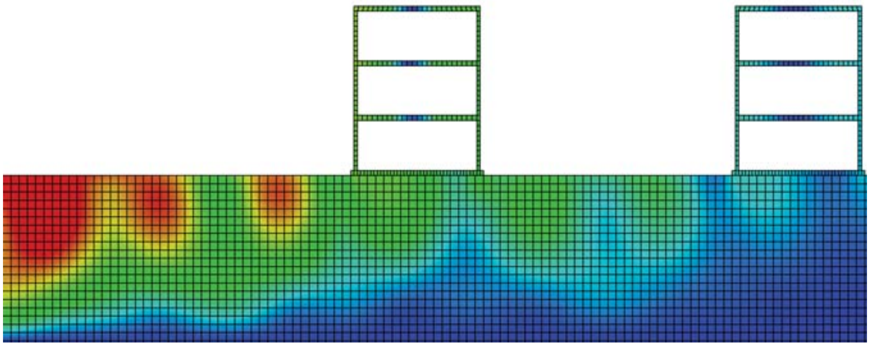
Lund University



STRUCTURAL EFFECTS ON EXTERNALLY INDUCED BUILDING VIBRATIONS

ALFRED JOHANSSON

Structural Mechanics

Master's Dissertation

DEPARTMENT OF CONSTRUCTION SCIENCES
DIVISION OF STRUCTURAL MECHANICS

ISRN LUTVDG/TVSM--18/5230--SE (1-49) | ISSN 0281-6679
MASTER'S DISSERTATION

STRUCTURAL EFFECTS ON EXTERNALLY INDUCED BUILDING VIBRATIONS

ALFRED JOHANSSON

Supervisor: **PETER PERSSON**, PhD, Division of Structural Mechanics, LTH.
Examiner: Professor **KENT PERSSON**, Division of Structural Mechanics, LTH.

Printed by V-husets tryckeri LTH, Lund, Sweden, October 2018 *(Pl).*

For information, address:
Division of Structural Mechanics,
Faculty of Engineering LTH, Lund University, Box 118, SE-221 00 Lund, Sweden.
Homepage: www.byggmek.lth.se

Contents

Acknowledgements

This thesis concludes my 5+ years at Faculty of engineering, Lund university. I would like to begin by thanking Prof. Kent Persson and my supervisor Dr. Peter Persson for providing me with the idea for this thesis. I would also like to thank them for their continued support and feedback during the work and the discussions we've had. I am also grateful to the Division of Structural Mechanics, where the work was performed, for welcoming me into the department with open arms, interesting conversations and good coffee.

Finally I would like to give thanks to my friends and family for their unwavering support throughout my entire life. Special thanks to my parents Åke and Marie Johansson, my brother Filip Märling and his wife Angelica Märling, my sister Linnea Szilas, her husband Noa Szilas and their daughter Ester Szilas and last but not least my girlfriend Emma Persson.

Alfred Johansson, Lund, May 2018

Abstract

Much focus is being laid on vibrations in the building industry today. Many times these vibrations are externally induced and caused by placing buildings closer to existing sources, such as railways and roads, or new transportation systems closer to existing buildings. Vibrations can be disturbing to both humans and sensitive equipment in, for example, hospitals and laboratories. The simulations needed to investigate the effects of these vibrations are complex. Because of this it is important to know which studies are needed in a project and what parameters need to be evaluated.

In the Master's dissertation, the important parameters for a building and its surrounding materials, when analysing externally induced vibrations in the built environment, are investigated. The focus of the study is on the effects of surrounding buildings in numerical models, i.e. how multiple buildings will respond to external vibrational sources compared to the response of a single building. Numerical parametric analyses were performed in the commercial software Abaqus using two-dimensional finite element models with different geometry, mass, stiffness and damping. Plain strain conditions were used in the layered ground model and the concrete buildings. Steady-state analyses were performed for the frequency spectrum between 1 and 80 Hz, with a linear step size of 0.5 Hz applying a unit load of 1 N, 50 m from the studied building.

Both the effects of a building being placed in front of a studied building and a building being placed behind the studied building was investigated. How nearby buildings affect the response to external vibrations on a building is difficult to predict and it's hard to find general principles that describe it. It is, however, clear that nearby buildings have an impact on the vibrational response. A large reduction in vertical response amplitude can be observed when a building is placed in front of a building that is similar in geometry. The largest reductions in displacement seem to coincide with the resonance frequencies of the buildings. A heavy building and a building with low damping being placed between the load and the studied building yielded similar results in that they both corresponded to a lowering of the vertical displacement amplitude. A building placed after the studied building in the direction of the propagating waves does not have a large impact on the vertical vibrational response. Only when the building behind is partly submerged into the soil i.e. having a cellar, is the difference in response for the studied building noticeable but still low.

Keywords: Building vibrations, finite element method, structural dynamics, soil dynamics, structure-soil-structure interaction.

1 Introduction

1.1 Background

Today, more focus is being laid on vibrations in buildings than previously. Many times these vibrations are externally induced and caused by placing buildings closer to existing sources, such as railways and roads, or new transportation systems closer to existing buildings. Vibrations can be disturbing to both humans and sensitive equipment in, for example, hospitals and laboratories. The effects of these vibrations depend on the amplitude and frequency of the vibrations, but also the sensitivity of the subject. To investigate these vibrations and their effects, studies can be conducted using large three-dimensional (3D) numerical models with finite elements (FE). The simulations needed to investigate the effects of these vibrations are complex and require a lot of computational power. Because of this it is important to know which studies are needed in a project and what parameters need to be evaluated.

The accuracy of simplified models where wave-impeding blocks are placed in an array either directly on the ground surface or partly in the ground and the effectiveness of these blocks in reducing vibration levels behind them was investigated in a study [1] by L.V. Andersen et al. The study concluded that reductions in vibration levels can be seen using only one block, but that an array of multiple blocks can be even better in this regard. Embedded blocks were shown to be even more effective but the authors also note that caution should be taken when drawing conclusions from the study because of large variations in the results. In a paper [2] by A. Kham et al. the phenomena called site-city interaction was investigated using conceptual city models. The parametric study concluded that when the fundamental frequency of the ground is the same as the building's eigenfrequencies, building and ground motion is decreased. In an article [3] by J. Liang et al. the structure-soil-structure interaction (SSSI) was investigated. The investigation was done for two walls, partly embedded in a soft layer with a hard bedrock beneath. The authors concluded that the resonances of the studied structures and the resonance of the soil are the most significant factors in the dynamic response, but also that neighbouring structures should be taken into consideration when predictions concerning dynamic response of buildings are made. In a Doctoral thesis by P. Persson, traffic-induced vibrations in a built environment and how to mitigate these is studied. The writer concludes that a trench can mitigate up to 60% of the vibration levels[4] and that shaping of the landscape surrounding a structure also can reduce the vibration levels significantly [5]. It is also shown that stiffening of the soil beneath a building has a positive effect [6]. Knowledge surrounding SSSI can give reductions in the amount and extent of the measures necessary to mitigate vibrations in a built environment. This can, for example, mean that buildings are placed in a certain pattern so that no measures at all are needed.

1.2 Aim and objective

In the Master's dissertation, the important parameters for a building and its surrounding materials, when analysing externally induced vibrations in the built environment, are investigated. The focus of the study is on the effects of surrounding buildings in numerical models, i.e. how multiple buildings will respond to external vibrational sources compared to the response of a single building. The aim is to show when the influence of surrounding buildings should be considered in prediction of externally induced building vibrations. This knowledge is important for the building industry because of the potential time savings, and therefore also cost savings, in construction projects due to a better understanding of building vibrations and the development of easy to use models because of this.

1.3 Method

A literature study was conducted to establish a knowledge base about the subject and approach the state-of-the-art. Numerical analyses were performed using finite element models in the commercial software Abaqus. The investigation of the structures was conducted using two-dimensional (2D) finite element (FE) models with differences in geometry, mass, stiffness and damping. By limiting the study to using only 2D FE-models more analyses could be performed. A layered ground model was employed for the cases studied. A desktop computer with access to the finite element method program Abaqus was used alongside the numerical computing environment Matlab.

1.4 Outline

- Chapter 1 contains the background, the aim and objective, the method and the outline of the dissertation.
- Chapter 2 contains an overview of externally induced building vibrations, describing transmission and the impact of vibrations.
- Chapter 3 contains the governing theory used in the dissertation.
- Chapter 4 contains the numerical models for the buildings and the ground, and a convergence study to determine the geometry and complexity of the FE model needed in the analysis.
- Chapter 5 contains the numerical parametric analyses, investigating the effects of a nearby building on the response of a building to an external vibrational source and the results from this.
- Chapter 6 contains the concluding remarks, including main conclusions and suggestions for future work.

2 Externally induced building vibrations

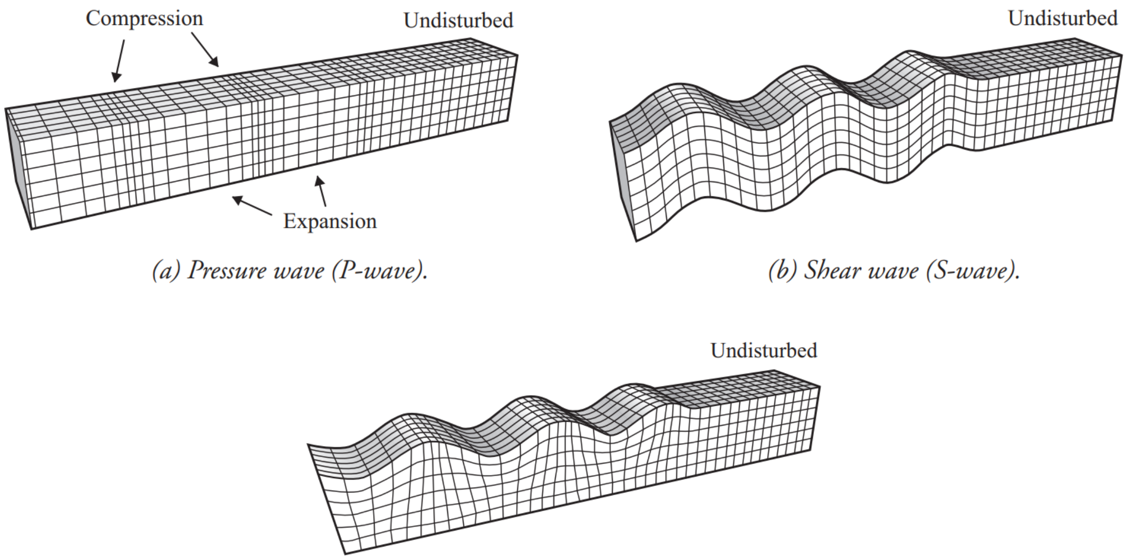
Externally induced vibrations can come from different types of traffic, but also from construction sites or industries. Vibrations from traffic can originate from cars and trucks on roads and trains on tracks.
Vibrations can be divided into three parts, the source, the medium and the receiver. To understand the transmission of vibrations it is important to understand all of these parts. Vibrations in a built environment can originate from two different types of sources, external and internal. External sources are located outside the studied structure, for example, different kinds of traffic on road or track. These vibrations mostly come from different kinds of unevenness in the roads and tracks and from connections between bridges and bridgeheads. The intensity of external vibrations is steadily increasing because of bigger, faster and heavier transportation vehicles being deployed. The intensity of vibrations varies over frequencies and different sources produce high energy vibrations in different frequency spectrums. Internal sources are located inside the building and are commonly manifested as vibrating machinery, like fans or pumps, or human activity, like walking, dancing, music, etc. The materials between the source and the receiver is called the medium. The characteristics of the medium has a big impact on the speed and intensity of the propagating waves and the displacements caused by these. For external sources the ground, and for long distance cases the bedrock, becomes the medium. Energy losses from the medium to the propagating wave come from geometrical damping and material damping, but reflection and refraction also give a reduction in how much of the propagating wave that reaches the receiver. The receiver is the object, structure or person for which the vibration levels are important. This can be because of physical limitations or psychological disturbance tolerances. The limitations varies for different structures but it can generally be said that a building is most vulnerable at its natural frequency, see Section 3.5.1, which for common buildings can vary from below 1 to over 50 Hz [7]. Lighter structures, like wood- or steel framed buildings, are more sensitive to vibrations.

The impact of vibrations can be divided into effects on humans, effects on machines and structural damage. The effect vibrations have on humans has to do with human perception and the effects can vary greatly. Between 1 and 80 Hz is, according to ISO 2631 [8], the frequency range to evaluate human exposure to vibrations in buildings. The frequency range where humans are most sensitive is between 0.5 and 10 Hz [9]. The main health issues caused by vibrations are sleep disturbance, cardiovascular diseases and, for small children, cognitive impairment [10]. For buildings the biggest risks concerning vibrations are cracks and settlements. The vibrations need to be quite large in magnitude to cause problems for well built, foundationally sound, structures. The effect on sensitive equipment can however be more noticeable. Manufacturers of sensitive equipment, used in research and precise manufacturing, specify limits which the vibration levels need to be kept below, but general limitations for vibration levels have not been established.

3 Governing theory

In the chapter the governing theory is presented, including sections on wave types, the FE method, plane strain, element types, structural dynamics and the evaluation methods used.

3.1 Wave propagation in ground



(a) Pressure wave (P-wave).

(b) Shear wave (S-wave).

(c) Rayleigh wave.

Figure 1: Common wave types, in ground, containing vertical displacements. Figure source: [7]

There are two types of waves discussed when talking about vibrations in ground. The first one is body waves and the second one is surface waves. The two main components of body waves are pressure waves (P-waves) and shear waves (S-waves). P-waves are periodically alternating zones of compression and zones of expansion moving through a medium, see Figure 1a. They can travel through both solids and fluids. That is not the case for S-waves, as fluids do not have shear strength in the same way as solids. Another difference between P-waves and S-waves is that P-waves are significantly faster in their propagation speed. S-waves are periodic shear deformations of the medium occurring perpendicular to the direction of the wave, see Figure 1b. The main components of surface waves are Love waves and Rayleigh waves. Love waves propagate through the medium with particle motion perpendicular to the direction of the wave and parallel to the surface i.e. no vertical component and they are therefore not discussed further in this dissertation. Rayleigh waves propagate through the medium containing a mix of pressure and shear motion, see Figure 1c. The pattern in which the particles move is elliptical. The propagation speed of Rayleigh waves are quite similar to S-waves. The relation between wave length, λ, and frequency, f, is given by the following equation:

$$\lambda = \frac{f}{c} \tag{3.1}$$

where c is the wave speed for the specific wave type in the studied medium.

3.2 Finite element method

The physical problems found in engineering mechanics are often modelled using differential equations. These can be very complex and are often not solvable using exact analytical methods. The finite element (FE) method allows these problems to be solved approximately by use of a numerical approach. This is done by dividing the studied region, be it one-, two or three-dimensional, into smaller parts. These parts are called finite elements and the collection of all the parts are called the finite element mesh. Even though the studied variable varies non-linearly over the studied region it is possible to assume a linear variation over each individual element which solves the problem, assuming a small enough element size. An infinitely small element size would make the solution exact but as long as the solution is close enough, for the purpose of the problem, the resulting solution can be used. The result from each individual element is then assembled to form a solution over the complete studied region, an integration is being made. The method is today widely used in the industry with many programs to choose from. Many of these are both relatively easy to use and are able to present results in a clear informative fashion. Though this is all good and well, a word of caution is recommended when interpreting the results because of the approximations made and the complex nature of said results. Different assumptions made when modelling physical problems can have a large impact on the results. A static system is, using a FE model, written as

$$\mathbf{K}\mathbf{u} = \mathbf{f} \tag{3.2}$$

where $\mathbf{K}$ is the stiffness matrix, $\mathbf{u}$ is the displacement vector and $\mathbf{f}$ is the force vector. [11]

3.3 Plane strain

The displacement per meter caused by stress in an object is called strain, see Equation 3.3.

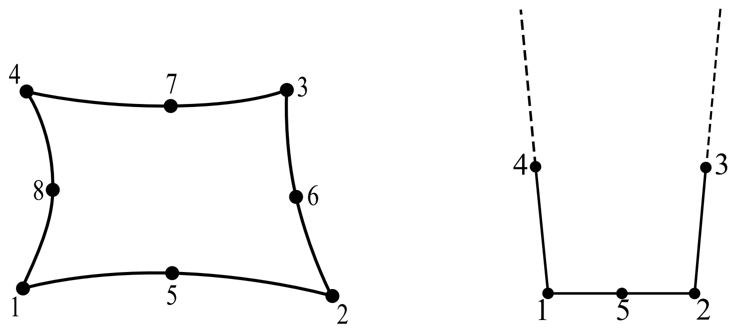
$$\varepsilon = \frac{du}{dx} \tag{3.3}$$

where ε is strain, du is the change in length and dx is the length of the object before deformation. For a long object with the same cross-section over the entire length, it can be assumed that all movement is restricted in the longitudinal direction. This means that strains only exist in the perpendicular plane to the longitudinal axis, which is called plain strain conditions.

3.4 Element types

There are many types of finite elements and the following element types are used in the analysis. An element with quadratic approximation in two directions is called biquadratic. This means that the displacements can vary non-linearly along the element boundaries. In the FE method, integration is used to determine the solution. This can be computationally expensive to solve but there are simplifications that can be made. Lowering the order of integration, called reduced integration, is one of these. When full integration is used, the stiffness matrix is overestimated and the solution can differ from real life behaviour. Reduced integration lowers the accuracy but can, because of no overestimation of the stiffness matrix, also give a solution that is more similar to real life behaviour.

A biquadratic plane strain element with 8 nodes, using reduced integration, is denoted CPE8R in Abaqus Standard 6.13 [12]. This element can be seen in Figure 2a. An element which is non-reflective on one of its boundaries is called one-way infinite. A quadratic element with 5 nodes and one non-reflective boundary is denoted CINPE5R in Abaqus Standard 6.13 [12] and can be seen in Figure 2b.



(a) CPE8R (b) CINPE5R

Figure 2: Element types used in the numerical model.

3.5 Structural dynamics

The type of structural analysis where structures are subjected to dynamic loading, as opposed to only static loading, is called structural dynamics. A dynamic load is a load that changes over time, like for example, loads from wind, earthquakes, people or machines with rotating parts like washing machines, just to name a few.

For a single degree of freedom (sdof) system, with a damper and a dynamic load acting on it, see Figure 3, Newton's second law of motion gives, using the same notation as in [13],

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

where m is the mass, $\ddot{u}$ the acceleration, c the damper, $\dot{u}$ the velocity and $f(t)$ the time dependent load. For a multi-degree of freedom (mdof) system, using matrix notation this gives

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

where $\mathbf{M}$ is the mass matrix, $\mathbf{\ddot{u}}$ the acceleration matrix, $\mathbf{C}$ the damping matrix, $\mathbf{\dot{u}}$ the velocity matrix and $\mathbf{f(t)}$ is the time dependent force vector.

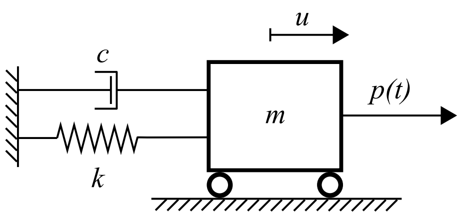


Figure 3: A single degree of freedom system including mass, m, displacement, u, damping, c, spring, k, and time dependent load, $p(t)$.

For an sdof system with damping included, the response to a harmonic load can be expressed with the following equation:

$$m\ddot{u} + c\dot{u} + ku = p_0 \sin \omega t. \tag{3.6}$$

The solution to this differential equation contains two different vibrational components. The particular solution is called transient and the complementary solution is called steady-state. The important difference between the two is that the transient response decays quite quickly over time, while the steady-state remains. The steady-state response can, using complex notation, be expressed as

$$u(t) = \hat{u}e^{i\omega t} \tag{3.7}$$

$$v(t) = |V|e^{i\omega t} \tag{3.8}$$

where $u(t)$ is the displacement, $\hat{u}$ the complex displacement amplitude, $v(t)$ the velocity, $|V|$ the complex velocity amplitude, i the complex number and ω is the angular frequency. The applied load written using complex notation is

$$p(t) = \hat{p}e^{i\omega t} \tag{3.9}$$

where $p(t)$ is the load and $\hat{p}$ is the complex load amplitude. This equation combined with Equation 3.7 and the first and second derivative of Equation 3.7 give the following:

$$\mathbf{D}(\omega)\mathbf{\hat{u}} = \mathbf{\hat{p}} \tag{3.10}$$

where

$$\mathbf{D}(\omega) = -\omega^{\mathbf{2}}\mathbf{M} + \mathbf{i}\omega\mathbf{C} + \mathbf{K} \tag{3.11}$$

and $\mathbf{D}$ is called the dynamic stiffness matrix.

3.5.1 Resonance

The frequency at which an object vibrates when given the chance to do so freely is its natural frequency. To find the natural frequency, f_n, the following equation is used

$$f_n = \frac{\sqrt{k/m}}{2\pi} \tag{3.12}$$

which for a system with damping included is

$$f_n = \frac{\sqrt{k/m}}{2\pi}\sqrt{1-\left(\frac{\eta}{2}\right)^2} \tag{3.13}$$

where η is the loss factor. For most civil-engineering structures the loss factor has a value below 0.4 [13]. A structure has, in reality, an infinite number of natural frequencies and the lowest is called the fundamental frequency. The frequency at which an object gives the biggest response to a dynamic load is called the resonant frequency. Resonance occurs when a dynamic load matches the natural frequency of the structure. The deformations will over time become infinite for an undamped system, but in reality this is never the case because there is always damping present. Also the material will of course fail before that happens. Figure 4 shows what happens to the deformation when the loading frequency, f, comes closer and closer to the natural frequency.

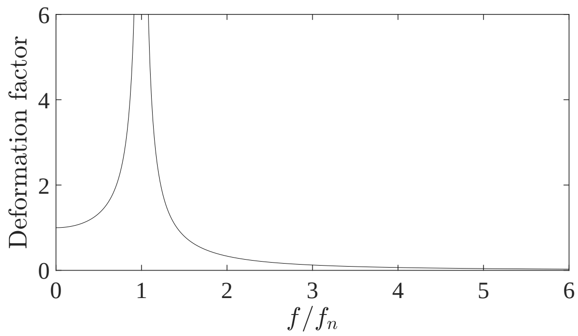


Figure 4: Showing how the deformation factor varies when the loading frequency is varied.

The deformation factor is calculated using

$$\text{Deformation factor} = \left|\frac{1}{1-(f/f_n)^2}\right|. \tag{3.14}$$

3.5.2 Damping

Vibration is a mechanical phenomena and the amplitude of the oscillations will in reality gradually reduce in size. The mechanical phenomena where the amplitude of vibrations gradually decrease is called damping and it happens because of various mechanisms that has to do with energy loss. These losses can come from both internal and external friction. The friction can appear in connections between structural components and between different building elements, but also from imperfections inside the different building materials. To identify and quantify these processes is very hard to accurately do and idealisations need to be made. This is most often done by combining all the damping mechanisms into one single damping coefficient which has an equivalent effect to all the different damping factors, both known and unknown. This coefficient can, because of its complexity, not be calculated and must be provided by doing experiments on actual structures. The loss factor, η, is a measure of how much of the energy is being lost because of damping and can be calculated using

$$\eta = \frac{E_D}{2\pi E_S} \tag{3.15}$$

where E_D is the energy lost because of damping and E_S is the strain energy put in to the structure. These measures of energy can be calculated using

$$E_D = \pi c \omega u^2 \tag{3.16}$$

$$E_S = \frac{ku^2}{2} \tag{3.17}$$

where c is the viscous damping constant, ω is the angular frequency, k is the stiffness and u is the displacement. The connection between the loss factor, η, and the damping ratio, ζ, can be expressed using the following equation:

$$\eta = 2\zeta. \tag{3.18}$$

3.6 Evaluation of vibration and error levels

When evaluating vibrations and error levels it is important to specify what is actually evaluated. This is important both when discussing and comparing results.

3.6.1 Vibration levels

To evaluate the vibration levels of a structure, the vertical complex velocity amplitude can be used. It can be helpful in the evaluation to calculate a root mean square (RMS) value over a number of nodes. This is done for each studied frequency using the following equation:

$$|V|^I_{RMS}(f) = \sqrt{\frac{1}{n}\left(\sum_{j=1}^{n} |V|_j^2\right)} \tag{3.19}$$

where $|V|$ is the vertical complex velocity amplitude, n is the number of nodes and j is each studied node. Another RMS value can be calculated over the studied freqencies using the following equation:

$$|V|_{RMS}^{II} = \sqrt{\frac{1}{m}\left(\sum_{k=1}^{m}\left(|V|_{RMS}^{I}(f_k)\right)^2\right)} \tag{3.20}$$

where m is the number of frequency steps studied and k is the frequency.

3.6.2 Error levels

To evaluate the accuracy of the model, when doing a parameter study, another RMS value can be calculated. The error, in percent, between the complex velocity amplitude for the studied model, V, and for a reference model, V_{ref}, is calculated for each frequency step, j, and the RMS value is calculated considering all of the studied frequency steps using the following equation:

$$Error_{RMS} = \sqrt{\frac{1}{m}\sum_{j=1}^{m}\left(100 \cdot \left|\frac{|V| - |V|_{ref}}{|V|_{ref}}\right|\right)^2} \tag{3.21}$$

where m is the number of frequency steps.

4 Numerical model

A 2D FE model was constructed using Abaqus 6.13 including a layered ground model and simple representations of concrete buildings. Plane strain condition was used in the numerical model because this was, in this case, more accurate. The reality is somewhere between plane stress and plane strain, but simplifications need to be made. The ground model was restricted in its horizontal movement along the left edge, and rotation was only allowed around the horizontal axis. The only external force was a concentrated instantaneous force with a magnitude of 1 N, applied in the upper left corner of the ground model. Both the ground and the buildings were modelled using deformable 2D elements and the connecting between the different parts were modelled using a *tie* constraint. The analysis type *Steady-State dynamics, Direct*, in Abaqus Standard 6.13 [12], was used. The studied frequency spectrum ranges from 1 to 80 Hz, with a linear step size of 0.5 Hz which gives a total of 159 studied frequencies.

4.1 Convergence study

To investigate the needed size and complexity of the model, a convergence study was conducted. This was done to minimise the time and effort necessary for each analysis. A 2D FE model was built using Abaqus including a layered ground model and a simple representation of a concrete building. The ground model was restricted in its horizontal movement along the left edge, and rotation was only allowed around the horizontal axis. The only external force was a concentrated instantaneous force with a magnitude of 1 N, applied in the upper left corner of the ground model. Both the ground and the building were modelled using deformable 2D elements and the connecting between the different parts were modelled using a *tie* constraint. The analysis type *Steady-State dynamics, Direct* was used. For detailed information surrounding geometry, materials, finite element mesh and element types for the building and the ground, see Sections 4.2 and 4.3, respectively. In the convergence study, one parameter at a time was varied and all of the others were kept constant.

4.1.1 Frequency step size

The first parameter varied was the frequency step size for the analysis. The frequencies between 1 and 80 Hz, with five different incrementation sizes of frequency steps, were studied. An RMS-value was calculated for each step size variation and a comparison was made to the others. The setup for the study can be seen in Figure 5a, with the evaluated node situated in the center of the first floor. The building shown in Figure 10a was used in the created model. For the results, including RMS-values, see Figure 5b.

Using both visual inspection and evaluation of the difference in RMS-value over the spectrum, it can be argued that only a step size of 1 Hz is significantly different and that the biggest discrepancy can be observed between 10 and 15 Hz. A step size of 0.5 Hz was, given the results, used in the analysis.

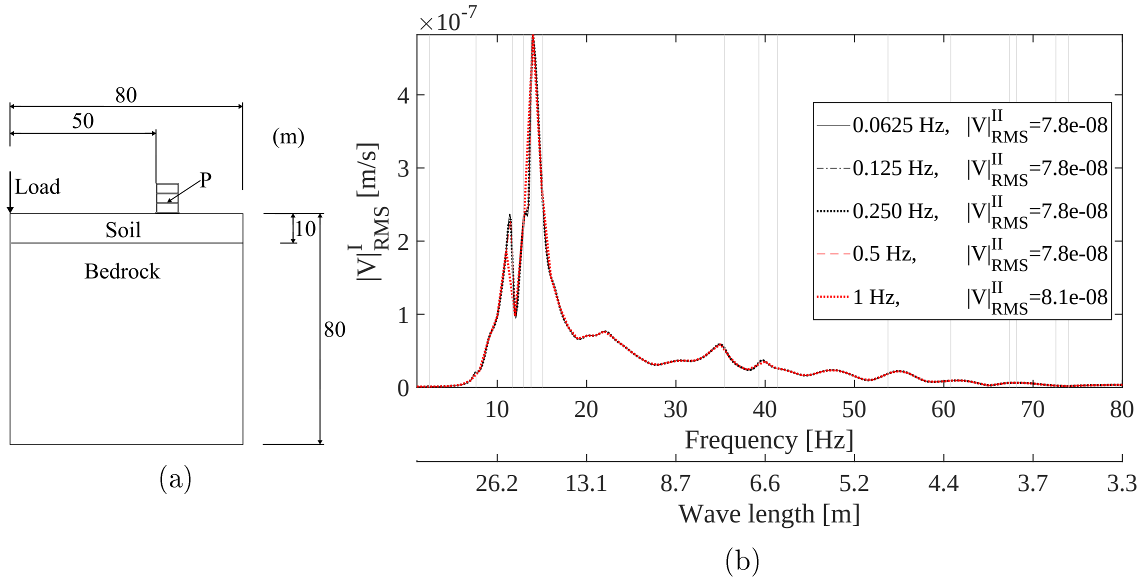
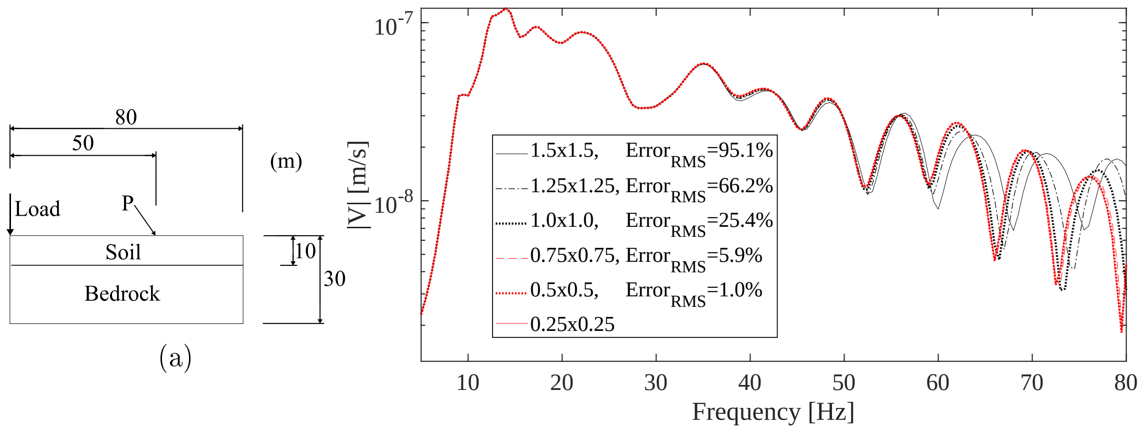


Figure 5: The setup used (a) and the results obtained (b) in the frequency step size convergence study.

4.1.2 Mesh size

The second parameter evaluated concerning convergence was mesh size. The frequencies between 1 and 80 Hz, with six different mesh sizes, were studied. An even quadratic mesh was used for the full model. To evaluate the results, the error levels were calculated using Equation 3.21, for each variation, comparing them to the smallest studied mesh size. The setup for the study can be seen in Figure 6a, with the evaluated node situated on the ground surface, 50 m from the applied load.

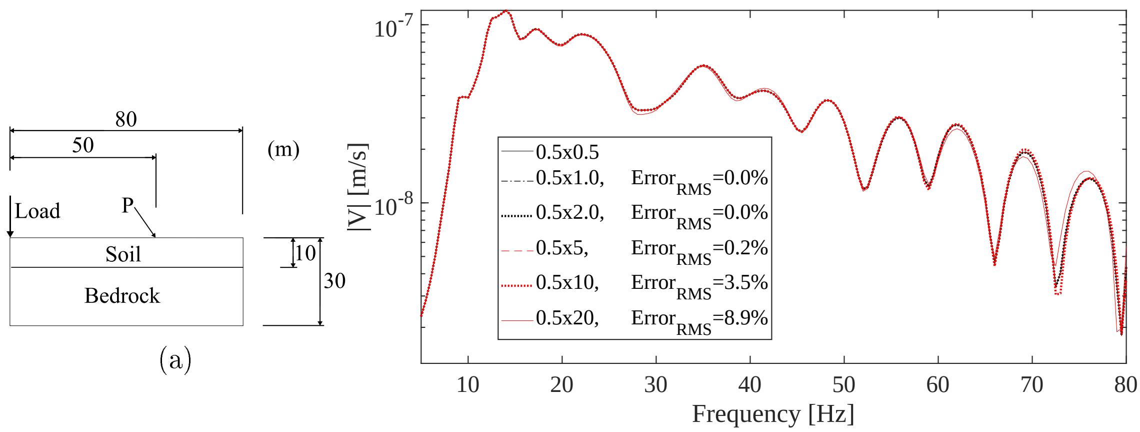


(a) (b)

Figure 6: The setup used (a) and the results obtained (b) in the mesh size convergence study.

From the results in Figure 6b it can be seen that the discrepancy, rather unsurprisingly, is most significant at higher frequencies. This is because of the shorter wavelength for higher frequencies. It can be seen that a difference in mesh size has a big impact on the results, seeing as the error values varies quite a lot. From these results it was concluded that a mesh size of 0.5×0.5 m^2 would be used in the soil layer.

An important consideration in the analysis is time, so further optimization was needed. A mesh size of 0.5×0.5 m^2 was used for the soil and the mesh size of the bedrock was varied. The horizontal size of each bedrock element was kept constant at 0.5 m and the vertical element size was varied from 0.5 to 20 m. The setup can be seen in Figure 7a, with, like the study prior, the evaluated node 50 m from the load. The results were compared to the mesh size of 0.5×0.5 m^2.



(a) (b)

Figure 7: The setup used (a) and the results obtained (b) in the bedrock mesh size convergence study.

From the results, see Figure 7b, it can be seen that the depth of the elements in the bedrock does not make a big difference. It is only for the element size of 0.5×10 m^2 and 0.5×20 m^2 that the error levels go above even one percent. As in the study prior the biggest discrepancy can be observed in the higher frequencies. An element size of 0.5×10 m^2 will be used for the bedrock in the analysis.

4.1.3 Geometry

The third parameter evaluated was the depth of the bedrock. The setup used is shown in Figure 8a, with the varied depth of the bedrock marked X. A mesh size of 0.5×0.5 m^2 was used for the soil and a mesh size of 0.5×10 m^2 was used for the bedrock. The same load and control point was used as in the two prior studies. The results were compared to the analysis with a 90 m depth.

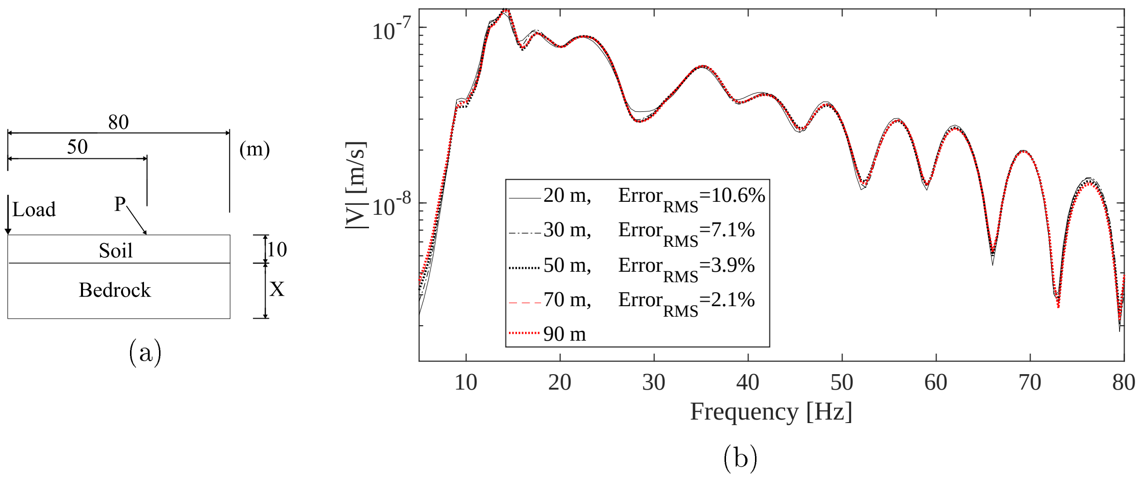


Figure 8: The setup used (a) and the results obtained (b) in the bedrock depth convergence study.

The results, in Figure 8b, show an evenly distributed difference over the studied spectrum. The error levels stay below 10% for most of the variations, except for the one with a depth of 20 m. Since the studies are of comparative nature a depth of 20 m will be used.

The fourth parameter evaluated was the width of the model. The setup can be seen in Figure 9a, with the varied width marked with an X. The same load, evaluated node and mesh size was used as in the depth test. The result for each setup was compared to the setup with a width of 200 m.

As can be seen in the results in Figure 9b, the differences between the setups are all below 10%. Since the studies are all of a comparative nature, a width of 80 m is seen as accurate enough and will be used in the analysis.

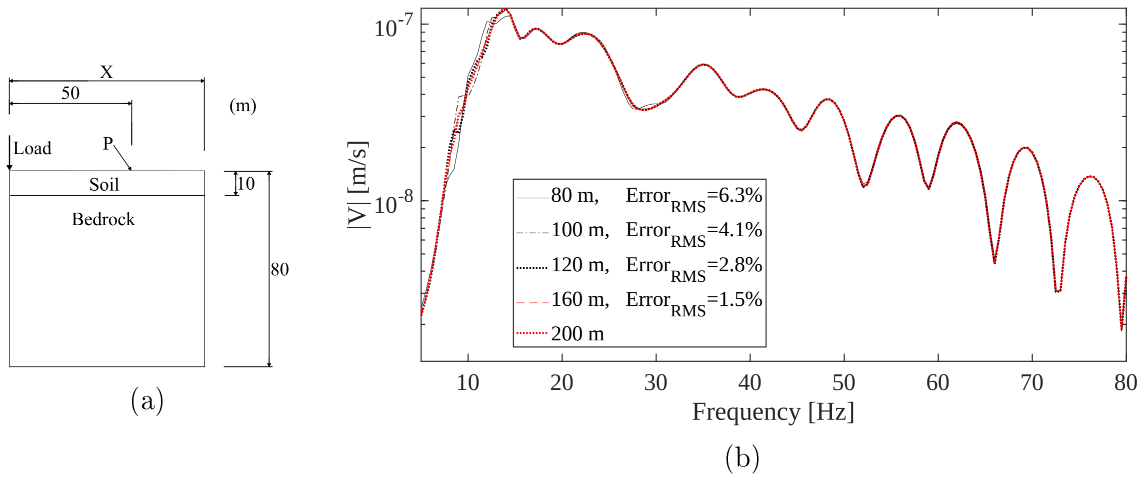
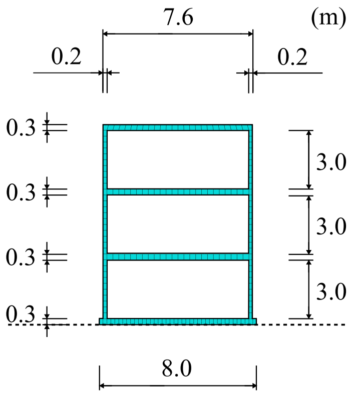


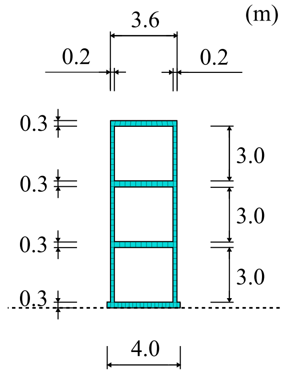
Figure 9: The setup used (a) and the results obtained (b) in the width of ground model convergence study.

4.2 Building model

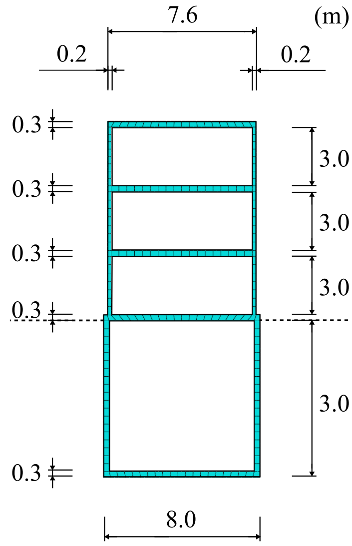
The buildings were modelled as simple representations of concrete buildings with three floors and, for some of the buildings, a cellar of varying depth. The element type used for the buildings were 8-node bi-quadratic with reduced integration(denoted CPE8R in Abaqus). The size of the elements of the buildings were chosen to be 0.3×0.3 m^2 with small variations depending on geometry. The geometry and mesh used for the different building models used in the analysis is shown in Figure 10.



(a) 8 m wide, no cellar



(b) 4 m wide, no cellar



(c) 8 m wide, with a cellar

Figure 10: The geometry and mesh used for the building models, with different width and with or without cellar. The dashed line represents the ground level.

Concrete was used for the buildings with, unless specified otherwise, the same material properties for all buildings. For the material properties, see Table 1.

Table 1: Material properties for the concrete.

Material property	Value
Density	2500 kg/m^3
Young's modulus	32 000 MPa
Poisson's ratio	0.2
Loss factor	4%

4.3 Ground model

The ground was modelled as one layer of bedrock in the lower part and one layer of soil in the upper part. For some of the studies one or two holes was added in the ground to fit a building with a cellar. The material properties for the soil can be seen in Table 2. For the material properties used for the bedrock, see Table 3.

Table 2: Material properties for the soil.

Material property	Value
Density	2000 kg/m^3
Young's modulus	500 MPa
Poisson's ratio	0.48
Loss factor	10%

Table 3: Material properties for the bedrock.

Material property	Value
Density	2500 kg/m^3
Young's modulus	10 000 MPa
Poisson's ratio	0.4
Loss factor	4%

The element types used for the soil and bedrock were 8-node bi-quadratic with reduced integration(denoted CPE8R in Abaqus) and 5-node quadratic, one-way infinite(denoted CINPE5R in Abaqus). The 8-node elements were used everywhere in the soil except along the right and bottom edge, where the 5-node elements were used. The size of the elements were, based on the previously conducted convergence study, chosen to be 0.5×0.5 m^2 for the soil and 0.5×10 m^2 for the bedrock. The mesh used for the analyses can be seen in Figure 11.

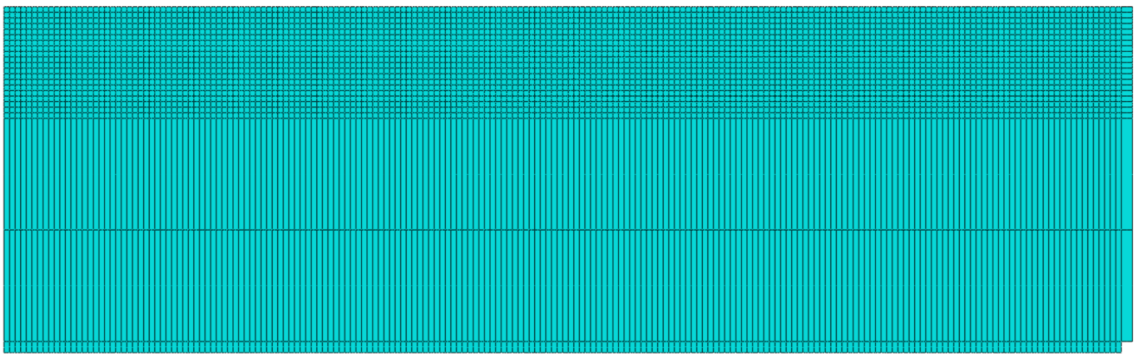


Figure 11: Mesh used for the ground models.

5 Numerical parametric analysis

The effects of a nearby building on the response of a building to an external vibrational source, was studied. The response of multiple buildings was also compared to that of a single building. The effect of different parameters were studied, including weight, width, depth and damping for the studied buildings and distance between the two buildings. The same three control points were used for all the performed studies. The first point, denoted P1, was placed in the intersection between the studied building and the ground surface, on the left side. The second point, denoted P2, was placed on the middle of the first floor, in the middle. The third point, denoted P3, was placed on the roof, in the middle. The vertical complex velocity amplitude, denoted $|V|$, was extracted from the conducted studies. The thin grey vertical lines in the results figures show the resonant frequencies for the studied building. The green line shown in some of the results is the green-field vertical response i.e. the response of the ground with no building on it at all.

A collection of all the analyses performed can be seen in Table 4.

Table 4: Analyses performed

Analysis	Section
Distance between buildings, building in front	5.1.1
Density of the building in front	5.1.2
Width of the building in front, studied building 8 m wide	5.1.3
Width of the building in front, studied building 4 m wide	5.1.3
Damping ratio for the building in front	5.1.4
Damping ratio for the studied building	5.1.4
Depth of the building in front	5.1.5
Distance between buildings, buildings having 4 m deep cellar	5.1.5
Distance between buildings, building behind	5.2.1
Depth of the building behind	5.2.2
Distance between buildings, building behind having 8 m deep cellar	5.2.3

5.1 Building in front of studied building

For each parameter studied, results from the three control points were collected. The results from one of the control points are shown for each study and for the results from the remaining control points, see Appendix A. To investigate the effects of a building placed between a source and a receiver, multiple parameters were studied. These parameters were distance between buildings, density of the material for the building in front, width of the studied buildings, damping ratio for the buildings and depth of the studied buildings.

5.1.1 Distance between buildings

The impact of the distance between the two buildings was investigated first. The studied building was placed 50 m from the source and the building in front was placed with varying distance, marked with X in Figure 12, to the studied building. The studied building was 8 m wide and without a cellar. For a visual representation of the setup, see Figure 12.

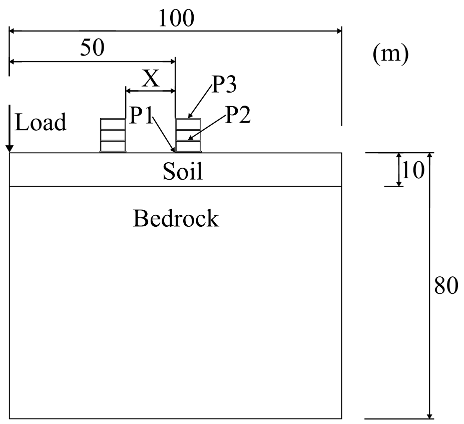


Figure 12: Setup used for the distance between buildings parameter study.

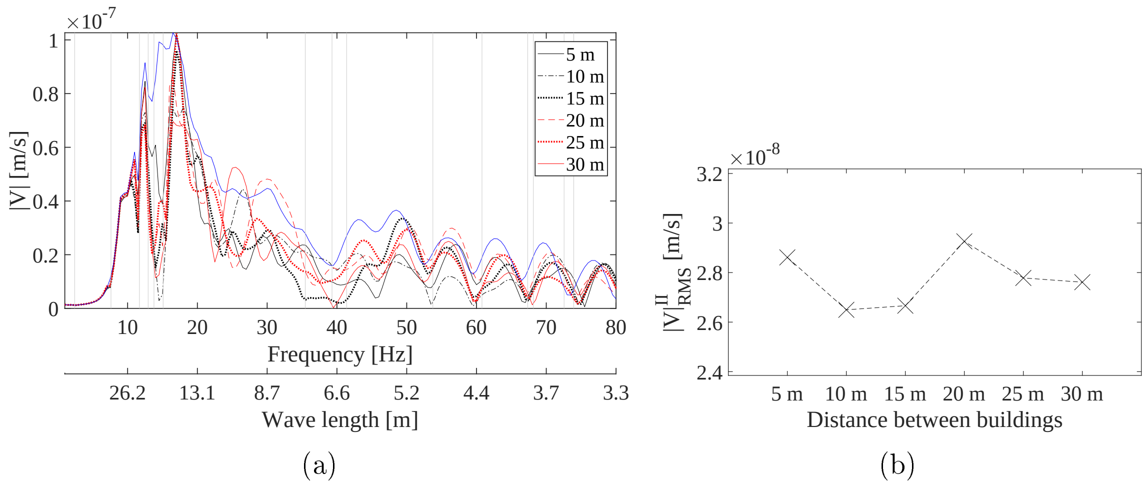


Figure 13: Vertical complex velocity magnitude (a) and RMS-value (b), for the node directly in front of the studied building, comparing different distances between the buildings.

From the results, in Figure 13, it can be concluded that it does make a difference to have a building between the source and the receiver. It is however hard to find an obvious connection between the observed difference and the distance between the buildings. A big reduction in vertical displacement can be seen in the spectrum between 12 and 18 Hz, possibly corresponding to the resonance frequencies of the buildings. No clear dependence can be seen from the RMS-values seen in Figure 13b, other than that the distance has an impact on the results.

5.1.2 Density of the material for the building in front

The second parameter to be investigated was the weight of the building in front. This was done by altering the density of the concrete material used for the building in front. The distance between the buildings was kept constant at 15 m and the depth of the bedrock was changed to 20 m. The studied building was 8 m wide and without a cellar. The setup can be seen in Figure 14.

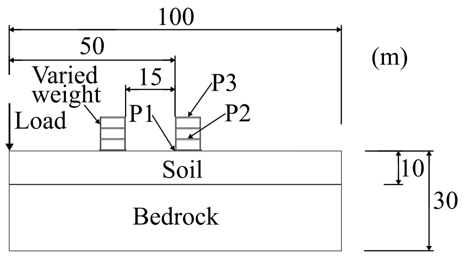


Figure 14: Setup used for the density of the building in front parameter study.

It is reasonable to suggest, from studying the results in Figure 15, that a change of density for the building in front has an impact on the vertical response of the studied building. It seems that the heavier the building is, the larger the reduction in displacement is. Apart from the lightest building, the RMS-values get lower the higher mass the building in front has.

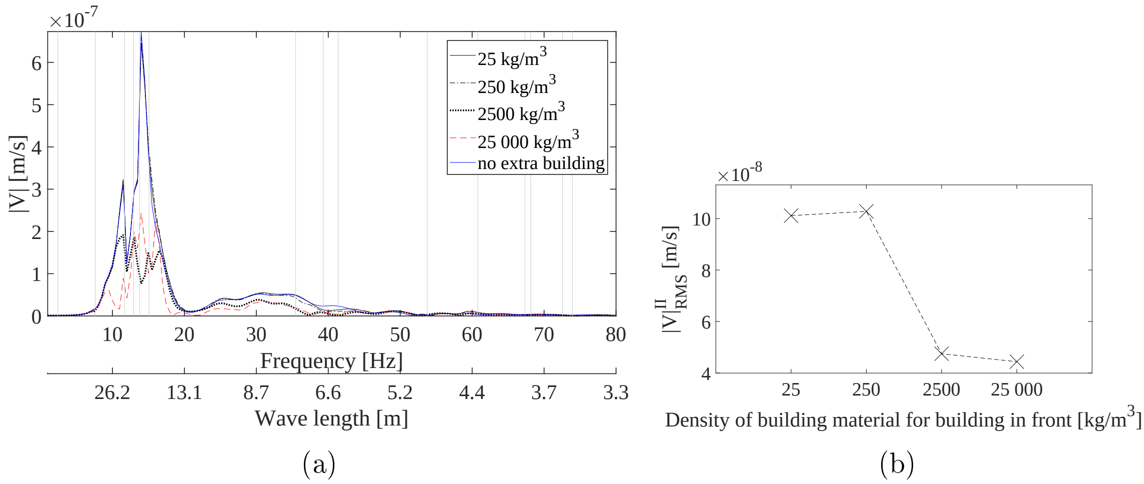


Figure 15: Vertical complex velocity magnitude (a) and RMS-value (b), for a node in the middle of the first floor of the studied building, comparing different weights for the building in front.

5.1.3 Width of the studied buildings

The width of the building in front was evaluated next, from 4 to 20 m. The distance between the buildings was kept the same at 15 m. The studied building was 8 m wide and without a cellar.

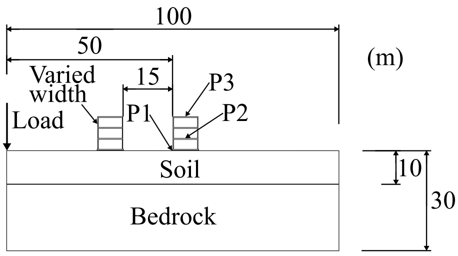


Figure 16: Setup used for the width of the building in front parameter study, with the studied building being 8 m wide.

The results, see Figure 17, show a difference in vertical response because of a difference in width for a building placed between the source and the receiver. It seems that a building similar to the studied building gives the largest reduction in vibrational response. This can clearly be seen in Figure 17b with the large reduction corresponding to the 8 m building.

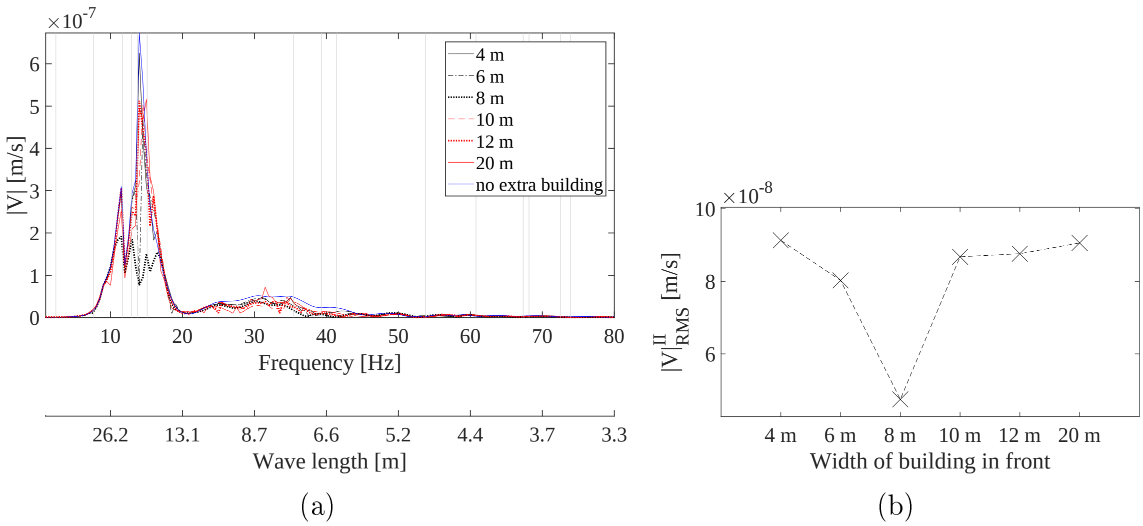


Figure 17: Vertical complex velocity magnitude (a) and RMS-value (b), for a node in the middle of the first floor of the studied building, comparing different widths for the building in front. The studied building is 8 m wide.

A similar analysis was done, but this time with a width of 4 m (instead of 8 m) for the studied building. The width of the building in front was, like previously, varied between 4 and 20 m. The setup can be seen in Figure 18.

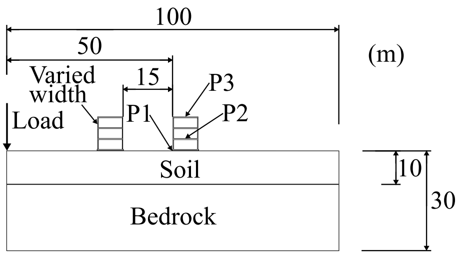


Figure 18: Setup used for the width of the building in front parameter study, with the studied building being 4 m wide.

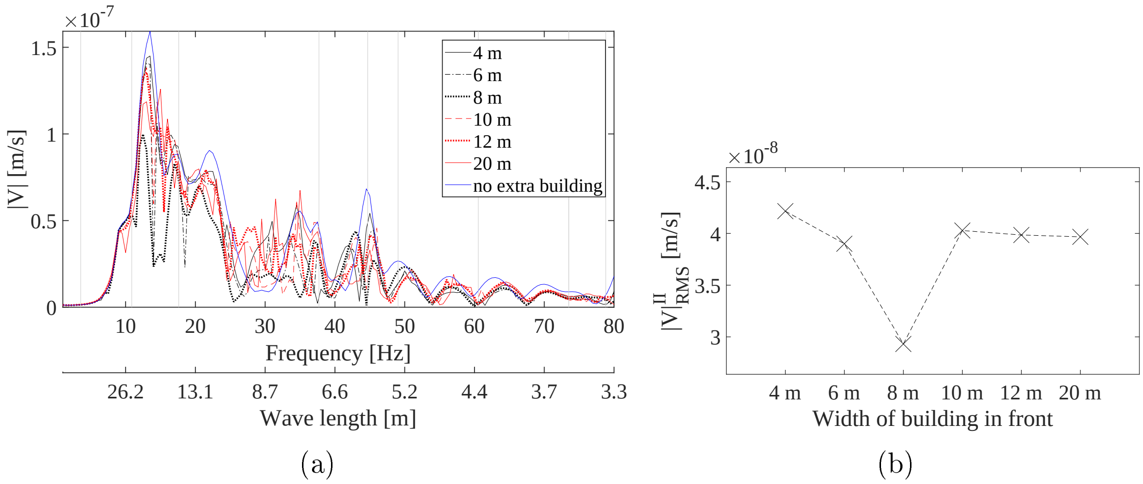


Figure 19: Vertical complex velocity magnitude (a) and RMS-value (b), for a node in the middle of the first floor of the studied building, comparing different widths for the building in front. The studied building is 4 m wide.

From the results, in Figure 19, it can be concluded that also for the 4 m wide building, the width of the building in front makes a difference in the response. It appears as if the pattern observed, concerning similarities in width, for the 8 m building doesn't translate to the 4 m building. The reduction pattern observed in Figure 19b is similar to the one in Figure 17b but no clear explanation could be made.

5.1.4 Damping parameters for the studied buildings

The next parameter to be investigated was the damping. Both buildings were modelled as 8 m wide for this investigation. The damping for the studied building was kept the same as previously, but for the building in front the damping ratio was varied between 1% and 20%. The setup for the study can be seen in Figure 20.

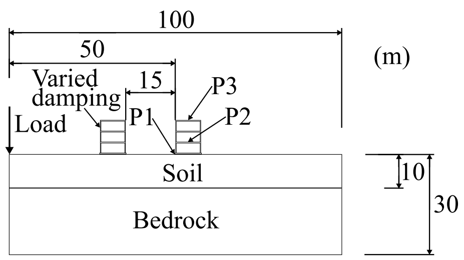


Figure 20: Setup used for the damping of the building in front parameter study.

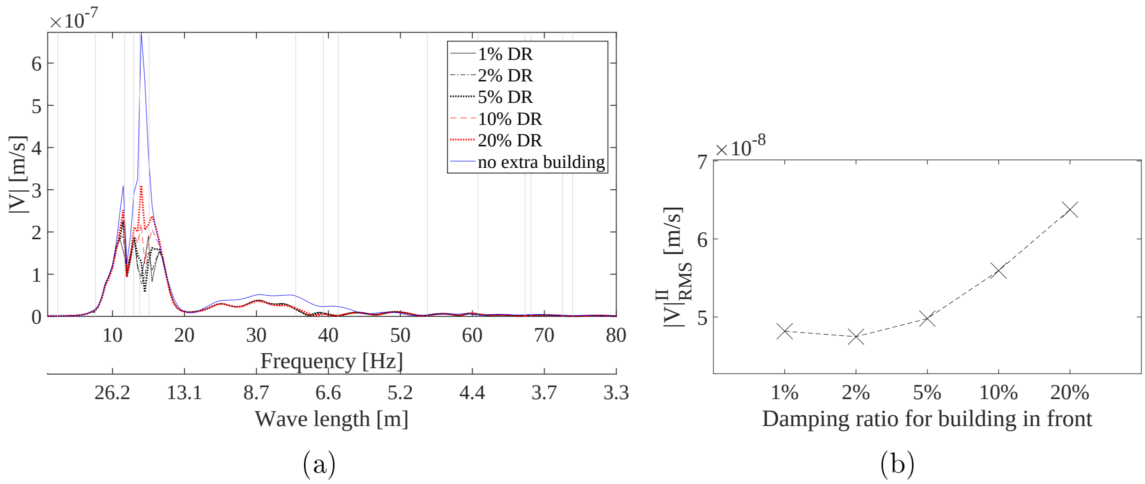


Figure 21: Vertical complex velocity magnitude (a) and RMS-value (b), for a node in the middle of the first floor of the studied building, comparing different damping ratio for the building in front.

When changing the damping for the building in front, the difference in the response is small. This is a possible conclusion from seeing the results in Figure 21. Even though the difference is small, an upward sloping pattern can be observed in Figure 21b. This means that a building in front with less damping will give a smaller reduction in the vertical response for the studied building.

The building in front was removed and the damping for the studied building was varied for the next study. As in the previous study, the damping ratio was varied between 1% and 20% for the building. See Figure 22 for a visual representation of the setup used.

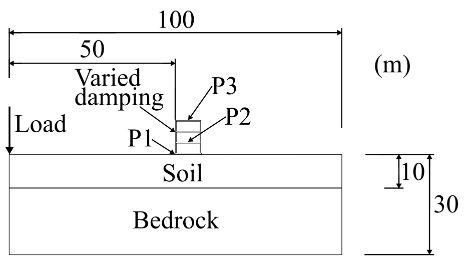


Figure 22: Setup used for the damping of the studied building parameter study.

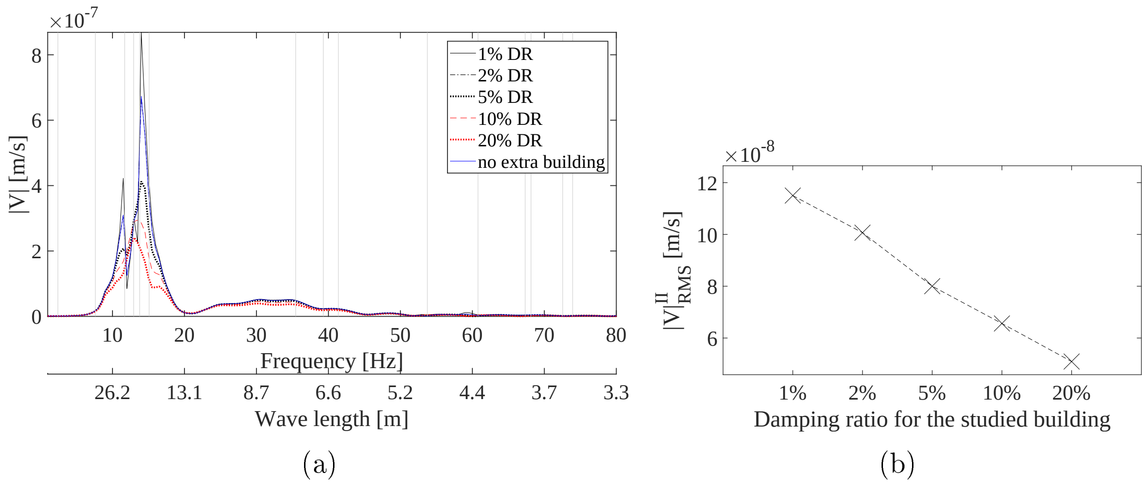


Figure 23: Vertical complex velocity magnitude (a) and RMS-value (b), for a node in the middle of the first floor of the studied building, comparing different damping ratio for the studied building.

From the results, shown in Figure 23, it seems clear that a change in damping ratio gives a difference in the vertical response. The higher damping in the building, the lower the amplitude for the response, as can clearly be seen in Figure 23b. This is not true for all the tested frequencies since for some frequencies no difference could be observed.

5.1.5 Depth of the studied buildings

A comparison of different depths for the building in front was made. The damping ratio and width was the same for both buildings at 2% and 8 m. There was no cellar on the studied building and the cellar depth was varied between 0 and 10 m for the building in front. The setup for this study is shown in Figure 24.

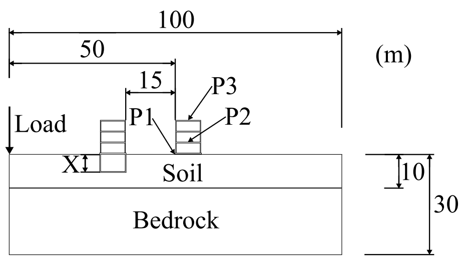


Figure 24: Setup used for the depth of the building in front parameter study.

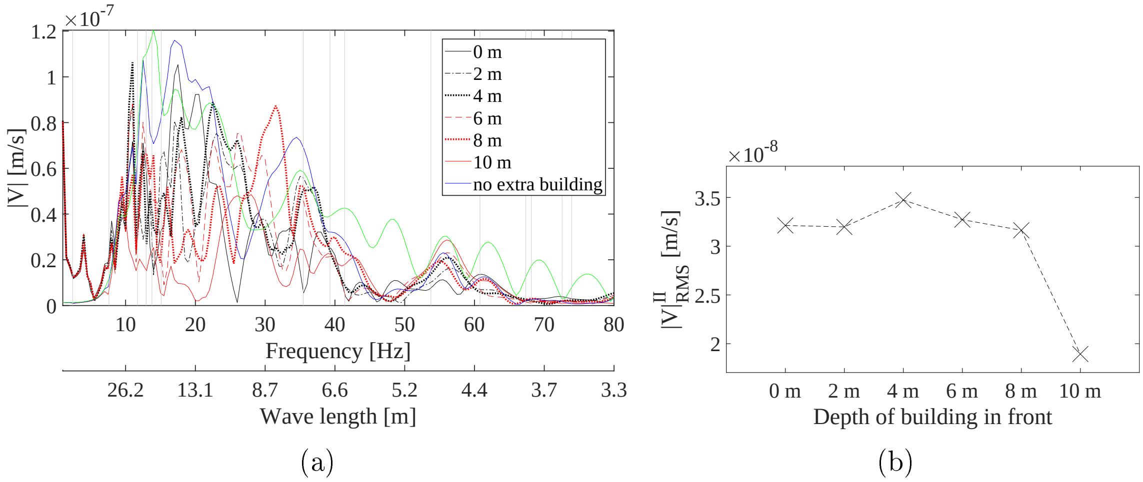


Figure 25: Vertical complex velocity magnitude (a) and RMS-value (b), for the node directly in front of the studied building, comparing different depths for the building in front.

The results, shown in Figure 25, indicate that a building, including a cellar, in front of the studied building, affects the response. It is, however, unclear in what way this is done, since for some frequencies the amplitude is higher and for some it is lower, compared to no building in front. The correlation between the depth of the cellar and the response of the studied building is not clear. The largest reduction in response can be observed for the cellar with a depth of 10 m, as seen in Figure 25b. That this configuration would give the largest difference is expected since this is the only configuration with a cellar all the way down to bedrock.

To further investigate the influence of the depth, a cellar was added to the studied building and the depth of the cellar was set to 4 m for both buildings. The distance between these buildings were then varied from 5 to 30 m. For a visual representation of the setup see Figure 26.

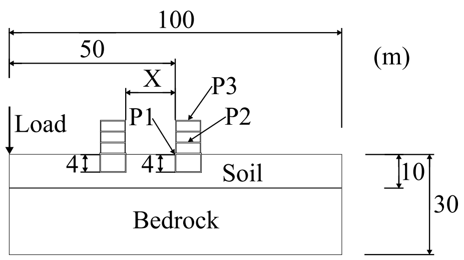


Figure 26: Setup used for the distance between the buildings parameter study, with both buildings having a 4 m deep cellar.

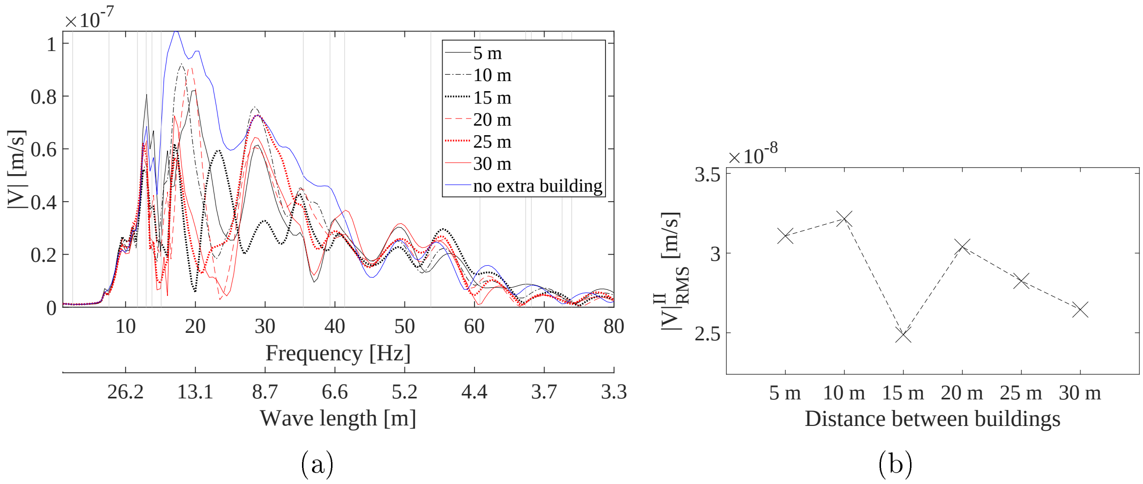


Figure 27: Vertical complex velocity magnitude (a) and RMS-value (b), for the node directly in front of the studied building, comparing different distances between the buildings and with both buildings having a 4 m deep cellar.

From the results, see Figure 27, it seems clear that the distance between the two buildings has an impact on the results, also for buildings with a cellar. A clear relation between the distance and how the accompanying results vary could not be found.

5.2 Building behind studied building

For each parameter studied, results from the three control points were collected. The results from one of the control points are shown for each study and for the results from the remaining control points, see Appendix B. To investigate the effects of a building placed behind the studied building, multiple parameters were studied. These parameters were distance between buildings, depth of the building behind the studied building and distance between buildings including a cellar on the building behind.

5.2.1 Distance between the buildings

The impact of the distance between the two buildings was investigated first. The studied building was placed 50 m from the source and the building in front was placed with varying distance, marked with X in Figure 28, to the studied building. Both buildings were 8 m wide and without a cellar. For a visual representation of the setup, see Figure 28.

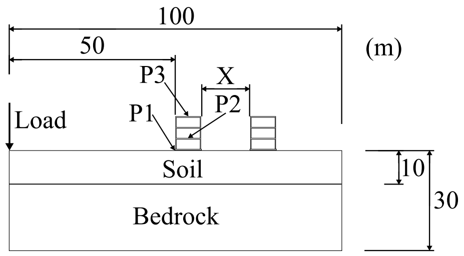


Figure 28: Setup used for the distance between buildings parameter study, with a building placed behind the studied building.

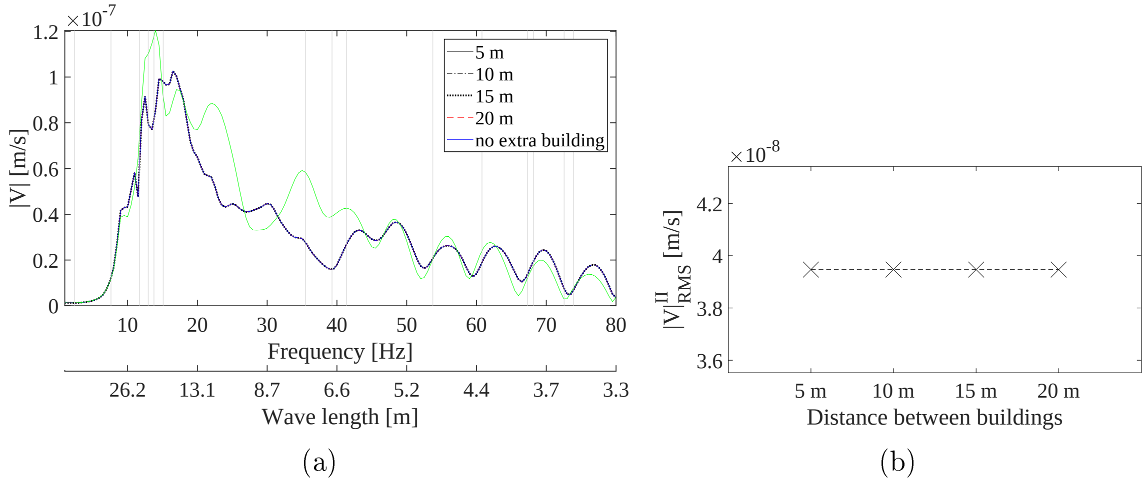


Figure 29: Vertical complex velocity magnitude (a) and RMS-value (b), for the node directly in front of the studied building, comparing different distances between the buildings when a building is placed behind the studied building.

It is clear, looking at the results in Figure 29, that a building placed behind the studied building does not make a difference in the response, as long as none of them have a cellar.

5.2.2 Depth of the building behind the studied building

To further investigate what parameters affect the vertical response, another analysis was done. The distance between the buildings was set to 10 m and the depth (marked with an X in Figure 30) of the building was varied between 0 and 10 m. The complete setup used can be seen in Figure 30.

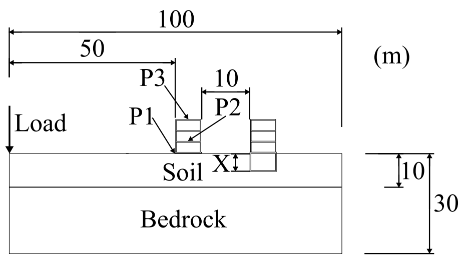


Figure 30: Setup used for the depth of the building behind parameter study.

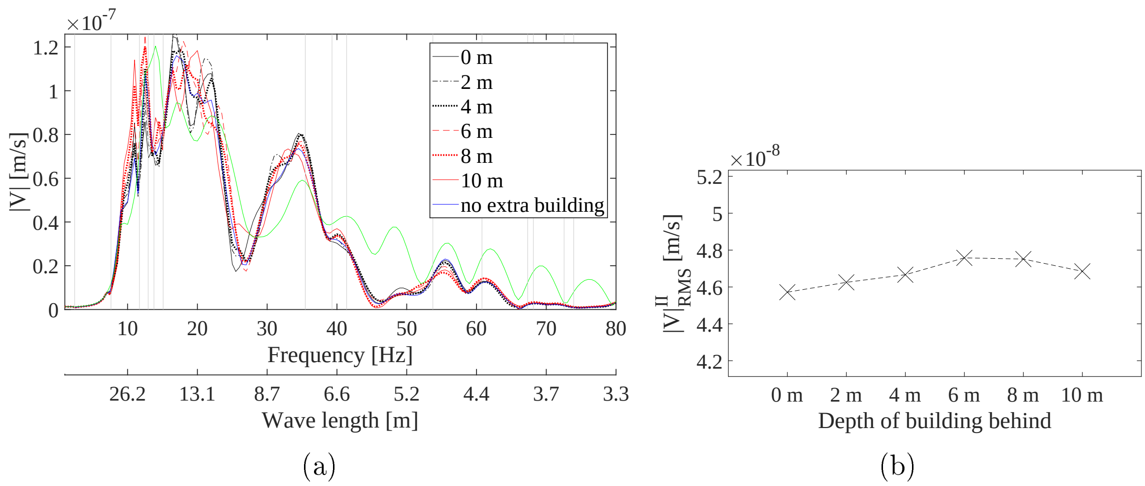


Figure 31: Vertical complex velocity magnitude (a) and RMS-value (b), for the node directly in front of the studied building, comparing different depths for the building placed behind the studied building.

The results in Figure 31 show, unlike the previous study, a difference between the different depths. The difference made is small compared to other parameters varied. There appears to be a tendency for the difference in vertical response to increase with an increase in depth of the cellar but it is not consistent, looking at the RMS-values in Figure 31b. The difference seen can be caused by reflections from the cellar, but this was not investigated further.

5.2.3 Distance between the buildings including a cellar on the building behind

A cellar with a depth of 8 m was added to the building behind and the distance between the two buildings was varied between 5 and 25 m. Figure 32 shows the setup used.

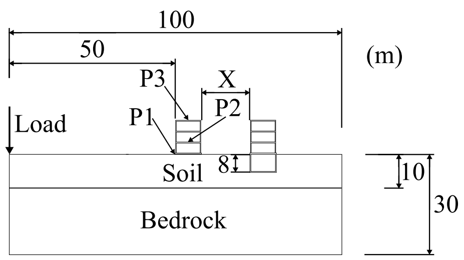


Figure 32: Setup used for the distance between buildings parameter study, with a building, including a 8 m deep cellar, placed behind the studied building.

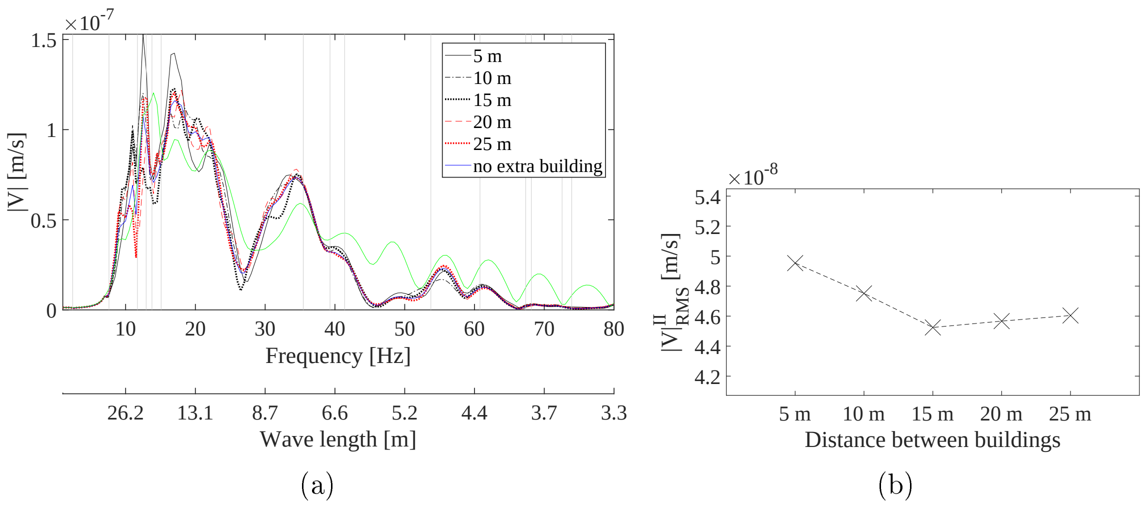


Figure 33: Vertical complex velocity magnitude (a) and RMS-value (b), for the node directly in front of the studied building, comparing different distances between the buildings when a building with an 8 m deep cellar is placed behind the studied building.

A difference in response can be seen when a building with a cellar is placed behind the studied building, according to the results seen in Figure 33. The difference seems to follow a periodic pattern and depend on the distance between the buildings, but it is quite small compared to some of the other tests done. Any clear conclusions on how the distance affects the response can not be found looking at the RMS-values in Figure 33b.

6 Concluding remarks

In the dissertation, structure-soil-structure effects on externally excited building vibrations have been investigated. The effects of a nearby building on the response of a building to an external vibrational source is studied using parametric numerical analysis. This is done to further extend the knowledge in vibrations of the built environment. In the study, different parameters are examined, separately investigating a building in front of and behind a studied building. The parameters investigated are distance between buildings, density of the material used for the building in front, width of the studied buildings, damping ratio for the buildings and depth of the studied structures. Three control points are used for the performed studies, including one on the ground directly in front of the studied building, one on the first floor and one on the roof. The vertical complex velocity amplitude is the output variable for all the simulations performed in the FE software Abaqus 6.13.

6.1 Main conclusions

A conclusion drawn from the analyses is that how nearby buildings affect the response to external vibrations on a building is difficult to predict and it's hard to find general rules that describe it. It is, however, clear that nearby buildings have an impact on the vibrational response. It is important to note that a lot of simplifications have been made in the analyses so connecting the results to real world effects should be done with caution. Although this is true, some conclusions can be drawn from the results.

The main conclusions are as follows:

- A large reduction in vertical response can be observed when a building is placed in front of a building that is similar in geometry. The largest reduction in the response seem to coincide with the resonance frequencies of the buildings.
- The heavier the building in front is, the larger the reduction in response is in general for the studied building.
- A high damping ratio of the structure in front correspond to a high vertical amplitude for the studied building and a high damping ratio of the studied building correspond to a lowering of the vertical displacement for the structure.
- A small difference in vertical response can be seen if the building in front is partly submerged in the soil and a large reduction can be noted if the building in front has a cellar reaching down to bedrock.
- Although the distance between the buildings has an impact on the results, a pattern could not been found.

- The presence of a building behind the studied building in the direction of the propagating waves does not have a large impact on the vertical vibrational response. The difference in displacement for the studied building is only noticeable when the building behind is partly submerged into the soil, but even then it's negligible.

There are similarities when comparing the conclusions made in the dissertation to those made in the study [1] by L.V. Andersen et al. saying that reductions in vibration levels can be achieved by placing a building in front, but no arrays are investigated in the dissertation. The conclusions regarding the effectiveness of embedded buildings, or blocks, in reducing the vibration levels are also similar but the results are not as clear in the dissertation. That neighbouring structures placed in a soft layer with a hard rock beneath impacts the dynamic response of the buildings was also concluded in the article [3] by J. Liang et al. Another similar conclusion is that the resonances of the structures and the soil are important factors when predicting the dynamic response of buildings. This conclusion is also drawn in the paper [2] investigating site-city effects by A. Kham et al.

6.2 Future work

Suggestions for future work concerning the investigation presented in the dissertation include:

- A similar analysis in three dimensions could be made to investigate if there are 3D-effects. The effects of more parameters concerning rotation of buildings, structural materials and building geometry could also be analysed using the same numerical analysis method.
- How different layers in the ground concerning depth, material parameters and distance between source and receiver affect the conclusions reached in the dissertation, could be investigated.
- Different ways to simplify the building models used in numerical analyses and how the accuracy is affected by these simplifications could be investigated. Simple blocks, or single degree-of-freedom, with the same total mass, damping and stiffness or modal properties could be used. In this way we may facilitate a more time-efficient analysis.

References

[1] L.V. Andersen, A Peplow, P Bucinskas, P Persson, and K Persson. Variation in models for simple dynamic structure–soil–structure interaction problems. *Procedia Engineering*, 199:2306–2311, 10, 2017.

[2] A. Kham, J.F. Semblat, P.Y. Bard, and P Dangla. Seismic Site-City Interaction: Main Governing Phenomena through Simplified Numerical Models. *Bulletin of the Seismological Society of America*, 96(5):1934–1951, 2006.

[3] J Liang, B Han, M.I. Todovorska, and D.M. Trifunac. 2D dynamic structure-soil-structure interaction for twin buildings in layered half-space I: Incident SH-waves. *Soil Dynamics and Earthquake Engineering*, 102:172–194, 2017.

[4] P Persson, K Persson, and G Sandberg. Numerical study of reduction in ground vibrations by using barriers. *Engineering Structures*, 115:18–27, 2016.

[5] P Persson, K Persson, and G Sandberg. Reduction in ground vibrations by using shaped landscapes. *Soil Dynamics and Earthquake Engineering*, 60:31–43, 05 2014.

[6] P Persson, K Persson, and G Sandberg. Numerical study on reducing building vibrations by foundation improvement. *Engineering Structures*, 124:361–375, 2016.

[7] P Persson. *Vibrations in a Built Environment - Prediction and Reduction.* PhD thesis, Lund University, 2016. TVSM-1026.

[8] International Organization for Standardization. *Mechanical vibration and shock - Evaluation of human exposure to whole-body vibration Part 2: Vibration in buildings (1 Hz to 80 Hz).* ISO 2631-2:2003.

[9] M Ögren. Vibrationer inomhus från trafik, 2016. `http://www.naturvardsverket.se/upload/miljoarbete-i-samhallet/miljoarbete-i-sverige/buller/`, [Accessed: 2018-04-17].

[10] M Basner, W Babisch, A Davis, M Brink, C Clark, S Janssen, and S Stansfeld. Auditory and non-auditory effects of noise on health. *The Lancet*, 383(9925):1325–1332, 2014.

[11] N.S. Ottosen and H. Petersson. *Introduction to the finite element method.* Prentice Hall New Jersey, 1992.

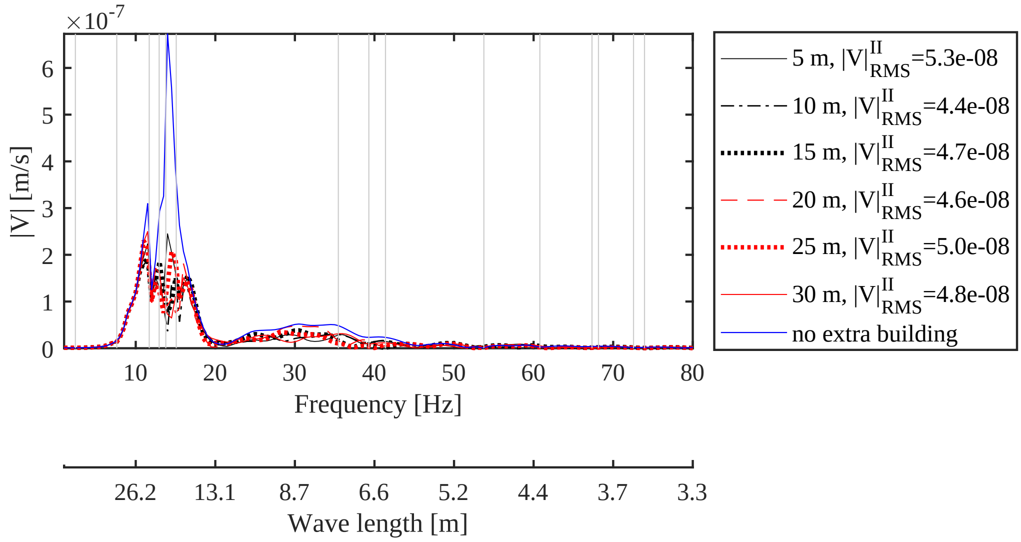
[12] Dassault Systèmes. *Abaqus 6.13 Online Documentation.* 2013.

[13] A.K. Chopra. *Dynamics of structures*, volume 3. Prentice Hall New Jersey, 1995.

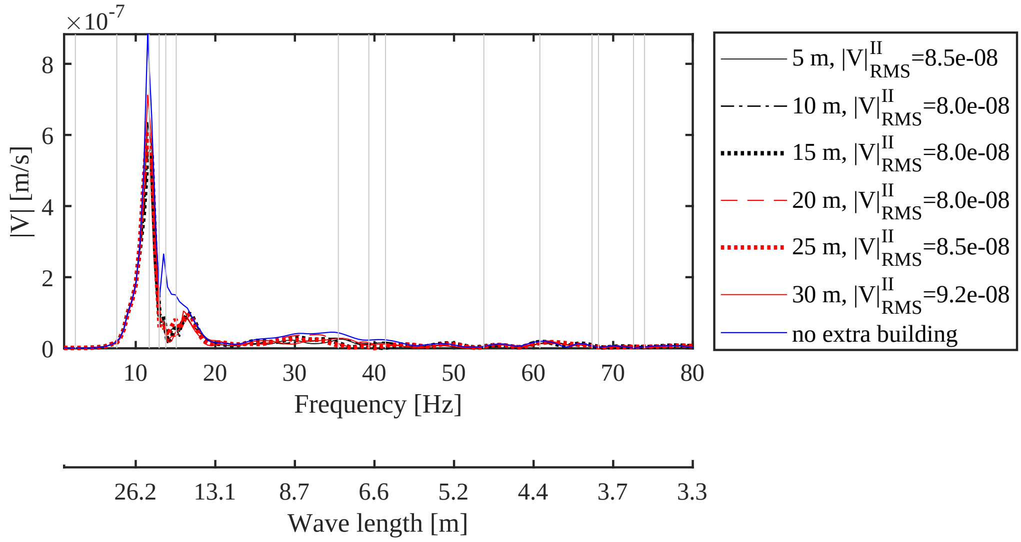
Appendix

In the analyses, three control points were studied. The two complementing control points to the one presented in Section 5 is shown in the Appendix for each analysis done. This includes results from both a building being placed in front and behind a studied building.

A Building in front of studied building, the remaining control points

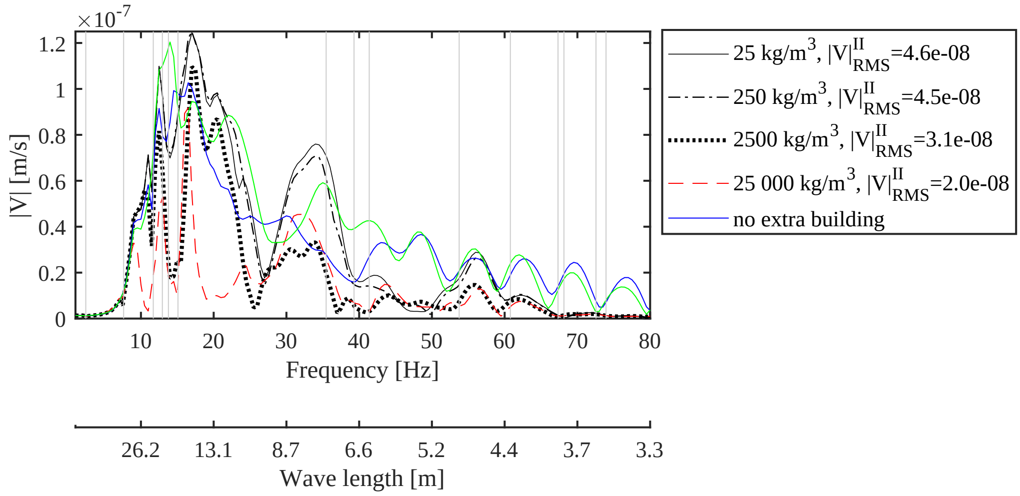


(a)

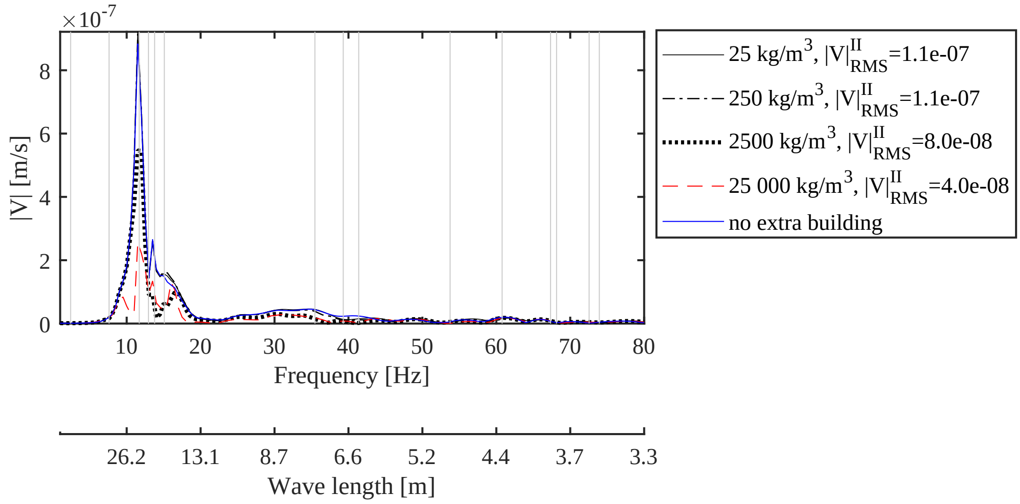


(b)

Figure A.1: Vertical complex velocity magnitude, for a node in the middle of the first floor of the studied building (a) and a node in the middle of the roof of the studied building (b), comparing different distances between the buildings.

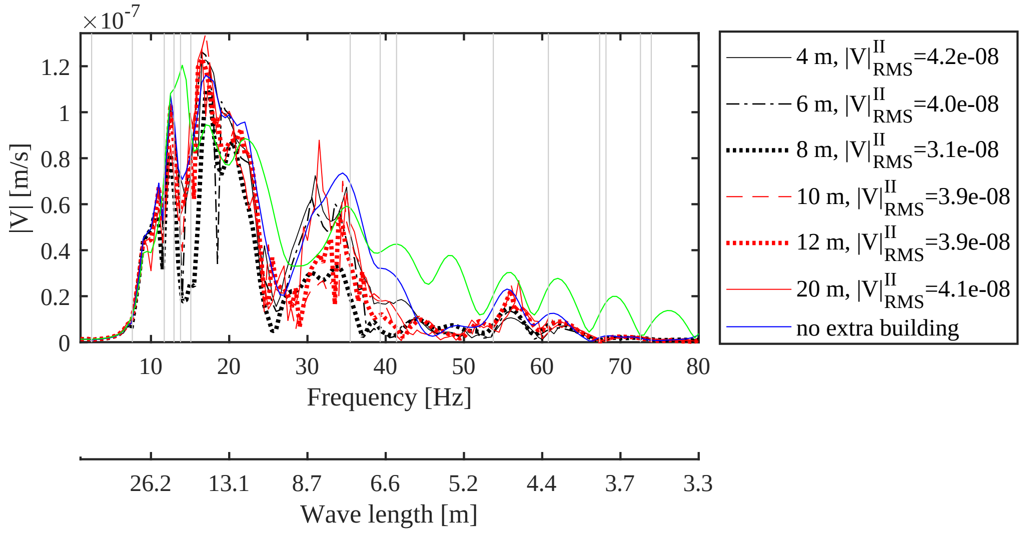


(a)

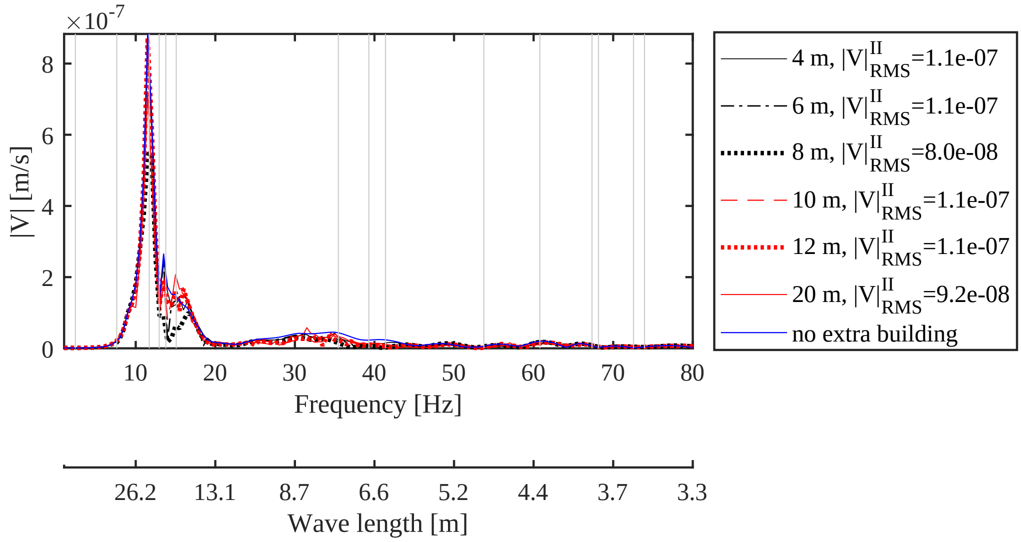


(b)

Figure A.2: Vertical complex velocity magnitude, for the node directly in front of the studied building (a) and in the middle of the roof of the studied building (b), comparing different weights for the building in front.

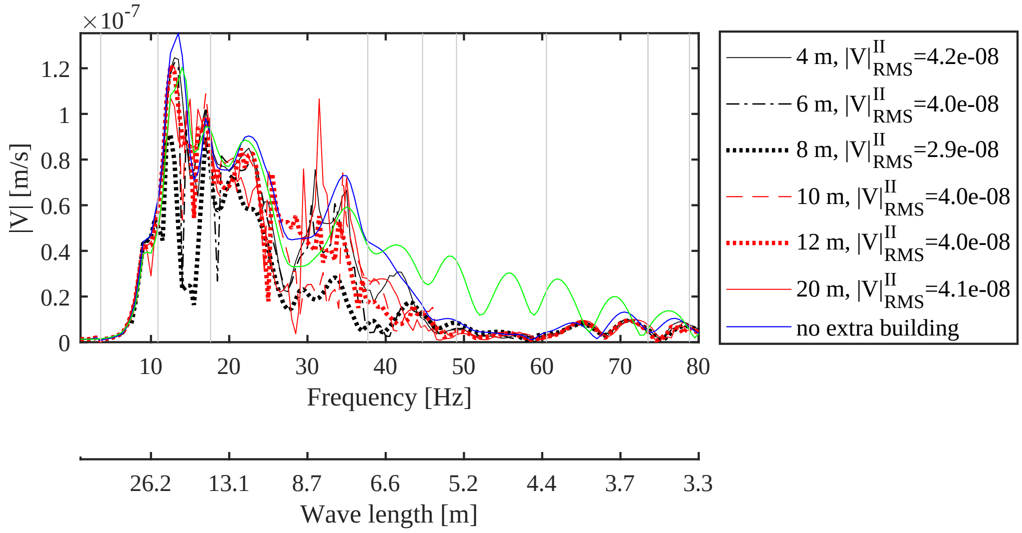


(a)

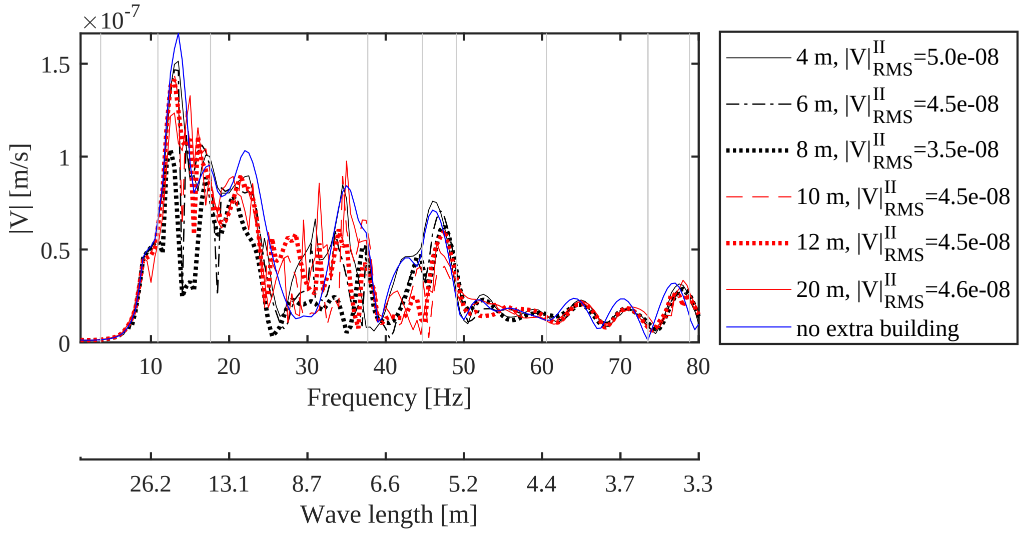


(b)

Figure A.3: Vertical complex velocity magnitude, for the node directly in front of the studied building (a) and in the middle of the roof of the studied building (b), comparing different widths for the building in front. The studied building is 8 m wide.

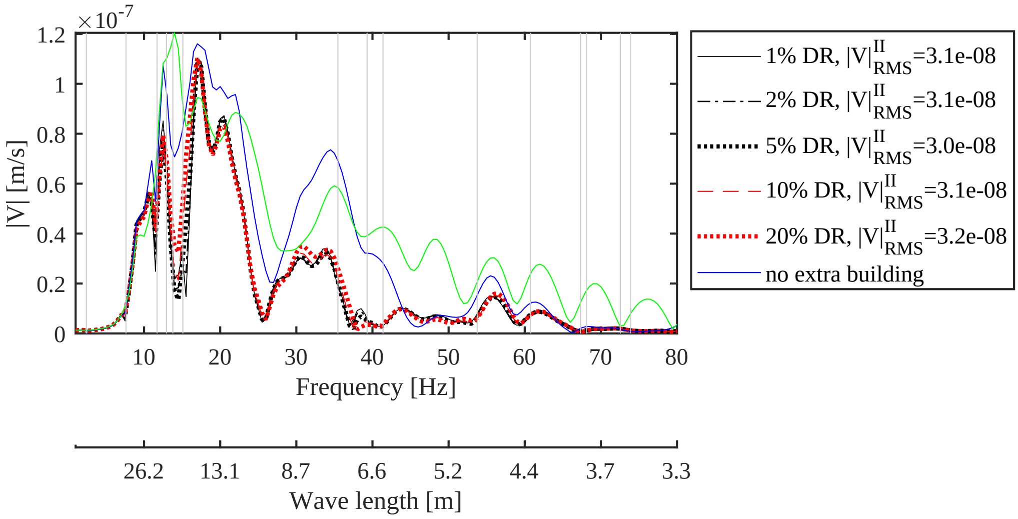


(a)

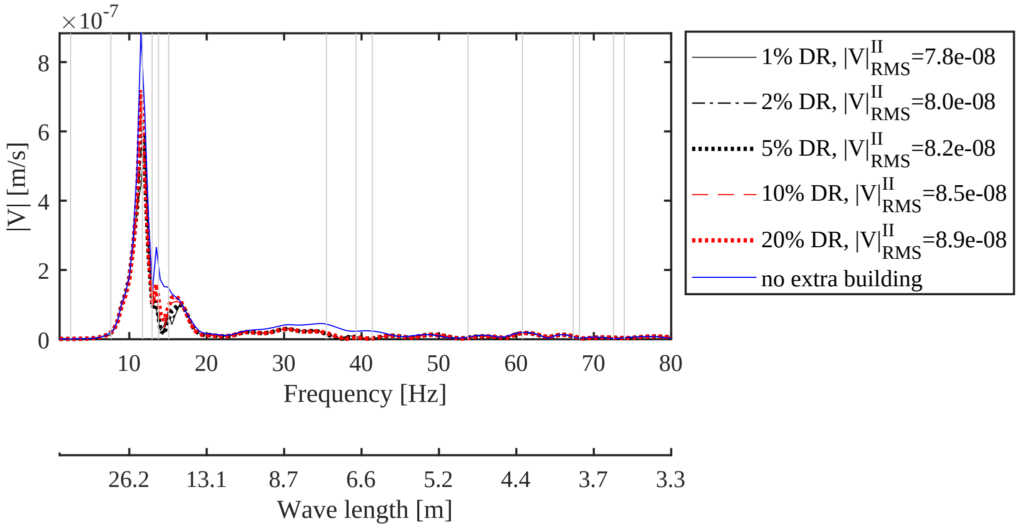


(b)

Figure A.4: Vertical complex velocity magnitude, for the node directly in front of the studied building (a) and in the middle of the roof of the studied building (b), comparing different widths for the building in front. The studied building is 4 m wide.

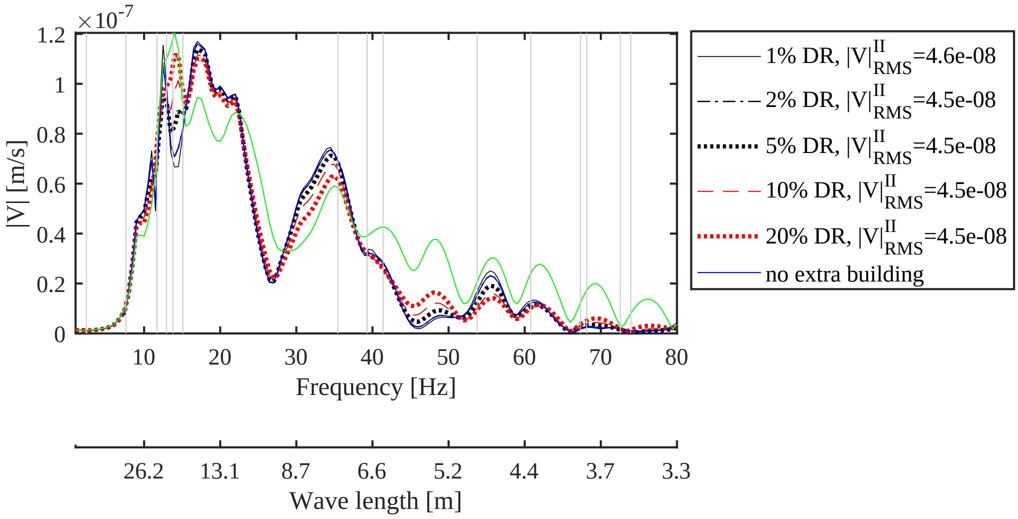


(a)

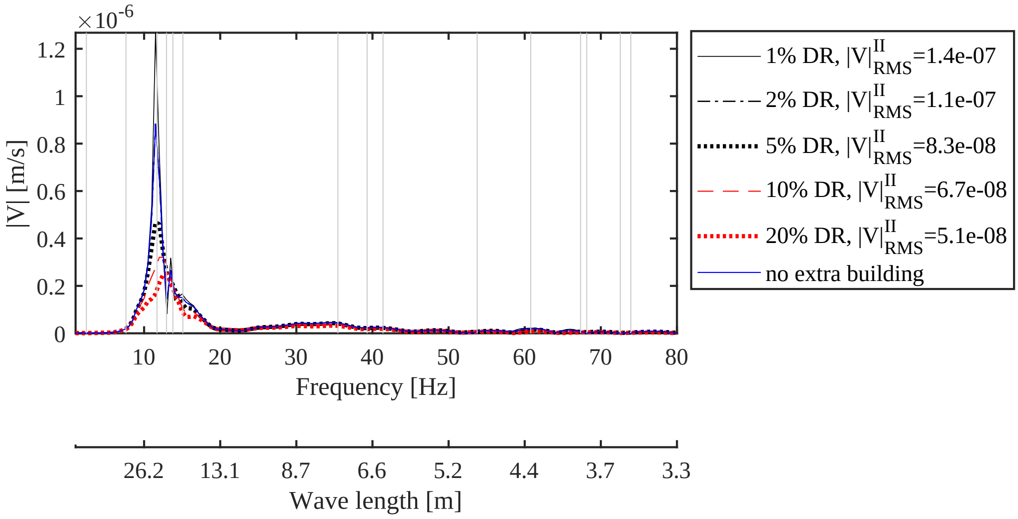


(b)

Figure A.5: Vertical complex velocity magnitude, for the node directly in front of the studied building (a) and in the middle of the roof of the studied building (b), comparing different damping for the building in front.

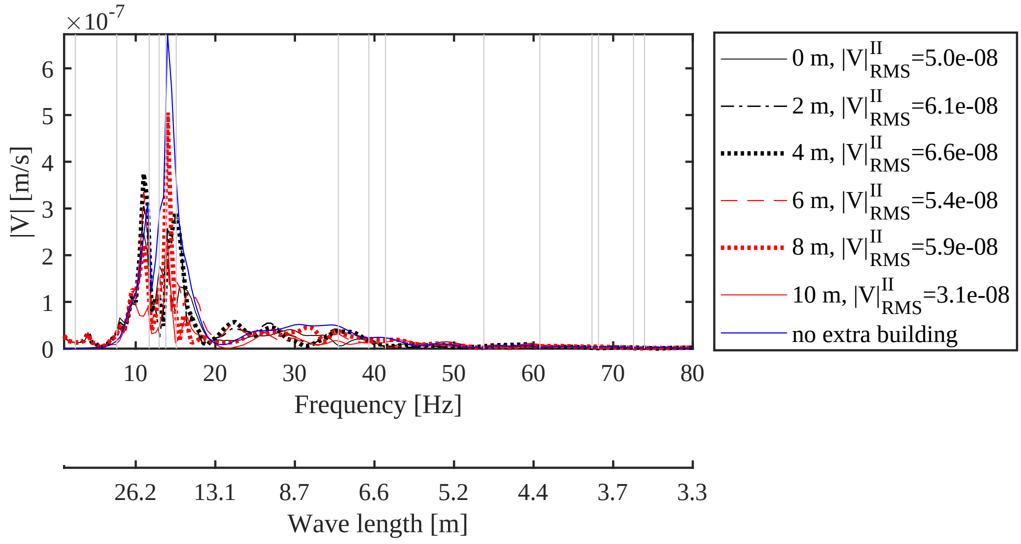


(a)

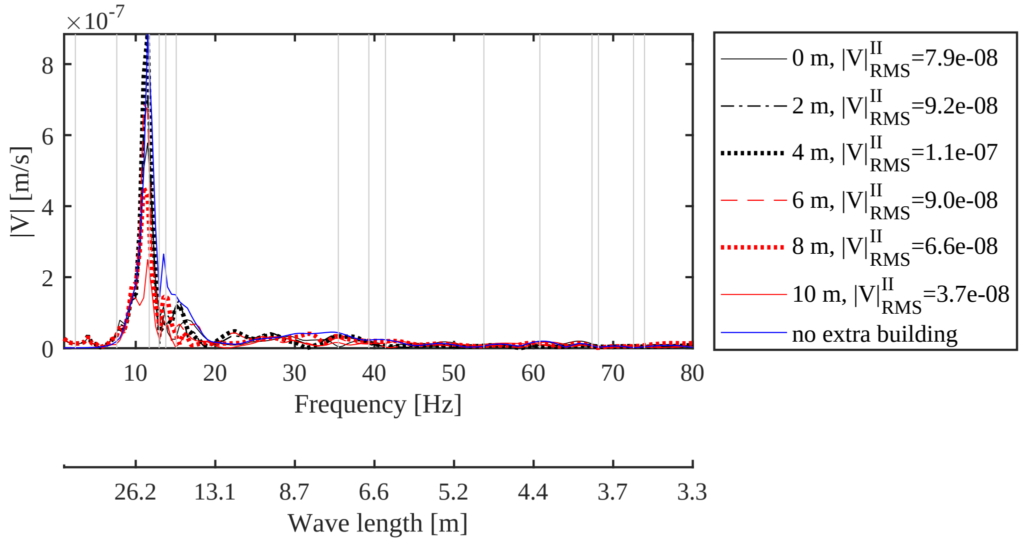


(b)

Figure A.6: Vertical complex velocity magnitude, for the node directly in front of the studied building (a) and in the middle of the roof of the studied building (b), comparing different damping for the studied building.

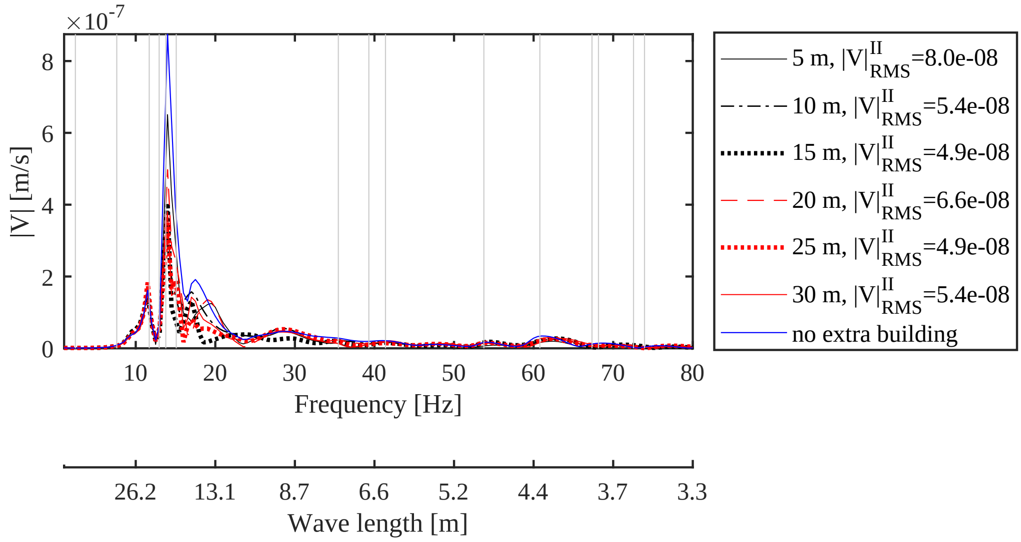


(a)

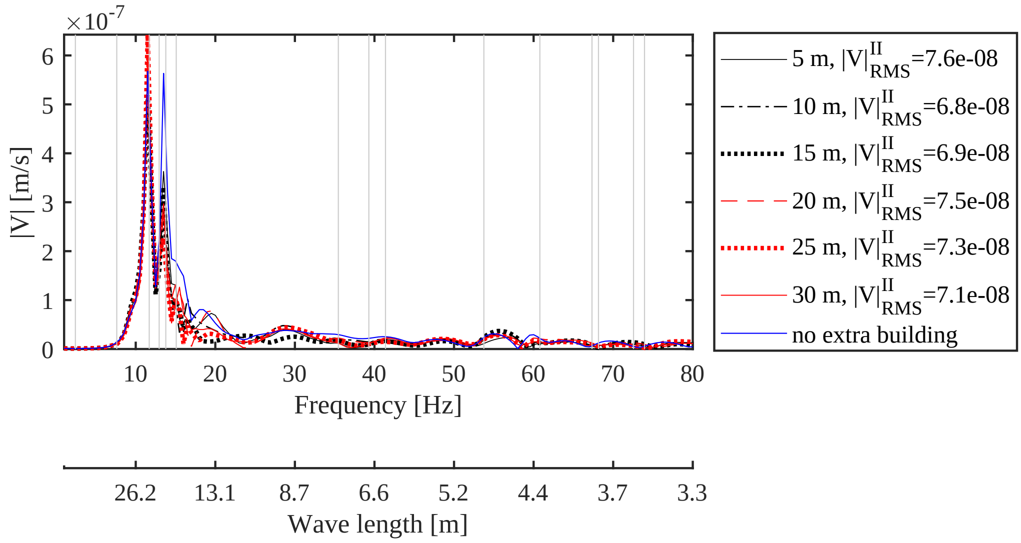


(b)

Figure A.7: Vertical complex velocity magnitude, for a node in the middle of the first floor of the studied building (a) and in the middle of the roof of the studied building (b), comparing different depths for the building in front.



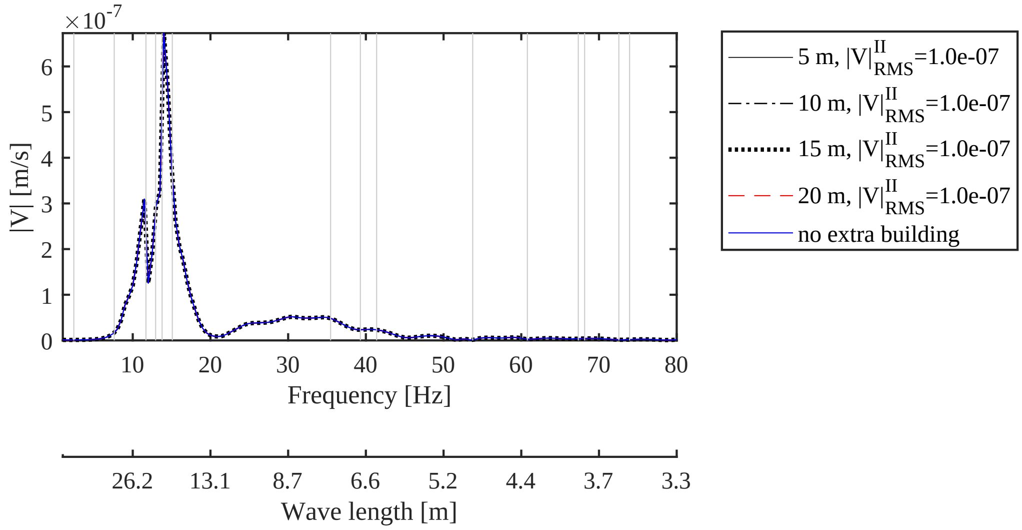
(a)



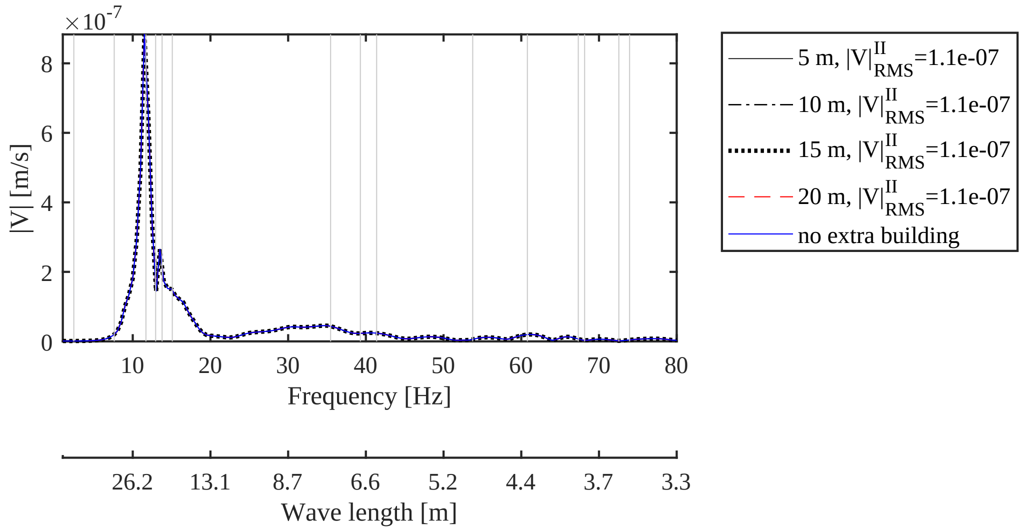
(b)

Figure A.8: Vertical complex velocity magnitude, for a node in the middle of the first floor of the studied building (a) and in the middle of the roof of the studied building (b), comparing different distances between the buildings with both buildings having a 4 m deep cellar.

B Building behind studied building, the remaining control points

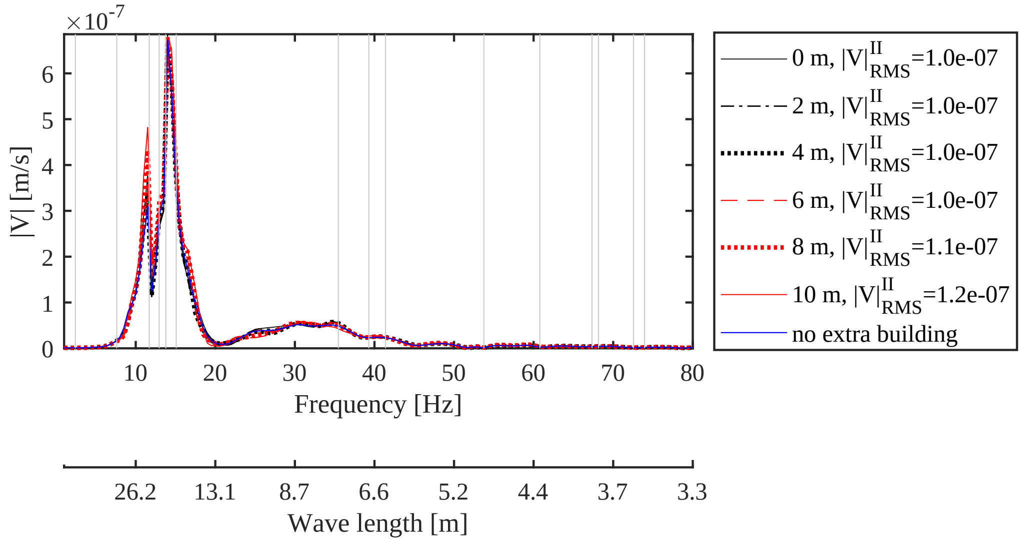


(a)

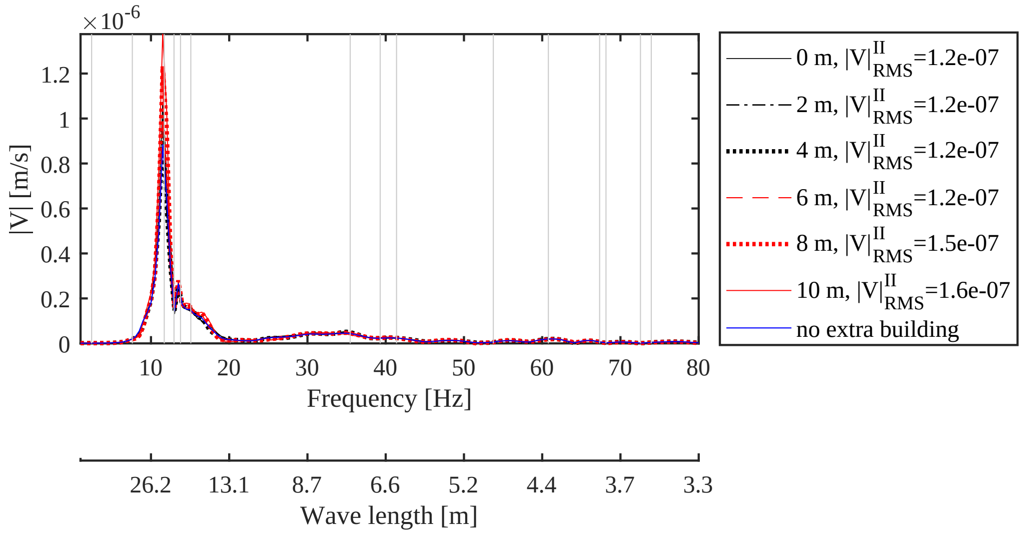


(b)

Figure B.1: Vertical complex velocity magnitude, for a node in the middle of the first floor of the studied building (a) and in the middle of the roof of the studied building (b), comparing different distances between the buildings when a building is placed behind the studied building.

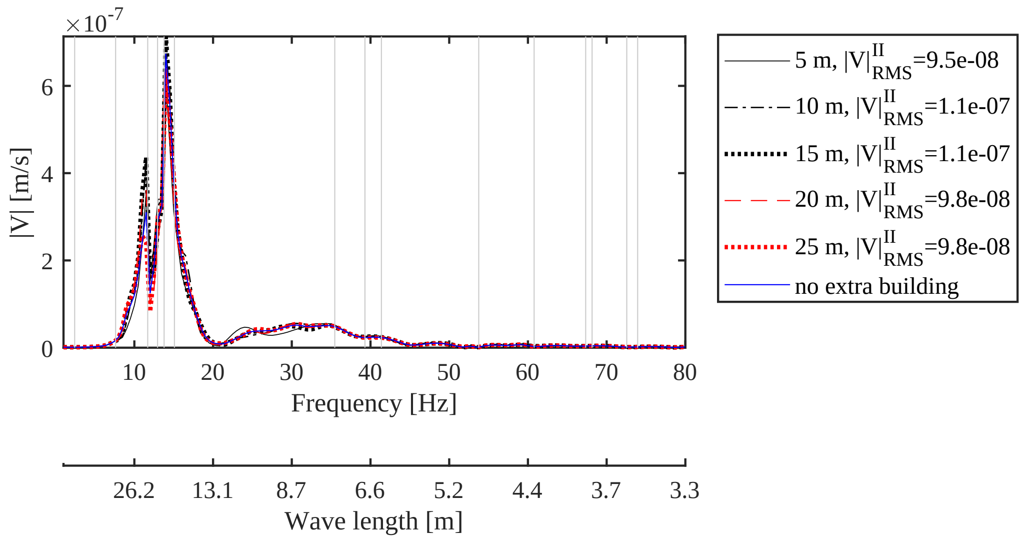


(a)

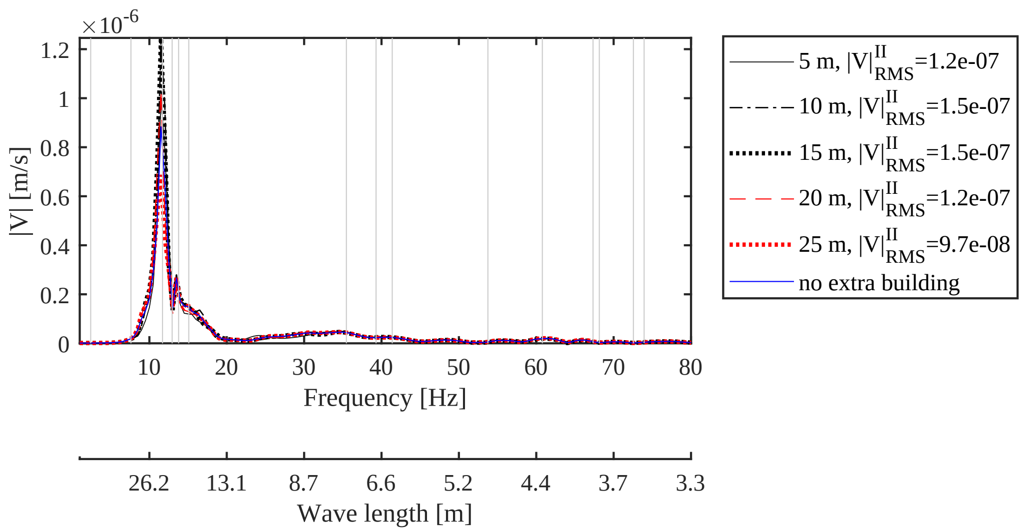


(b)

Figure B.2: Vertical complex velocity magnitude, for a node in the middle of the first floor of the studied building (a) and in the middle of the roof of the studied building (b), comparing different depths for the building placed behind the studied building.



(a)



(b)

Figure B.3: Vertical complex velocity magnitude, for a node in the middle of the first floor of the studied building (a) and in the middle of the roof of the studied building (b), comparing different distances between the buildings when a building with an 8 m deep cellar if placed behind the studied building.