Study of Concrete Foam Blocks for Mitigating Train-Induced Low-Frequency Ground Vibrations

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19/01/24

Abstract

Keywords Ground vibrations; Concrete foam blocks; vibration reduction; train-track model

This paper explores the issue of ground vibrations caused by railway traffic and suggests a practical solution using concrete foam blocks to alleviate these vibrations. The research entails creating an Abaqus software model to assess the efficacy of different geometrical configurations of concrete foam blocks in diminishing ground vibrations. The study outlines the challenges associated with the long wavelengths of train-induced vibrations and emphasises the boundaries in the model. Additionally, the research discusses the feasibility of real-life testing for the proposed configurations. The results reveal that the primary frequency of ground vibrations is approximately 18 Hz, which remains unaffected by concrete foam blocks. Furthermore, the paper recommends exploring variations in train masses and speeds, along with developing spatial arrangements capable of attenuating a broader range of low-frequency vibrations. Overall, this paper provides insights into the potential of concrete foam blocks for effectively mitigating ground vibrations induced by freight trains.

Contents

1 Introduction

Trains are indispensable arteries in the intricate tapestry of modern transportation, connecting distant destinations and fostering economic growth. However, there is a frequently disregarded side effect that lies beneath the wheels and rails that move our cargo across wide-open spaces: ground vibrations [1]. Because of their potential to cause both short-term disruptions and long-term harm to the environment and surrounding environment, these subtle but pervasive tremors caused by train passage have become a growing source of concern.

This paper delves into the complex world of ground vibrations, with a particular emphasis on the formidable influence of freight trains. These vibrations, stemming from the dynamic interaction between train wheels and tracks [2], can lead to a spectrum of adverse effects, ranging from structural damage to nearby buildings, disruption of sensitive equipment, and even disturbances to human well-being [3]. As the demand for freight transportation continues to rise, understanding and mitigating these ground vibrations becomes paramount for sustainable urban development and the preservation of critical infrastructure.

The primary aim of this integration project is to explore a proactive approach to mitigate the detrimental impacts of ground vibrations caused by freight trains, which operate at a slower speed than passenger trains. To that end, this paper focuses on the strategic placement of concrete foam blocks, developed by Nederboom [4], beneath railway tracks, a promising method recognised for its ability to attenuate and dissipate ground vibrations to some extent. By optimising the geometrical configuration of these blocks, the most effective design can be identified that mitigates ground vibrations while ensuring the structural integrity of the railway system. This challenge sparked a multidisciplinary project spanning engineering, materials science, transportation, and environmental studies.

In the pursuit of understanding and mitigating the complex dynamics of ground vibrations induced by passing trains, advanced modelling software is used. The utilisation of modelling tools provides a nuanced and comprehensive approach to studying the propagation and attenuation of ground vibrations with precision and accuracy. The finite element analysis (FEA) software [5], Abaqus, stands out as a tool for modelling and studying the intricate dynamics of ground vibrations. Abaqus is renowned for its robust capabilities in simulating complex mechanical phenomena, making it an ideal choice for investigating the propagation and attenuation of vibrations through diverse materials and structures.

The modelling approach allows us to explore a wide range of scenarios and test hypotheses under controlled conditions, providing insights that are challenging to attain through empirical studies alone. In the context of this thesis, Abaqus enables the creation of a virtual environment that reproduces the real-world conditions of railway tracks and their interaction with concrete foam blocks with sufficient accuracy for follow-up experiments. The software enables the simulation of the dynamic behaviour of the entire system under the influence of passing freight trains by leveraging Abaqus' advanced numerical algorithms, providing valuable insights into the efficacy of various concrete foam block geometries in mitigating ground vibrations. Ideally, a geometrical configuration that works best for reducing low-frequency ground vibrations is identified.

2 Problem analysis

2.1 Problem context

Train-induced vibrations result from a wide variety of contributing factors, including wheel roundness, train speed, and the mass of the train [2]. These vibrations manifest audibly at various frequencies in the air and tangibly on the ground. While vibrations in the air predominantly generate noise, which can be mitigated through methods like acoustic barriers [6], this project does not address noise reduction or air vibration mitigation. Instead, the focus is on the more challenging aspect of ground vibrations.

The propagation of waves through the ground, akin to seismic waves, represents a complex phenomenon with extensive implications across disciplines such as seismology, geophysics, civil engineering, and environmental science. Train-induced vibrations typically exhibit frequencies between 1 and 100 Hz, characterised by large wavelengths that pose greater challenges for attenuation compared to shorter wavelengths [7]. Vibrations in this frequency range, specifically between 1 and 20 Hz, can endanger structures and equipment near train tracks. If left unaddressed, structural deterioration not only incurs maintenance and repair costs, but it also poses a potential threat to safety.

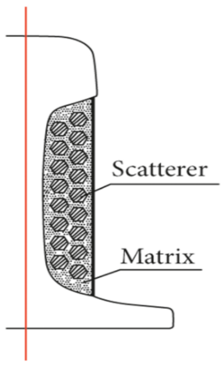
There are two ways to reduce vibration intensity: at the source of the vibrations or at the receiver's end. For the latter, there are several methods for reducing vibration intensity. They are dictated by the frequency range of the vibrations, which is controlled by previously mentioned elements like train velocity and track characteristics. Methods for attenuating vibrations at the receiver's end encompass the use of vibration screens, reinforcing building foundations, and incorporating damping materials. However, many of these receiver-focused solutions tend to be relatively expensive and less effective compared to the objective of this paper, which aims to diminish low-frequency vibrations at the source.

Reducing ground vibrations at the source

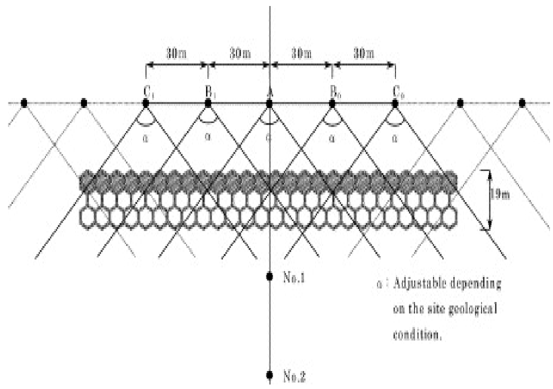
Addressing the issue of reducing low-frequency ground vibrations requires a proactive approach aimed at reducing vibrations in the foundation beneath train tracks. Some methods for mitigating ground vibrations at their source include the placement of vibration screens beneath the track, improving wheel roundness and track flatness, and imbuing damping properties into the train track. Many of these methods, however, are also relatively expensive and are often unable to tackle the most harmful vibrations with frequencies below 20 Hz. To overcome this issue, innovative engineering and materials science solutions are being investigated, with a primary focus on testing a newly developed 'foamed concrete'. This material, designed by Nederboom, should be able to attenuate low-frequency vibrations to some extent. Nederboom is already using concrete foam blocks to dampen vibrations in the foundation of houses and plans to use the same technique on train tracks. The proposed solution for this project involves utilising foamed concrete blocks as a vibration screen directly beneath the track. The primary emphasis, however, is not on the damping properties of the vibration screen but, instead, on optimising the spatial configuration of this layer to create destructive interference for low-frequency vibrations.

2.2 Alternatives

Various alternatives exist for mitigating ground waves induced by trains, with interventions falling into two primary categories, as was previously mentioned. At the receiver end, strategies such as installing resilient foundations, isolating structures with damping materials, and employing ground-borne vibration barriers have been explored. These methods, while effective to a certain extent, often entail significant costs and may have limitations in their overall efficacy.



(a) Damped rail with two-dimensional honeycomb phononic crystals [8]



(b) Honeycomb wave propagation foundation from viaduct [9]

Fig. 1: Two alternative methods of stopping vibrations at the source.

In contrast, focusing on interventions at the source of vibrations presents a promising avenue. Modifying train design elements, including wheel characteristics and suspension systems, offers a proactive approach to minimising the generation of ground waves. Additionally, optimising track properties, such as rail fastening systems and ballast configurations, can influence the transmission of vibrations to the ground. A tried-and-true method for reducing low-frequency train vibrations at the source is to give rails more damping features, such as the design of a damped rail with two-dimensional honeycomb phononic crystals [8], which has even resulted in an absolute band gap in which no shear waves are propagated. However, one disadvantage of this method is that the obtained band gap is not in the low frequency range and thus is not a viable solution for this paper.

Another investigation utilises a wave-impeding barrier designed to transform incoming wavelengths into shorter ones, effectively mitigating low-frequency vibrations [9]. Notably, this study focuses on high-speed trains, in contrast to the slower freight trains under consideration in this project. Furthermore, the damping layer detailed in the paper by Takemiya [9] incorporates a honeycomb structure serving as a pile foundation, utilising different in-fill materials compared to the concrete foam employed in this project. It is noteworthy that the model in the referenced study pertains to a viaduct scenario rather than

being applied directly to soil, as is the focus of our study.
All in all, these source-oriented solutions require a delicate balance, considering the broader implications for train performance, safety, and infrastructure maintenance.

2.3 Concrete foam blocks

Concrete blocks, designed by Nederboom [4], should be able to attenuate low-frequency vibrations to some extent underneath the train track. Nederboom is already using concrete foam blocks to dampen vibrations in house foundations and plans to use the same technique on train tracks. Hanze Groningen and TU Derft have tested some of the relevant material properties of the concrete foam blocks, which can be used to simulate vibration reduction for train tracks. One of the benefits of this type of concrete foam is its ability to maintain its shape and not deform in the face of disruption caused by vibrations similar to earthquakes. The tested blocks in this study were uniformly sized at 80 by 80 by 40 centimetres. To maintain precision in our project, we will adhere to these exact material dimensions. Foamed concrete, in contrast to conventional concrete, is relatively lightweight due to air bubbles introduced during the mixing process, providing it with inherent damping properties, as outlined by Amran, Farzadnia, and Abang Ali [10]. The combination of its lightweight composition and the presence of air voids makes foamed concrete notably lighter than its traditional concrete counterpart. Regarding the setup and placement in the model, the blocks will not be placed directly underneath the rails but will instead be used, initially, as foundations for the sleepers that support the rails, as illustrated in figure 14a.

Fig. 2: Foamed concrete block

2.4 Conceptual design

2.4.1 Problem statement

Why-What analysis

In order to illustrate the structure of the problem, a why-what analysis is performed [11]. This model makes the distinction between the questions 'why do we want to solve this problem' and 'What is stopping us from solving this problem'. The model is visualised in figure 3, which is meant to organise the problem in the order from broad to narrow.

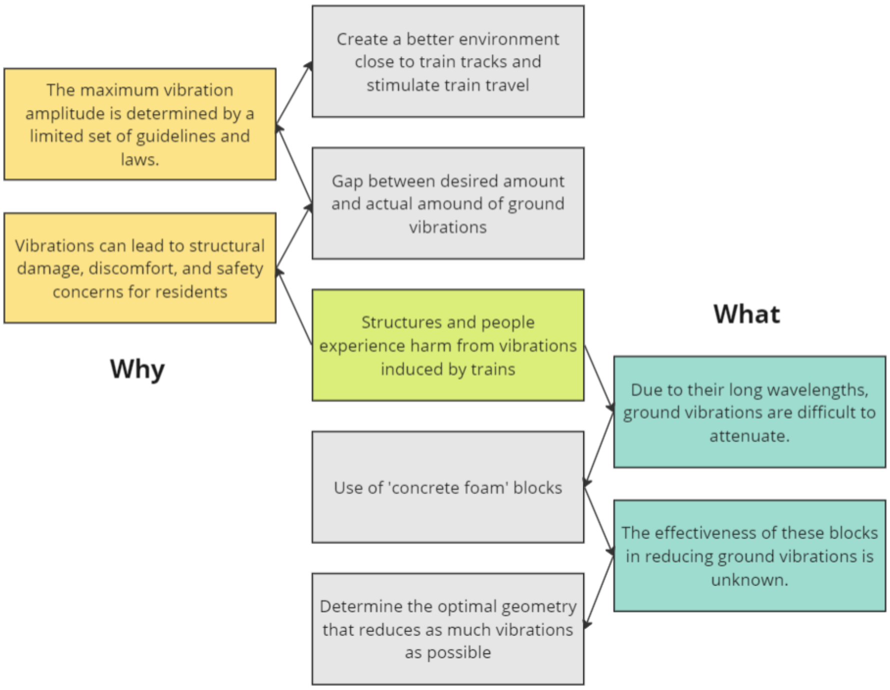


Fig. 3: Why-what analysis

Problem statement

The pervasive issue of ground vibrations stemming from train activities necessitates innovative solutions to minimise their negative effects on neighbouring structures. Foamed concrete blocks have been introduced as a promising technology with the capacity to attenuate a significant proportion of these vibrations. However, the current understanding of the ideal configurational geometry for these blocks, ensuring optimal attenuation properties between 1 and 20 Hz, is still incomplete.

2.4.2 Research objective

The research objective of this project is the following:
In three months, explore the capability of foamed concrete blocks to reduce ground vibrations induced by railways within the 1 to 20 Hz frequency range. If present, Identify the most promising and practically realisable configurations for placing these blocks

To assess the quality of the research objective, SMART conditions are used ([12]). The objective is ***Specific*** as it clearly defines the research goal, which is to find the optimal geometry for foamed concrete blocks for a specific purpose: reducing ground vibrations induced by railways within a specific frequency range (1 to 20 Hz). The objective includes a ***M**easurable* outcome, as the effectiveness of the foamed concrete block geometry will be measured through its ability to reduce vibrations, indicating that there will be quantifiable results. Furthermore, it is ***A**ttainable* to conduct research using already published material, develop a numerical model for the analysis, and run experiments within a three-month time frame using existing technology.
The research objective directly addresses a real-world issue (railway-induced ground vibrations), provides a practical solution, and is therefore ***R**elevant*.
Lastly, the statement specifies a clear ***Time*** frame of three months, indicating a realistic deadline for completion.

2.4.3 Research strategy

The main goal of this project is to develop a model for analysing the geometrical configuration of concrete foam blocks that reduces ground vibrations caused by freight trains as much as possible. Models, however, are only as accurate as the given parameters and boundary conditions allow them to be, which introduces some challenges. Freight trains usually induce ground vibrations below 40 Hz, which can be felt by lineside residents and buildings [13]. These waves have relatively long wavelengths that can propagate in soils over large distances without considerable attenuation because their wavelength is very large[14]. Another disadvantage of long wavelengths is that they necessitate large model dimensions in order to produce reliable simulations. Furthermore, once model boundaries are reached, the vibrations should not be reflected back into the system to represent realistic scenarios. This can be avoided by incorporating absorbing boundaries into the model, which dampen the vibrations at the model's end. If the model is set up properly, wave interactions will be studied for different geometrical concrete foam configurations. Different configurations and distances between the blocks alter the period and directions of waves, according to Bloch's theorem [15].

Initially, a reference model will be constructed with the known properties of a train track without any dampening or attenuation features present. Upon validation of this reference case, a new model with specified dampening features and properties will be developed. This model integrates various wave theory laws and properties, aiming to create a comprehensive simulation of a real environmenta detailed exploration of which is presented in the Abaqus© model section. The identification of the optimal geometrical arrangement for concrete foam blocks involves a thorough comparison and adjustment of results between the reference and desired models. Following the development and analysis of an optimal design, Nederboom will proceed to a real-life testing phase. It's important to note, however, that this testing phase falls beyond the purview of this project. A visual summary of the steps and features of this model can be observed in figure 4. To validate simulations and test results, various key performance indicators (KPI's) are employed, encompassing the vibration frequency, reduction in vibration amplitude, and structural integrity. Initially, the vibration frequency is measured to identify the predominant frequency in the system, guiding the development of suitable countermeasures. Subsequently, the vibration amplitude serves as a performance indicator, allowing for a comparison between the reference case and the case incorporating vibration countermeasures. Finally, to ensure the model's accuracy in a real-world environment, its structural integrity is crucial and, therefore, undergoes examination through Abaqus©, which is able to indicate weak points in the model.

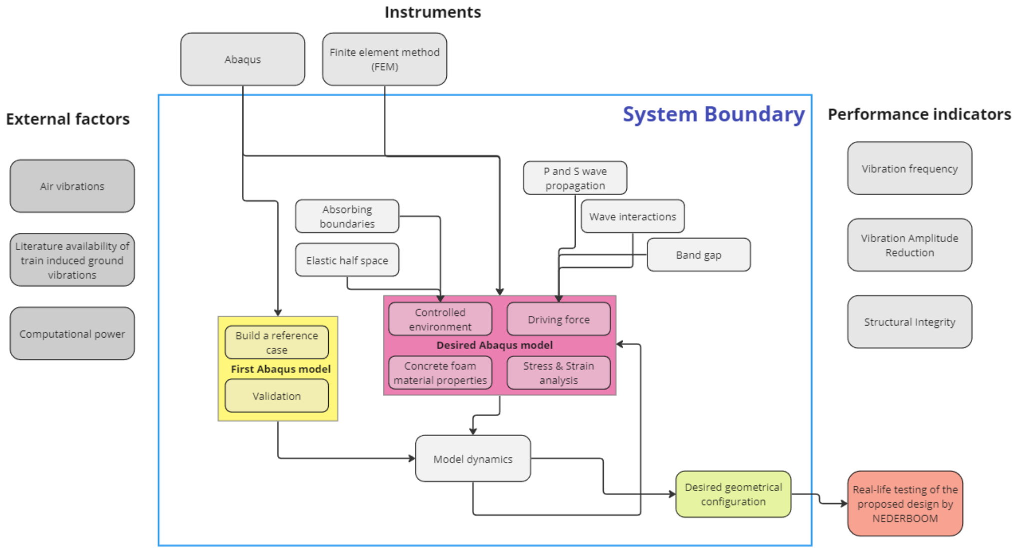


Fig. 4: Research framework. This model lists the external factors in this case that are not taken into consideration. Performance indicators for this project are vibration frequency, vibration amplitude, and block structural integrity. The instruments to measure these metrics can be found in Abaqus and in finite element material analysis

2.4.4 Research questions

The following research questions follow the research objective and are supported by six sub-questions:

"Can foamed concrete blocks attenuate vibrations in the target frequency, from 0 to 20 Hz, and if so, what is the most suitable configuration of concrete blocks beneath railways for mitigating ground vibrations induced by freight trains?"

The following sub-questions aid in being able to answer the question above:

- How do vibrations propagate through solid materials?
- Which frequency or wavelength of vibrations is most harmful for structures?
- How can vibrations from trains be mitigated or reduced?

- What are the properties of concrete foam blocks?
- What is an accurate Abaqus FEM model to predict foamed concrete's ability to attenuate vibrations at low frequencies?
- What impact do damping and the geometric arrangement of a material have on its ability to reduce ground vibrations?

3 Abaqus model

3.1 Model development

In order to find the optimal geometrical configuration of concrete foam blocks underneath train tracks, a numerical simulation will be performed using existing literature and modelling software Abaqus© [16]. This modelling software is able to simulate the propagation of waves in different types of soil based on predefined and controlled parameters. Ground vibrations are propagated by p and s waves, the velocity of which is determined by the material through which the waves travel. P-waves (primary or compressional waves) and S-waves (secondary or shear waves) are waves with distinct characteristics [14]. P-waves, also known as primary waves, are compressional seismic waves that travel through the Earth. These waves are characterised by their ability to locally compress and expand the material through which they travel. P-waves are classified as longitudinal waves as the particle motion occurs parallel to the direction of wave propagation. As a result, they can travel through a variety of mediums, including solids, liquids, and gases. P-waves exhibit the fastest velocity among waves in solids, making them the first to reach a distant location. P-waves' compressional nature indicates their ability to cause particles to move back and forth along the wave's direction.
S-waves, or secondary waves, represent another category of waves in solids that traverse the Earth. S-waves, unlike P-waves, are transverse waves, which means particle motion occurs perpendicular to the direction of wave propagation. This distinguishing feature limits their ability to propagate through liquids and gases, allowing them to travel solely through solids. S-waves travel at a slower rate than P-waves and typically arrive after P-waves, but they are more damaging. S-wave-induced shear motion is caused by particles shifting side to side, which shears the material when the S-waves are passing through. Formulas for estimating the propagation velocity of s and p waves are displayed in equations 1 and 2 respectively. (μ) is the shear modulus of the solid material, (ρ) is the density, and (k) is the bulk modulus.

$$V_s = \frac{\mu}{\rho} \tag{1}$$

$$V_p = \sqrt{\frac{k+4/3\mu}{\rho}} \tag{2}$$

Finite element analysis will be performed in order to investigate the behaviour of the different layers of soil beneath the track as well as its vibration attenuation properties.

Modelling and measuring wave attenuation are crucial for comprehending how waves in solids lose energy during propagation. The reduction in vibrations is affected by soil structure (such as multi-layered soil with varying thickness) and subsurface material properties, including viscosity, density, and elasticity [14]. In the context of low-frequency vibrations induced by trains, the relevance of P and S waves lies in their ability to assess the impact on the Earth's subsurface. Because trains cause ground vibrations, it is critical to understand how these waves propagate through different materials in order to assess their potential effects on the surrounding environment and infrastructure.

3.2 Dimensions

As mentioned before, most of the dimensions for the Abaqus© model are replicated from the reference case [17]. There is one significant difference, however: the model is divided through the middle of the train tracks. This action is performed in order to reduce the simulation time to a feasible one and to get a more comprehensive view of wave propagation right below the train tracks. The soil model dimensions are as follows:

Material	**Height (m)**	**Width (m)**	**Length (m)**
Stiff sand layer	10	22.5	130
Clay layer	10	22.5	130
Fill layer	0.5	22.5	130
Embankment	3.5	13.5	130
Ballast	1	5	130

TABLE I: Model soil dimensions in metres.

The exact relevant dimensions of the model are displayed in table I. Most of the geometrical configurations of the model are exactly the same as those of the reference case, apart from the configuration of the track system structure. The dimensions of the sleepers and rails, as well as the number of sleepers, differ in the track system structure. As the reference case does not specify the rail and sleeper dimensions, some estimations were made. Although these dimensions deviate from the reference case, they should not result in noticeable differences in the wave propagation process because they are comparatively small. Another estimate was made for the number of sleepers based on a picture from the reference case [17]. There is a small margin of error (+/- 5) as the image becomes increasingly pixilated when zoomed in, resulting in an estimated number of sleepers of 205. Once again, this should not result in a noticeable difference in the propagation of waves. The rail dimensions were not provided in the reference case; thus, some assumptions were made based on similar models. Furthermore, rather than two pairs of rails, only one half of a pair of rails is modelled, splitting the train track and leaving only one half. The dimensions of the rail and sleepers are displayed in table II.

Material	**Height (m)**	**Width (m)**	**Length (m)**
Sleepers	0.150	0.200	1.2
Rail head	0.100	0.225	129
Rail web	0.005	0.225	129
Rail foot	0.035	0.135	129

TABLE II: Rail & sleeper dimensions in metres.

Finally, a sketch, including spatial dimensions and the order of layers, is provided in figure 5 and enlarged in Appendix B.

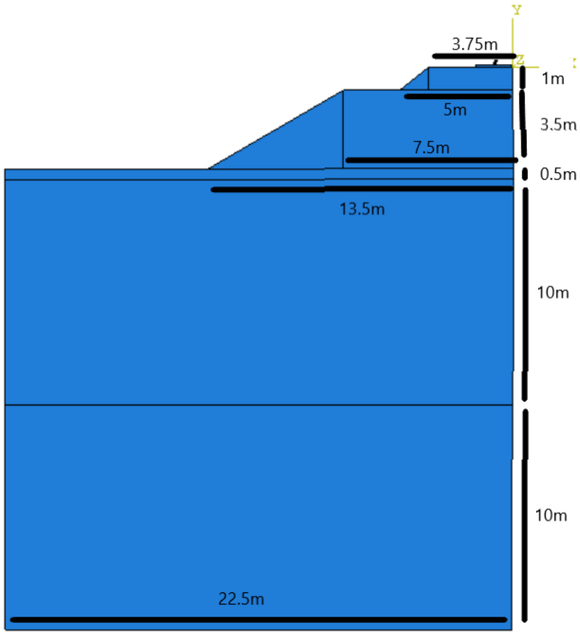


Fig. 5: Ground dimensions. From bottom to top, the layers are: stiff sand, clay, fill, embankment, and ballast, on top of which the train track is placed.This Image is enlarged in the Appendix.

3.3 Model properties

Several key model properties affect the simulation's accuracy and dependability when it comes to an Abaqus© model that simulates wave propagation and the attenuation of vibrations caused by moving trains. These properties are discussed in this section.

The material properties of the various layers of soil as well as the track itself are listed in table III. These material properties are similar to those in the reference case, apart from the clay layer, which had an incorrect value and has been corrected [17].

Material	E/**Pa**	μ	ρ/**kg/m**^{3}	V_S	V_R
Ballast	$3.89E+8$	0.3	2200	260.8	241.9
Embankment	$2.5E+8$	0.3	1800	231.1	214.4
Fill	$9.075E+7$	0.3	1800	138.7	128.6
Clay	$1.605E+9$	0.35	1600	76.6	71.6
Stiff sand	$1E+8$	0.3	1800	146.2	135.6
Rail	$2.1E+11$	0.17	7800	3392	3074.2
Sleeper	$2E+10$	0.2	2500	1826	1664.5

TABLE III: Material properties.

Rather than modelling an entire train, this model simulates the moving load on a single wheel along the train track. The force that this wheel exerts on the track over an area of $0.02\,\text{m}^2$ is 70 KN, which is a distributed load of 3.75 MPa, similar to the load in the reference case.

3.3.1 Elastic half spaces

The simulation will be modelled using elastic half spaces and absorbing boundaries. Elastic half-spaces are simplified models used in structural analyses to simulate the mechanical behaviour of materials, particularly soils or deformable media [18]. This modelling approach assumes that the soil behaves elastically, meaning that when the applied load is removed, the soil returns to its original shape. The assumption of linear elasticity simplifies the relationship between stress and strain within the material. The term "half-space" signifies that the model considers only one-half of an infinite medium. This simplification is made for computational efficiency while retaining the ability to capture essential features of the soil's behaviour. The upper half-space influences the soil's response in the case of a train moving on the surface, and boundary conditions are applied accordingly. Dynamic loading is a key aspect in this context. As the train moves along the track, it imparts dynamic loads to the soil, inducing stress waves that propagate through the soil [19]. Understanding how these stress waves attenuate as they travel through the soil is crucial for assessing their impact on nearby structures, such as buildings or foundations.

3.3.2 Absorbing boundaries

Furthermore, it is necessary to model absorbing boundaries in order to ensure that vibrations are not reflected back into the model. Absorbing boundaries are computational features built into finite element models that simulate wave dissipation and prevent unwanted reflections at the model's edges [20]. Outgoing waves are absorbed by these boundaries, preventing them from bouncing back into the modelled domain and influencing simulation results. Absorbing boundaries, in essence, serve as a virtual buffer zone, allowing the modelled waves to dissipate without interference. As the modelled train load imparts dynamic loads to the soil, stress waves propagate through the soil medium. Without proper boundaries, these waves might reflect back into the modelled domain, leading to artificial interference and inaccurate simulation results. The model in Abaqus© is configured in such a way that vibrations are not reflected back into the model at the edges using boundary conditions.
This boundary condition consists of two components: a fixed bottom and partially fixed sides. The bottom is fixed by drawing an encastre on the model's bottom plane, which sets both movement and rotation at this plane to zero at all times. Only displacement in directions other than the direction of the moving load is set to zero for the sides of the model. These settings ensure that vibrations are not reflected back into the model but can still be observed carefully.

3.3.3 Time step & domain

The choice between a time domain and a frequency domain approach in the analysis of ground vibrations caused by trains using Abaqus© has significant implications. Depending on the study's objectives, each approach has distinct advantages. A time-domain analysis that focuses on the temporal evolution of the system's behaviour is ideal for capturing transient phenomena like the dynamic response of soil to passing trains. Furthermore, time-domain methods provide greater flexibility in terms of model line shapes [21]. Frequency domain analysis, on the other hand, emphasises the frequency content of the system's response, making it useful for identifying the frequency spectrum of propagating waves and comprehending dominant frequency components. Furthermore, when dealing with the real part of the frequency-domain MRS signal, which is far from trivial, appropriate phasing is required for frequency domain models [21].

The simulations of this project are executed in the time domain, but some results will be transferred to the frequency domain for further analysis. The selection of an appropriate time step is a critical parameter influencing simulation accuracy and stability in time-domain analysis. A smaller time step improves accuracy by capturing rapid changes in the system's behaviour, which is critical when dealing with high-frequency vibrations or transient loading conditions. This precision, however, comes at the expense of increased computational demands. Larger time steps, on the other hand, speed up simulations, making them more computationally efficient, but they increase the risk of numerical instability and may result in missing important details in the system's response. The optimal time step is determined by carefully considering the expected frequency content of vibrations and the desired level of temporal detail in the simulation. As this project's model only considers vibrations with a frequency range between 1 and 20 Hz, the necessary time step will not be too computationally demanding. The time step for the simulation is determined by equation 3, where Δt refers to the time increment and T is the time period corresponding to the largest frequency.

$$\Delta t = \frac{T_{max}}{10} \tag{3}$$

For this integration project, where the maximum frequency considered is 20 Hz, the selected increment size should be at least 0.01 or smaller. In this case, a choice of 0.01 is made to optimise computational efficiency during the simulation and to be able to run multiple simulations within the time frame of this project.

After running the simulations in the time domain, some results can be transferred to the frequency domain in order to identify dominant frequencies. This predominant frequency will effectively signal which vibrations pose a potential threat, enabling the implementation of suitable countermeasures informed by this data. Moreover, this information will be useful for determining the effectiveness of the measures proposed in this paper.

3.3.4 Model mesh

The mesh, consisting of discrete elements that represent the geometry, allows for the numerical approximation of physical phenomena and influences the accuracy and efficiency of the simulation [22]. In the context of soil-structure interaction, the importance of meshing lies in capturing the complex and dynamic response of the soil to the passing train's load. A well-designed mesh is essential for accurately representing wave propagation and attenuation through the layers of soil.

The first consideration is the spatial distribution of elements. Adequate mesh density is required to ensure that the model captures the intricate details of the soil response, especially in regions where stress concentrations or wave interactions are anticipated. In areas of interest, such as beneath the train tracks or near critical structures, refining the mesh provides a finer resolution to capture localised effects. The choice of element type is equally crucial. Different elements in Abaqus© , such as solid, shell, or beam elements, offer varying levels of complexity and computational cost. Furthermore, considering the potential for large deformations in the soil during dynamic loading, elements must be appropriately shaped and oriented to prevent numerical instabilities. This becomes particularly relevant when modelling wave propagation and attenuation, where accurate representation of deformation is crucial. The mesh quality also directly impacts the simulation's computational efficiency. An overly dense mesh may lead to excessive computation times, while an insufficiently refined mesh may compromise the accuracy of the results. Achieving a balance requires careful consideration of the model's geometry, the anticipated response, and available computational resources.

In this model, hexahedral element meshing is used. This method allows for providing directional sizing without losing accuracy [23]. As the parts in this model do not have complex three-dimensional shapes, using a standard hexahedral mesh will be sufficient. The global seeds in the mesh are determined by the size and complexity of the part and have been made small enough to not significantly alter the simulation results while also being large enough to reduce computational time.

The mesh size is dependent on the material and is computed using the formula displayed in formula 4. In this formula, ΔX stands for the width of the mesh size in every dimension (height, length, and width) in metres, and λ_{min} is the minimum wavelength size in metres as computed by formula 5. As can be seen, '7' is used as a rule of thumb to divide the minimum wavelength by in order to obtain a sufficient mesh [24]. In formula 5, G stands for the shear modulus of a material in N/m^2, ρ is the mass density in kg/m^3 and $f_{\max}$ is the maximum frequency this is to be examined, namely, 20 Hz. Finally, the shear modulus of a material is calculated using the shear velocity in metres per second and the density, as shown by formula 6.

$$\Delta X = \frac{\lambda_{min}}{7} \tag{4}$$

$$\lambda_{min} = \sqrt{\frac{G}{\rho}} / f_{max} \tag{5}$$

$$G = \rho * V_s^2 \tag{6}$$

Appropriate mesh sizes are determined by using these formulas for all of the materials in the model. The size of the seeds in these mesh dimensions can be found in table IV.

Material	computed mesh size (m)	Chosen mesh size (m)
Stiff sand	2.0886	2
Clay	1.0943	1
Fill	1.9814	1
Embankment	3.3014	1
Ballast	3.7257	1

TABLE IV: Mesh seed dimensions. Note that the meshes of the fill and ballast are only as large as the height of the layer itself.

From the table, it can be noted that some of the chosen mesh sizes are not close to the computed mesh. The reason for this discrepancy is that the model mesh should not deviate too much per layer, as this can introduce artificial wave reflections or instabilities. As the load is applied to the model from the top down, the mesh size should increase from small to large, not the other way around.

3.3.5 Interactions

In the context of investigating the propagation and attenuation of vibrations induced by passing trains using numerical simulations in tools like Abaqus© , the interaction between various layers of soil and the foundation is a critical factor. Different soil layers may exhibit varying stiffness, damping characteristics, and impedance, influencing the reflection and transmission of stress waves. The accurate representation of these interactions is critical for studying how waves propagate through the soil and soil interfaces and how they attenuate as they encounter different layers, corresponding to realistic scenarios. Additionally, the interaction between different soil layers and the foundation significantly contributes to the dissipation of energy during wave propagation, allowing for a detailed examination of attenuation mechanisms.

Abaqus© automatically recognises interactions between different layers within a model, but for some interactions, explicit conditions must be set up. The interaction between the load and the rails, in particular, should be well defined because it can be either rough or smooth. Rough contact is defined by tangential behaviour with a rough friction formulation and is applied to the loading step, which is the pressure application onto the rails. This loading is applied to the model for one second. Smooth contact, on contrast, is defined by tangential behaviour with a smooth friction formulation and is applied in the dynamical 'movement' step of the simulation. This time step takes one second.

3.4 Results

Because the primary goal of this paper is to investigate the propagation of vibrations in different layers of soil, vertical displacement is the most important parameter in question. Displacement can be plotted at all mesh points, but the most relevant area of interest is directly beneath the moving load. Two points are chosen for the clay layer at a distance of 12 metres from the model's left side and 4 metres apart in depth. For the first simulation, the train is modelled at 60 km/h (16.67 m/s). So, for one second, the load will move over the plotted mesh points. For the stiff sand layer, two points are chosen at 10 metres from the left side of the model and also 3 metres apart, as illustrated in figure 8. The displacement is plotted against time for these layers in figures 6 and 7. The findings reveal that there are no indications of worrisome displacements in components like the rails and sleepers, suggesting that the structural integrity of the model is satisfactory.

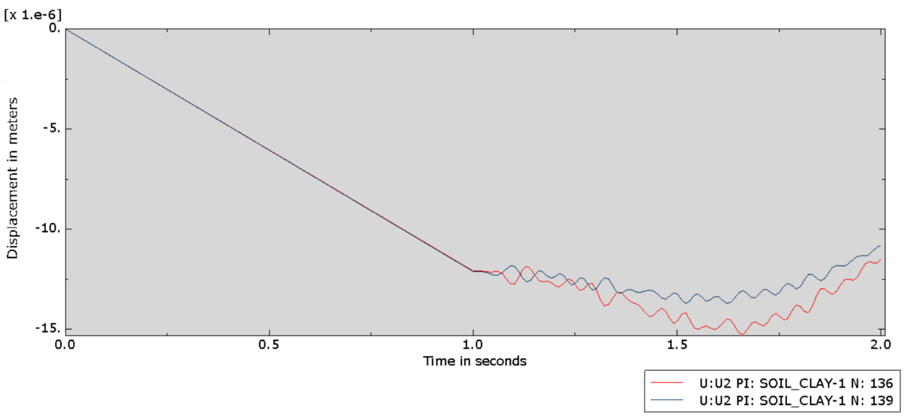


Fig. 6: Displacement against time of the clay layer at a distance of 12 metres from the left side of the model. Displacement is measured in metres and time in seconds.

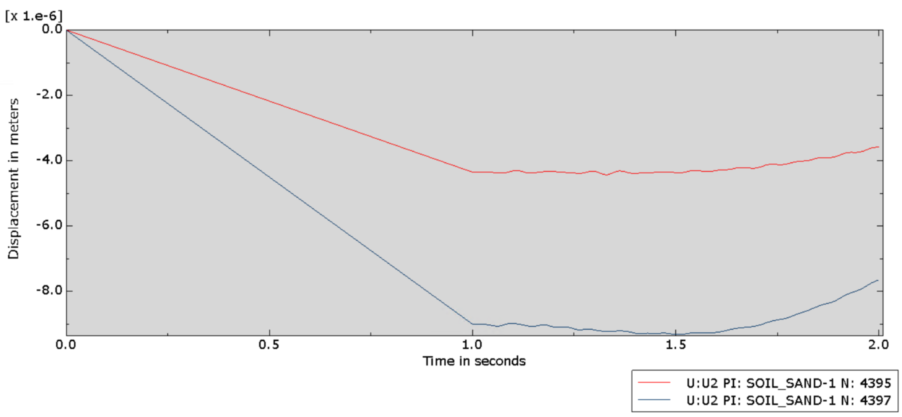


Fig. 7: Displacement against time of the stiff sand layer at a distance of 12 metres from the left side of the model. Displacement is measured in metres and time in seconds.

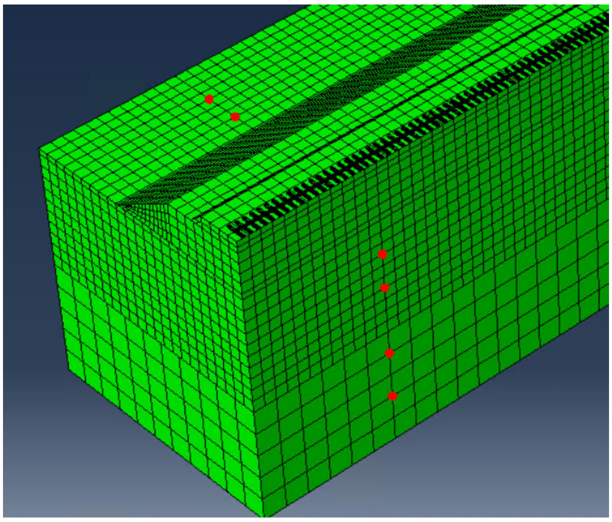
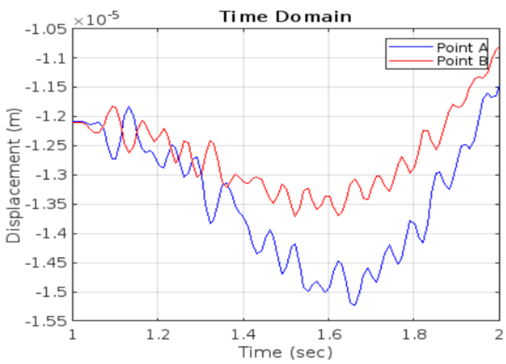
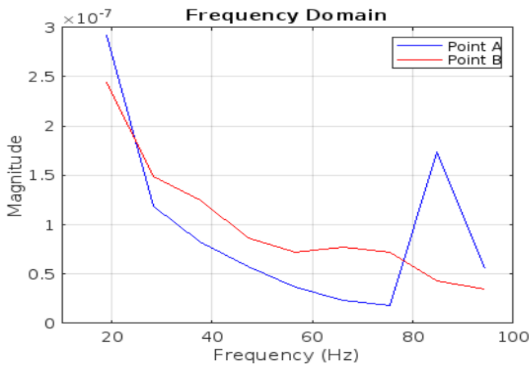


Fig. 8: Measurement points are designated in the model, with two closely situated points identified for each area of interest. These areas encompass the surface of the clay layer, the region beneath the track within the clay layer, and the area beneath the track within the sand layer.

Now that the model has been simulated in the time domain, the results can be transferred into the frequency domain to investigate the frequency spectrum in this reference case. The transformation from the time domain to the frequency domain is done with a Matlab script, which is provided in Appendix C.



(a) The difference between point A and point B in the reference case model in the time domain.

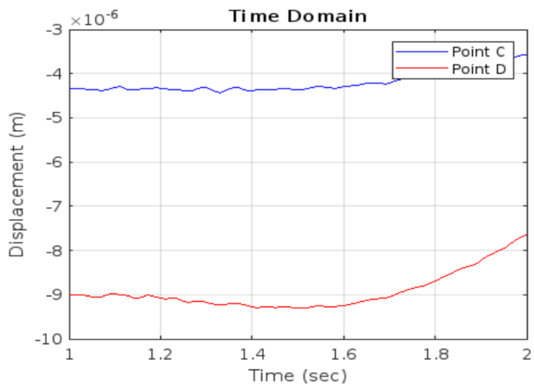


(b) Differences in the frequency domain between point A and point B

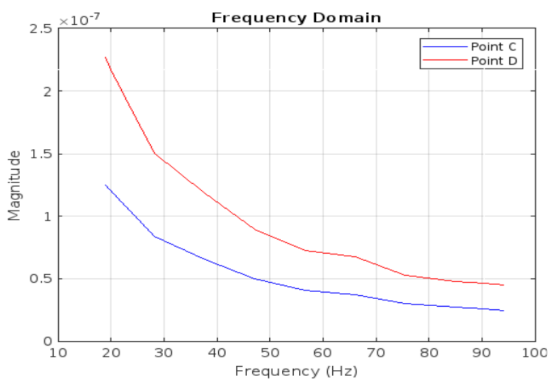
Fig. 9: Results from the time and frequency domains are presented for two specific points within the **clay** layer of the reference model. The data depicted in both graphs corresponds to the same two locations in the modelpoint A, situated 12 metres from the left side and 3 metres down from the top of the clay layer, and point B, located 3 metres below point A.

Starting with the analysis of the time domain graph (figure 9a), noticeable differences in displacement become evident at the two specified points. Specifically, point B, situated at the lower extremity, exhibits less displacement in comparison to point A. This disparity is explained by the expected decrease in wave magnitude as it travels a greater distance, which is consistent with the fundamental principles of wave propagation [7]. Furthermore, during the dynamical step of the simulation, there are some oscillations in the displacement at both points, the majority of which are located at the point closest to the load. One possible explanation for these oscillations is that the soil-train system may exhibit oscillating behaviour due to the rolling contact of the dynamical load. Other explanations for these oscillations could be the absence of damping properties in the model, interactions between different material layers, or the numerical accuracy of the mesh in the model.

Examining the frequency domain, it becomes evident that the predominant frequencies for both points cluster around 18 Hz, posing a potential risk of inducing harmful vibrations in buildings and adjacent structures. Notably, there exists an additional peak at approximately 85 Hz for point A, a phenomenon absent in the frequency spectrum of point B. This divergence can be attributed to the dissipation characteristics of higher-frequency vibrations, which diminish more rapidly in comparison to their lower-frequency counterparts in the ground.



(a) The difference between point C and point D in the reference case model in the time domain in the sand layer.

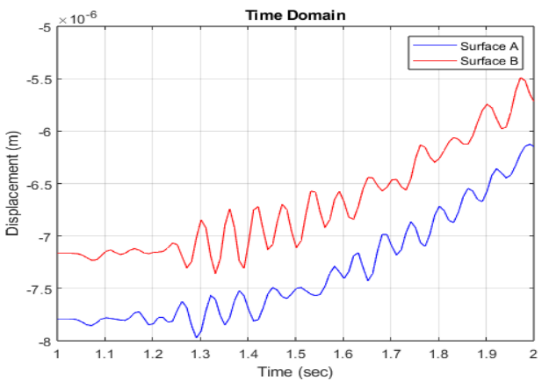


(b) Differences in the frequency domain between point C and point D in the frequency domain in the sand layer

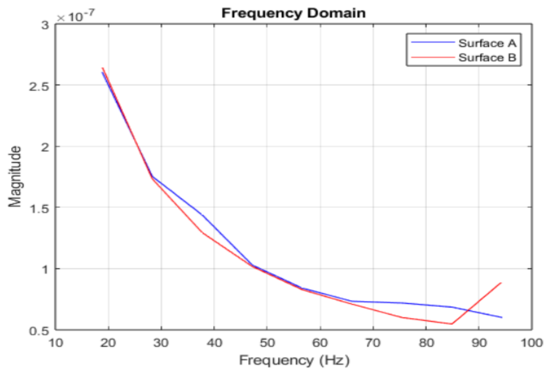
Fig. 10: Results from the time and frequency domains are presented for two specific points within the **sand** layer of the reference model. The data depicted in both graphs corresponds to the same two locations in the modelpoint C, situated 12 metres from the left side and 2 metres down from the top of the sand layer, and point D, located 4 metres below point C.

As can be observed in figure 10a, the displacement in points C and D varies more compared to the results in the clay layer. One possible explanation for this is the fact that point D is close to the boundary of the model and, therefore, is more affected by the train load. Given this disparity within the sand layer, the subsequent sections of this paper will predominantly focus on the analysis and interpretation of results within the clay layer The results from the frequency domain, however, are closer to each other, and there is no peak around 85 Hz like in the clay layer. The sand layer is beneath the clay layer, so it is possible that more of the higher-frequency vibrations have already been attenuated. The low-frequency vibrations are still present, albeit at a lower magnitude. It should be noted that displacement oscillations in the sand layer appear weaker compared to the clay layer.

Finally, displacement is estimated at two points on the surface near the train track to investigate wave propagation in a more horizontal direction. This is particularly relevant in situations where structures are located adjacent to the tracks. From figure 11b, it can be observed that the peak of frequencies is still located around 18 Hz and that there is no peak around 80 Hz as was the case beneath the track. Furthermore, the amplitude of the frequency band between 18 and 30 Hz is higher compared to the area beneath the train track. So, low-frequency vibrations are attenuated less along the surface compared to the ground.



(a) The difference between surface point A and B in the reference case model in the time domain.



(b) Differences in the frequency domain between surface point A and point B in the frequency domain

Fig. 11: Results from the time and frequency domains for two specific points at the top of the **clay** layer. The data depicted in both graphs corresponds to the same two locations in the model. Surface point A, situated 12 metres from the left side and 2 metres away from where the embankment starts, and point A, located 3 metres further away from the track than point A.

4 Concrete foam model

Now that the reference model has been constructed, the behaviour of concrete foam can be examined.

4.1 Material properties

As opposed to the initial Abaqus© model, this model introduces an additional layer beneath the sleepers of the train tracks in an effort to further reduce the vibrations induced by trains. The layer under the sleepers consists of concrete foam blocks, which were designed by Nederboom [4]. The material properties of concrete foam are displayed in Table V.

Mass density	500 kg/m^3
Young's Modulus	3501 MPa
Poisson ratio	0.15
Block mass	128 Kg

TABLE V: Material properties of concrete foam blocks of 80cm x 80 cm x 40 cm. The damping ratio corresponds to 60% attenuation of the leading peak at frequencies between 0.1-4 Hz.

4.1.1 Damping

Damping, defined as the dissipation of energy in a material during dynamic loading, is critical in vibration attenuation. Its primary function is to absorb and dissipate the energy associated with dynamic loads [25]. This attenuation aids in preventing excessive vibration propagation through the ground. Damping becomes critical in preventing resonance, which occurs when the natural frequencies of the soil-structure system coincide with the frequencies of train-induced vibrations. Vibrations are amplified by resonance, exacerbating structural and environmental impacts. Damping that is properly managed is an important preventive measure against resonance-related issues. Materials with appropriate damping properties can be chosen to reduce vibration transmission and improve the overall performance of the soil-structure system.

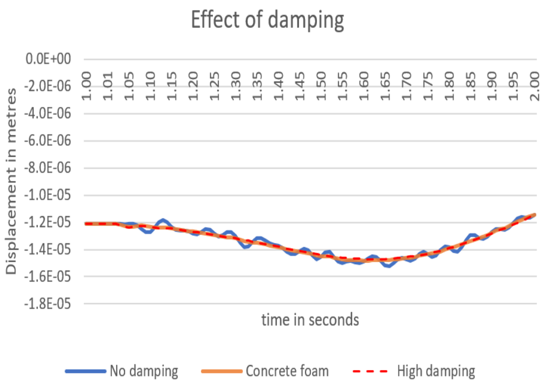
In this case, Rayleigh damping is implemented in the material properties [26]. Rayleigh damping is a structural dynamics technique that introduces damping into numerical models, providing a convenient and efficient way to simulate energy dissipation in a system subjected to dynamic loads. Rayleigh damping uses a linear combination of the mass and stiffness matrices to create a simple and effective representation of structural damping. In Rayleigh damping, the total damping matrix c is expressed in formula 7.

$$c = \alpha k + \beta m \tag{7}$$

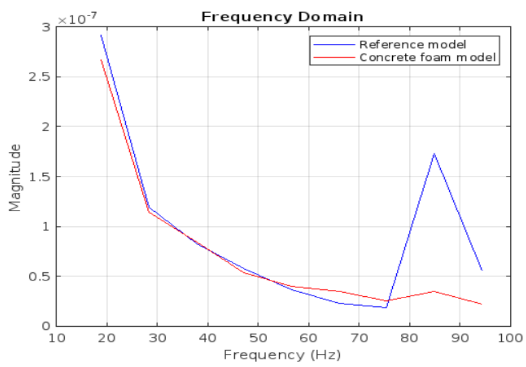
In this formula, m is the mass matrix, k is the stiffness matrix, and α and β are the Rayleigh damping coefficients, which can be assigned in Abaqus©. By adjusting these values, we can control the amount of viscous damping introduced into the model, providing a flexible and practical approach for incorporating damping effects. To assess the influence of damping, various values for these coefficients are examined. Nevertheless, it is anticipated that damping will yield only a marginal reduction in vibrations. The primary expectation is that the arrangement of the concrete foam blocks will exert a more substantial influence on the attenuation of vibrations. With the information that the damping ratio corresponds to 60% attenuation of the leading peak at frequencies between 0.1-4 Hz, α and β are computed as 0.73556 and 0.046582 (Appendix D), respectively. Finally, an additional simulation is run with both Rayleigh damping variables alpha and beta set to 0.9 to investigate the overall effectiveness of damping for reducing low-frequency ground vibrations.

4.1.2 Testing the effect of damping

In order to investigate the actual influence of the damping properties of concrete foam blocks, ground wave propagation in the concrete foam model is weighed against the reference case model in both the time and frequency domains. For this scenario, the arrangement involves placing concrete foam blocks adjacent to each other without any spacing, as illustrated in Figure 14a. These concrete blocks are positioned atop the ballast and beneath the sleepers, providing a basis for comparison with the reference case where concrete foam blocks with damping properties are absent.



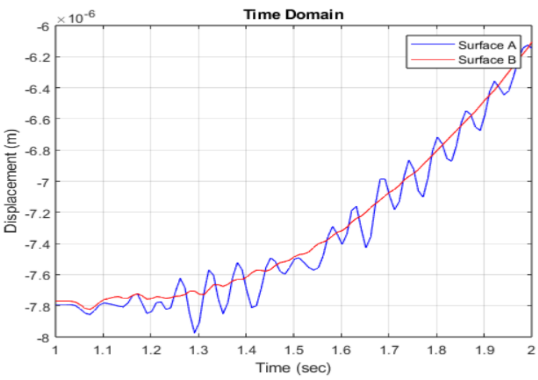
(a) This graph compares the effectiveness and relevance of the reference case model with no damping, the concrete foam model with implemented damping, and a hypothetical 'high damping' case.



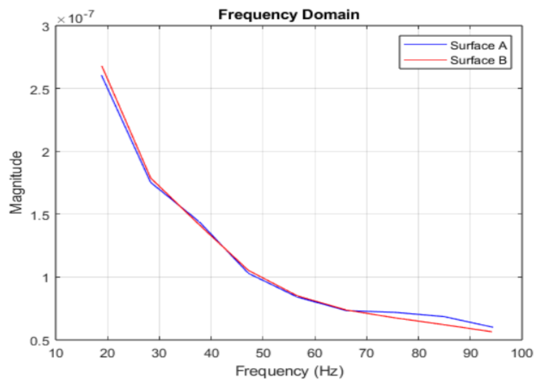
(b) Differences in the frequency domain from the dynamical part of the simulation of both the reference case with no damping and the concrete foam model with implemented damping.

Fig. 12: Time and frequency domain results from both the reference model and the concrete foam model in the ground. The data in both graphs is taken at the same spot in the model, which is 12 metres from the left side of the model and 3 metres down from the top of the clay layer

From figure 12a, it can be observed that the implementation of concrete foam blocks with damping has a minimal impact on the amount of ground displacement as a result of passing trains. It does, however, slightly dampen high-frequency oscillations. Furthermore, when comparing the inherent damping of the concrete foam blocks with a hypothetical 'high damping case,' it becomes evident that enhancing the damping properties of the concrete foam is unlikely to significantly impact the ultimate attenuation of low-frequency vibrations. In order to examine the reduction of vibrations within different frequencies, the results are once again converted to the frequency domain using a similar script as in Appendix C. The differences in the frequency domain are displayed in figure 12b. This illustration indicates that while higher frequencies, approximately 85 Hz, experience a reduction, low-frequency vibrations largely remain consistent and are not significantly affected by damping alone. Furthermore, as the reference case model results show, vibrations around the 85 Hz frequencies are attenuated relatively quickly, indicating that further efforts are necessary in order to make a noticeable difference in the reduction of ground vibrations. Finally, the effect of damping is also tested at the surface of the clay layer in figures 13a and 13b. While the variation in oscillations in the time domain may indicate a greater reduction in vibrations, the results in the frequency domain show that there is little difference in the attenuation of frequencies around 20 and 85 Hz.



(a) This graph compares the effectiveness and relevance of the reference case model with no damping and the concrete foam model with implemented damping.



(b) Differences in the frequency domain from the dynamical part of the simulation of both the reference case with no damping and the concrete foam model with implemented damping.

Fig. 13: Time and frequency domain results from both the reference model and the concrete foam model at the surface. The data in both graphs is taken at the same spot in the model, which is 12 metres from the left side of the model and 2 metres from where the clay and ballast layer intersect.

4.1.3 Band gap

A band gap is defined a range of frequencies within which the propagation of waves is strongly attenuated or prohibited [27]. In ideal circumstances, a band gap is found at which no vibrations are propagated. The goal of reducing train-induced ground vibrations is to design structures or configurations with band gaps at frequencies corresponding to the dominant vibrations generated by trains. By strategically placing materials or elements with specific properties, it becomes possible to create zones where vibrations are effectively blocked or minimised, contributing to the overall attenuation of ground vibrations. An attempt at a band gap is made in this Abaqus© model by arranging the concrete foams in specific formations that attenuate the peak frequencies, as will be explained in the following section.

4.2 Spatial configuration

As previously noted, the spatial arrangement of concrete blocks significantly influences the material's attenuation properties in the soil. To explore the optimal configuration of concrete foam blocks, it is necessary to convert results from the time domain to the frequency domain to elucidate dominant frequencies. Each of these frequencies corresponds to specific wavelengths, and to minimise these dominant wavelengths by the destructive interference effect [28], the distance between the concrete foam blocks needs to be constrained to fractions of these wavelengths. From the results of figure 12b, it becomes apparent that the dominant low-frequency vibrations are around 18 Hz. This peak frequency can be converted into a minimum wavelength following the formulas 5 and 8.

$$G = \frac{E}{2(1+v)} \tag{8}$$

The following minimum wavelength was calculated for a frequency of 18 Hz in clay soil:

$$G = \frac{E}{2(1+v)} = \frac{1.605E9}{2(1+0.35)} = 5.94E9, \lambda_{min} = \sqrt{\frac{G}{\rho}}/f_{max} = \sqrt{\frac{5.94E9}{1600}}/18 = 33.86m \tag{9}$$

After determining the minimum wavelength for the peak frequency in clay, different distances are investigated to address ground vibrations. The initial strategy involves halving the minimum wavelength to establish destructive interference [19] in an optimal geometric configuration. However, at a length of 16.93 metres, the structural integrity of the rails would be compromised, making this approach impractical. It is imperative to select a distance between the blocks that, given their role in supporting the weight of the rails and the train, does not result in excessive deformation of the rails. Therefore, an alternative distance must be chosen or an alternative band-gap generation mechanism should be activated.

Beyond the challenge of preventing rail deformation, another issue arises concerning the placement of sleepers. As sleepers are positioned atop the concrete foam blocks, their arrangement is influenced by the distances between these blocks. In both the reference model and the current state of the concrete foam model, the distance between concrete foam blocks is set to zero, allowing for the even placement of all 205 sleepers across the model. However, introducing a non-zero distance between the blocks alters this scenario. This adjustment may necessitate less frequent sleeper placement or the variation of distances between sleepers to ensure their complete placement on the surface of the concrete foam blocks beneath them. A method for overcoming this issue is to integrate the concrete foam configuration into the ballast layer, ensuring that the sleepers can still be placed anywhere on top of the new layer.

4.2.1 External damping

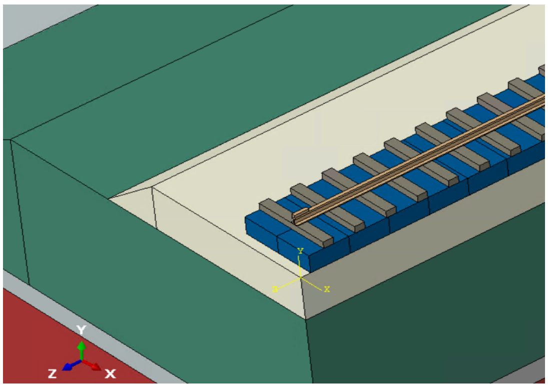
Apart from regular damping and changing spatial configurations in an attempt to create destructive interference, external damping is also a possible solution to reduce ground vibrations. This approach entails the use of specialised damping systems or materials to absorb and dissipate vibrational energy, preventing it from being transmitted to the structure [19]. Tuned mass dampers, base isolation systems, and vibration absorbers are common external damping mechanisms. These systems can be strategically placed to counteract specific vibration frequencies, increasing overall structural stability and reducing the risk of damage or discomfort caused by persistent external forces. Positioning external dampers necessitates consideration of variables such as the targeted vibration frequency and the system's mass. Regrettably, this damping method surpasses the capabilities of the current project due to its demanding computational requirements and time constraints. Furthermore, the spatial constraints imposed by external dampers make them expensive and impractical for locations with limited space, particularly in cities or near structures where accommodating these systems is difficult and economically unfeasible.

4.3 Configurations & Results

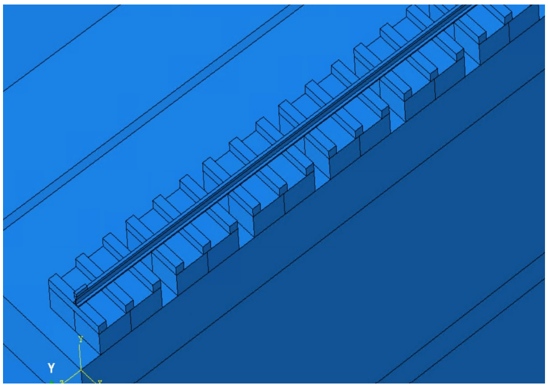
Now that both the system's capabilities and limits have been discussed, a simulation is executed with a different spatial configuration in an effort to tackle the aforementioned problems.

A case is tested with a small space beneath the concrete foam blocks, which are placed on top of the ballast, which is compared to the initial concrete foam model as tested in the damping section and in figure 14a. There are restrictions for the configuration with distance between the blocks, as the sleepers should still be placed evenly on top of the concrete foam blocks. To overcome this limitation, a system with groups of four concrete foam blocks is formed, on top of which three sleepers are placed, as depicted in figure 14b. In this configuration, the distance between groups of blocks is 0.4 metres, and the distance between the sleepers on the group of concrete blocks is 0.5 metres.

From figures 15a and 15b, a couple of conclusions can be drawn. First and foremost, the difference in attenuation properties is negligible. What is more, situation B contains more oscillations compared to situation A. This can be explained by the fact that fewer concrete foam blocks result in less damping. This can also be observed in the frequency domain around 80 Hz, as vibrations around this frequency are reduced less compared to situation A. For low-frequency vibrations, however, there is not much of a difference present, indicating that this configuration will not be sufficient for the purpose of this project. Furthermore, as with the reference case, there are no signs of concerning displacements in components such as the rails, concrete foam blocks, and sleepers, confirming that the model's structural integrity is adequate. A favourable outcome arising from this experiment is that if the goal is to reduce frequency amplitude solely within the 80 Hz range, a significant reduction can still be attained using fewer concrete blocks, leading to cost savings and a more efficient

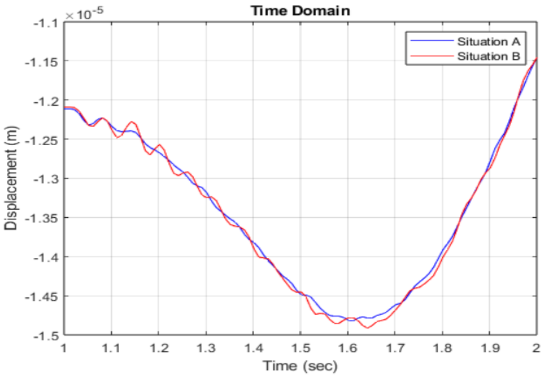


(a) The initial configuration of concrete foam blocks and sleepers. In this configuration, there is no distance between concrete blocks.

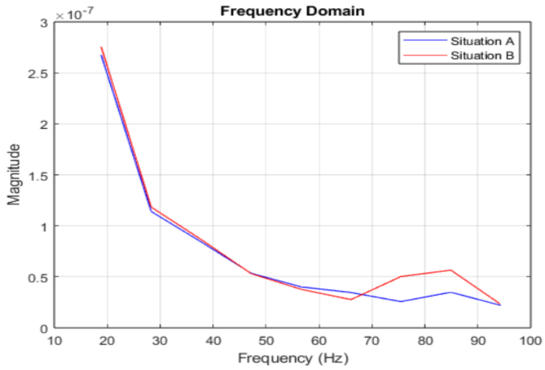


(b) The second configuration of concrete foam blocks with sleepers, with groups of concrete blocks with distance in between blocks.

Fig. 14: Configurations of the initial and second setup of concrete foam blocks and sleepers in the model.



(a) Time domain graph of situation A and B.



(b) Frequency domain graph of situation A and B.

Fig. 15: Results from both the time and frequency domains for Situation A, which corresponds to the concrete foam case with all blocks positioned on top of the ballast, and Situation B, representing the case with a 0.4-meter distance between the blocks. The data in both graphs is taken at the same spot in the model, which is 12 metres from the left side of the model and 3 metres down from the top of the clay layer.

use of materials.

In order to still solve the problem of reducing low-frequency vibrations, alternative configurations have to be tested that encompass more extensive structures and configurations. Incorporating the concrete foam blocks into the ballast layer would, for example, allow for fewer changes in the sleeper configuration. Yet, exclusively decreasing the layer of concrete blocks appears to be an improbable resolution for the entire situation. More intricate systems, like interconnected concrete foam blocks secured with metal rods and integrated into the ballast layer, might enforce a more substantial reduction in the relevant frequency range. Unfortunately, the testing of such systems demands considerable computational resources and time, as the model mesh needs to be much smaller, placing it beyond the scope of this project.

5 Discussion

Although the purpose of this paper has been defined and executed, there are still a few points worthy of further elucidation. The topics in question are covered in this section.

5.1 Elastic half space

It is important to recognise that elastic half-space models are simplified representations. While they may not capture all the nuances of soil behaviour, especially in complex geological conditions, they offer a valuable compromise between realism and computational efficiency for engineering analyses.

5.2 Reference case validation

In order to establish an accurate model for simulating vibration propagation through concrete foam blocks, a reference model is constructed. The accuracy of this reference model is then validated using a reference case from ref. [17]. This article explores the dynamic response of a track-embankment-ground system under the influence of high-speed trains' moving loads, using Abaqus© as a reference model. The validation process involves comparing the outcomes of this paper's analysis to those of the reference case. If the results of the reference case align with the findings presented in this paper, it confirms the model's validation. In reality, however, the reference paper is investigating different parameters and concepts compared to this case, so exactly replicating results will not be beneficial to the goal of this paper. Furthermore, certain dimensions, material properties, and boundary conditions in our model involve assumptions and educated guesses that, while essential for constructing a functional model, were not explicitly addressed in the reference case. Consequently, some of the results may differ from the results in the reference case. It's important to note that the reference case primarily serves as a basis for comparison with the concrete foam case. Given that all parameters are identical across both models, the reference case remains adequate for this purpose.

5.3 Model flexibility

Whereas the model has proven to be useful in predicting the behaviour of vibrations induced by trains, the model is limited to some constraints. First, the number of wheels in this case is set to one, which allows for accurate analysis of a singular load, but as freight trains are usually relatively long, more wheels could be tested for a more realistic model. Next, the speed and pressure of the load on the rails remain constant in this scenario. In real-world situations, though, the train's weight and velocity fluctuate, potentially leading to a diverse spectrum of propagated vibrations. It is essential to acknowledge that conducting simulations with varying train velocities and loads may require some time for execution. However, it is relatively straightforward to configure such simulations using the current Abaqus© model, rendering it flexible.

5.4 Boundary conditions

As was mentioned before in the results section of the Abaqus© model, the propagation of waves seems to behave differently closer to the model's edge compared to the middle of the model. Though this could be attributed to a number of different factors, such as, but not limited to, layer interactions, wave reflections, simulation sensitivity, and accuracy, the results are still not preferable. This problem is not thoroughly investigated in this project due to time constraints, but it is still noteworthy.

6 Conclusion

In conclusion, this paper thoroughly examines the potential application of concrete foam blocks for mitigating ground vibrations induced by railway traffic, emphasising the critical need to address this issue due to its adverse effects on lineside residents and structures. The proposed solution involves strategically placing concrete foam blocks beneath railway tracks to reduce and dissipate ground vibrations.

The paper introduces a successful Abaqus© model representing a train track in the frequency range relevant for moving freight trains. The model accurately simulates soil displacement around and beneath the track, validating the effectiveness of the simulations. The Abaqus model facilitates the analysis of diverse geometrical configurations of concrete foam blocks and their impact on ground vibrations.

Despite these efforts, the study reveals that the damping characteristics of concrete foam blocks have a limited effect on mitigating ground vibrations. While certain vibrations around 85 Hz are attenuated, the impact on frequencies below 20 Hz is minimal. Notably, the soil itself predominantly attenuates vibrations around 80 Hz, but this may be different in a model with a higher load or more wheels.

Lastly, the paper underscores the significance of advanced modelling software, such as Abaqus©, in providing a nuanced and comprehensive approach to studying the propagation and attenuation of ground vibrations with precision. This modelling approach enables the exploration of diverse scenarios and the testing of hypotheses under controlled conditions, offering insights that may be challenging to obtain solely through empirical studies.

7 Future work

As outlined in the research framework, the scope of this integration project is constrained to situation analysis within a virtual environment. However, the problem owner, Nederboom, extends this scope by conducting real-life tests on various geometrical configurations of concrete foam blocks beneath train tracks. Certain tests might draw inspiration from the results presented in this paper, serving to assess the practical validity of the simulations conducted herein.

Furthermore, all simulations within this model presuppose uniform train loads and speeds. Given that these parameters are either averages or derived from the reference case, their applicability to all scenarios may be limited. Moreover, for computational efficiency, time increments are not set smaller than 0.01 seconds. While it is improbable that substantial changes will emerge with increased increments, there remains the potential for impact. Subsequent research endeavours could delve deeper into these aspects, exploring wave propagation under diverse conditions, including variations in train masses and speeds.

Furthermore, there is considerable potential in research dedicated to crafting spatial arrangements capable of attenuating a more extensive range of low-frequency vibrations below 20 Hz. As indicated in the results, these configurations can pose significant computational challenges, thereby falling beyond the project's scope. However, delving further into the exploration of such configurations could potentially yield success in effectively mitigating low-frequency ground vibrations.

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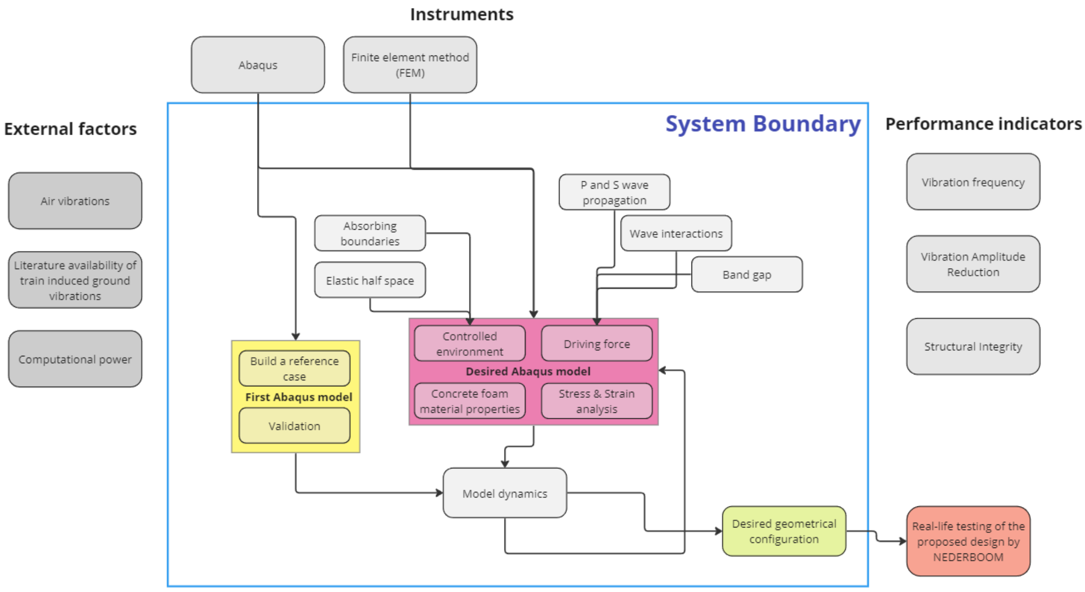
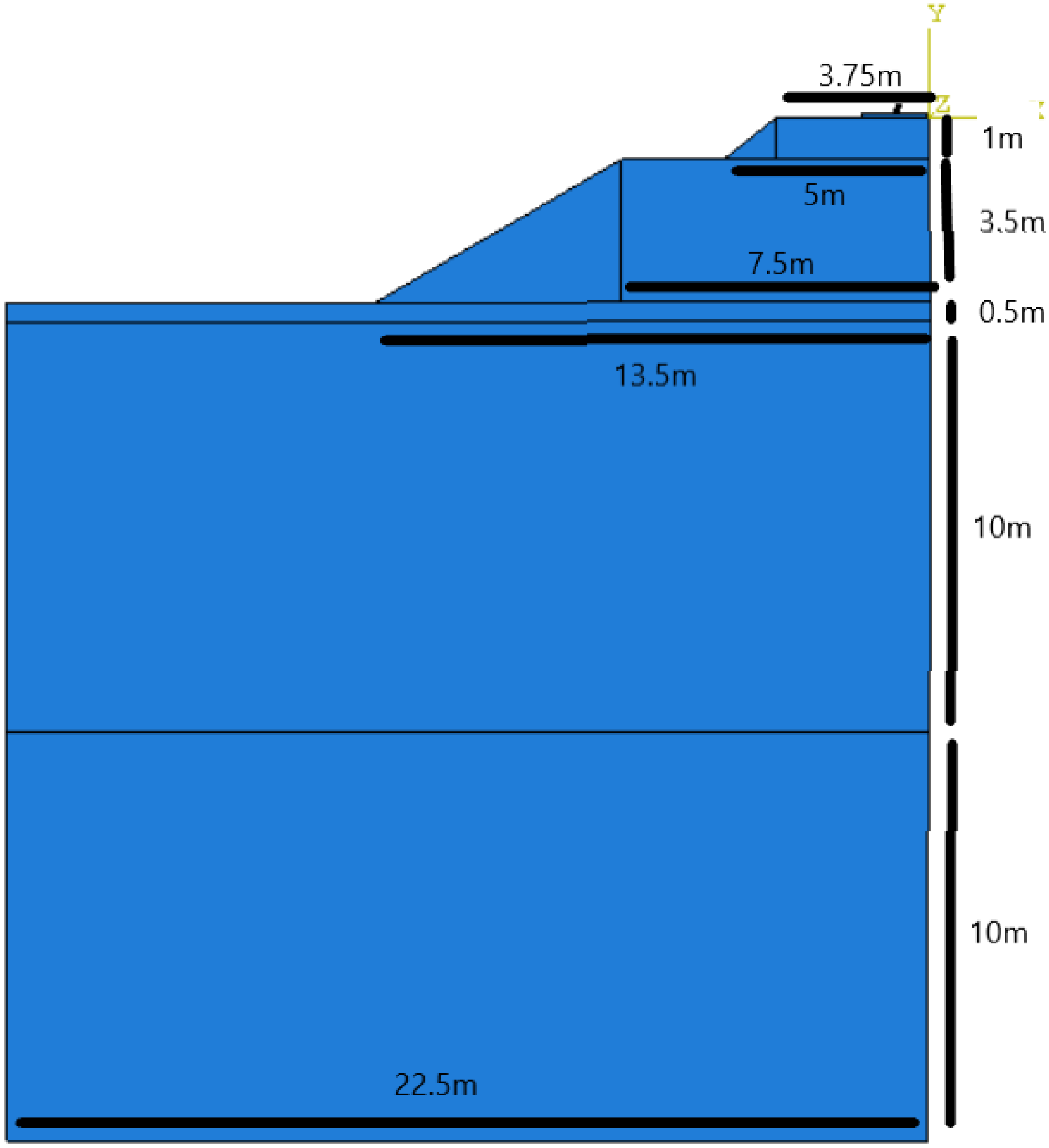
9 Appendix

In Appendix A, the framework of this integration project is displayed. This model starts by listing the external factors in this case, namely the availability of literature on ground vibrations induced by trains and the computational power of accessible computers. Performance indicators for this project are vibration frequency, vibration amplitude, and block structural integrity. The instruments to measure these metrics can be found in Abaqus and in finite element material analysis [5].

The system boundary, as shown in A, will work as follows: First, a reference model will be built, which will be explained in the validation section. When the reference case is validated, a new model with the desired features and properties will be built. This model incorporates a wide range of wave theory laws and properties to create a comprehensive simulation of a real environment, which will be discussed in greater detail in the technical design. To find the ideal geometrical arrangement of concrete foam blocks, the results of the reference and desired models will be compared to one another and tweaked. Once an optimal design has been developed and subjected to analysis, NEDERBOOM will conduct a real-life testing phase. It's important to note, however, that this testing phase falls beyond the purview of this project.



Appendix A. Research framework



Appendix B. Ground dimensions. From bottom to top, the layers are: stiff sand, clay, fill, embankment and ballast, on top of which the train track is placed.

```
% MATLAB script for Fourier Transform from Time to Frequency Domain

% Step 1: Load data from Excel file
filename = 'Concrete_foam_test.xlsx'; % Replace with the actual file name
data = xlsread(filename);
time = data(:, 1); % Assuming time is in the first column
signal = data(:, 2); % Assuming signal is in the second column

% Step 2: Perform Fourier Transform
Fs = 1 / (time(2) - time(1)); % Sampling frequency
N = length(signal); % Number of data points
frequencies = Fs * (0:(N/2))/N; % Frequency axis

% Use fft function to perform Fourier Transform
fft_result = fft(signal);
magnitude_spectrum = 2/N * abs(fft_result(1:N/2+1));

% Narrow the frequency range to 10-100 Hz
frequency_range_mask = (frequencies >= 10) & (frequencies <= 100);
frequencies = frequencies(frequency_range_mask);
magnitude_spectrum = magnitude_spectrum(frequency_range_mask);

% Step 3: Plot the results
figure;
subplot(2, 1, 1);
plot(time, signal);
title('Time Domain');
xlabel('Time');
ylabel('Amplitude');

subplot(2, 1, 2);
plot(frequencies, magnitude_spectrum);
title('Frequency Domain (10-100 Hz)');
xlabel('Frequency (Hz)');
ylabel('Magnitude');
xlim([10 100]); % Set x-axis limit to 10-100 Hz

% Display the plot
sgtitle('Fourier Transform from Time to Frequency Domain (10-100 Hz)');
```

Appendix C. MATLAB script for Fourier transform from time to frequency domain. This code makes the assumption that the data starts after one second or after the loading step.

$$
\begin{aligned}
2\zeta\omega_n &= \alpha + \beta(\omega_n)^2 \\
n &= \text{frequency modes} \\
\zeta &= 0.6 = 60\% \\
f_1 &= 0.1 \\
f_2 &= 4 \\
\text{Calculations:} & \\
\omega_1 &= 2\pi f_1 = 2\pi \cdot 0.1 = 0.6283 \\
\omega_2 &= 2\pi f_2 = 2\pi \cdot 4 = 25.13 \\
2(0.6)(0.6283) &= \alpha + (0.6283)^2\beta \\
2(0.6)(25.13) &= \alpha + (25.13)^2\beta \\
\text{Solving for } \alpha \text{ and } \beta: & \\
0.754 &= \alpha + 0.395\beta \\
30.156 &= \alpha + 631517\beta \\
\alpha &= 0.73556 \\
\beta &= 0.046582
\end{aligned}
$$

Appendix D. Equation and Calculations