of vibrations in terms of root mean square (RMS) values, unless substantial peaks (peak values 9 times the RMS value) are found in the signal. Vibrations in buildings are discussed in ISO 2631-2 [18], where the frequency range relevant to human perception is specified as 1–80 Hz.

The Swedish Transport Administration (Trafikverket) states guidelines for maximal vibration levels as weighted RMS values of velocity. For residential buildings this value is 0.4 mm/s [45]. The Swedish standard SS 460 4861 [43], which is based on ISO 2631-2, provides guidelines for comfort related assessments. Figure 2.9 shows the vibration guidelines as RMS velocity. Between velocities 0.4–1 mm/s, there is a risk of moderate disturbances, and above 1 mm/s, disturbances are likely.

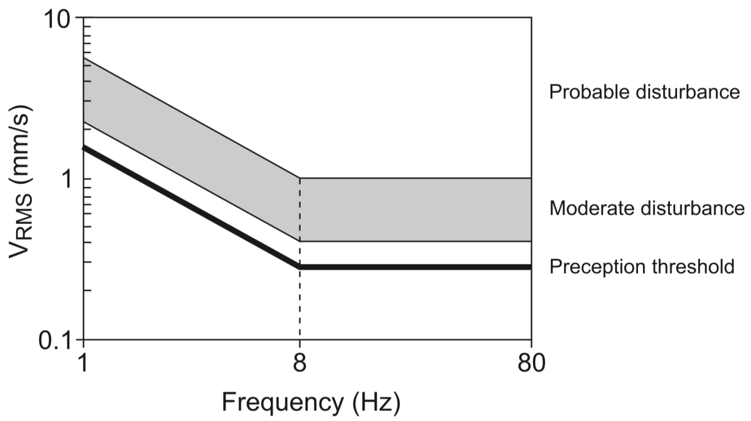


Figure 2.9: Vibration levels for perception threshold and disturbance. From [37].

Structural damage is typically not an issue in the case of railway-induced vibrations, as these vibrations are of relatively low magnitude. Some buildings can however be more sensitive to vibrations than others, for instance concert halls or facilities with sensitive equipment where the performance can be affected by vibrations. Advances in technology have led to devices, such as microscopes and other scientific instruments, with very strict vibrational requirements during operation. The vibrational requirements for these devices are usually far more strict than for human comfort. There are several standardised classes of sensitive equipment, in the form of vibration criterion (VC) curves, that can provide general guidance. The VC-curves are seen in Figure 2.10, which also includes ISO guidelines for people in buildings.

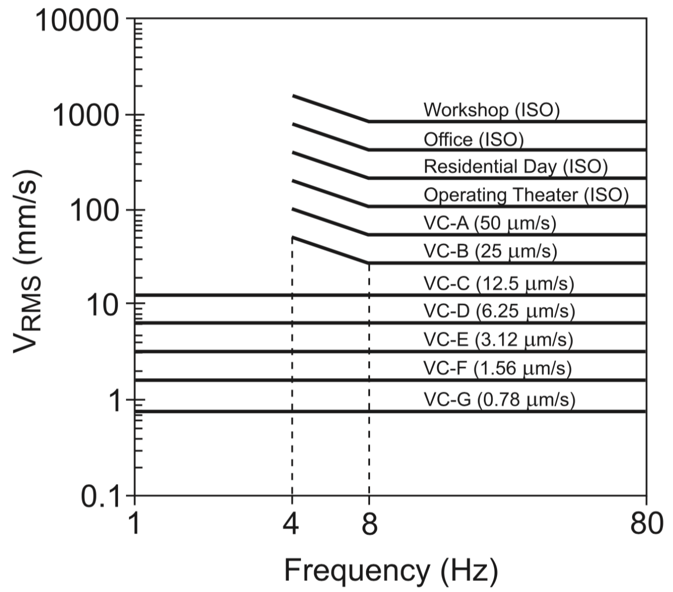


Figure 2.10: VC-curves and ISO guidelines. From [37].

2.4 Vibration-reduction measures

If vibration levels are predicted and considered too high or if there are high risks involved, measures in order to reduce vibrations can be applied. These mitigation measures can be applied at each of the three stages in the transmission process, i.e. vibrations can be reduced at the source, in the medium where the vibrations propagate and in or around the receiving structure.

Vibration-reduction at the source

Mitigation at the source involves reducing the vibrations generated or reducing the vibrations transferred through the track structure, i.e. limiting the effects of the mechanisms described in Section 2.2.1. Improvements can be made in the contact surfaces between train wheel and rail, e.g. making sure wheel flats are avoided and keeping rail and wheels as smooth as possible. Welded rails are preferable and maintenance should be ensured to avoid roughness. Rail grinding is especially important for rail that develops corrugations and wheel truing is used to smooth the wheels and remove wheel flats [15].

The design of the track and supporting structure affects the vibration levels. General soil improvements under the track is a possible reduction method [3], for instance by replacing soil of poor quality with stiffer soil or stabilising through jet grouting. Improved fastening of the rail using resilient direct fixation fasteners [33] can be implemented. Ballast mat, a mat of an elastomeric material, can be placed under the ballast [15]. Floating slabs, where the rail is supported by a slab resting on a resilient mat, is another method of reducing vibrations [29]. General improvements of the train, such as an improved suspension system can provide a more steady riding of the vehicle. As a last resort, train speed can be limited.

Vibration-reduction in the propagation path

To reduce the levels of vibration reaching the receiver, mitigation methods can be applied in the propagation path. These measures involve limiting the propagation of waves, primarily by diffracting the surface waves and reducing their amplitude. These methods may have less effect on body waves as it is possible for them to ”bend around” obstacles [16].

Barriers such as open or in-filled trenches can be used as means of screening the vibrations [1, 2, 39]. Open trenches are generally more effective than in-filled [6], but depending on the soil conditions and depth, they can be problematic in terms of stability. Since deep trenches can require significant soil excavation, a row of piles can be an alternative if the required barrier depth is large [22]. A shaped landscape between the source and receiver is another method of reducing vibrations in the propagation path, acting as a wave obstacle [38]. Barriers and soil improvement in the context of railway-induced ground vibrations is discussed in [3], where it is concluded that vibration screening generally is more efficient than soil improvement, especially open trenches.

Vibration-reduction at the receiver

Measures in order to limit the vibrations transferred to the receiver can be applied in or around the building itself. In general, the design of the building is important, e.g. avoiding resonances or light structures in general. Foundation improvement through stabilisation of the supporting soil can be used to reduce vibrations transferred in the soil–structure interaction [37]. Another possible mitigation method is to isolate the building foundation using elastic support [4].

2.5 Prediction models

Models can be used to predict the vibration impact, for instance on a planned construction project. There are no building codes, such as Eurocode, that must be followed when analysing vibrations induced by railway traffic. There are however models that have been developed by individuals or groups that can be used to predict vibration levels. In this section, general information of different classes of models will be presented and some existing prediction models will be examined.

2.5.1 Model classes

Since there are no current standards regarding railway-induced vibration and all mechanisms are not yet fully understood, new prediction models will continue to be developed. As a guidance when developing models, the document ISO 14837-1 [19] states some important considerations and describes different classes of models. The document suggests that it is beneficial to separate the process into the three main components; source, propagation path and receiver. The components should be analysed further by considering the relevant parameters that affect each region. It is also of importance to recognise the problem as frequency dependent. In mathematical terms, the magnitude of vibration $A(f)$ is a function of the source $S(f)$, the propagation path $P(f)$ and the receiver $R(f)$, where f is the frequency. According to ISO 14837-1, prediction models can be separated into three different classes, depending on the stage of assessment. As information regarding the receiving structure, soil conditions, and other site parameters advances throughout the design process, a more detailed model with more specific input parameters can be utilised. The three classes of prediction models are

- Scoping model
- Environmental assessment model
- Detailed design model

Scoping model

At early stages of design, regardless of whether the plan is developing new buildings or making alterations to existing railways, the initial objective is to determine if vibrations will be an issue. At this stage of assessment, a simple scoping model is appropriate, according to ISO 14837-1. The model should be easy to use and only be based on generic parameters that are available at an early stage. These parameters include the type of trains on the track (light, heavy, high-speed), location of track, general ground conditions (soft, hard), and requirements for the receiving building.

The output of scoping models can be whether the building will require mitigation or if it is suitable to build at a certain location. The model can also aid when deciding the location and alignment of a new railway track by estimating distances from the track to where vibrations will not be considered a problem, as well as finding problematic zones along a railway track.

Environmental assessment model

In the preliminary design phase, the location of a building or railway will be proposed and specific geotechnical information may become available. With access to detailed data, a more complex model can be used. This class of model is the environmental assessment model, as suggested by ISO 14837-1. The purpose of such model is to, compared to the scoping model, give a more quantitative and accurate description of the problem and approximate the effects of vibrations. If any mitigation methods are needed, their generic form and extent should be stated. The methods can be theoretical and empirical, or a combination of both.

Detailed design model

The third and final class of models, according to ISO 14837-1, is a detailed design model which is to be used in connection with the design phase of a new building or railway track. At this point, the location of a building or railway track will be specified and details regarding materials in railway, soil and receiving structure will be known which will allow for the model to consider all relevant parameters. The model should verify the levels of vibration, in terms of absolute values, to make sure they comply with the requirements set for the specific case. The mitigation method and its form will be specified in detail, as will requirements for the building in terms of structural design.

2.5.2 Analytical models

With a rapidly growing transport industry during the 20th century, numerous moving load problems have been studied throughout the years. Frýba [11], for example, covers many solutions to moving loads on structures and solids. In the context of railway-induced vibrations, a simplified approach, which can be used for studying the response in the track for a passing train, is to consider the rail as infinite beams supported by an elastic foundation representing the soil. For a moving concentrated force, the following differential equation can be used to describe the vertical displacements of the beam, y, with respect to position x on the beam and time t

$$EI\frac{\partial^4 y}{\partial x^4} + m\frac{\partial^2 y}{\partial t^2} + ky = P\delta(x - vt) \tag{2.9}$$

where E is the elastic modulus of the beam, I is the moment of inertia for the beam cross-section and m the mass per unit length of the beam. The third term represents the foundation which is assumed to be of Winkler type, i.e. the displacements in the ground are proportional to the beam deflection with the coefficient k. Furthermore, P is the load applied and $\delta(x - vt)$ is the Dirac's delta function. It is a generalised function and can in this case be thought of as a function that moves the force over the beam with a speed v.

Several analytical models consider the soil as an elastic or viscoelastic half-space, resulting in a three-dimensional model. Krylov [25] presented an analytical model for railway-induced ground vibrations, particularly studying the propagation of Rayleigh waves and the effects of high-speed trains. Kaynia, et al. [23], Takemiya [44] and Karlström and Boström [21] have developed analytical models that all compare favourably with measurements at Ledsgård, Sweden.

2.5.3 Empirical models

An empirical model is based on empirical observations of a phenomenon. Empirical models are often simple and can for railway-induced ground vibrations often be used as prediction models at an early stage of planning.

Norwegian Geotechnical Institute (NGI) developed a semi-empirical model [31] based on data from measurements and statistical analysis of the results. It can be used to predict vibration levels in buildings and is based on six general parameters: ground conditions; train type; line quality and embankment design; train speed; distance from track to building; the building in terms of foundation, structure and number of floors. The model is given as a mathematical function and is adjusted using several factors according to Equation 2.10

$$V = F_V F_R F_B = [V_T F_S F_D] F_R F_B \tag{2.10}$$

where F_V is the basic vibration function, consisting of a train type specific vibration level V_T for a reference speed and reference distance from track. Furthermore, F_S is a speed factor, F_D is a distance factor, F_R is a track quality factor and F_B is a building amplification factor.

Another semi-empirical model was developed by Bahrekazemi [4]. It is based on measurements on four sites in Sweden and incorporates train speed, wheel force and vibration decay. The measurements included trains with mainly lower speeds, a majority between 70–130 km/h, and for speeds outside this range, the relationships established in this model may not be accurate. A Geographical Information System (GIS) was implemented to visualise particle velocities over an area. The model is classed as a scoping model and is suitable for the preliminary design phase of a project. The mathematical function for the estimation of particle velocity, V_{rms} in mm/s, is given as

$$V_{rms} = (a \cdot speed + b) \left(\frac{r}{r_0} \right)^{-n} \tag{2.11}$$

where a and b are site specific functions of the wheel force, F_{rms}. The variable *speed* is the train speed in km/h, r is the distance to the track centreline, r_0 is reference distance (0.85 m) and n is an attenuation factor.

Bahrekazemi also developed a more advanced semi-empirical model based on both measurements in Sweden and Finland. It is presented as a MATLAB program with a user interface. The model is divided into four subsystems, each describing a different part of the transmission process. Output from one sub-model is used as input to the next. Statistical methods are used to simulate the stochastic nature of the problem. Transfer functions are used to relate vibrations outside the building to vibrations at a point inside the building.

2.5.4 Numerical models

Numerical models, for instance employing the finite element method, can be used as tools for predicting railway-induced ground vibrations, evaluating vibration-reduction measures, or studying structures exposed to vibrations in general. With advancements in computational power, larger and more detailed models become feasible. Detailed models however usually require that many input parameters, such as material properties and geometric properties, are known beforehand. For this reason, numerical models are typically better suited for detailed analysis. A drawback of numerical simulations is that they can be time consuming (compared to the use of empirical models), both in terms of creating the model and computation time.

A difficulty when modeling railway-induced vibrations using the finite element method is describing the source. As specified in Section 2.2.1, there are many mechanisms involved in the generation of vibrations. With the continued improvement of computers, finite element models have become increasingly advanced. Multi-body approaches [7, 24], where coupling of train and track can be modelled using contact mechanics, are capable of simulating some of the dynamic excitation mechanisms. Connolly et al. [8] have further used a numerical model as a basis for a scoping model.

2.5.5 General assessment methods

An analysis method for railway-induced ground vibration can be in the form of a procedure or step-by-step approach. Similar to the classes of prediction models, the steps can increase in detail as more information about the site and other conditions become available. In this section, some existing procedures for analysing vibrations are presented.

US Federal Transit Administration

The *Guidance Manual for Transit Noise and Vibration Impact Assessment*, from the US Federal Transit Administration [15], includes a procedure for assessing vibrations induced by railway traffic. It uses a three-step approach, similar to the three classes of prediction models. The three steps are screening, general assessment, and detailed analysis. In the screening step, it is determined wether railway-induced vibrations need to be considered. The method uses a table of distances, as a function of train speed and the type of land use. If the building is within these distances, further analysis will be required.

In the general assessment step, generalised curves describing RMS velocity level (VdB) as a function of distance from track centreline are used. The curves were developed from numerous measurements and provide a basic vibration level. This vibration level is further adjusted using several factors related to the source, propagation path and receiver. The usage of vibration level may not be compatible with other national guidelines however, as vibration requirements are not always stated using this measure.

Detailed analysis is the final step of the procedure and can be used when the general assessment indicates high vibration impact or in the final design phase of a project. This step consists of surveying existing vibration through measurements, predicting vibration impact and designing vibration-reduction measures. To analyse the vibration impact, all available tools in order to make the most accurate prediction of the vibration impact can be used. A method that is recommended is the use of transfer mobility functions, where relationships between the excitation force and resulting vibration level at a point on the surface are established. Equation 2.12 is used to calculate the RMS vibration velocity level, L_V, in 1/3 octave bands

$$L_V = L_F + TM_{line} + C_{build} \tag{2.12}$$

where L_F is the force density for a line vibration source, TM_{line} is the transfer mobility function from the track to the point of interest, and C_{build} is the building factor. For further detail, see [15].

Swedish Transport Administration (Trafikverket)

The *TK Geo 13* document by the Swedish Transport Administration [20] mainly deals with design requirements for various geotechnical structures. It contains some requirements regarding vibrations from high-speed trains, suggesting a simple step-by-step approach. For rail speed limits (*sth*) over 160 km/h, high-speed phenomena need to be considered. The analysis is divided into two steps: initial dynamic analysis and detailed dynamic analysis.

In the initial dynamic analysis, the S-wave speed is determined using either empirical methods ($c_{s,empirical}$) or measurements ($c_{s,measured}$). To avoid the problem of a ground vibration boom, i.e. when the train speed exceeds the Rayleigh wave propagation speed, Equation 2.13 is verified.

$$sth < \left\{ \frac{c_{s,empirical}}{1.5}; \frac{c_{s,measured}}{1.4} \right\} \tag{2.13}$$

The S-wave speed is typically just above the Rayleigh wave speed, meaning that if the above equation is satisfied, there are no risks related to high-speed phenomena.

If the train speed however exceeds the limits stated above, detailed dynamic analysis is required. The detailed analysis consists of determining the dynamic soil properties at the site through empirical methods or on-site measurements. With accurate soil parameters, calculations using two- and three-dimensional models, including a moving load simulating a relevant train, are performed to determine the critical velocity and the resulting vertical deflections beneath the sleepers. The calculated deflections are verified against a maximum allowed value which is set on a case-by-case basis.

3. Structural dynamics

Structural dynamics is the study of structures subjected to dynamic excitations, such as wind, earthquakes, moving loads and impacts. When introducing dynamics it is easiest to study a simple structure. An example of such structure is seen in Figure 3.1. The model consists of a mass m, connected to spring with a stiffness k and a viscous damper with a damping coefficient c. The structure is excited by a time dependent force $p(t)$, causing a displacement u. The structure can only displace in one direction, making it a single degree of freedom (SDOF) system.

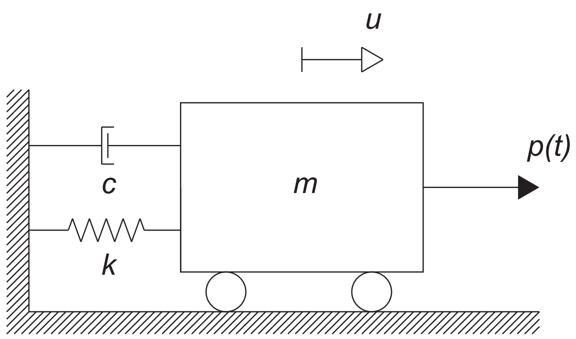


Figure 3.1: SDOF model.

For a linear elastic system the force in the spring f_S is proportional to the displacement according to Hooke's law.

$$f_S = ku \tag{3.1}$$

In a viscous damper, the damping force f_D is proportional to the velocity $\dot{u}$.

$$f_D = c\dot{u} \tag{3.2}$$

The sum all forces and Newton's second law of motion implies

$$\sum F = p(t) - f_S - f_D = m\ddot{u} \tag{3.3}$$

which after rearrangement results in the equation of motion for an SDOF system.

$$m\ddot{u} + c\dot{u} + ku = p(t) \tag{3.4}$$

To describe motion in more complex structures, multi degree of freedom (MDOF) models are used. Analogous to the SDOF system, the equation of motion for an MDOF system on matrix form can be written as

$$\mathbf{M}\ddot{\mathbf{u}} + \mathbf{C}\dot{\mathbf{u}} + \mathbf{K}\mathbf{u} = \mathbf{p}(t) \tag{3.5}$$

where $\mathbf{M}$, $\mathbf{C}$, $\mathbf{K}$ are the mass, damping and stiffness matrices, respectively. $\mathbf{p}$ is the force vector with respect to time, t. $\mathbf{u}$, $\dot{\mathbf{u}}$ and $\ddot{\mathbf{u}}$ are the displacement, velocity and acceleration vectors.

3.1 Resonance

Resonance is a phenomenon where a system vibrates with a much larger amplitude at specific frequencies, known as resonance frequencies or eigenfrequencies. For an undamped SDOF system under free vibration, the equation of motion can be written

$$m\ddot{u} + ku = 0. \tag{3.6}$$

A trial solution is assumed, where

$$u = A\sin\omega t \qquad \text{and} \qquad \ddot{u} = -A\omega^2 \sin\omega t. \tag{3.7}$$

Insertion into Equation 3.6 yields

$$(-\omega^2 m + k)A\sin\omega t = 0. \tag{3.8}$$

Assuming $A \neq 0$, the above equation is fulfilled when

$$\omega = \omega_n = \sqrt{\frac{k}{m}} \tag{3.9}$$

which is the natural frequency for an SDOF system. To illustrate the response under resonance, an undamped SDOF system under harmonic loading can be used, as given by

$$m\ddot{u} + ku = p_0 \sin\omega t. \tag{3.10}$$

Assuming the trial solution

$$u = u_0 \sin\omega t \qquad \text{and} \qquad \ddot{u} = -u_0\omega^2 \sin\omega t, \tag{3.11}$$

insertion into Equation 3.10 yields

$$(-\omega^2 m + k)u_0 \sin\omega t = p_0 \sin\omega t. \tag{3.12}$$

With the natural frequency

$$\omega_n = \sqrt{\frac{k}{m}}, \tag{3.13}$$

the static displacement

$$u_{st} = \frac{p_0}{k} \tag{3.14}$$

and rearrangment of the terms, the response of the system can be written

$$\frac{u_0}{u_{st}} = \frac{1}{1 - \left(\frac{\omega}{\omega_n}\right)^2}. \tag{3.15}$$

As seen in Figure 3.2, when the frequency of the exciting force is close to the natural frequency, the response is magnified. Theoretically this magnification reaches infinity for an undamped system. In reality however, damping is present in structures.

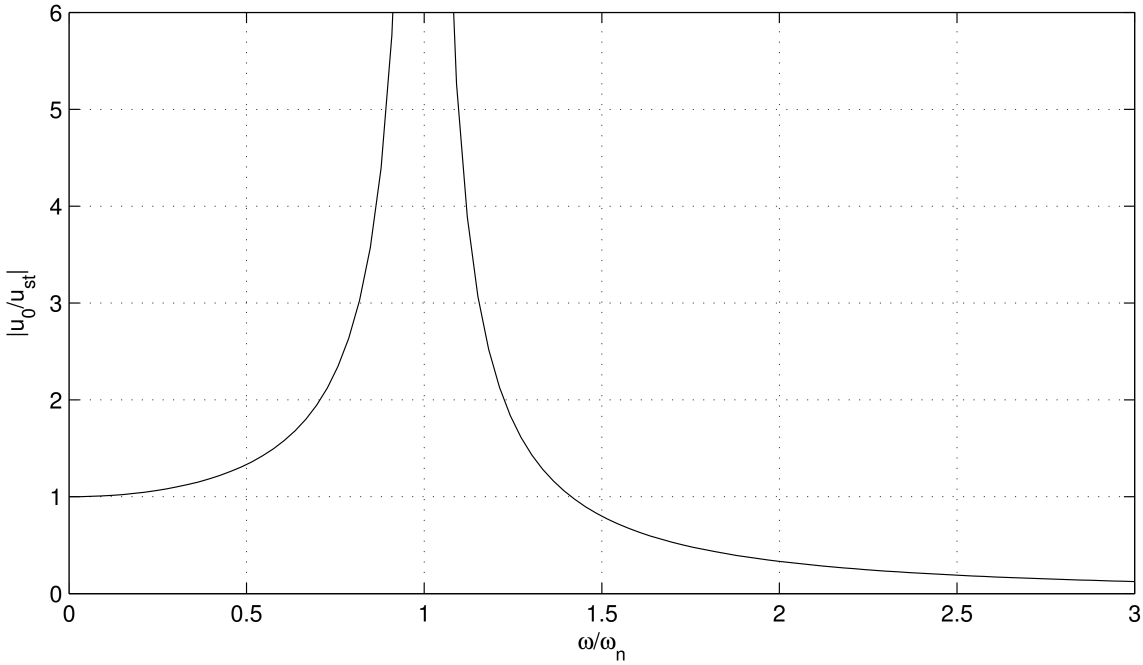


Figure 3.2: Displacement response for an undamped SDOF system under harmonic loading.

3.2 Damping

Damping is used to describe the energy loss in an oscillating system, resulting in a decay of vibration over time. In structures, damping can for instance occur due to friction in joints or internal material properties. The loss factor, described in Section 2.1.3 is one way of modelling damping. Rayleigh damping is another common damping model, where the damping matrix is constructed as a linear combination of the mass matrix and the stiffness matrix according to

$$\mathbf{C} = \alpha\mathbf{M} + \beta\mathbf{K}. \tag{3.16}$$

The damping ratio at the n-th mode is given by

$$\zeta_n = \frac{\alpha}{2}\frac{1}{\omega_n} + \frac{\beta}{\omega_n}. \tag{3.17}$$

If the damping ratio is assumed to be constant over a frequency range, the coefficients α and β can be calculated as

$$\alpha = \zeta\frac{2\omega_i\omega_j}{\omega_i + \omega_j} \qquad \beta = \zeta\frac{2}{\omega_i + \omega_j} \tag{3.18}$$

where ω_i and ω_j determine the frequencie range where the damping ratio is valid.

3.3 Steady-state dynamics

When a harmonic load is applied on a structure, the system will, after an initial transient response, start oscillating in the same frequency as the load, thus reaching steady-state. Generally, the response of a system under harmonic loading varies with different forcing frequencies. Steady-state analyses can be used to study the response of a system under different harmonic loads, giving an indication of how the system responds to other types of excitations.

The steady-state response can be written using complex expressions for the load and the displacements:

$$\mathbf{p}(t) = \hat{\mathbf{p}}e^{i\omega t} \tag{3.19}$$

$$\mathbf{u} = \hat{\mathbf{u}}e^{i\omega t} \tag{3.20}$$

where $\hat{\mathbf{p}}$ and $\hat{\mathbf{u}}$ are the complex load and displacement amplitudes, respectively. Differentiation of Equation 3.20 with respect to time and insertion into Equation 3.5 yields

$$\mathbf{D}(\omega)\hat{\mathbf{u}} = \hat{\mathbf{p}} \tag{3.21}$$

where $\mathbf{D}(\omega)$ is the frequency dependent dynamic stiffness matrix, defined as

$$\mathbf{D}(\omega) = -\omega^2\mathbf{M} + i\omega\mathbf{C} + \mathbf{K} \tag{3.22}$$

4. Field measurements

In many fields of science, measurements and experiments can be important for understanding the problem at hand. In this project, field measurements of vibrations induced by railway traffic were performed in order to obtain a general understanding of typical vibration levels for various types of trains, but also to use the data together with numerical models.

A first series of measurements was carried out near the railway station in the city of Lund, Sweden. The instrumentation used during these measurements were accelerometers, mounted in the soil. Unfortunately, the recorded vibration levels were low and it proved difficult to draw any conclusions from the results. Instead, a second series of measurements was performed near a railway track in the southern part of Lund, Sweden. The instrumentation used for these measurements were seismometers. The test site was chosen due to the ability to get close to the railway track without actually entering the track area, something that would have required special permissions.

This chapter gives a brief introduction to vibrational measurements, details the seismometers used, describes the test set-up and finally presents results from the measurements.

4.1 Measurement techniques

4.1.1 Instrumentation

Modern instrumentation for measuring vibrations generally consist of two main components; a transducer that registers the motion and a system that records and digitises the data. Measurement systems come in many shapes and forms, and are made for different purposes. In some cases the components can be separate units that have to be connected and sometimes a single unit.

To register vibration, some type of sensor is used. In the area of ground vibrations, sensors such as accelerometers, geophones and seismometers are common. When measuring vibrations, velocity and acceleration are usually the quantities of interest. Most modern transducers register the motion as an electronic signal. This signal is then proportional to velocity or acceleration depending on the type of transducer.

When digitising a signal, i.e. storing the signal for use with a computer, the stream of continuous analogue data has to be sampled at discrete points. If the signal is sampled at a high enough rate the digital data will be a good representation of the analogue signal. Figure 4.1 illustrates the sampling of an analogue signal. Generally, higher sampling rates are better, but will involve handling and storing much more data, which can be cumbersome. The Nyquist-Shannon sampling theorem states that the sampling frequency must be at least twice the highest frequency in the signal in order to capture the complete frequency content of a signal.

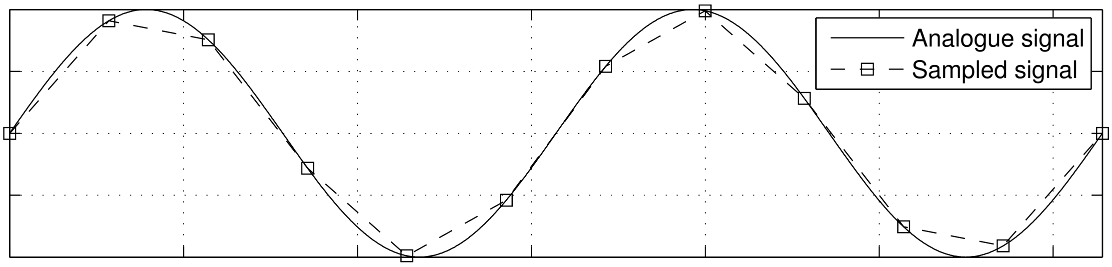


Figure 4.1: Analogue and sampled signal.

4.1.2 Signal processing

A signal can be analysed as the recorded waveform, i.e. the amplitude as a function of time. In the time domain, vibration levels can for instance be evaluated using an RMS value or as a maximum value of magnitude. For a discretised signal, X, with N values, the RMS value can be calculated according to

$$X_{RMS} = \sqrt{\frac{1}{N}\sum_{i=1}^{N} X_i^2}. \tag{4.1}$$

To analyse the frequency content of the signal, a conversion to the frequency domain is necessary, which can be done using a Fast Fourier Transform (FFT). A signal in the time domain and frequency domain are shown in Figure 4.2.

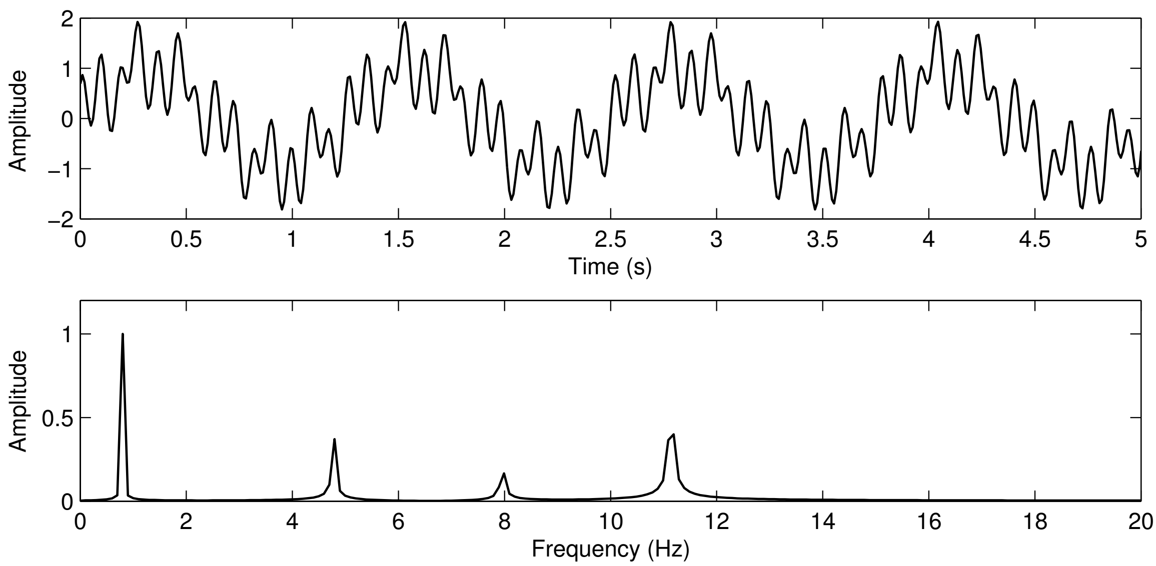


Figure 4.2: Signal in time domain (top) and frequency domain (bottom).

Filters can be used to remove unwanted content, such as noise, from a signal. A low-pass filter attenuates high frequencies and a high-pass filter attenuates the low frequencies. An example of a low-pass filtered signal is shown in Figure 4.3.

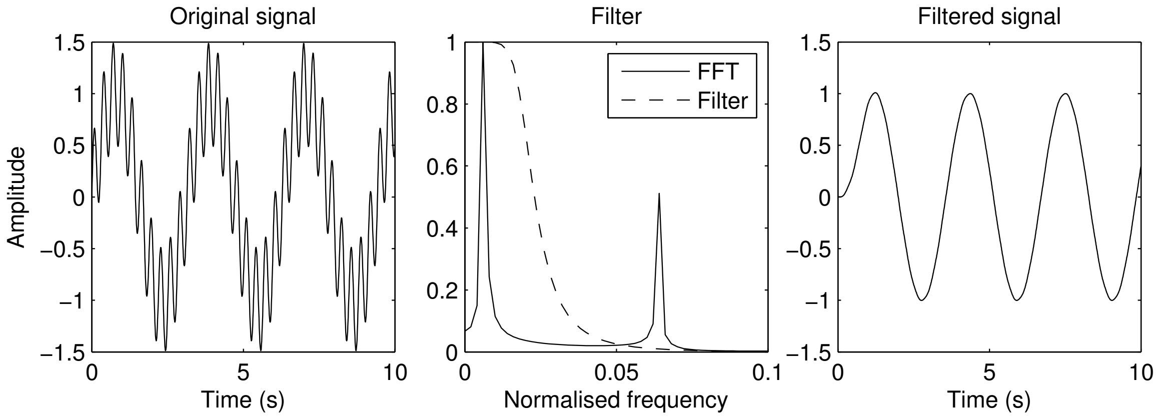


Figure 4.3: Original signal (left), low-pass filter applied (middle) and resulting filtered signal (right).

4.2 Seismometers

The measurement devices used in this project are broadband seismometers of model *Güralp CMG-3EX-EAM*, pictured in Figure 4.4. The unit combines a three-axis seismometer with a built in digitiser and data acquisition module [13]. It measures ground motion in the north/south, east/west and vertical directions. A connected GPS antenna can record time and position of the unit. It is powered by an external power supply which allows for a standalone operation for up to 72 hours. Three seismometers of the aforementioned model were used for the measurements.

The seismometer has three internal modules: a triaxial sensor assembly, a digitiser and an acquisition module for storing data. Similar to classic seismometers, the sensors inside the CMG-3EX-EAM have internal masses that are held in place by electrical forces. As the ground moves, the components attempt to hold the masses steady through the use of a feedback circuit. The voltage required to hold the mass steady is recorded as a time signal, and is proportional to the velocity of the ground motion.

By clicking a button on the device, the internal masses can be locked for transport or unlocked for measurement. When the unlock function has been activated, the device will automatically try to centre the masses. When masses are unlocked and centred, the seismometers are configured to automatically start recording data.

The instruments are calibrated up to 100 Hz and have a differential output sensitivity of 6000 V/ms^{-1} [12]. The signal recorded is digitised by the built in analogue-to-digital converter. The sampling rate can be configured from 1 to 1000 samples per second. The data is first stored on an internal buffer. Periodically, data is flushed from the buffer to the built-in 16 gigabytes of flash storage. Data files can be accessed using a USB connection or through Güralp's monitoring software, Scream. The

Figure 4.4: Photograph of the seismometer used in the measurements.

data files, one for each seismometer, are split up in thirty-minute segments, containing continuous data for each direction of motion.

4.3 Test site

The site of the measurements was in southern Lund, Sweden. The double-track railway runs in a straight line in the south-west/north-east direction. Since the railway track is within the city's borders, the trains passing are not reaching their maximum speed at this location. The purpose of the measurements however, were not to focus on high-speed related problems, but rather to study vibration levels from railway traffic in urban environments, where trains necessarily do not travel at their full speed.

Typical soil conditions around the city of Lund are layers of clay till on top of bedrock. Previous work applying the soil in the region [37] has shown that material properties can differ considerably even within a smaller area, as the composition of clay tills vary greatly. The Geological Survey of Sweden (SGU) provides geological maps (see examples in Figure 4.5) that estimate distances to bedrock, soil type and bedrock type [34]. The soil is assumed to be a clay till and the distance from ground surface to bedrock is approximately 30–50 meters. Unfortunately it is not possible to be more specific without further soil investigations on the actual site.

Figure 4.5: SGU geological maps at the site [34].

4.4 Set-up and measurement

Three seismometers of model CMG-3EX-EAM were placed at three distances from the railroad in a straight line perpendicular to the railway track. For stability, a shallow hole was dug at the spot where each seismometer were to be placed. The holes were levelled with stone dust and 30×30 cm^2 paving stones were placed there. A seismometer placed on top of each paving stone, ready for measurement, is shown in Figure 4.4. A connected external GPS antenna for recording time and exact location was mounted in the ground next to each seismometer. The instruments were powered by an external power supply (not pictured).

Measurements were carried out on April 18 and April 22, 2016, for about two hours at each day. A schematic overview of the location and the placement of the seismometers are shown in Figure 4.6. The distance from the track to each seismometer are shown in Table 4.1. The reason for placing the seismometers at different distances from the track was to measure the vibration decay. The measurements on both days took place before noon, when a variety of different train types were passing, including commuter trains, high-speed trains and freight trains. The type of train, the train direction and point in time for each passage were noted. In addition, some passages were filmed to estimate the train speed. The measurement location with a passage of a train can be viewed in Figure 4.7.

Table 4.1: Approximate distance from centreline of the closest railway track to each seismometer.

	Seismometer 1	Seismometer 2	Seismometer 3
Day 1	5 m	15 m	30 m
Day 2	5 m	30 m	55 m

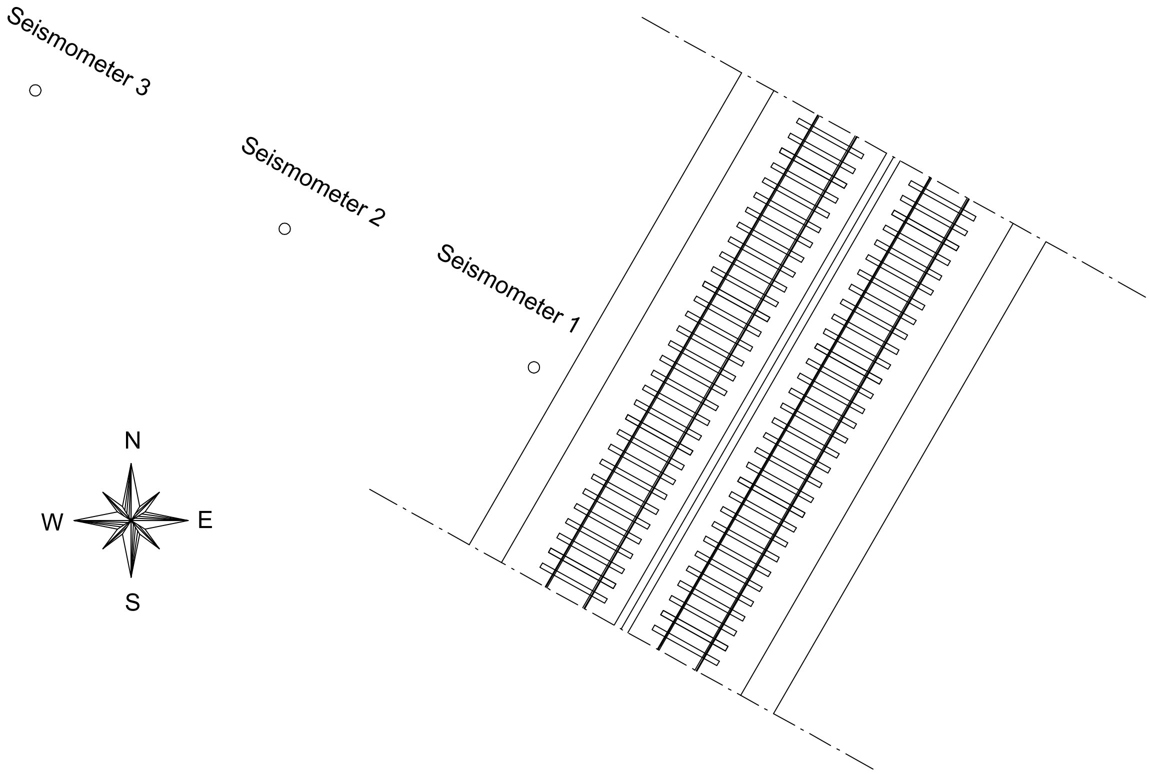


Figure 4.6: Seismometer locations during measurements.

Figure 4.7: An X2000 train passing by the test site.

4.5 Measurement results and analysis

In total, 63 train passages were recorded during the two measurement occasions. For each train passage there is data from three seismometers, with three directions on each. As such, there is a considerable amount of data available and everything will not be presented in this report. The signals that are regarded as the best representative or the most relevant will be used. The train speeds were estimated using video recordings. Most passenger trains had a speed of 100–130 km/h, while freight trains were slower at 60–70 km/h.

A problem that became apparent when analysing the results was the presence of baseline drift in the north/south and east/west channels, particularly for one of the seismometers. This was corrected digitally using a high-pass filter, but the measurements involving this specific seismometer and the two horizontal directions were interpreted with caution. The high-pass filter applied was a third order Butterworth filter, available in the MATLAB signal processing toolbox. Cutoff frequency was specified at 1 Hz. Figure 4.8 shows an example of a non-filtered signal, the filter used and the resulting filtered signal.

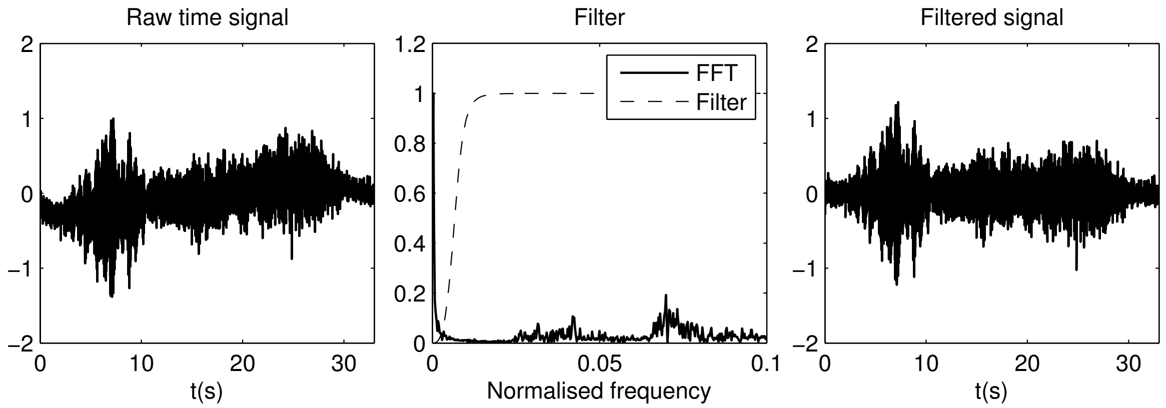


Figure 4.8: Example of a signal being filtered.

4.5.1 Time signals and vibration levels

The measurement results showed a large variation, primarily due to the type and speed of the train. A typical commuter train and a freight train is here selected to serve as examples of trains causing different vibrations. Vertical velocities at different distances from the track for the commuter train are shown in Figure 4.9. Due to the region not being a particularly sensitive spot and the fact that the trains are not operating at their maximum speeds, the vibration levels are moderate. The maximum 1 second RMS value of the velocity, 10 m from the track, is 0.22 mm/s. At the seismometer 25 meters further away, the RMS value is only about 0.016 mm/s; showing a rapid decay.

Freight trains generally show higher vibration levels than passenger trains. Vertical velocities at different distances from the track for a freight train are shown in Figure 4.10. The maximum 1 second RMS value of the velocity, 10 m from the track, is 0.37 mm/s. Typical for all freight trains measured, were that noticeably higher

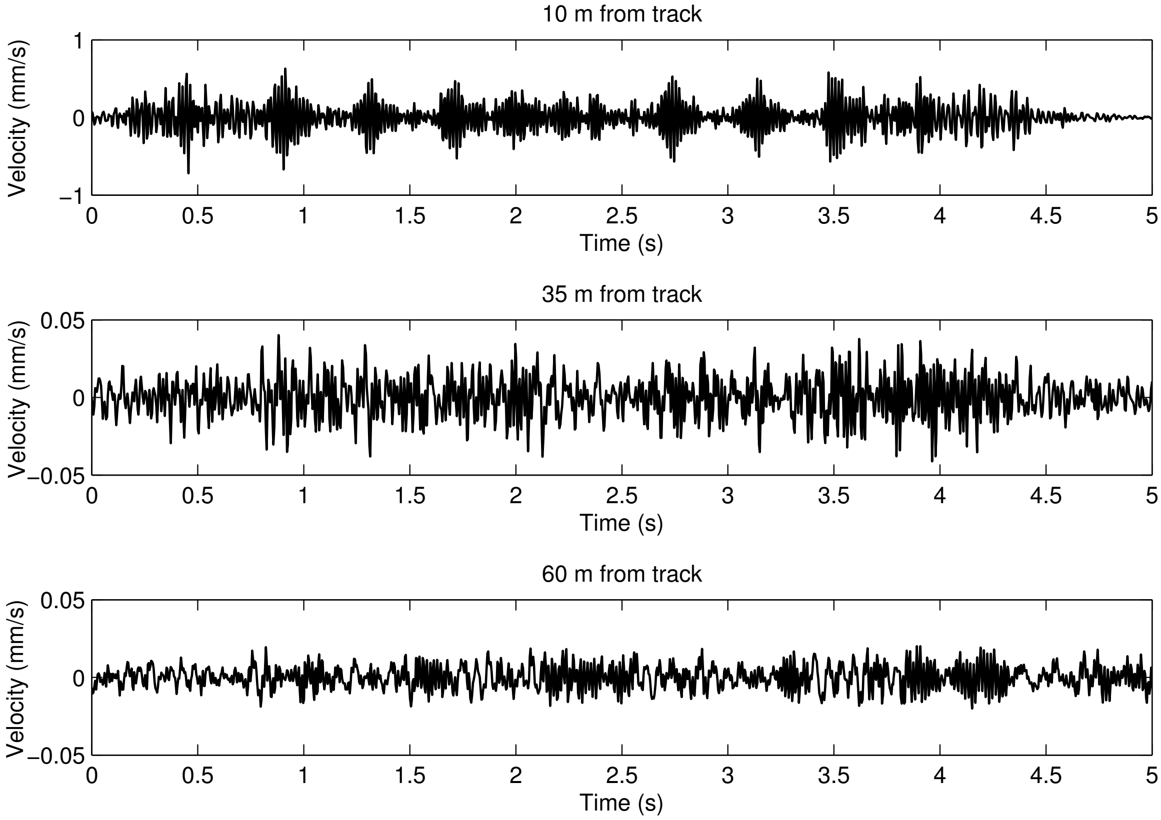


Figure 4.9: Velocity at different distances for a commuter train. Note that the y-axes are scaled differently.

velocity amplitudes was found in the beginning of the signal, presumably because of a pulling locomotive passing first.

To get an impression of the vibrational decay, as well as the variability in the measurements, maximum 1-second RMS values and peak particle velocities for all measured trains are plotted in Figure 4.11 as a function of distance from the track. In this figure, it can also be seen that the freight trains, although few measured, show higher vibration levels than the majority of other passenger trains at the same distance from track. It is especially noticeable as the distance from the track increases. Some passenger trains, however, result in higher vibration levels. The maximum recorded vibration level was almost 0.9 m/s RMS.

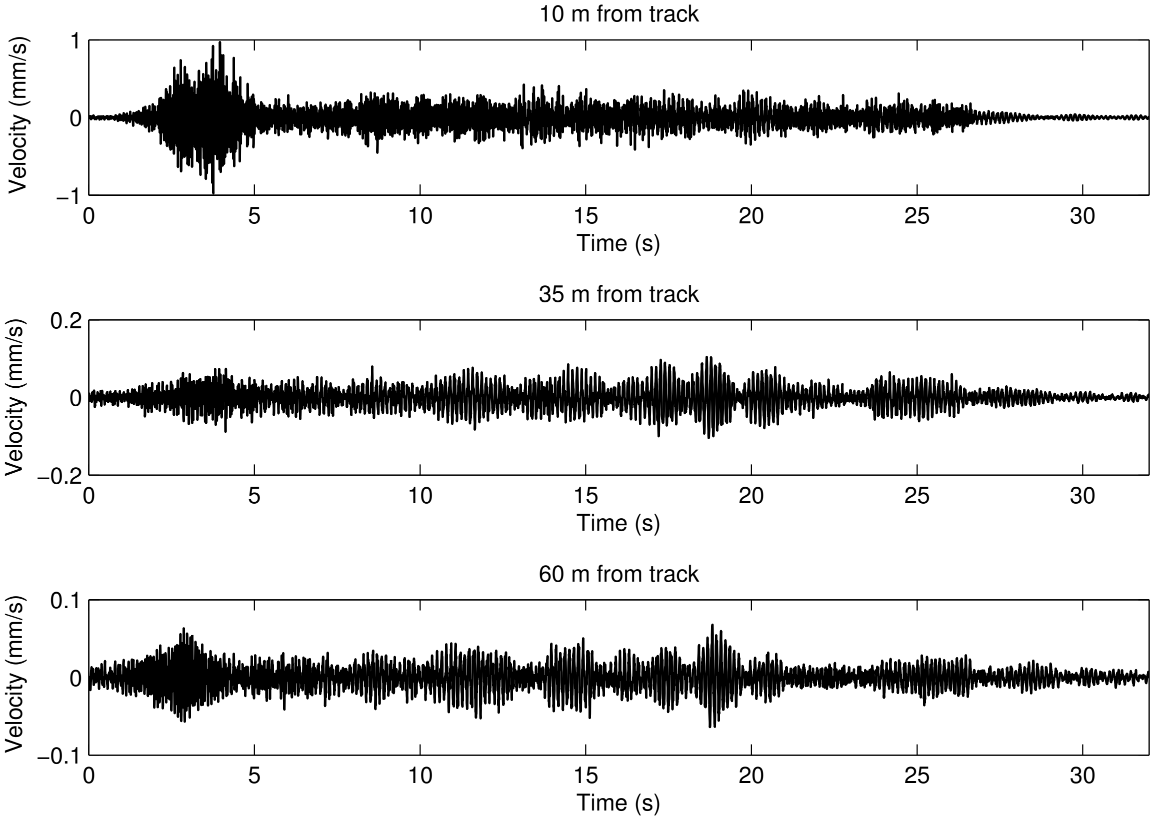


Figure 4.10: Velocity at different distances for a freight train. Note that the y-axes are scaled differently.

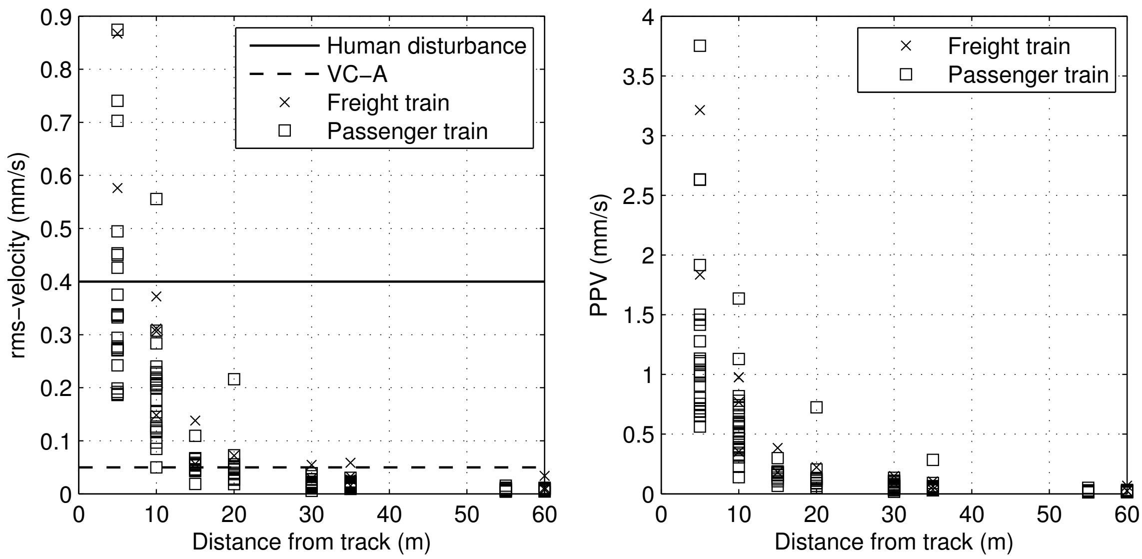


Figure 4.11: RMS values (left) and peak particle velocities (right) of vertical velocities for all trains as a function of distance from the track.

4.5.2 Freqency content

Signals were converted to the frequency domain using an FFT. The FFT of vertical velocities for three different freight trains are displayed in Figure 4.12, to compare three trains of the same type. At 10 m from the track, the signal contained a great variety of frequencies. As the distance from the track increases, peaks become easier to distinguish. The peaks also seem to be at the similar frequencies for the three freight trains. This trend was more apparent for freight trains compared to commuter trains. This can be due to the fact that commuter trains are relatively short in length and pass quickly, thus making random differences more pronounced.

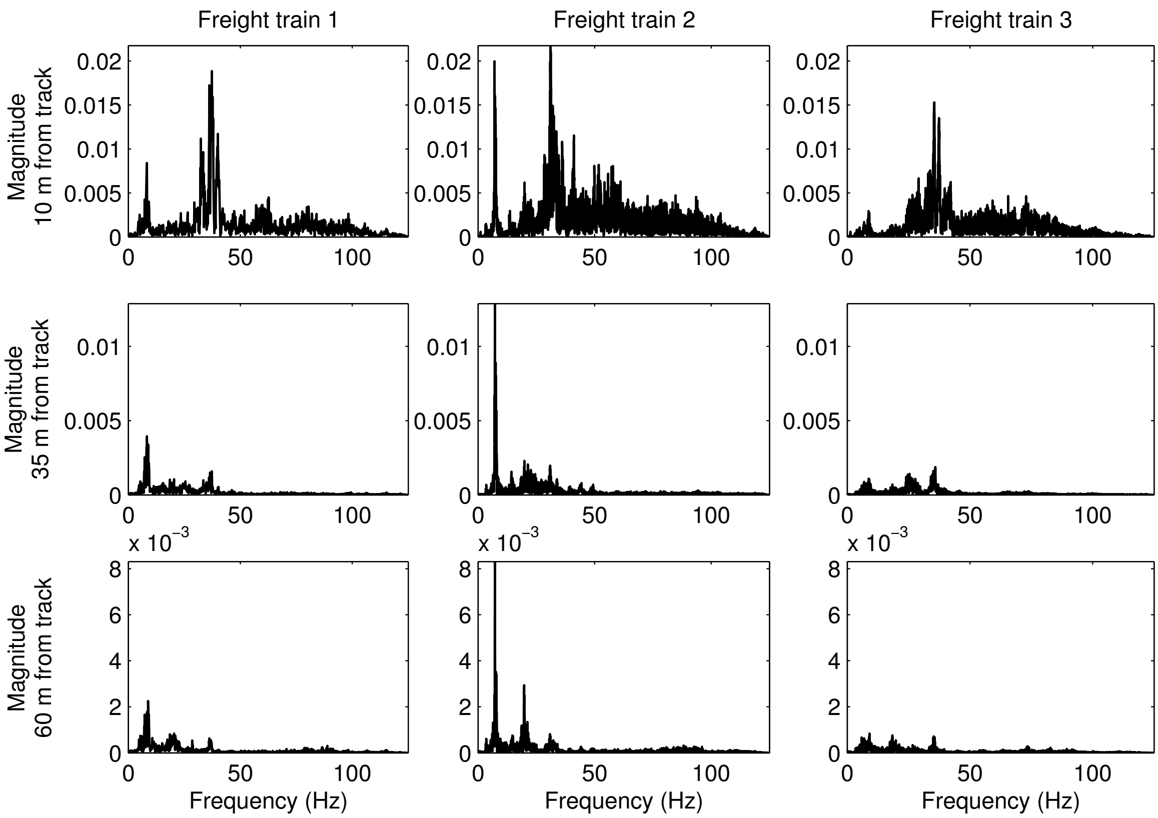


Figure 4.12: FFT for three different freight trains and distances from the track.

The results in the time domain showed a rapid decay of vibrations as distances to the track increased. They did not however tell anything about how the decay was distributed over frequency. In Figure 4.13, the frequency spectra at different distances from the track for a freight train is shown. A moving average of the FFT-curve was applied using MATLABs built-in function, in order to smooth the curve and to better demonstrate the result. The magnitudes were normalised to the maximum amplitude. It is seen that the high frequencies present at 10 m from the track have attenuated at further distances from the track. In relative terms, the vibrations of high frequency have attenuated far more than vibrations of low frequency. Additionally, some of the peaks are present at all distances, most notably the peak at around 7 Hz. Similar behaviour can for a commuter train be observed in Figure 4.14.

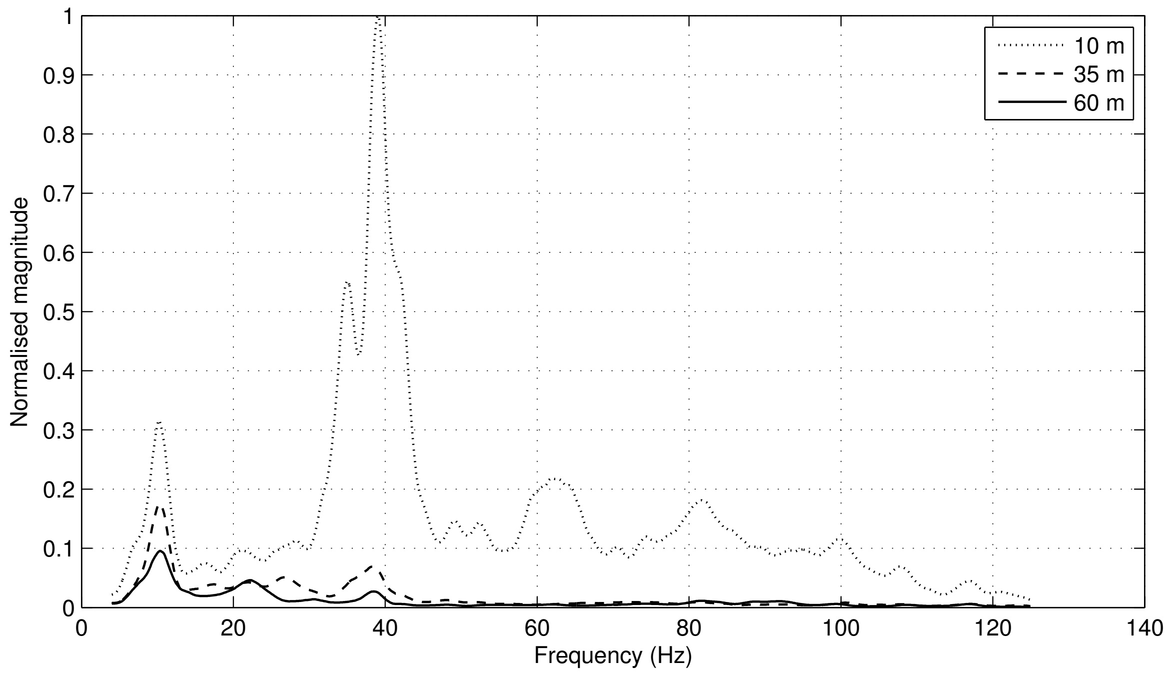


Figure 4.13: FFT by distance from track for a freight train. Normalised to the maximum amplitude.

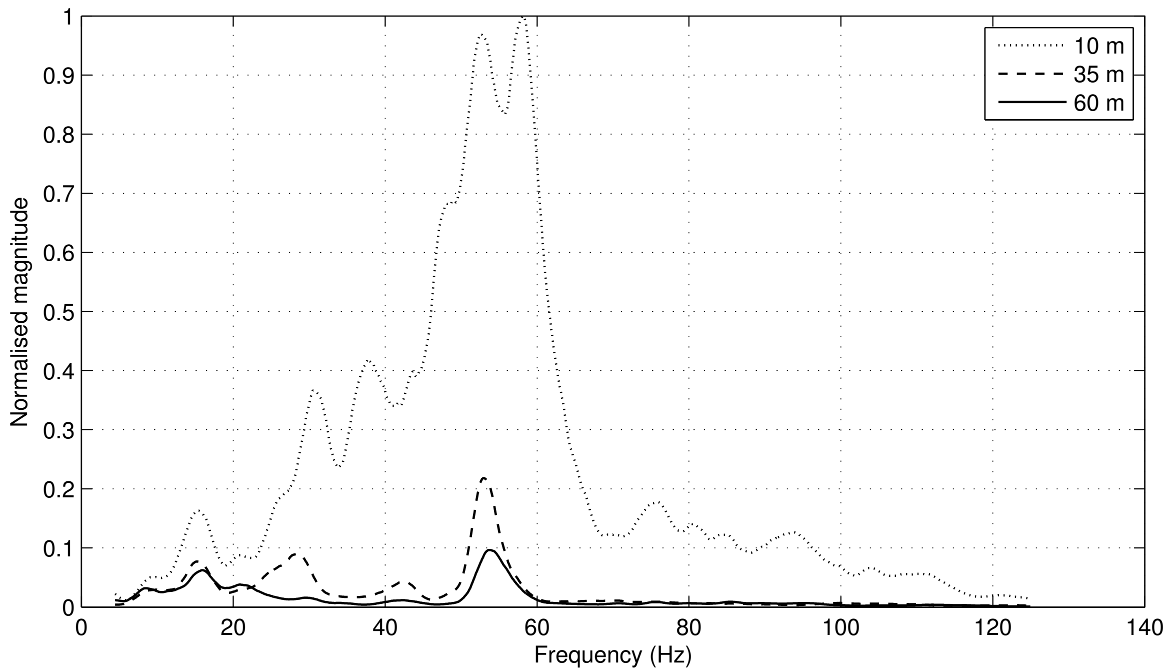


Figure 4.14: FFT by distance from track for a commuter train. Normalised to the maximum amplitude.

5. Numerical simulations

Numerical simulations can be used as a tool to predict vibration levels and evaluating a site or a structure in general. In this thesis, finite element models are used to study how different geometric and material parameters affect the vibration levels. This is done through a parametric study of a soil model. The model is further extended to include a building where some building related parameters are studied. Finally, simulations that relate to the previously performed field measurements are carried out.

The test site (see Section 4.3) was used as basis for the numerical models in terms of geometrical and material parameters. Since recommendations regarding vibrations often are given in velocity, the results from the numerical simulations will also be given in terms of velocity.

5.1 The finite element method

Many physical phenomena are described in one or multiple dimensions by partial differential equations. These equations can be too complicated to solve using analytical methods. The finite element method is a numerical technique for solving partial differential equations and is widely used in many engineering disciplines. The method is developed particularly for utilising the power of computers to carry out the calculations.

The finite element method is based on subdividing a region or body into smaller parts, referred to as finite elements. With this, a transformation of the original continuous system into a system with discrete points is made. The finite elements together define a finite element mesh, and within each finite element, the behaviour is usually approximated by a polynomial (e.g. linear or quadratic). Generally, a finer mesh results in a more accurate solution, with the downside of increased computation time. Boundary conditions, which describe the behaviour at the boundaries of the body, are necessary for the differential equations to be solved. Further description of the finite element method and derivation of the finite element tormulation, can for instance be found in [36].

Solving wave propagation problems using the finite element method has a shortcoming in that the propagation is usually not confined within a finite region, i.e. the waves are usually gradually damped out as the distance from the source increases. Simulating wave propagation can therefore quickly lead to very large models, requiring substantial computational power to solve the equations. A way of controlling this is the use of non-reflecting elements at the boundaries, simulating an infinite region and thus reducing the size of the model. This method will be used in the performed simulations.

5.2 Software

The finite element software package Abaqus 6.14 [9] was used in all numerical simulations. The general workflow when using Abaqus involves:

- Pre-processing: creation of a finite element model to be analysed. An input-file, which contains all the necessary information about the model, is generated.
- Processing: analysis of the model which produces a result.
- Post-processing: viewing and handling the results of an analysis.

Abaqus/CAE was used for pre- and post-processing. Abaqus/Standard, which is a general-purpose finite element analyser, was used for analysis. Results were exported as text-files and the figures presented in this report were plotted using MATLAB.

5.3 Influence of soil properties

To determine how the different soil parameters affect the vibration levels, a parametric study was carried out. The purpose of this study was to evaluate the importance of each parameter and conclude which parameters are necessary to accurately measure in order to predict the vibration levels. The parameters studied were

- Elastic modulus of soil, E
- Soil density, ρ
- Poisson's ratio, ν
- Loss factor of soil, η
- Depth of soil layer, d

Steady-state analyses were used to evaluate the response in the soil as a function of frequency. The frequency range of interest was selected to 1-25 Hz.

5.3.1 Finite element model

For the purpose of analysing the influence of soil properties, a simple two dimensional model, composed of plane strain elements, was used. A plane strain model assumes that the strains in one dimension are zero which can be a reasonable assumption for soils, depending on the load case. Applying a load on a plane strain model is equivalent of a line load. An axisymmetric model can be used for a point force, which experiences geometrical attenuation. However, to keep consistency with a later model and since the parametric study is comparative, a plane strain model was opted for.

Geometry and materials

The model consistsed of a 30 m layer of soil above a 50 m layer of bedrock as illustrated in Figure 5.1. A unit load was applied at the top left point of the soil. Reference material properties (which were subsequently varied) are shown in Table 5.1. The properties of the bedrock were kept constant.

Table 5.1: Reference materials used in the parametric study.

Material	E (MPa)	ρ (kg/m^3)	ν	η
Soil	100	2000	0.48	0.10
Bedrock	10,000	2500	0.40	0.04

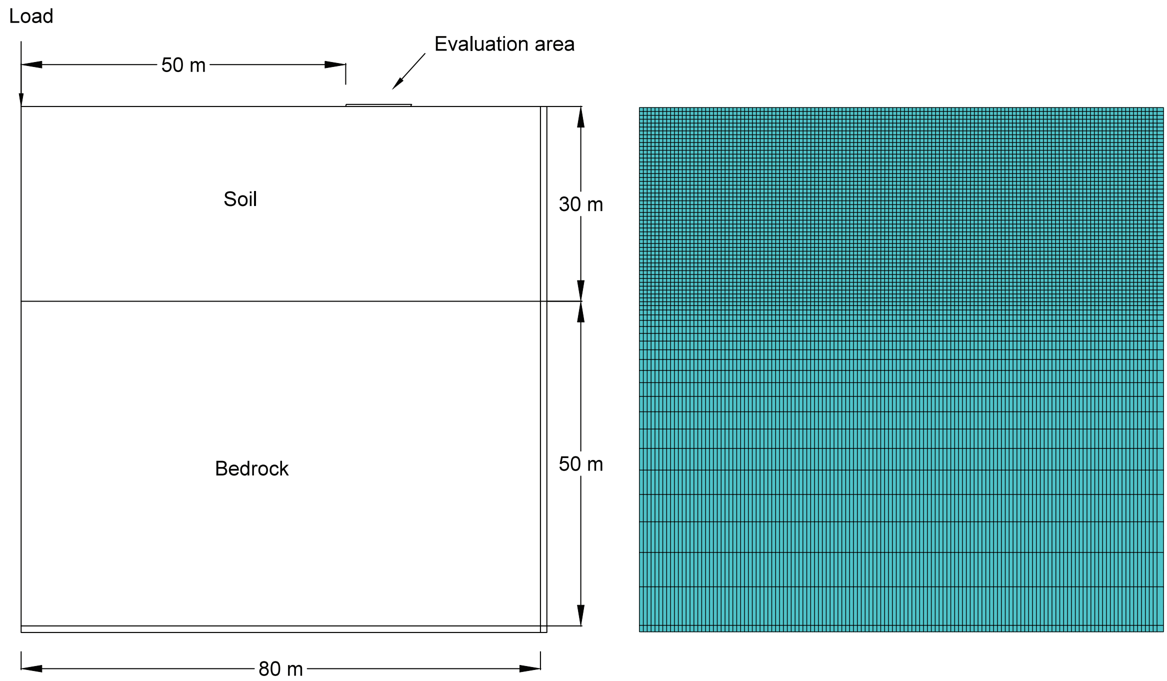


Figure 5.1: Soil model (left) and mesh (right).

Boundary conditions and mesh

The vertical boundary where the load was applied is a symmetry line. Displacements here were constrained in the horizontal direction. Additionally, non-reflecting elements were used at the right and bottom boundary to simulate an infinite region.

Eight-node quadratic plane strain elements with reduced integration, named *CPE8R* in Abaqus, were used in both soil and bedrock. To simulate infinite boundaries, *CINPE5R*-elements were used. Non-reflecting elements are not supported in the Abaqus CAE environment, and were added by meshing the boundary as *CPE8*-elements and manually changing the elements in the input file before running the analysis.

The size of the elements were selected to accurately model the propagation of waves. In accordance with [27], eight linear elements per wavelength, i.e. nine nodes or four quadratic elements, provide enough accuracy. The element size is therefore dependent on the material properties and the frequency of interest. In the parametric study, a width and height of the soil elements were selected to 0.6 m. Since the bedrock is much stiffer than the soil (and wavelengths therefore are longer), the height of the elements simulating bedrock were gradually increased to 6 m, in order to save computational power.

5.3.2 Results

In all the following comparisons, vertical velocities at the surface, 50–60 m from the load application point (see Figure 5.1), were extracted. RMS values over the points in the evaluation area were plotted against frequency, comparing the different choices of material properties. Moreover, the comparisons were quantified through RMS values over frequency.

Effect of elastic modulus

The vertical velocities at the evaluation area for different elastic moduli are compared in Figure 5.2. A change in elastic modulus has a marked effect on both vibration levels and the frequencies of the peaks in magnitude. The general shape of the curves are similar, but for stiffer soils the curves are shifted and stretched, with the corresponding peaks occurring at higher frequencies. In Table 5.2, it is seen that the overall vibrations levels are lower for stiffer soils.

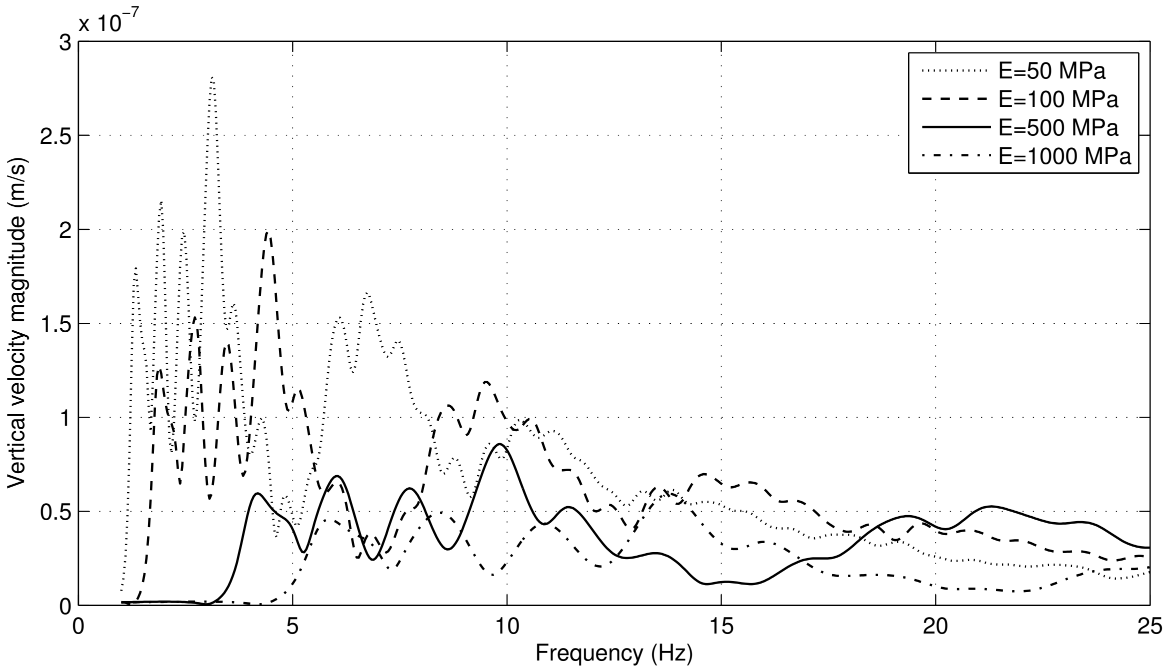


Figure 5.2: Effect of elastic modulus, E, on the vertical vibrations in the soil model.

Table 5.2: RMS of velocity over frequency for different elastic moduli, E.

E (MPa)	RMS (nm/s)
50	85.6
100	71.0
500	40.5
1000	27.3

Effect of soil density

The vertical velocities at the evaluation area for different mass densities of the soil are shown in Figure 5.3. The soil density has a relatively small impact on the vibration levels, both in terms of magnitude and the frequencies of the peaks. In part, this can be explained by the fact that it is not physically possible for the density to vary as much as other parameters; most soils have a density of around 2000 kg/m^3. As shown in Table 5.3, higher densities generally lead to lower vibration amplitudes.

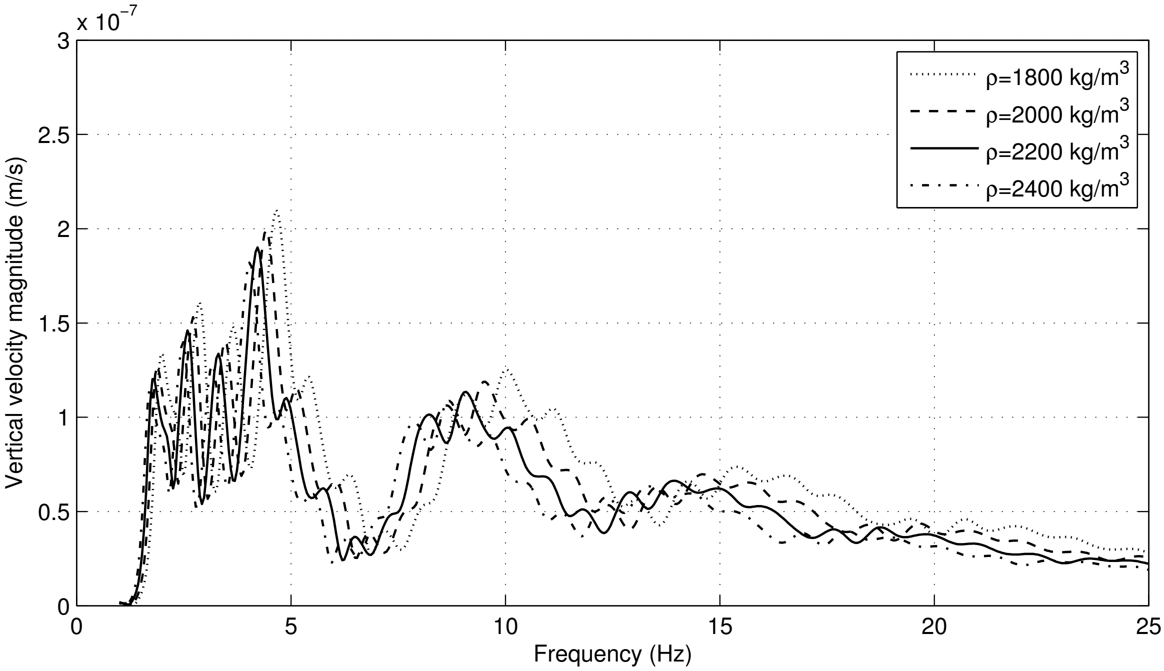


Figure 5.3: Effect of soil density, ρ, on the vertical vibrations in the soil model.

Table 5.3: RMS of velocity over frequency for different densities, ρ.

ρ (kg/m^3)	RMS (nm/s)
1800	76.5
2000	71.0
2200	66.3
2400	62.2

Effect of Poisson's ratio

In Figure 5.4, the vertical velocities at the evaluation area for different values of the Poisson's ratio are shown. The curves are shaped slightly differently for each variation, not simply stretched, moved or amplified as the previous parameters showed. In Table 5.4, the RMS values of the different variations are shown. Higher Poisson's ratios generally result in lower vibration levels, but the difference is small.

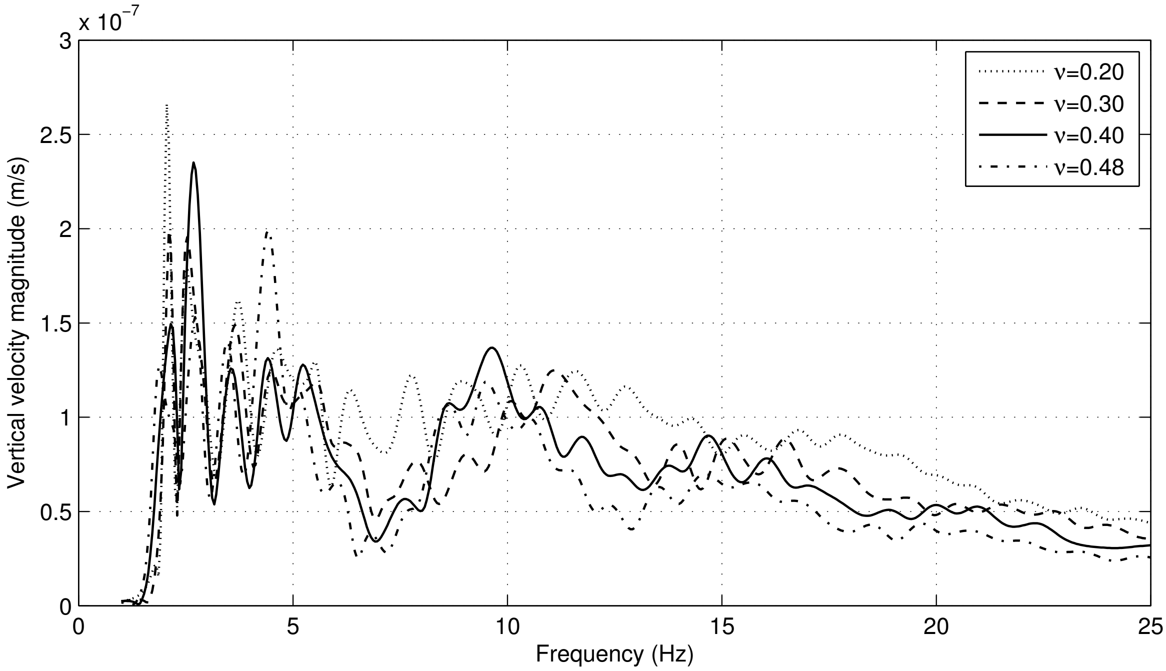


Figure 5.4: Effect of Poisson's ratio, ν, on the vertical vibrations in the soil model.

Table 5.4: RMS of velocity over frequency for different Poisson's ratios, ν.

ν	RMS (nm/s)
0.20	94.4
0.30	81.4
0.40	79.2
0.48	71.0

Effect of loss factor in soil

In Figure 5.5, the vertical velocities at the evaluation area for different loss factors are compared. Since the loss factor is a means of describing the energy loss in the system, the loss factor in the soil only affects the amplitude of vibrations. Contrary to the effect of elastic modulus, varying the loss factor does not change the frequencies where the peaks in magnitude are occurring. The RMS values of the different configurations are shown in Table 5.5, where it is seen that soils with higher loss factors have lower magnitudes of vibrations.

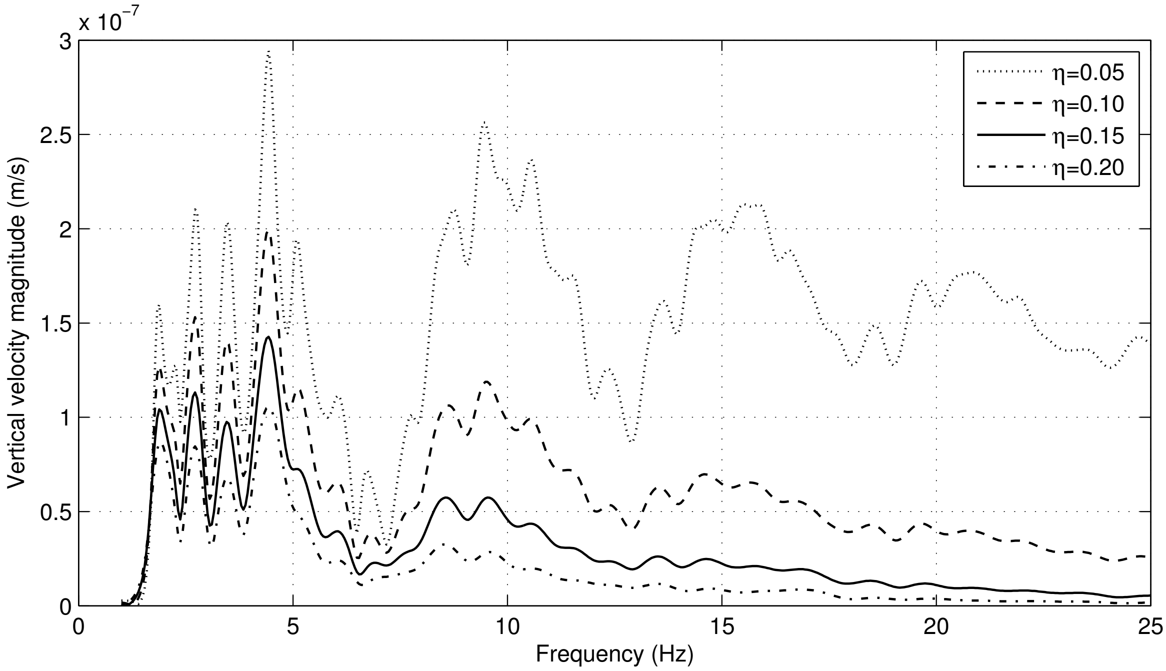


Figure 5.5: Effect of loss factor, η, on the vertical vibrations in the soil model.

Table 5.5: RMS of velocity over frequency for different loss factors, η.

η	RMS (nm/s)
0.05	158.8
0.10	71.0
0.15	42.3
0.20	29.3

Effect of soil layer depth

Vertical velocities at the evaluation area are for different soil layer depths are shown in Figure 5.6. With a variation of soil depth, the response is different. With deeper soil layers, the first resonances in the soil occur at higher frequencies. The overall vibration levels of the different configurations are shown in Table 5.6. It is hard to see a correlation between layer depth and vibration level, especially for the shallow depths. However, for the deeper soil layers, the vibration levels seem to decrease with increasing soil depths, most likely as the effects of reflections at the bedrock are reduced.

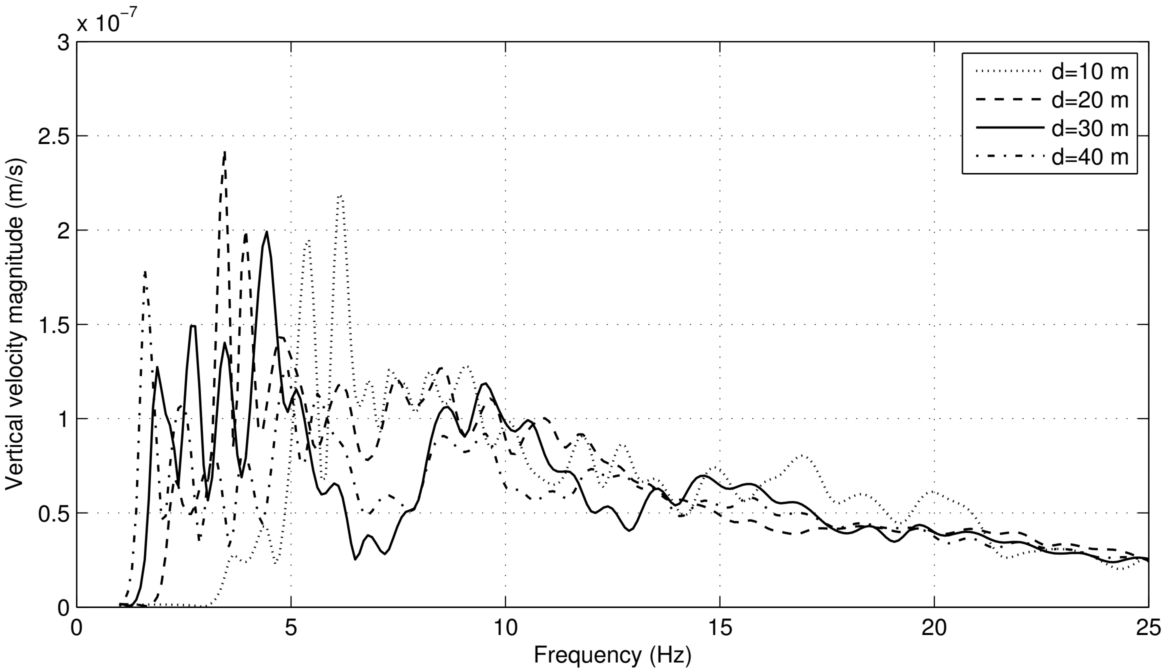


Figure 5.6: Effect of soil layer depth, d, on the vertical vibrations in the soil model.

Table 5.6: RMS of velocity over frequency for different soil layer depths, d.

d (m)	RMS (nm/s)
10	74.8
20	77.9
30	70.9
40	62.6

5.4 Effects on structures

In the end it is the receiver, typically a person inside a building, that will notice vibrations induced by railway traffic. It is therefore of interest to study the behaviour of a structure exposed to vibrations. For this purpose, a simple building was added to the soil model previously used in the parametric study (Section 5.3.1).

Steady-state analyses were again performed to evaluate the frequency response in the soil and structure. It was of interest to compare vibration levels outside and inside the building, i.e. wether amplification was present or not, and to study the effects of resonance in the building elements.

5.4.1 Finite element model

To study some effects of building design, the same soil geometry as the model used in the parametric study was used, with the addition of a simple building. The building has three storeys above ground level. Each floor in the building was 3 m in height and the width of the building was 10 m as shown in Figure 5.7.

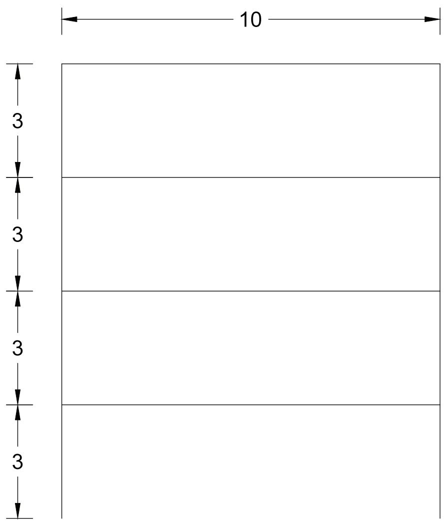


Figure 5.7: Dimensions of the building (m).

The vertical elements simulating walls were steel beams, equivalent of one square hollow section every two meters. The horizontal elements are equivalent of concrete slabs, each with a thickness of 0.2 m. Material properties used in the model are shown in Table 5.7. The cross-sectional properties for the parts of the building are shown in Table 5.8.

Table 5.7: Material parameters used in the model with a building.

Material	E (MPa)	ρ (kg/m^3)	ν	η
Soil	100	2000	0.48	0.10
Bedrock	10,000	2500	0.40	0.04
Steel	200,000	7850	0.30	0.04
Concrete	30,000	2400	0.20	0.04

Table 5.8: Cross-sectional properties for the building.

Section	A (m^2/m)	I (m^4/m)
Walls	0.0025	$1.013 \cdot 10^{-5}$
Floors	0.2	$6.67 \cdot 10^{-4}$

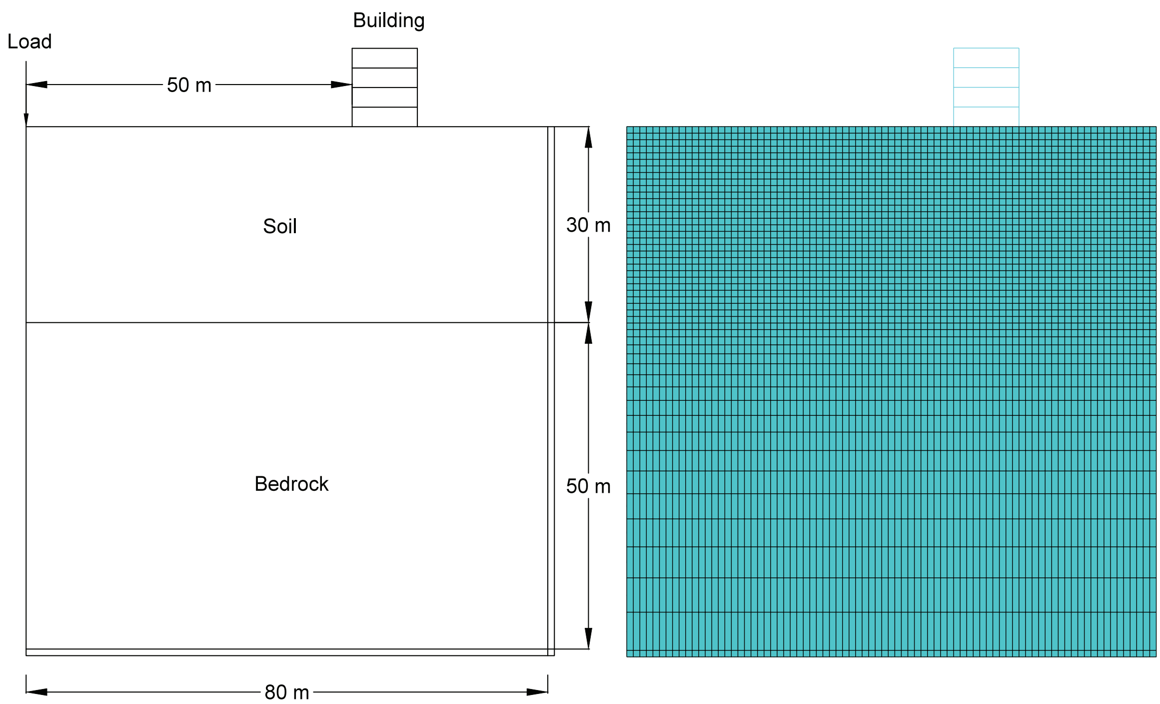


Figure 5.8: Soil model (left) and mesh (right)

The beam elements in the model were linear Bernoulli-Euler elements, named *B21* in Abaqus. The length of the beam elements were approximately 0.5 m. Quadratic plane strain elements as well as non-reflecting boundaries as described in the parametric study were again used in the soil. The size of the elements in the soil was again selected to accurately model the propagation of waves. In this study, the frequencies of interest are around the lower building modes and the elements were thus chosen as 1 m. The traction between the soil and building was assumed to be significant, thus a full tie interaction was used. The complete geometry and mesh are displayed in Figure 5.8

5.4.2 Results

Vertical velocities were evaluated in the soil at the footprint of the building and at the top floor. In Figure 5.9, the frequency response of the top floor and the building footprint, respectively, are displayed. At the footprint of the building, the amplitudes are increased at the resonance frequencies of the soil. An increase in amplitude is also seen in the top floor at the corresponding frequencies, i.e. the motion of the soil is driving the building. It can also be noted that for this particular case, the vibrations are amplified inside the building. At just above 4 Hz, a further increase in amplitude is seen, due to a resonance in the top floor slab. This results in high vibration levels compared to other frequencies.

In Figure 5.10, the fundamental frequency of the floor has been moved to 3.6 Hz by decreasing the stiffness of the floor. The oscillations of the soil and floor slab at 3.6 Hz are in this case of opposite sign and the peak vertical velocity was reduced by almost 40%. This is something that is realistically very difficult to control, but shows that the behaviour at resonance can vary considerably from case to case.

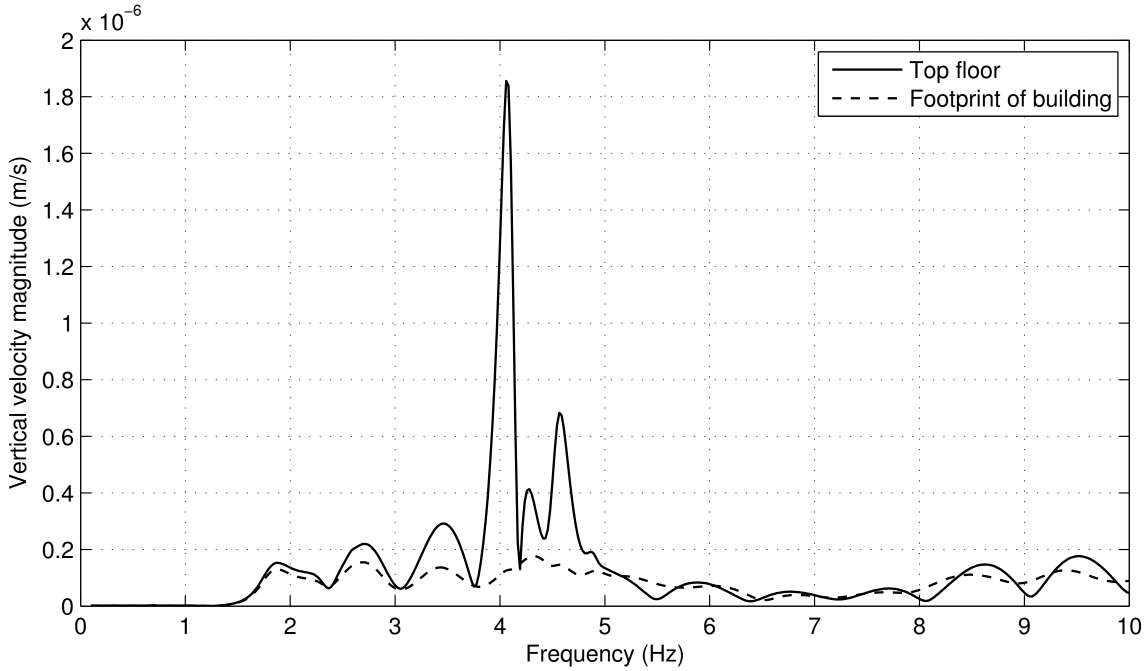


Figure 5.9: RMS velocities in nodes in the top floor of the building and at the footprint of the building.

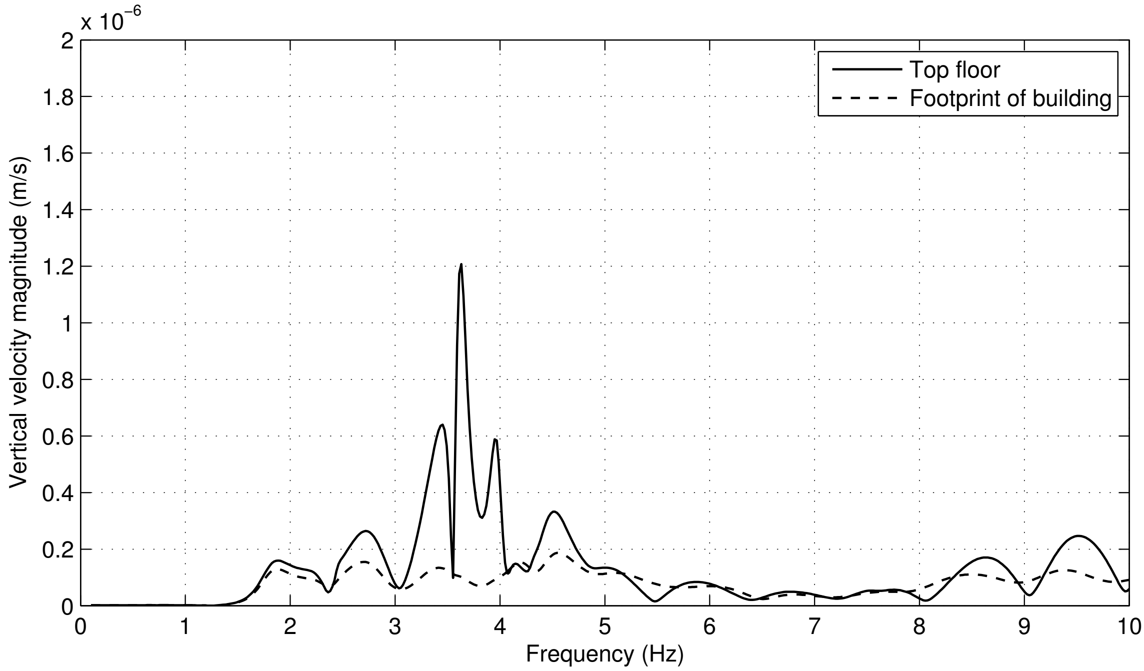


Figure 5.10: RMS velocities in nodes in the top floor of the building and at the footprint of the building when the eigenfrequency of the top floor has been lowered.

5.5 Simulations related to measurements

In the following analyses, the results from the measurements will be incorporated in the numerical models. This was done by scaling the harmonic load that is used in the steady-state analyses to the measured frequency response, with the intention that the load will contain similar frequencies as the measurements. The new, scaled load, was be applied on a model. The material parameters listed in Table 5.9 were used in the models, as they resulted in relatively good agreement between measurements and simulations in terms of peaks in magnitude.

Table 5.9: Material parameters in simulations related to measurements

Material	E (MPa)	ρ (kg/m^3)	ν	η
Soil	400	2000	0.48	0.10
Bedrock	10,000	2500	0.40	0.04

5.5.1 Scaling the harmonic load

The measured frequency response from a freight train was selected for use in the numerical analyses. The load was scaled using the measurements at 60 m from the track, according to the following equation

$$\text{Scaling factor at frequency } f = \frac{v_{measured,f}}{v_{model,1N,f}} \tag{5.1}$$

where $v_{measured,f}$ is the vertical velocity magnitude at frequency f acquired from measurements and $v_{model,1N,f}$ is the vertical velocity at frequency f from the finite element model using a unit harmonic load (1 N).

The response from measurements, $v_{measured}$ for the freight train, and the simulated response for a 1 N harmonic load, $v_{model,1N}$, are shown together in Figure 5.11. The finite element model used the same geometry as the previous models. The resulting scaling factors at every 1 Hz are plotted in Figure 5.12. This scaling factor was used as a frequency dependent amplitude for the harmonic load in the following steady-state analyses.

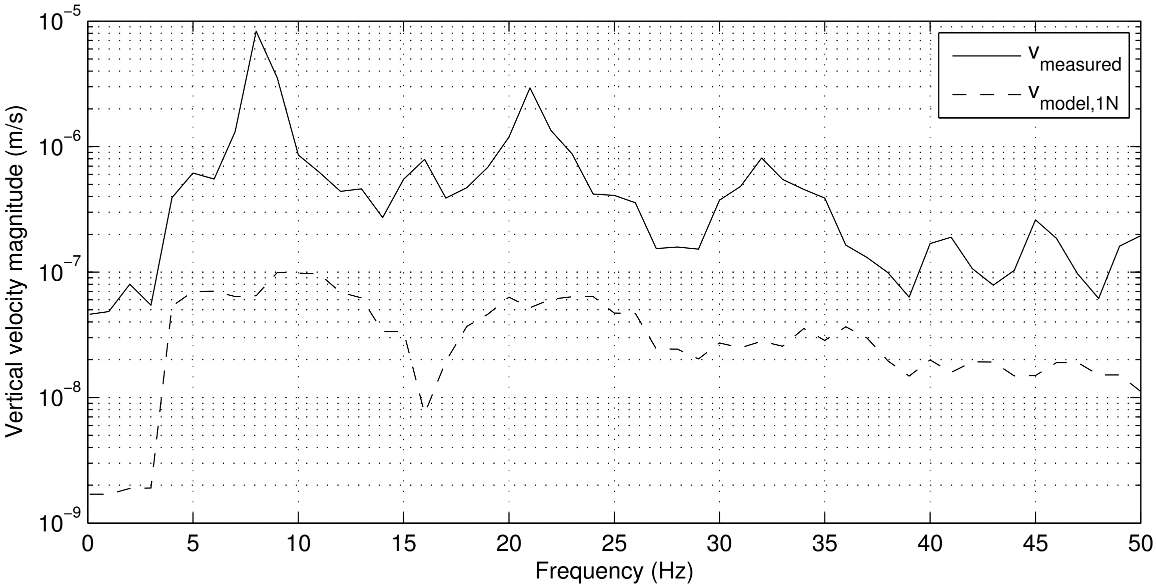


Figure 5.11: Measured response for a freight train and simulated response for a 1 N load at 60 m from track.

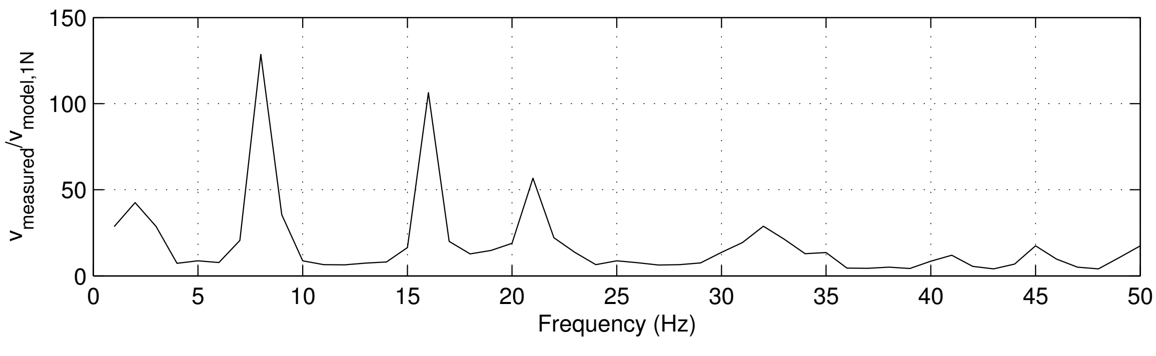


Figure 5.12: The scale factor at every 1 Hz.

5.5.2 Predicting vibrations at another point on the surface

The first numerical model related to measurements attempted to predict vibrations at another point on the soil surface by applying the scaled harmonic load on the soil model. The model has the same geometry as the model in the parametric study (see Section 5.3.1) and material properties according to Table 5.9. The steady-state response, 35 m from the railway track, was evaluated to compare with measurements.

In Figure 5.13, the frequency response from the model is compared to the response according to measurements at 35 m from the track. The model shows peaks at similar frequencies as the measurements, but heavily underestimates the amplitude at 7.5 Hz for instance. Since it is a line load, it has a different geometric attenuation, which can explain differences in amplitude. Additionally, the geometry and material parameters in the model may not be accurate.

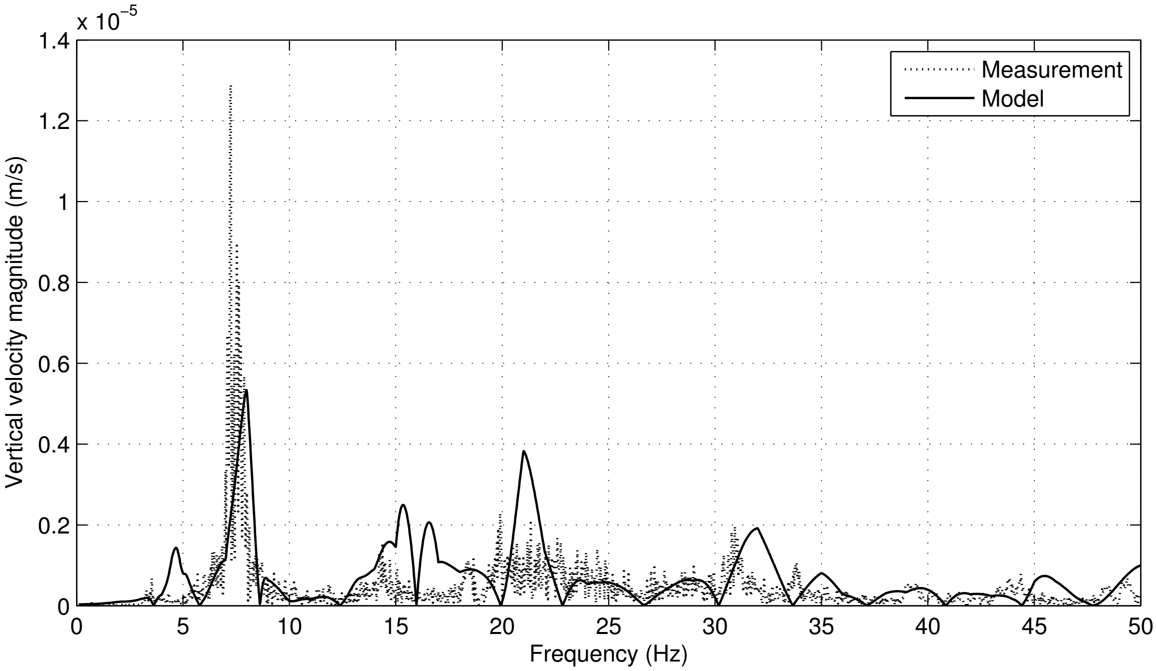


Figure 5.13: Predicted response 35 m from track.

5.5.3 Predicting vibrations inside a building

The second numerical model related to measurements attempts to predict vibrations inside a building through application of the scaled harmonic load. The left wall of the building is placed 60 from the railway track, i.e. the bottom left corner of the building coincides with the point where the scaling was made. The geometry is the same as previous model with building (see Section 5.4.1), with the exception of the building being moved 10 m further away from the source. Moreover, material parameters according to Table 5.9 were used. A steady-state analysis was carried out and the response inside the building, evaluated at the top floor, was compared to the response at the footprint of the building.

Figure 5.14 shows the vertical velocities at the footprint of the building and at the top floor (as RMS values over the nodes constituting these regions). There is a large peak at 8.1 Hz, due to the high magnitude that was also present in the measurements. At the resonance frequencies of the top floor slab, for instance around 5 Hz, the vertical velocity magnitudes are increased. They are not however of greater magnitude than the peak at 8.1 Hz. This suggests that, even though the natural frequencies of the building elements are very important, the frequency content induced by the load is very influential. In this example, the increased response at 8.1 Hz has a greater effect than the peaks due to eigenfrequencies of the floor slab.

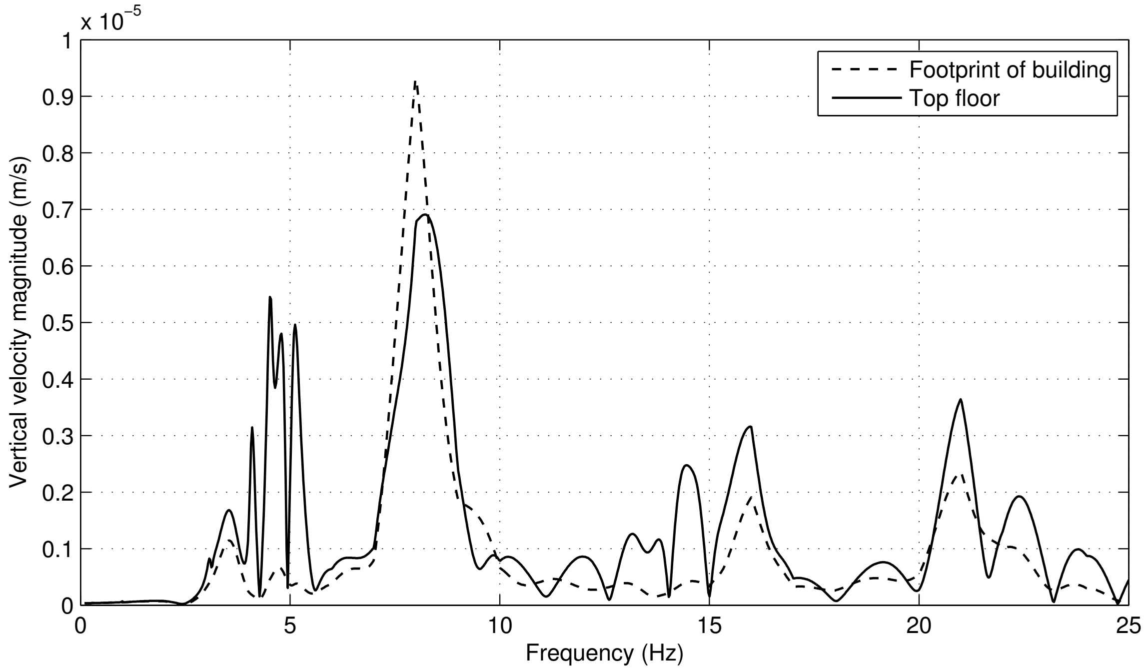
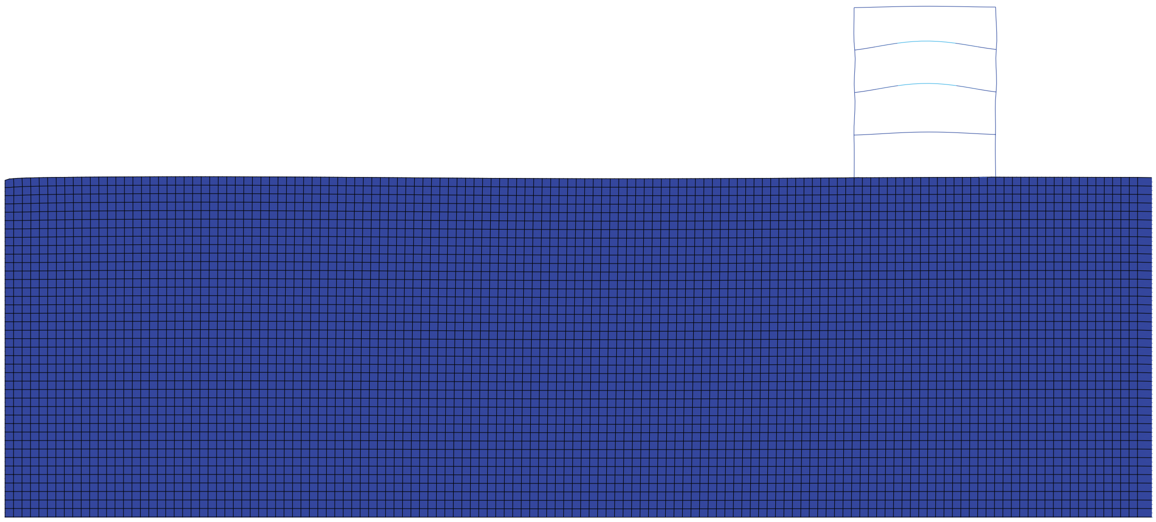
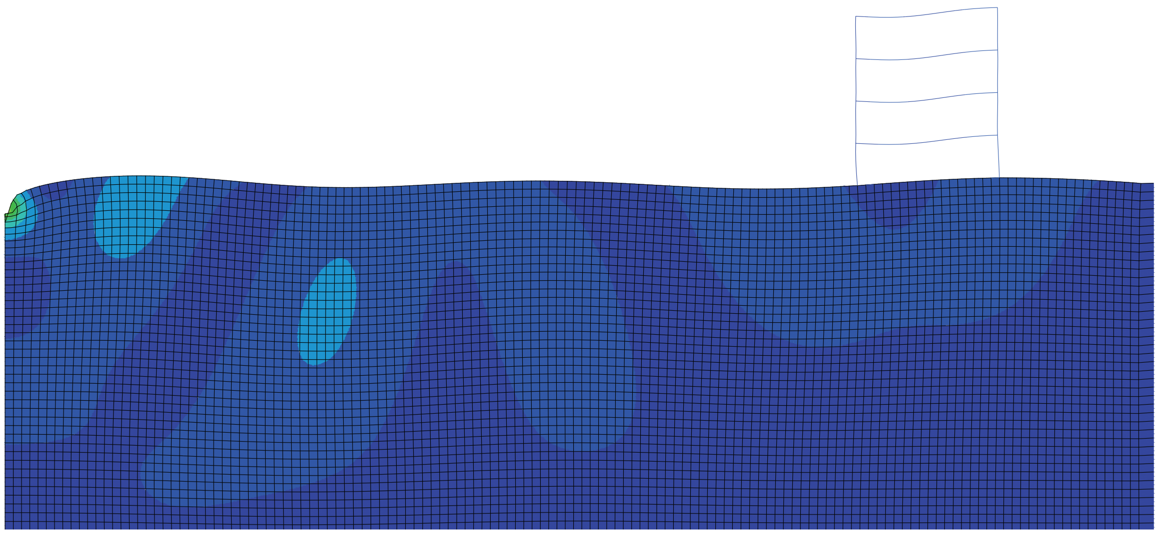


Figure 5.14: Predicted response inside a building.

A snapshot of the deformed mesh for the steady-state analysis at 4.9 Hz is shown in Figure 5.15a. The vibrations in the building are caused by the resonance in the floor slab. In Figure 5.15b, the deformed mesh at 8.1 Hz is shown, where the response of the top slab is increased due to the high magnitudes of vibration in the soil.



(a) $f = 4.9$ Hz.



(b) $f = 8.1$ Hz.

Figure 5.15: Visualisation of displacement at different frequencies, upscaled by 10^6. The uppermost 20 m of the soil is displayed.

6. Discussion and concluding remarks

6.1 Discussion of measurements

One of the aims of this thesis was to obtain more knowledge of the characteristics of vibrations induced by railway traffic. This was mainly done through the field measurements. The measurements showed a large variation for different train passages, both in terms of the waveform and vibration level, as well as, frequency content. This agrees with theory (e.g. some excitation mechanisms are due to random irregularities) and previous work, in that railway-induced vibrations are stochastic in nature.

Measurements showed that the decay of vibrations was rapid as distance from the source increased. At distances further than 10 m from the track, the vibration levels in the ground were for all trains below the level relevant to human disturbance (see Figure 4.11). The measurements also showed that the decay is frequency dependent. Vibrations of higher frequencies are damped out quicker, and certain frequencies remain. It is possible that these frequencies are resonances in the soil, which highlights the importance of knowing these frequencies when predicting ground vibrations.

When comparing differences in vibration levels from passenger trains and freight trains, measurements indicated that freight trains result in higher vibrations levels. Freight trains are characterised by high magnitudes at the beginning of the signal, most likely due to a pulling locomotive. There is not enough data of freight trains to draw definite conclusions regarding differences, but the measurements gave the aforementioned indications. Another factor worth mentioning is that freight trains were operating at lower speeds (almost half the speed) compared to the passenger trains which also results in differences.

Since the train speeds were roughly approximated using video recordings, no conclusions regarding the affect of train speed were drawn. A better method of measuring train speed, such as a radar gun, would be helpful. Another method is to mount an accelerometer on the track itself, in order to measure the deflection. With a known axle spacing and the time it takes each wheel-axle to pass, the velocity can be estimated. This was unfortunately not possible in this project since special permissions are required for entering a railway track area. Measurements directly on the track, or at least closer to the track, can also be useful in terms of understanding the vibrations.

A downside with the chosen test site was that the soil conditions were not known on a detailed level. This means that it is difficult to put the results acquired in relation to other soil types. Moreover, no measurements were performed inside buildings near a railway track, something that could have provided further insight regarding how railway-induced vibrations propagate in buildings.

Ultimately, the use of seismometers proved successful, and can be a useful way of determining vibration levels. The main advantage of seismometers of this kind is the ease of use and quick set-up. The quick set-up means there is a possibility of quickly be performing measurements on many different sites with ease.

6.2 Discussion of simulations

In the parametric study, the influence of different soil parameters were studied. The soil properties affect the frequency response in different ways. The loss factor, for instance, is a very important factor for determining the magnitude of vibrations, but it does not affect the resonance frequencies in the soil. The elastic modulus and the Poisson's ratio, however, have a marked effect on the resonance frequencies and are important if the resonance frequencies are to be determined. Additionally, the elastic modulus has a great effect on the vibration levels. Since the elastic modulus can potentially vary a lot between different sites, it is an especially important parameter to accurately measure if any numerical models are to be used. This is in contrast to the soil density, which does not have a particularly noticeable effect on the vibration levels or resonance frequencies, in part due to the fact that the density can not physically vary as much. The soil layer depth is also important to describe the resonance frequencies of the soil.

The effects on structures were studied using a model with soil and a simplified building. The analyses showed a potential of vibrations getting amplified at the building parts. In the models analysed, there was an increase in response at the resonance frequencies of the soil, which was generally amplified in the building. A further increased response was seen at the eigenfrequencies of the floor slabs. This shows that the resonance frequencies, both in the soil and the building can be important factors for the overall vibration levels. The soil–structure interaction was done using full ties, which is a simplification as the connection to the ground is not completely rigid and can provide a mechanism for energy dissipation.

The measurements were incorporated in the numerical models by scaling the amplitude of the harmonic load to the measurements. The results indicated that, in regards to the vibration levels inside the building, the contents of the vibration can be of great importance, in addition to the effects of resonance. Combined with measurements, scaling the frequency response can be a method for evaluating a building that is to be constructed, although the accuracy of this method was not studied in this thesis. Studying a model that includes a building however, requires extensive knowledge of the building itself, such as information regarding structural system, structural elements and material properties, which makes this method more suited for detailed analysis.

6.3 Predicting railway-induced vibrations

The prediction of railway-induced vibrations, for instance in a proposed building, is a complicated matter since a vast amount of factors are involved in the process. In this thesis, some methods that can be used to predict ground vibrations were examined.

Measurements can in general be used to evaluate a specific site exposed to vibrations, for instance at the proposed location of a planned structure. If the vibration levels are considered too high, measures of reducing the vibration levels can be applied. Analysis of measurements in the frequency domain can further provide information about sensitive frequencies in the soil.

Numerical simulations with the finite element method can be used to evaluate a ground model if sufficient material data is available. With steady-state analyses, sensitive frequencies in the soil can be estimated. Numerical models involving a building however require knowledge of material properties and structural information, making these types of models likely better suited for detailed analysis.

Other prediction models, such as empirical methods, are possible tools for predicting railway-induced vibrations, especially at early stages of a project. Some existing prediction models were described in Section 2.5. The accuracy of these models or a comparison between them was not included in the scope of this thesis, however.

To conclude, some important aspects relevant to the prediction of railway-induced ground vibrations are presented.

- Vibrational requirements can be decided on case by case basis, but general guidelines by the Swedish Transport Administration (Trafikverket) suggest that vibrations in newly developed residential buildings shall be below 0.4 mm/s RMS. For additional guidelines, ISO 2631 can be used as guidance for different building usages or VC-curves for sensitive equipment (see Section 2.3).

- Knowledge of soil conditions is very important when analysing vibrations induced by railway traffic. Softer materials, such as clay, are associated with higher vibration levels. Elastic modulus, Poisson's ratio and thickness of the soil layers are essential for determining resonance frequencies in the ground using numerical simulations. The depths of the soil layers and distance to bedrock can often be available in regular geotechnical investigations, but to measure the dynamic soil properties, in-situ geophysical methods are preferred. For determining absolute values of vibration levels, the loss factor is a very important parameter. Density of the soil is not particularly important to measure accurately and can be estimated using existing literature or empirical models.

- Knowledge of resonance frequencies in both building and soil can be beneficial and be used to avoid high vibration levels, as significant increase in response occurs at these frequencies. Ultimately, without these frequencies present in the vibrations, they will not be excited. Information about the frequency content of the vibrations, for instance from measurements, is therefore very important.

- If the predicted or measured vibrations levels are considered too high or the project involves high risks, there are methods available for reducing the vibrations. Several vibration-reduction measures are described in Section 2.3.

6.4 Suggestions for future work

The field measurements in this thesis focused on vibrations in the ground and no measurements were performed inside buildings. In future studies, buildings can be included, since the problem of railway-induced vibration in urban environments primarily concerns human disturbance. Coupling between the soil and building and wether vibrations are amplified inside a building or not are possible areas of studies. Transfer functions between a point in the soil outside the building and a point inside the building can be established. Future measurements for this purpose are preferably carried out at a site where soil properties are known in greater detail, in order to put the measured vibration levels in context.

Another interesting area of study is numerical models related to the prediction of railway-induced vibrations. With continued advancements in computer power, there is an opportunity to explore more advanced finite element models, such as three-dimensional models or models that attempt to describe the source in a more accurate way.

In general, railway-induced ground vibrations is a wide-ranging field with many potential areas that can be studied. A more in depth study of any of the stages in the transmission process (source, propagation, receiver) can be performed. Ultimately, it is of interest to create a reliable prediction model or strategy for railway-induced ground vibrations in buildings. It is beneficial if the prediction model can be used at an early stage of planning, so that requirements for the planned building can be stated early during the project or vibration-reduction measures can be designed.

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